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REVIEW OF HYDROGEN FUEL FOR INTERNAL COMBUSTION ENGINES

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ABSTRACT

In the world that we live in today, non-renewable sources of energy are being depleted at an exponential rate. Thus, alternative sources of fuel have become more important to prevent the occurrence of an energy crisis. Seeing that hydrogen is not a source of energy but rather, a carrier of energy, it is very useful as a compact source of energy to power up batteries and fuel cells. Various methods of producing, storing and transporting hydrogen have been discovered to accommodate the demands for hydrogen, making it as easily accessible as petroleum but not as environmentally harmful. The hydrogen market is a niche market that is slowly gaining popularity. This review paper further delves into the topic of hydrogen fuel, bringing to light various controversies and theories, proving that hydrogen fuels will be the next big wave.

KEYWORDS

Internal Combustion Engines, Hydrogen, Alternative Fuel, Emission, Renewable Energy.

1. INTRODUCTION

Hydrocarbon fuels have been taking the world by storm in power and propulsion generation for over a century. An increase in the number of rules and regulations imposed onto exhaust emissions, alongside with the possibility of the depletion of non-renewable fuels have been a driving force that propels research in looking for alternative sources of fuels [1]. Thus, a wide list of fuels which are known to leave a less impactful carbon footprint on the environment have been suggested as a substitute for hydrocarbon fuels [2]. Among these suggested fuels, hydrogen was found to be renewable and less polluting to the environment, combined with its clean burning effect which emits no carbon dioxide into the atmosphere upon combustion, hydrogen fuels have been a topic of interest since it also delivers great performance [3]. There are several crucial properties of hydrogen that immensely impact the technological development of an internal combustion engine that uses hydrogen as fuel.

1.1 Great range of flammability

When contrasted against other fuels, hydrogen evidently displays a wide range of flammability which ranges from 4 – 75% volume in air. Such a drastic range of flammability is a major concern when handling hydrogen. However, this also implies that it is possible to obtain a lean fuel-air mix which means that the mix consists of an amount of fuel that is less than the chemically ideal amount. An engine that functions on a lean air-fuel mix makes it possible to achieve a greater fuel economy because the fuel undergoes complete combustion. Besides that, the combustion temperature of the fuel is reduced, causing a decrease in the emissions of pollutants [4].

1.2 Minor quenching distance

Hydrogen is known to have a minute quenching distance of just 0.6mm. This quenching distance is the actual distance originating from the internal cylinder wall in which the flame of combustion is extinguished. This proves that it would be more of a hassle to extinguish a hydrogen flame as the chances of backfiring are higher considering that the flame readily passes through an almost closed intake valve [5,6]. Hydrogen also ignites with a great flame speed. Thus, such a feat makes it possible for hydrogen engines to function close to a thermodynamically ideal engine cycle during the scenario in which a chemically ideal fuel mix is utilised. Flame speeds however, slow down drastically when a lean fuel mix is used [5]. Adiabatic flame temperature and flame velocity are two important factors for engine control and operation, in certain thermal efficiency, emissions and combustion stability.

1.3 Minimal Ignition Source Energy

Minimal ignition source energy refers to the minimum amount of energy needed to ignite an air-fuel mixture using an ignition source. A hydrogen-air mixture requires only 0.02 mJ to ignite compared to a petrol-air mix which requires 0.24 mJ. However, such a low ignition energy would mean that premature ignition and flashback could occur, resulting from hot gases and spots on the cylinder that serve as a source of ignition. Such a low ignition energy of the hydrogen-air mixture would just require a simple resistance hot wire or glow plug to promptly set the mixture on fire.

1.4 Great Diffusivity

Hydrogen is found to have a very high level of diffusivity which is greater than gasoline. Thus, this proves to be an advantage for two reasons. The first being that it encourages the formation of an air-fuel mixture that is uniform. Besides that, when a hydrogen leak occurs, the hydrogen disperses quickly. Therefore, risky conditions can be reduced [5].

1.5 Low Density

The most crucial effect of having a low density is that hydrogen requires a certain amount of compression or conversion to liquid, if not, a very great volume will be required to store enough hydrogen to power a vehicle. This low density of hydrogen also implies that the air-fuel mix has low density of energy. Thus, a larger amount of hydrogen is needed to produce the same amount of energy needed to run a vehicle when compared to other fuels [5].

1.6 Great Auto-Ignition Temperature

Auto-ignition temperature is defined as the minimum temperature needed to start a self-sustained combustion within a combustible mixture when an external source of ignition is not present. As the auto ignition temperature of hydrogen is 585°C, it is difficult to get the fuel mixture to undergo a self-sustained combustion without the aid of an external ignition source. Table 1 shows various fuels alongside their auto ignition temperatures [7].

Table 1: Data of hydrogen and other fuels.

Fuel	Auto Ignition Temp. (°C)
Methane	540-630
Propane	450
Octane	415
Methanol	460
Hydrogen	585
Gasoline	260 - 460
Diesel	180 - 320

The auto ignition temperature is very important because it helps to determine what maximum compression ratio is needed by the engine. This statement is further backed up by the fact that the rise in temperature of a system during compression is directly related to the ratio of compression [7]. The great auto ignition temperature of the hydrogen permits greater compression ratios to be utilised in the hydrogen engine as compared to a hydrocarbon engine.

2. HYDROGEN AS A FUTURE FUEL

Hydrogen is recognized for its special characteristics, making it one of the most resourceful alternatives to fossil fuel in this current era. Hydrogen is easily sourced as it is one of the most abundant elements present in the environment [8]. This element is also used in several applications in the industry, being a source of fuel to generate power for machines. Hydrogen has been recommended to be a future fuel due to its many advantages, one of it being that it is a form of renewable energy that can be quickly replenished and is also non-polluting to the environment [9].

2.1 Production of Hydrogen

In order to obtain hydrogen, it must first be separated from other elements which are present together with it in a mixture. Hydrogen can be obtained from various sources such as hydrocarbons, natural gas, biomass and water. Below are the various ways to obtain hydrogen.

2.1.1 Steam Methane Reforming

This process is the cheapest method currently known to obtain hydrogen. This method is definitely a go-to method when producing hydrogen commercially. Steam Methane Reforming requires a methane source such as natural gas to be exposed to high-temperature steam within the ranges of 700 °C to 1000 °C under 3 to 25 bar pressure with a catalyst present. This method of acquiring hydrogen is endothermic, meaning that heat has to be constantly supplied in order for the reaction to continue [10]. A water-gas shift reaction is sometimes used to generate even more hydrogen out of the products of the steam methane reformation process which are mostly carbon monoxide. The carbon monoxide is reacted with steam and a catalyst to produce carbon dioxide and also hydrogen. In a final process known as pressure swing absorption, all other impurities are removed from the gas stream, leaving behind pure hydrogen. The methane needed for this process can be swapped out for other sources of fuels such as propane, gasoline and ethanol.
Steam Methane Reforming equation of reaction:

$$CH_4 + H_2O\,(+heat) \rightarrow CO + 3H_2 \qquad (1)$$

Gas-Water Shift equation of reaction:

$$CO + H_2O \rightarrow CO_2 + H_2\,(+small\ amount\ of\ heat) \qquad (2)$$

For a scenario in which oxygen is too little to completely oxidise the methane, the reaction is said to be partially oxidised. Thus, this process gives off heat seeing that it is exothermic. This partial oxidation reaction is also much quicker than standard steam reforming processes and needs a much smaller vessel for reaction, however it produces less hydrogen for the same amount of fuel used when compared to the standard steam methane reformation process.
Partial oxidation of methane equation of reaction:

$$CH_4 + {}^{1}\!/_{2}\,O_2 \rightarrow CO + 2H_2\,(+heat) \qquad (3)$$

2.1.2 Electrolysis

This is a process of utilising electricity to divide water molecules into hydrogen and oxygen. Such a reaction is done in an electrolyser that can come in various sizes depending on the amount of hydrogen that needs to be produced. An electrolyser consists of a cathode and an anode that is separated through the means of an electrolyte. Below are a few commonly used electrolytes along with their electrolysers [11].

2.1.2.1 Polymer Electrolyte Membrane Electrolysers

The electrolyte of such an electrolyser is a solid type of plastic material. The anode of the electrolyser reacts with water to generate hydrogen ions which are positively charged. At the cathode, the hydrogen ions receive electrons to create hydrogen gas.
Anode Reaction:

$$2H_2O \rightarrow O_2 + 4H^+ + 4e^- \qquad (4)$$

Cathode Reaction:

$$4H^+ + 4e^- \rightarrow 2H_2 \qquad (5)$$

2.1.2.2 Alkaline Electrolysers

These electrolysers function through the transportation of hydroxide ions across the electrolyte. Alkaline electrolysers usually consist of electrolytes that contain either potassium hydroxide or sodium.

2.1.2.3 Solid Oxide Electrolysers

These electrolysers use an electrolyte that is made from ceramic material in solid form. This makes it possible for the electrolyte to selectively conduct oxygen ions that have been negatively charged at high temperatures. Solid oxide electrolysers produce hydrogen differently from conventional electrolysers because water reacts at the cathode and combines with electrons to generate hydrogen gases, alongside oxygen ions that are negatively charged. The negatively charged oxygen then goes through the electrolyte, causing a reaction at the anode to create oxygen gas and electrons.

2.1.3 Coal Gasification

Coal is a highly adaptable substance that has many uses. Coal gasification is a means to producing liquid fuels, hydrogen, chemicals and power. When coal is exposed to oxygen and steam at high pressures and temperatures, synthesis gas is produced. This mixture is mainly composed of hydrogen and carbon monoxide.
Unbalanced equation of reaction for coal gasification:

$$CH_{0.8} + O_2 + H_2O \rightarrow CO + CO_2 + H_2 + other\ elements \qquad (6)$$

Impurities present in the gas are removed and carbon monoxide mixture is exposed to more steam to initiate a water-gas shift process that produces even more hydrogen and carbon dioxide. Hydrogen is then removed from the mixture through a separation system [12].

2.1.4 Biomass Gasification

This is a process in which organic carbon-based materials are converted at high temperatures of above 700°C under controlled conditions into hydrogen, carbon dioxide and carbon monoxide [13]. Carbon monoxide is once again able to react with water through the water-gas shift process to form more hydrogen.

Example of a reaction (simplified):

$$C_6H_{12}O_6 + O_2 + H_2O \rightarrow CO + CO_2 + H_2 + other\ elements \quad (7)$$

Since biomass does not turn to gas easily when compared to coal and it produces a mixture of other compounds, an extra process must be introduced to the mixture. This process yields a mixture of carbon monoxide, carbon dioxide and hydrogen in the presence of a catalyst. Then just like the gasification process in the coal gasification reaction, carbon monoxide is introduced to steam, and hydrogen is separated from the mixture and later purified.

2.1.5 Biomass-Derived Liquid Reforming

Biomass sources can be transformed into liquid biofuels. A portion of such liquids can be transferred for a low price to a certain point of interest and also be changed into hydrogen. This process is quite similar to the reformation of natural gas. Firstly, the liquid is introduced to steam at critical temperatures while having a catalyst present in the process. This produces a reformate gas then undergoes the water-gas shift process to generate even more hydrogen. Lastly, the hydrogen is separated from the mixture and purified [14].
Steam Reforming equation of reaction (ethanol):

$$C_2H_5OH + H_2O\ (+heat) \rightarrow 2CO + 4H_2 \quad (8)$$

2.1.6 Microbial Biomass Conversion

This process makes use of microorganisms as their feeding process causes them to release hydrogen. These microorganisms, mostly bacteria cause organic matter to ferment as it is broken down to release hydrogen. Microbes produce hydrogen on their own during direct hydrogen fermentation. These microorganisms leave behind “waste” as they feed. These wastes can be reacted with enzymes to form hydrogen [15].

2.2 Storage of Hydrogen

Hydrogen storage is a major catalyst for hydrogen and fuel cell advancements. Hydrogen has the greatest energy per mass when compared to other fuels, but it has a poor ambient density of temperature which causes it to have a low energy density. Thus, advanced storage procedures need to be taken in order to efficiently store hydrogen.

2.2.1 Compressed Gas Storage

This storage method requires hydrogen gases to be stored in compressed gas tanks that have pressures of 5,000 to 10,000 psi. The gas tanks are either made of copper alloys, steel or aluminium and sometimes may be wrapped around fibreglass [16]. Steel tanks are mostly used in applications where the weight of the tank is not a liability to the system seeing that such tanks are very heavy.

2.2.2 Liquid Hydrogen

At -251.95°C, under standard pressure conditions, hydrogen can be stored in the form of a liquid. Liquid hydrogen has to be maintained under cool and pressurized containers with large volumes due to the fact that hydrogen has a very low density [17]. Hydrogen in liquid state has been the optimal choice for rocket fuel since the early days.

2.2.3 Cryo-compressed Hydrogen

Similar to liquid storage, cold hydrogen is used to achieve a high energy density. However, unlike storage in liquid hydrogen, the tank goes through pressures that are much greater (350 bars versus a few bars) compared to the pressure apparent in liquid hydrogen storage. Thus, more time is taken before the hydrogen vents [18].

2.2.4 Chemical Storage

This form of storage requires the hydrogen to be bonded to other compounds, creating a new compound that is very dense with hydrogen. The release of hydrogen from such bonds usually create an exothermic reaction or has a tiny endothermic enthalpy. Therefore, the rehydrogenation process involves the off-board rehydrogenation of a dehydrogenated product. The dehydrogenation process can be done either hydrolytically through reaction with water or thermolytically which involves the compound to be heated [18]. However, complex hydrides have reaction pathways that are rather unpredictable. Thus, it is sometimes best to try to keep the dehydrogenated product in a liquid or slurry form for ease of handling [19].

2.3 Fundamental Safety Considerations

Hydrogen cylinders or tanks must be kept at a distance from structures and items that could possibly cause a disaster such as structures, vehicle routes and ventilation intakes [20]. This rule should be applied even when hydrogen is in use. The most optimal condition would be to have hydrogen kept outside while having welded lines connected to equipment indoors. However, if hydrogen needs to be stored indoors, a few safety precautions must be taken into consideration:

- Structures are required to be built from non-combustible material.
- Ventilation systems need to have inlets laid low to the ground and have exhausts placed at the peak of the room.
- Hydrogen sensors must be fixed to the exhausts that are within an enclosed area.
- An automatic shutoff system needs to be implemented in case of a leak or fire within the premise is being detected.
- Any source of ignition should be removed from the enclosed storage area.
- Electrical equipment must be utilised near to the storage systems.
- Hydrogen systems that store or transport gas need to be bonded electrically and also grounded.

2.3.1 Ventilation

Good ventilation is important to reduce the chances of hydrogen building up in an enclosed area in case of a leak. The ventilation system of an enclosed area should be efficient enough to dilute a hydrogen leak of up to 25% of the lower flammability limit. Passive ventilation additions such as the ceiling and roofs should be checked to make sure that any form of hydrogen leaking will be able to be diverted out of the enclosed area safely. Active ventilation has to be implemented in a case where passive ventilation is not enough to dissipate a hydrogen leakage. Ventilation regardless of it being passive or active should not be at a rate of less than 0.3048 $Nm^3/min/m^2$ of the area of the floor over the storage area.

2.3.2 Leak Detection

Leak detection can be accomplished by setting up hydrogen detectors around a premise. Besides that, the pressure and flow rates of internal piping systems should be constantly monitored for changes as a change might suggest that a leak has occurred within the system. Regardless of the leak detection methods used, an automatic shutoff system if hydrogen is detected within an enclosed area is necessary. Sensors tasked with detecting hydrogen leakage on the other hand should provide personnel with visual and audio warnings if a certain environment has started to become a hazard.

2.3.3 Flame Detection

Hydrogen flames are near to being invisible to the human eye. Thus, optical and thermal sensors are needed to identify burning hydrogen. Detectors that are used to identify a possible fire outbreak must be able to quickly and reliably alert personnel about a hydrogen flame. The system must also:

- Automatically shut off and isolate the hydrogen flame
- Control and monitor active ventilation
- Generate visual and audible alerts
- Control accessibility to locations with great concentrations of hydrogen fires

2.3.4 Electrical Equipment

Firstly, fans used in active ventilation systems must have a rotating element that is made from spark-resistant material. The hydrogen system must also be grounded and bonded electrically. Besides that, equipment that do not fit the NEC requirements are to be placed outside of hazardous zones. Table 2 shows the electrical equipment requirements in bulk systems [21].

Table 2: Electrical Equipment Requirements in Bulk Systems

Location	Classification	Distance
Area containing gaseous hydrogen storage, compression or ancillary equipment	Class 1, Division 2	Up to 15 ft from storage/equipment
Area containing liquefied hydrogen storage	Class 1, Division 2	Up to 25 ft from the storage equipment, excluding the piping system, downstream of the source valve
	Class 1, Division 1	Within 3 ft from points where connections are regularly made and disconnected

2.3.5 Material Selection

Materials for parts that come in contact with hydrogen must be carefully selected as the exposure of certain metals to hydrogen can cause, cracking, embrittlement, significant loss in tensile strength, fracture toughness and also ductility. Such occurrences will lead to premature failure which will facilitate conditions for catastrophe. Therefore, nickel and nickel alloys should be avoided as such materials are prone to embrittlement. Ductile, malleable and grey cast irons should also not be used during hydrogen servicing.

2.3.6 Piping Design and Layout

Piping systems used to transport hydrogen have to be designed according to certain standards to:

- Reduce leaks
- Ensure ease of accessibility
- Reduce or prevent injury
- Reduce stresses in piping parts and other related equipment

Besides that, flow restrictors should be present to control the rate of leaking and also to limit the flow rate of supply. Piping must be labelled too, this is done to identify flow direction, content, design and test pressures.

2.3.7 Safety Considerations for Liquid Hydrogen

Cryogenic liquid hydrogen contains additional hazards that must be contained [22]. A few considerations that must be considered before using liquid hydrogen are that:

- Liquid hydrogen can cause extreme frostbite and hypothermia
- The formation of ice on valves or vents could be the cause of a malfunction
- Condensed air in close proximity to a liquid hydrogen storage system can cause an explosion
- Air leakage into a storage vessel will cause a component to malfunction

2.4 Distribution of Hydrogen

A large majority of hydrogen are produced in close proximity to its respective area of usage, which usually is in massive industrial sites. Despite the fact that the current infrastructure utilized in hydrogen distribution still requires a lot of development, the primary methods of hydrogen distribution are listed below.

2.4.1 Pipeline

This method of transportation requires hydrogen to be distributed through a network of pipes. The pipeline system is utilized to connect the point in which hydrogen is produced to another point where there is demand for hydrogen. In general, these areas of demand are always within 80 to 160-kilometre radius of the site at which hydrogen is produced.

2.4.2 High Pressure Tube Trailers

Tube trailers used to transport hydrogen are in fact semi-trailers that contain 10 to 36 clusters of high-pressure tanks. These hydrogen tanks can be as long as 6.1 metres and reach up to maximum lengths of 11.58 metres. The cost of transporting hydrogen through trailers are very high and these trailers are used mainly for distances of 320 kilometres and below [23].

2.4.3 Liquefied Hydrogen Tankers

Cryogenic liquefaction is achieved when gaseous hydrogen is cooled to 20.28 K (-252.87°C) in which it turns into a liquid [17]. Thus, a hydrogen tanker is a ship which transports liquid hydrogen. Even though such a process is costly, it is the most efficient means of long-distance transportation as compared to the other methods. However, if the liquid hydrogen is not consumed at a rate that matches the point of consumption, it will evaporate into the atmosphere.

3. HYDROGEN ENGINES

In its natural form, hydrogen is found to be among the most abundant elements in the universe [24]. In fact, it's been used in space programs for decades because of its energy to weight ratio. It has the highest amount of energy for a given gram of any fuel. Moon and Saturn missions of Nasa all used hydrogen fuel at advanced stages in the launch [28].
In present time, the significance of hydrogen as fuel in land vehicles have become a topic of interest due to the severe externalities that are brought due to largescale effects of global warming and air pollution. Hydrogen shows high potential due to the numerous properties that encourages it as a reliable fuel.

3.1 Hydrogen Use in Diesel Engines

Hydrogen has a very high self-ignition temperature of around 850 kelvins, making it hard to ignite by means of compression alone. Therefore, an ignition source is required to burn in an IC engine [26]. For ignition source, low self-ignition temperature is required so first obvious choice will be Diesel fuel because it has low an autoignition temperature of 525 K. This diesel engine with hydrogen in dual fuel mode is beneficial since the diesel fuel is being replaced by carbon less hydrogen, which reduces emissions impacts.

3.1.1 Process of combustion for Hydrogen-Diesel Engine

Combustion process in dual fuel engine is a mixture of combustion process of spark ignition (SI) engine and compression ignition (CI) engine. As hydrogen is a S I Engine fuel it needs an ignition source such as a spark plug but since we are using hydrogen in C I Engine therefore we use diesel fuel. Hydrogen is injected in intake manifold therefore we get homogenous mixture of air and hydrogen. Then towards top dead centre diesel fuel is injected which creates multiple ignition source therefore it causes volumetric combustion of premixed hydrogen or it will create multiple turbulent flame [30].

Generally, in dual fuel engine major portion of the energy is released from the combustion of gaseous fuel and a small portion of energy is provided by diesel liquid fuel. But for addition of hydrogen in diesel engine in dual mode major energy is released from diesel engine and small portion of energy up to 40 % is provided by Hydrogen. A gaseous fuel induction in hydrogen-diesel dual fuel engine also gives higher efficiency [34-35].

In dual fuel engine there are two strategies for gaseous fuel introduction in the cylinder. First will be easy, cost effective induction in the intake manifold and second will be direct injection method. The flame front travel in case of induction is more rigorous and uniform because of homogenous mixture of Hydrogen and air. Where for direct injection flame front is not uniform and slow. In induction method, the combustion velocities are at least 23% higher than that of direct injection method [35]. Gregory K. Lilik reported that by using induction method engine volumetric efficiency drastically reduces [46].

3.1.2 Rate of Heat Release

E. Tomita investigated effect of Hydrogen addition on single cylinder diesel engine keeping equivalence ratio 0.4 and found that heat release rate does not change much compare to diesel operation between injection timing 2.5 and 23.7 degrees BTDC and in general it is lower [32]. M. Masood also find similar result of low heat release rate but at low load only [35]. As the load and percentage of hydrogen substitution increases the heat release increases. When we compare heat release rate of diesel engine and dual fuel engine with hydrogen at higher load and at higher hydrogen level is always higher because hydrogen burns faster having flame speed nine times higher than diesel. For diesel – hydrogen duel fuel engine, there are two methods in which we can supply hydrogen to engine either induction of hydrogen in intake manifold or direct injection of pressurized hydrogen in the combustion chamber. M. Masood shows that heat release rate per crank angle in case of induction is around 17% higher than that of injection because of higher premixed combustion [35].

3.1.3 Ignition Delay

The ignition delay period may be defined as the time lag between diesel injection and detectable rise in cylinder pressure [36]. Ignition delay period increased slightly with the addition of hydrogen and LPG [32]. This is due to the addition of hydrogen or LPG or a mixture of LPG and hydrogen in the charge reduces the air intake ultimately oxygen in the cylinder or loss of the very reactive OH radical in the reaction with molecular hydrogen because of formation of intermediate compounds. At higher concentration of hydrogen plus LPG in the mixture, ignition delay decreases due to addition of significant amounts of energy and species [37].

Because of Longer ignition delay the more diffusion of diesel and then lean premixed combustion occurs. Specific heat ratio for both hydrogen and air is same but heat transfer coefficient for Hydrogen is higher. Therefore, heat transfer losses increase which leads to lower gas temp and this may lead to higher ignition delay [32].

3.1.4 Crank Angle Curve Vs. Pressure

Eiji Tomita investigated effect of different injection timing on performance of dual fuel (Diesel –Hydrogen) engine and found that for all injection timings peak pressure is always higher for hydrogen substitution however effect of load clearly visible [22]. As load on engine increases rate of pressure rise and peak pressure both are high where more complete combustion of the fuel occurred but for lower load this effect diminishes [25-26], [32-33], [40]. Also, at higher load diesel percentage is higher therefore higher number of ignition centres is available. S. Bari, M. Mohammad Esmaeil also pointed out that faster hydrogen combustion result in higher peak pressure closer to TDC, which in turn will produce a higher effective pressure to do work [26]. N. Saravanan found that at 7.5 lPM hydrogen flow rate the peak pressure occurs 5^{0}C earlier than that of diesel [33]. W. B. Santoso investigated effect of hydrogen enrichment specifically at low load condition [40]. During the hydrogen addition, the load and speed were kept constant. Hydrogen flow rates of 21.4, 36.2, and 49.6 lPM were used which replaces diesel fuel around 50%, 90%, and 97% respectively and found that Hydrogen enrichment lowers the peak pressure, rate of pressure rise and retarded the start of combustion. This is due to the non-availability of diesel fuel needed to ignite the premixing of hydrogen with air.

3.1.5 Brake Thermal Efficiency

Most of the researcher found that as hydrogen enrichment increases the brake thermal efficiency [41]. Since hydrogen has higher flame velocity and diffusivity than diesel fuel, therefore it mixes with diesel very well and complete heat release rate occur which results in higher brake thermal efficiency. However gaseous complete combustion also increases heat transfer rate because cylinder wall directly come into contact with combustion zone and especially at low load where diesel content is low results in poor combustion therefore brake thermal efficiency may decrease by hydrogen enrichment which is reported by some researcher [41].

Lata, Ashok Misra and Medhekarstudied the effect of addition hydrogen and LPG in intake manifold and found that the best performances of dual fuel engine obtained by the substitution of 40% of mixture in the ratio LPG: hydrogen; 70:30 [37]. This situation is most suited in terms of efficiency and emissions.

Masood, Ishrat and Reddy investigate the effect of hydrogen induction through inlet manifold versus that of direct hydrogen injection on brake thermal efficiency [35]. This study found that for both methods brake thermal efficiency increases as hydrogen enrichment increases. However, the efficiency was higher by around 19% in case of induction through inlet manifold when compared to that of direct injection in cylinder. This is due the homogenous mixer of hydrogen and air (by induction method), burnt completely by the flame initiated by the multiple diesel ignition centre and resulted in complete combustion [35].

In addition, Vinod investigated the effect of EGR and found that addition EGR results in lower engine efficiency [27]. Due to presence of inert gases which replaced oxygen negatively affected the combustion process. This explains result of lower brake thermal efficiency in case of EGR [27].

3.1.6 Emission Characteristics

Emissions from automobiles are currently a major source of air pollution representing 70% of carbon monoxide, 41% of oxides of nitrogen, and 38% of hydrocarbon emissions globally. In diesel engines, there is a trade-off between smoke and nitrogen oxide. Smoke and nitrogen oxides cannot be reduced simultaneously. There have been many strategies for this problem. One of the promising strategies is utilization of gaseous fuel. Among various gaseous fuel Hydrogen is considered as a best fuel because of advantageous properties such as a high flame speed, short quenching distance, high heating value and high diffusivity [27].

3.2 Hydrogen-Natural Gas Mixtures

In the past decade the use of natural gas vehicles has grown exponentially globally. The largest player in this is the Asia-Pacific and Latin American regions [38]. The emissions from the exhaust of natural gas-powered vehicles are lower than gasoline powered ones making them the cleanest fossil fuel in use today. The efficiency of natural gas can be further increased by the addition of hydrogen. The blend of hydrogen and natural gas is referred to as HCNG. Natural gas is mainly composed on methane. The composition of the gas varies depending on the origin of the gas field.

3.2.1 Combustion Characteristics

The laminar combustion speed of hydrogen is eight folds larger than the same amount of methane therefore providing a reduced ignition time when combined with natural gas at small amounts. Studies have been carried out to determine the flame speed of hydrogen and natural gas mixtures at different amounts. Ilbas conducted these tests at ambient temperatures with blends of hydrogen and natural gas up to 100% hydrogen [39].

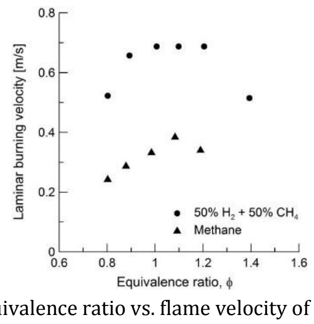

Figure 1: Equivalence ratio vs. flame velocity of different fuels [18]

Figure 1 shows the flame velocity of methane and 50% methane-hydrogen mix plotted against ratio. The blend has a flame velocity of 0.69 m/s whereas the virgin methane gas only came to 0.39 m/s for the same equivalence ratio of 1.1. It is also noted that when the hydrogen content is increased in the mixture, regions of flammability are widened.

Mandilas used stainless steel vessels to perform experiments to study the effect of hydrogen addition on turbulent and laminar methane – air flames at initial temperatures and pressures of 600 Kelvin and up to 1.5 MPa respectively [43]. The study found that methane can be ignited at equivalence ratios between 0.6 and 1.3 with the highest burning velocity occurring at the equivalence ratio of 1.0. Ignition limits are widened by the addition of hydrogen as seen by the new equivalence ratios of between 0.5 and 1.4.

3.2.2 Impact on Engine Efficiency with The Use of HCNG Blends

In a natural gas engine, the efficiency is increased when hydrogen is put into the equation. Hydrogen also promotes combustion stability which in turn reduces the cycle by cycle variation. In a study done by Nagalingam, the results showed that to obtain the Maximum Brake Torque, HCNG blends requires a lower ignition time than that of natural gas [44].

Figure 2 illustrates the relationship between spark timing and hydrogen content for different equivalence ratios [42]. Hydrogen addition affects the results significantly especially for lean air-fuel mixtures. The graph also highlights that for mixtures containing higher amounts of hydrogen, changes to ignition timing is necessary when the equivalence ratio is altered.

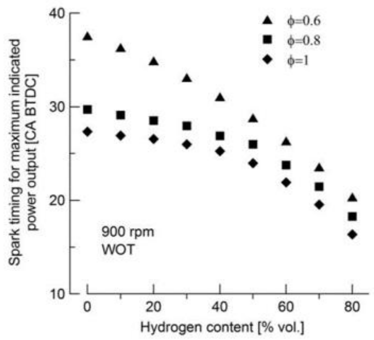

Figure 2: Spark Timing Vs. Hydrogen content

The efficiency of the engine is increased by fuelling the engine by HCNG mixtures. Sierens & Rosseel articulated a fuel system that provides natural gas and hydrogen mixtures in variable proportions to the engine [45]. At low break mean effective pressure conditions, high efficiency is possible by increasing the content of hydrogen and in turn decreasing the throttling losses. The heightened hydrogen and carbon ratio alongside high efficiency of the engine, reduces CO2 emissions as a result. The consequence is that NOx emissions are increased due to the nature of faster combustion and higher temperature in HCNG fuelled engines. This can be brought down if the engine is operated with lean mixtures. Sierens & Rosseel conducted a study that found that NOx is found to be at maximum when the air fuel ratio is $\lambda = 1.1$ [24]. On the other hand, Hoekstra found low NOx emissions operating with HCNG blends close the lean limit [25].

3.3 Hydrogen Fuel Induction Techniques

The structure of a hydrogen fuelled engine is almost similar as a conventional internal combustion engine. However, a few modifications are required to be done to the fuel supply system and its combustion system to avoid problems such as small power output, high NO_x emissions and abnormal combustions. Analysis have shown that a unit volume of stoichiometric hydrogen air mixture provides only 85% of calorific value as compared to a gasoline air mixture [47]. Additionally, hydrogen fuelled engines suffers from erratic intake backfire which results in rough engine operations when certain air-fuel ratios are used. Evidently, this has shown to be one of the main obstacles in the successful practical utilization of hydrogen engines. On the other hand, the amount of NO_x formed also depends on the air-fuel ratio and the combustion temperature. Therefore, techniques of rich-lean combustion or staged combustions are usually implemented to control unwanted emissions [48]. Ultimately, the mode of fuel induction has a critical role in the development of a practical hydrogen engine system. Therefore, three different fuel induction techniques are reviewed to explore the progression of its potential as a fuel cell [49].

3.3.1 Fuel Carburetion Method (CMI)

Known to be one of the simplest and oldest technique, carburetion through a gas carburettor has its advantages for a hydrogen engine. In this system, the hydrogen supply pressure does not need to be as high as other methods during central injection. Additionally, the hydrogen fuel carburetion method can be easily implemented to convert a standard gasoline engine to a hydrogen engine due to the common usage of carburettors in gasoline engines as well. However, central injection in an internal combustion engine using hydrogen fuel results in a power output loss of 15%. Therefore, the carburetion method is not suitable for hydrogen engines as it causes uncontrolled combustions at unscheduled points in the engine cycle. To further elaborate, the effects of pre-ignition is elevated as the amount of hydrogen/air mixture within the intake manifold increases. Consequently, as pre-ignition occurs when the inlet valve is opened in a premixed engine, the flame would propagate past the valve which results in the backfire of the fuel-air mixture in the inlet manifold. Hence, extreme precaution should be taken in a carburetted hydrogen engine as its inlet manifold consists of a combustible fuel-air mixture which has a risk of igniting [50]. For further illustration, a schematic diagram depicting the operation of fuel carburetion method is shown in Figure 3.

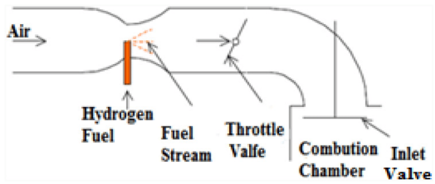

Figure 3: Fuel Carburetion Method [48]

3.3.2 Inlet Manifold and Inlet Port Injection Method

Contrary to the fuel carburetion method, the inlet port injection method delivers the hydrogen fuel directly to the intake manifold directly through mechanically or electronically operated injectors, rather than drawing it in from the carburettor. At the beginning of each intake stroke, hydrogen fuel is injected into the manifold with the utilization of electronic injectors; which have quick responses under high speed conditions to accurately control the injection timing and duration. Additionally, the air is also injected separately during the beginning of the intake stroke to dilute the hot residual gases which in turn lowers the temperature in the combustion chamber [51]. Throughout the engine cycles, less air-fuel mixture is held in the inlet manifold as compared to the fuel carburettor engine; hence, the occurrence of pre-ignition has a lower damaging impact. Among the three fuel induction methods, the inlet supply pressure for port injections is higher than fuel carburettor engines but lower than direct injection systems [52]. On the other hand, lean operations can be achieved through the port injection method by keeping the volume of inducted air constant in every cycle, whereas the power output is controlled through the amount of fuel injected into the chamber. This can be done by regulating the injection pressure of hydrogen or manipulating the duration of injection through the injector signal pulse [51]. For further illustration, a schematic diagram depicting the operation of the port injection method is shown in Figure 4.

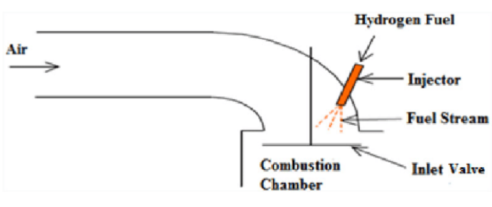

Figure 4: Inlet Port Injection Method [51]

3.3.3 Direct Injection Systems

Instead of using carburettors or port injectors, direct injection systems inject hydrogen directly into the combustion chamber using high pressure at the end of every compression stroke. The hydrogen is then forced to diffuse quickly and mix with the air inside almost instantaneously, which will be ignited using a spark plug. In this case, the main concern of having a drop in the power output can be eliminated through in-cylinder ignition. Therefore, the direct hydrogen injection system is the most efficient fuel induction technique among the other methods involving hydrogen fuel. It has a power output of 20% more than a gasoline engine and 42% more than hydrogen engines with a carburettor. Compared to a hydrogen engine which operates in a pre-mixed state, injecting hydrogen fuel directly into the combustion chamber of a compression ignition engine would result in twice the power output [53]. Additionally, compared to a traditionally fuelled engine, a typical hydrogen engine using direct injection system would have a higher power output as the stoichiometric heat of combustion per kilogram of air is higher for hydrogen (gasoline produces about 2.83 MJ of heat energy only while hydrogen produces 3.37 MJ of energy). Ultimately, this mode of fuel induction resolves the issue regarding pre-ignition in the intake manifold as fuel is injected directly into the combustion chamber. However, the combustion chamber is still susceptible to pre-ignition and the reduced mixing time of air and fuel might result in a non-homogenous air-fuel mixture [54]. For further illustration, a schematic diagram depicting the operation of the port injection method is shown in Figure 5.

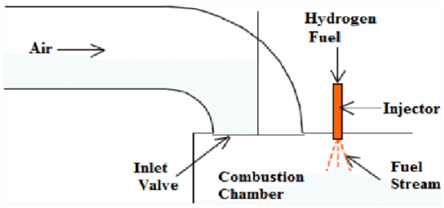

Figure 5: Direct Injection Method [51]

3.3.4 Injector Specifications

The fuel injection system of an engine comprises of two essential functions, which are fuel metering and fuel pressurization. However, in the case of gaseous fuel, only the metering function will be used as the pressurization of fuel has been done separately [53]. Ultimately, a hydrogen injector is required to accurately gauge the rate of hydrogen injected into the combustion chamber; the amount of hydrogen injected is actively regulated by varying the injection duration. Hence, the actuation of the injector should be flexible in terms of an adjustable injection duration.

The basic operational requirements for a hydrogen injector are:

i. Short Travel Time. It is defined as the time used to move the injector needle from one maximum position to the other. Hence, it is recommended to minimize the time of low flow injection during the opening and closing of the valve; which in turns maximize the average mass flow rate during injection. Additionally, the internal mixture formation can be further enhanced. The requirement of a short travel time is also supported based on the conjecture that a linear relationship between the duration of injection and amount of injection is favourable [55]. However, compensation can be made as well for the non-linearity by using an electronic control system instead of a mechanical one.
ii. Quick Response. It is defined as the time required between the start of the actuation and the initial movement of the needle. The upper limit of a response time is typically close to the period of one engine cycle. Therefore, a slow response time is not possible to accommodate high speeds such as two stroke engines.
iii. Injection Duration. The injection duration should be accurately controlled to obtain the precise value of air/fuel ratio desired. Hence, an electronic control system should be considered to optimize engine performance through an efficient microprocessor controller [56].
iv. Minimal Leakage. Injection valve leakage should also be considered as it is constrained by the probability of having pre-ignition during the compression of induction phase. During the exhaust stroke, valve leakage would lead to hydrogen wastage. On the other hand, valve leakage during the induction stroke would lead to a decrease in volumetric efficiency.
It has also been cited that a slight pre-mixing would be beneficial in the combustion process [57]. However, the current review paper shall consider zero leakage valve as the ideal condition to avoid any spurious effects of possible pre-mixing due to injector leakage.
v. Durability. The actuation occurs at a frequency of 50 Hz and the short travel time would suggest high impact loadings on the travel limit faces. Therefore, the injector valve should be designed withstand this impact while having optimum flow and leakage performance [58].

In consideration of the above requirements, there are two types of injectors that can be used for a direct injection hydrogen system: a low-pressure direct injector (LPDI) and a high-pressure direct injector (HPDI). LDPI operates by injecting fuel as soon as the intake valve closes and during low pressure in the cylinder. On the other hand, HPDI operates by injecting fuel at the end of the compression stroke [51].

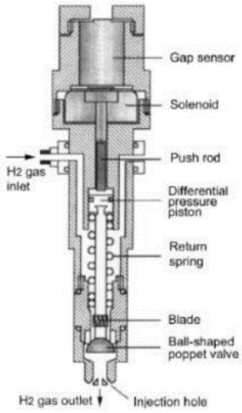

Figure 6: Hydrogen Injector [15]

4. ABNORMAL COMBUSTION

The use of hydrogen as fuel in internal combustion engine causes a few problems such as wide flammability range, low required ignition energy and high flame speeds. These problems are the reason why hydrogen is not considered an efficient fuel which can cause undesired combustion phenomenon usually summarised as combustion anomalies.

4.1 Pre-ignition

Pre-ignition must be avoided in an internal combustion engine. These abnormal combustion phenomena will happen inside the chamber of combustion, along with the start of combustion prior to spark timing throughout the engine compression stroke. Pre-ignition will facilitate the start of combustion and increase chemical heat-release. These events will result in a rapid pressure rise, higher peak cylinder pressure, acoustic oscillations and increased heat rejections which will cause the cylinder pressure temperature to increase. The latter effect can also further advance the pre-ignition phenomenon leading to runway effect which causes engine failure [60].

According to Figure 7, the minimum ignition energy for hydrogen is a strongly decreasing function of the equivalence ratio with the minimum at $\varphi \approx 1$ when the lean side ($\varphi < 1$) gets closer to the stoichiometric condition. This graph also shows that operating an H_2 ICE at or near the stoichiometric condition without frequent pre-ignition phenomenon is exceedingly difficult.

Consequently, the pre-ignition limit restricts the maximum φ and peak power output for practical application. A study from Stockhausen et al show that a 4-cylinder 2.0-*l* engine has a pre-ignition limit when the engine speed reaches 5000 rpm. Even though the limit for pre-ignition is only specific for a particular engine, the constant trends with engine properties and operational conditions have been discovered: The limited φ pre-ignition decrease with high compression ratio (CR) and increased mixture temperature [61]. Pre-ignition also has an effect on engine speed, but the trend is complex because of the coupled effect of residual mass fraction [62].

From the explanation above, the pre-ignition has the ability to develop into peak power output of hydrogen engine and the performance of vehicles that is powered by H_2 ICE will be decreased compared to gasoline powered vehicle [63]. Hence, establishing the process and system of pre-ignition, practical operational limits and control plan are the main priorities of countless research studies.

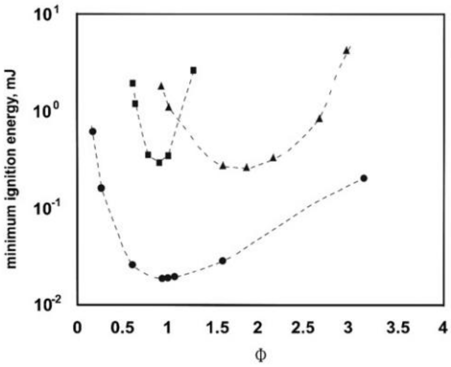

Figure 7: Minimum ignition energies of (●) hydrogen–ai4, (■) methane–air and (▲) heptane–air mixture in relation to at atmospheric pressure [65].

Unfortunately, there is no method to prevent pre-ignition with assurance, but we can still minimize it by recognizing the source of pre-ignition which are shown below:

- Hot spark plugs or spark plug electrodes.
- Hot exhaust valves in the combustion chamber
- Remaining gas from combustion process
- Combustion in crevice volumes [66].

Pre-ignition will become a bigger problem when the hydrogen-air mixture approach stoichiometric levels since the minimum ignition energy is affected by equivalence ratio. When the engine speed and load is higher, pre-ignition will be more likely to occur in operating conditions due to increased gas and components temperature [67]. However, there are some methods to reduce the occurrence of pre-ignition which are [67]:

- Good design of spark plug
- Reduce residual charge in ignition system design
- Practical design for ventilation of crankcase
- Sodium powered exhaust valve
- Improved design of the engine cooling passage to avoid hot spot
- Optimized hydrogen direct injection systems.
- Various valve timing for efficient
- Variable valve timing for successful use of exhaust residuals [66].

Kondo utilised an ignition system that can prevent residual energy and water-cooled spark plug [66]. Table 3 shows the variance of equivalent ratio emanate from advanced control strategies.

4.2 Backfire

One of the main problems faced when using hydrogen fuelled engine is backfire. During the intake stroke in the combustion chamber, uncontrolled combustion of fresh hydrogen-air mixture will occur. The combustion chamber with opening of the intake valves will allow the fresh hydrogen-air mixture to flow in. The occurrence of backfiring is caused by combustion chamber hot spots and the hot residue gas. The remaining charge in the ignition system will also ignite the hydrogen as fresh charge due to its low ignition temperature [64]. Ultimately, backfire occurs due to the concept of pre-ignition. The only difference being the point at which it occurs. Unconstrained combustion happens in pre-ignition during the compression stroke when the intake and exhaust valves close before spark plug fires in cylinder. [66]. On the other hand, pre-ignition initiates backfire during the compression stroke when the intake valve is opened and then the backfire moves forward to the ignition of intake mixture [65].

Table 3: Effect of advance control strategies to the equivalence ratio limit to the pre-ignition occurrence [66]

Equivalence ratio	Advance control strategies
$\varphi \approx 0.35$	Without any advanced control
$\varphi \approx 0.6$	Elimination of residual energy in the ignition system
$\varphi \approx 0.8$	With addition of the water-cooled spark plug

Backfire can result in a rise in combustion and pressure in the intake manifold which can be easily detected and damage the intake system. The low ignition energy is more likely to occur when using PFI-H_2ICE. The reason is because the hydrogen is administered before the intake valve opens so that it will create a mixture with air in the intake manifold before entering the combustion chamber.

Lately, the intake design and injection strategies have been optimized to avoid backfiring. Moreover, the methods to reduce the chances of pre-ignition can also avoid the occurrence of backfiring. Some of the methods include:

1. Cooling the potential hot spots by allowing pure air to flow into the combustion chamber before exhaling the fuel-air mixture
2. The occurrence of backfiring is very dependent on concentrations of H_2 residual at intake ports in a manifold injection H_2ICE. The leaner the concentration of residual, the lower the chances of the backfire.
3. Combination of variable valve timing and optimization of the fuel-injection method for intake and exhaust valve can enable the working of a port injected hydrogen engine at stoichiometric mixtures over the entire speed range.

4.3 Auto-ignition

When the end gas impulsively auto ignites, the remaining energy creating high-amplitude pressure waves will be released. This phenomenon is known as engine knock. The engine can be damaged by the amplitude of the pressure waves due to high mechanical and thermal stress. The engine design and fuel-air mixture properties affect the tendency of an engine to knock. To measure the knock properties of liquid fuels, we use octane rating. The knock properties of a specific fuel can be determined by cooperative fuel research (CFR) engine which can compare the knock resistance to a mixture of regular heptane and iso-octane. The Research Octane Number (RON) and Motor Octane Number (MON) is the most common standardized test to calculate the knock resistance on a CFR engine [68-69].

The range of values of these tests are reported to be RON<88 to RON=130 and RON of 130+ for lean mixtures [70-72]. The method to calculate these values are unclear but they must either be approximated values or calculate with similar methods but not based on the ASTM methods. Research has been done to produce an emulation of the knock calculation on the CFR engine by using low-pass filtered rate-of- change of the pressure signal. Until now, only primary fuel can be used in this research [73]. Constant spark advance 13 degrees BTDC (before the dead centre) for RON and 19 – 26 degrees BTDC is used to determine the octane rating which is dependent on compression ratio for MON. Extremely high flame speeds around stoichiometry will causes inconsistencies in nominal knock resistance of hydrogen. This flame speed is dependent on the air-fuel ratio which is why the standard procedure to calculate knock resistance is controversial. The methane number (MN) can be used to calculate the knock characteristic of fuels in gas form because of the high knock resistance of methane (115<MON<130). The methane number utilizes the reference fuel blend of methane with MN of 100, and hydrogen with a MN of 0 [75]. Hydrogen has a very low knock resistance with a MN of 0 which refuted some of the octane numbers shown in other research cited above

[71-71]. Many researches have been attempted to estimate the knock behaviour of hydrogen-fuel engines. The results obtained from experiment displays high quality agreement for difference of compression ratio, air-fuel equivalence ratio and intake air temperature [75]. The phenomenon of knocking combustion strongly limits the operating system of hydrogen engine. However, despite the compression ratio, knock was not observed in any of the hydrogen testing that was performed on a multi-cylinder hydrogen engine at compression ratios of 15.3:1, but it was observed on gasoline engines [76].

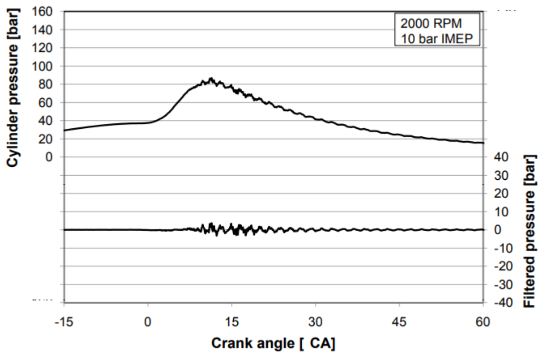

Fig. 8. Typical cylinder pressure trace for light knocking cycle

Figure 8 shows the cylinder pressure trace and filtered signal for hydrogen DI operation at 2000RPM as well as an engine load of 10 bar IMEP which is recorded 40 on a cylinder research engine with compression ratio of 12:1.

Pressure fluctuations that are common for knocking combustion are shown by the cylinder pressure signal; maximum pressure amplitude of around 3.6 bar are also shown by the high-pass filtered signal. For the same engine speed and load, a record of an operating point with heavy knock was made which causes the spark timing to advance further. For this operating point, the normal peak pressure is approximately 90 bar but the highest pressure with knocking operation is 150 bar with fluctuations in the high-pass filtered signal close to 65 bar. By conducting test on a CFR engine with compression ratio of 12:1, we can determine the knock behaviour of hydrogen and its quality of being relevant for standard automotive knock-detection system. After analysis of knock strength of gasoline and hydrogen, it was revealed that the knocking pressure traces shows identical peak amplitudes, durations and decays of pressure fluctuations [77].

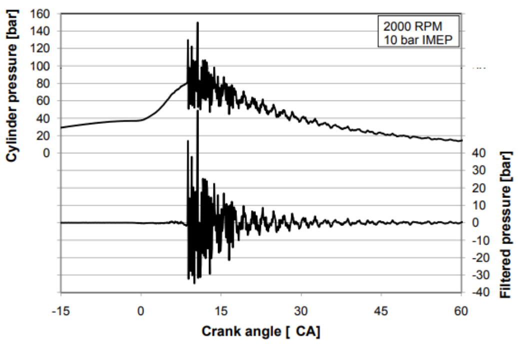

Figure 9: Generic cylinder pressure trace for heavy knocking

4.4 Avoiding Abnormal Combustion

One of the methods that is effective in avoiding abnormal combustion is to limit the maximum fuel-to-air equivalence ratio. This method involves a lean-burn strategy which reduces the combustion temperature efficiently and the components temperatures consequently because the excess air in lean operation acts as an inert gas. However, the power output of hydrogen engine will be limited despite the highly effective lean operation. Pre-ignition requirements can be controlled by using thermal dilution technique, such as water injection or exhaust gas recirculation (EGR). The EGR system can re-circulate a portion of the exhaust gases into its intake manifold. By introducing the exhaust gases, the temperature of hot spots can be reduced, and the chances of pre-ignition is also reduced. Moreover, the recirculation of exhaust gases will reduce the peak combustion temperature and as a result, the NO_x emissions is also reduced. In most cases, 25% to 30% of recirculation of exhaust gases is effective in removing back fire [77]. The fuel mixture can be thermally diluted by injection of water. If the hydrogen stream is injected with water before mixing it with air, it will produce a better result than injecting water into the hydrogen-air mixture within the in-take manifold.

5. PRESENT CHALLENGES

Although the hydrogen fuel cell has a lot of benefits, but there are some issues that are so far preventing their universal release into the energy market. There are some challenges that are quite hard to overcome, which is why the scientist are still working on it to produce a better, more efficient and safer hydrogen fuel cell. Therefore, in the future hydrogen fuel cell will be an alternative of fossil fuel. The very first challenge to overcome in the pursuit of an efficient hydrogen fuel cell will be the cost. Figure 10 shows the projected hydrogen cost in the future.

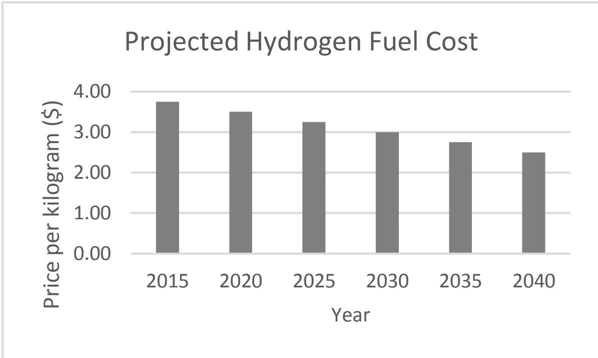

Figure 10: Projected hydrogen fuel cost in the future

Based on Figure 10, hydrogen fuel has a very high potential of becoming more available for the general public as the price is expected to drop over the decades. The problem right now is that, fossil fuels are currently more affordable than hydrogen fuel which makes it unreasonable to make the switch. Multi-national companies would not benefit from the use of hydrogen as there is no business potential for it as of today as it's still a novelty. Hydrogen fuel is also dependent to the surroundings and environment. This means contamination and temperature difference can reduce their usability. This is especially true in countries where there are extreme conditions. The next concern is safety. Hydrogen is considered to be highly combustible which brings along some concerns on the safety of the user. The challenge of safe use of hydrogen fuel has always been a concern and many steps are needed before they can be commercialized [79].

6. FUTURE POTENTIALS

The hydrogen fuel has a great potential in the future. There are few improving key elements of the hydrogen fuel cell for better performance in future. The cost has to be reduced with a non-precious metal catalyst. In most designs, platinum will be the catalyst in the anode and cathode layers which is a which is very expensive [80]. Ballard has recently proposed a new idea of the world's first non-precious metal catalyst based on the PEM FC product, which is supplied in collaboration with Nisshinbo Holdings [81]. The new fuel cell design will use 80% less platinum and will be more tolerant to air contaminants, such as sulfur oxides, as compared to platinum- based catalyst. Besides that, cathode layer design will deliver higher performance and greater durability. Cathode catalyst performance can be improved by alloying metals such as cobalt and nickel with platinum, but these metals will not be stable in fuel cell environment. This challenge is overcome by replacing with a novel catalyst layer design which has higher performance with greater durability compares to conventional catalyst layers. It will result in 5 times the durability improvement when compared to a more conventional design using the same alloy catalyst. Other than that, nanotechnology also plays an important role for a better performance of hydrogen fuel cell. It improves the efficiency of the fuel cell and it will be affordable and can accessed by almost everyone in developing nations [80]. With the help of nanotechnology, a safer fuel cell will be developed to replace the conventional hydrogen fuel cell. The process of the hydrogen fuel cell is shown in Figure 11.

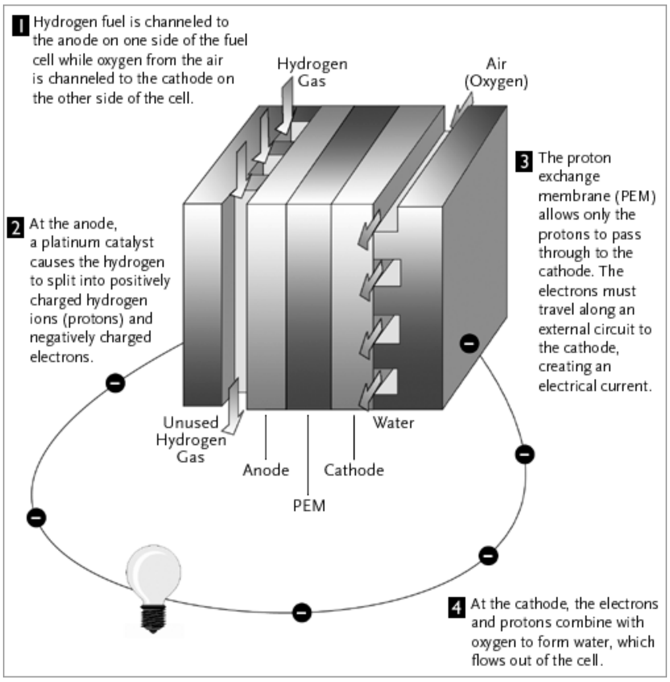

Figure 11: A typical proton-exchange membrane (PEM) hydrogen fuel cell [84]

Essentially, the proposed hydrogen fuel cell will convert the chemicals, hydrogen and oxygen into water, which in turn will be used to produce electricity. The hydrogen sensors will be built using single-walled carbon nanotubes to increase its efficiency [83].

7. CONCLUSION

The sources of energy to be used in the future will have to be cleaner and more efficient than current sources. Hydrogen fuel accomplishes these criteria with relative ease. Many challenges need to be solved before wide-spread hydrogen use can be feasible, these include restrictions with size, cost, reliability and safety. Among other alternative fuels, hydrogen proffers the best solution to reduction or complete elimination of hazardous vehicle emissions and their environmental effects. Efforts of efficient production, storage and distribution of hydrogen is currently underway. This shows that there is a great prospect for hydrogen fuel in automobiles.

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