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.

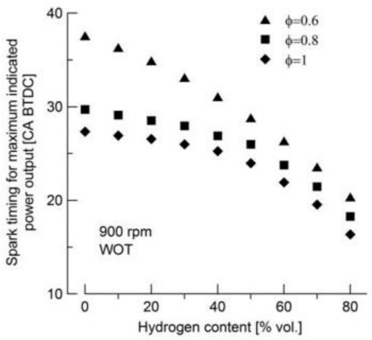

Figure 2: Spark Timing Vs. Hydrogen content

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.

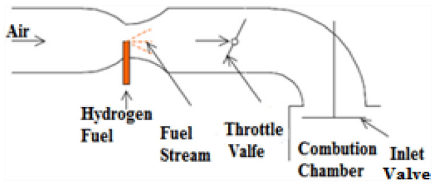

Figure 3: Fuel Carburetion Method [48]

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.

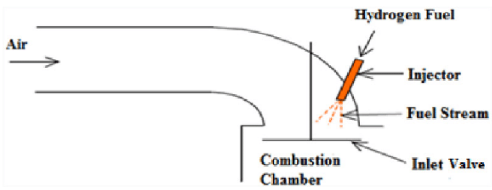

Figure 4: Inlet Port Injection Method [51]

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.

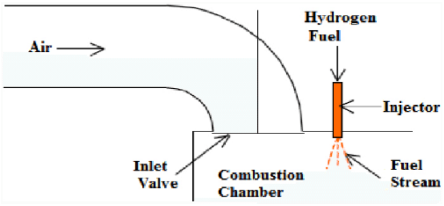

Figure 5: Direct Injection Method [51]

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].

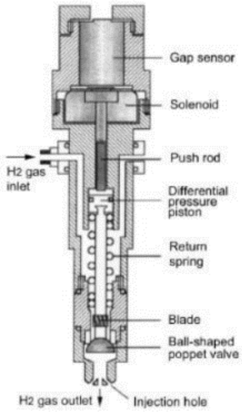

Figure 6: Hydrogen Injector [15]

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.

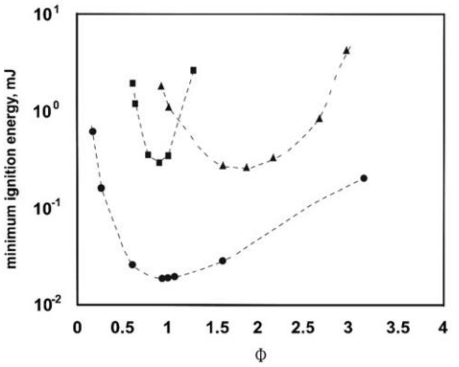

Figure 7: Minimum ignition energies of (●) hydrogen–ai4, (■) methane–air and (▲) heptane–air mixture in relation to at atmospheric pressure [65].

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].

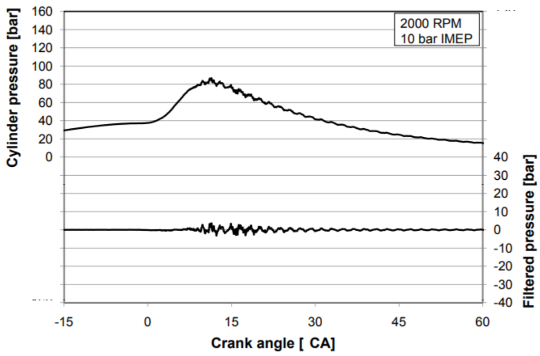

Fig. 8. Typical cylinder pressure trace for light knocking cycle

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].

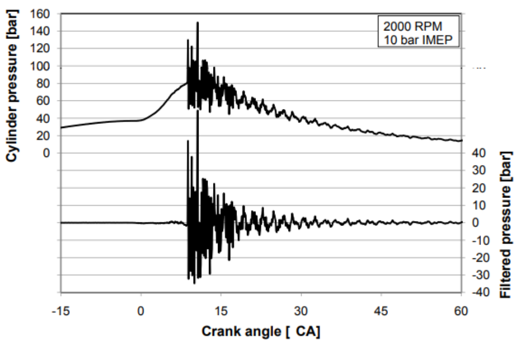

Figure 9: Generic cylinder pressure trace for heavy knocking

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.

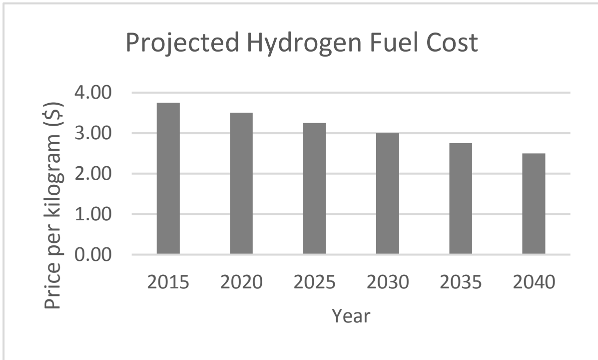

Figure 10: Projected hydrogen fuel cost in the future

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.

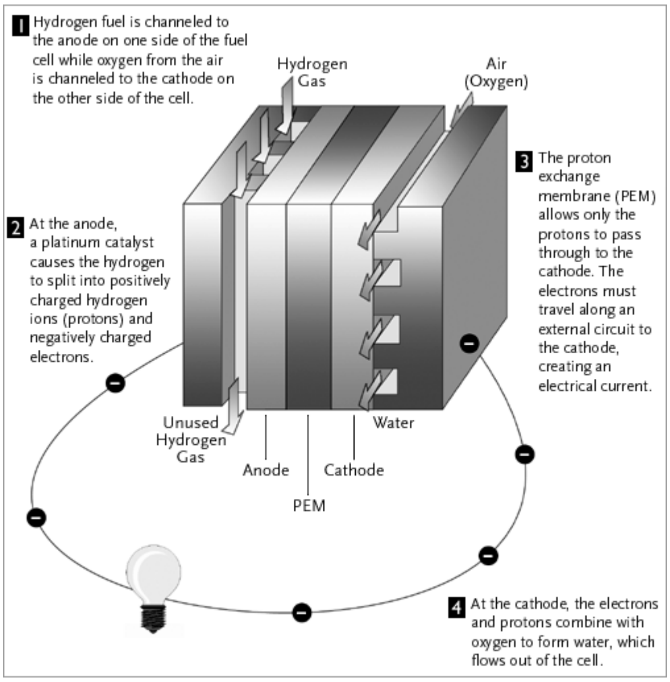

Figure 11: A typical proton-exchange membrane (PEM) hydrogen fuel cell [84]

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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