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# Effects of Equivalence Ratio on Performance and Emissions of Diesel Engine with Hydrogen and Water Injection System at Variable Injection Timing

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***Abstract*-- This paper aims to develop a comprehensive development and research for performance and emissions of diesel engine fuelled with hydrogen and water at variable injection timing. Experiments have been conducted to compare the performance and emissions between diesel alone, diesel with hydrogen and hydrogen-diesel and water injection pressure. addition of hydrogen into diesel engine resulted in higher pressure which lead to huge indicated work. Furthermore, injecting water into diesel engine with hydrogen mixture indicated a desirable outcome. Existence of water in combustion slightly decreased the amount of emissions but opposite in term of performance. The fact is water injection exist in combustion will absorb a portion of heat release which will result low in combustion process thus lead to low in performance production otherwise production of NOx emission is low. In conclusion, humidification in combustion engine is a great idea toward a high performance and low in emissions production compared to diesel alone operation which leads to a green technology production.**

***Index Term*-- Air Fuel Ratio, Hydrogen Fuel, Diesel Engine.**

## I. INTRODUCTION

The worldwide use of diesel engines with their low fuel consumption, high durability and efficiency outcomes increase nitrogen oxide (NOx) emissions every day. Higher efficiency and lower fuel costs makes diesel engines a clear choice in applications requiring relatively large amounts of power such as in large ships, heavy trucks and power generation units [8]. Regularly, diesel engines used both on and off roads due to their low hydro carbon, high thermal efficiency and carbon monoxide emissions which contribute to large NOx emissions [1]. Besides that, elevated oxygen levels increase the maximum temperature during combustion and accelerate NOx formation [15].

Due to stricter emissions standards for diesel engines with respects to NOx and carbon dioxide ($CO_2$) emissions and fuel consumption, there are major concerns about the applicability of clean energy technologies [5]. Nitrogen oxide emissions from diesel engines cause unavoidable damage on environment and people health [9]. Higher numbers of smaller particles emerged from internal combustion engines are relatively more harmful to human health compared to smaller number of larger particles because smaller particles penetrate deeper into human lungs [13]. Plus, the rapid growth of vehicle usage increases the rate of pollution which mostly come from diesel engine [14]. Therefore, there is strong initiative in looking for alternative fuels for different applications, including that for motor vehicles [18].

Hydrogen is one of the initiative renewable fuel for internal combustion engines [16]. It has the potential advantages of ultra-low pollutions, high efficiency and long-term availability [2]. In addition, hydrogen has some unique features compared to hydrocarbons, such as high mass and thermal diffusivity, wide range of flammability limits, low minimum ignition energy, and high stoichiometric air-to-fuel ratio [7]. There are some experimental investigations that have been conducted by other researcher to investigate the effect of hydrogen addition on the performance and emissions of single-cylinder diesel engines [11].

In a super-charged diesel engine, high level of hydrogen addition was attempted and has been confirmed that up to 90% substitution of diesel fuel energy by hydrogen could be achieved which contributed to ultra-low smoke, carbon monoxide and hydrocarbon emissions [10]. In fact, in other study, they verified that delayed injection timing and exhaust gas recirculation combined with hydrogen addition could achieve low temperature combustion so as to reduce both smoke and NOx emissions [6].

Another paper claimed that the hydrogen addition narrowed the operational compression ratio range and increased he knocking tendency, but NOx emissions decreased with no significant influence on hydrocarbon emission [4]. Furthermore, an experimental study on a turbo-charged common-rail split-injection light-duty diesel engine, found that NOx reduced by 25% compared with diesel fuel operation with 31% of exhaust gas recirculation ratio and 10% of total fuel energy substitution by hydrogen [12]. Other research investigated that for hydrogen enrichment of 5 and 10 Nm, the peak cylinder pressure decreased respectively, whereas pressure rise was almost the same with that of diesel [3].

Moreover, a study has identified that the cylinder pressure and heat release rate first increased and then decreased with the enhancement of $H_2$ addition, nitric oxide emissions increased, while particulate matter emissions decreased. Both the pressure

and heat release rate reached the maximum value at the addition of 17% $H_2$ [17].

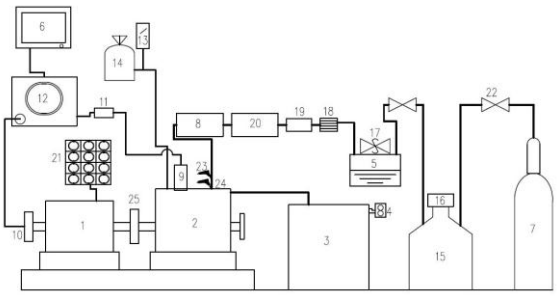
## II. METHODOLOGY

Diesel engine is one of internal combustion engine family member which is apply high compression pressure to ignite combustion for generating energy, in simple word this type of engine requires no spark to ignite the fuel. Auto ignition taken place in the cylinder due to high temperature caused by high pressure during compression stroke, diesel fuel which is contain low octane number will straight away self-ignite once the temperature inside the cylinder exceeding the temperature of diesel which it can combust automatically. In addition, the diesel engine has the highest thermal efficiency instead of any type of internal combustion engine ever exist. Hence, application of diesel engine throughout the industry is getting popular due to its advantages. Many industries have been involved in developing the diesel engine to become more efficient and reliable. Now automotive industries have focus more on developing diesel engine as primary power generation toward an environmental awareness as well. This research used a single piston diesel engine and these engine specifications are listed below.

Table I
Yanmar engine specifications

| Model | L100N5 |
|---|---|
| Type | Air-cooled 4 cycle diesel engine |
| Bore x Stroke | 86mm x 70mm |
| Maximum RPM | 3600 RPM |
| Displacement volume | 435 $cm^3$ |

This engine is provided with air cool system in which there is no radiator attach on the engine to cool down cylinder temperature all cooling process is done by cooling fan attach in front of engine fins. Air is generated automatically by cooling fan that is connected to the crankshaft. The clear look of the engine can be seen in figure below.



| Experimental Apparatus | | | |
|---|---|---|---|
| 1 | Synchronous Generator | 14 | Diesel Fuel Tank |
| 2 | Diesel Engine | 15 | Hydrogen Storage Tank |
| 3 | Surge Tank | 16 | Pressure Regulator |
| 4 | Mass Flow meter (Air) | 17 | Safety Valve |
| 5 | Water-Flame Trap | 18 | Flash Back Arrestor |
| 6 | Computer | 19 | Hydrogen Mass flow Meter |
| 7 | Hydrogen Cell | 20 | Water Tank |
| 8 | Water Pressure Regulator | 21 | Load Bank |
| 9 | Pressure Transducer | 22 | Control Valve |
| 10 | Crank Angle Encoder | 23 | Water Injector |
| 11 | Signal Conditioner | 24 | Hydrogen Injector |
| 12 | Data Acquisition System | 25 | Torque Transducer |
| 13 | Diesel Flow rate Pipette | | |

Fig. 1. Schematic diagram of experimental setup

Pressure transducer is an electronic device and used to collect pressure change inside the engine, this device is converting pressure which is cannot be seen by bare eye into signal in such way is readable by human. An electronic device becomes important in order to detect the level of pressure in which taken place inside the cylinder. The model and item that used in this research to read the pressure inside the engine is Kistler Model 607C Quartz High Pressure Sensors. Meanwhile, Crank encoder is an electronic device use to record crank angle taken for certain cycle in such way enable to integrate with

pressure reading taken by pressure transducer. This application is useful to determine $P-\theta$ diagram in which most of the performance experiment dealing with this method. There is no such way high rotation of engine crank can be detected by mechanical device. Data acquisition is the process of sampling signal that measure real world physical conditions and conversion of the resulting sample into digital numeric values that can be manipulated by a computer.

Data acquisition is important for converting analog signal produced by pressure transducer and crank angle encoder to the readable signal. This electronic device is a medium for computer to read in digital signal in such way computer only can read or analyses signal in form of digital signal. Gas analyzer is used to determine the content of residual gas flow through exhaust manifold in which data obtained can be used for comparison of gas content in diesel alone, hydrogen diesel and hydrogen- diesel-water test. Gases test including CO, $CO_2$, HC, $O_2$ and $NO_x$. The main purpose of using this gas analyzer is to determine $NO_x$ reduction by injecting water in diesel-hydrogen compare to diesel alone. Since this research are about finding the effect of emission to equivalence ratio, the most suitable way to probe the percentage of emission content is through gas analyzer which it can simply tracking the amount of emission. Types of gas analyzer used for this experiment intention are Bacharach Model 300 and AutoChex. This devices can perform better whereby it can collects a such number of gasses emission such as CO, $CO_2$, HC, $O_2$ , NOx and many more and easy to calibrate as well.

Equivalence ratio is determined by the ratio between the mass flow rate of the air and the fuel supplied to the engine. As the speed of the engine increase, the air flow rate will increase significantly compare to diesel supply as well. The mass flow rate of the air is determined by placing a mass flow gauge or meter at the air intake during the experiment. As the engine starts, the piston will pull more air into the cylinder for combustion. To increase the mass flow rate of air, the throttle body of the engine will be adjusted by increasing the area of air that can be pulled by the piston during intake stroke. As the throttle body area is increase, the engine speed will increase as well. Hence, increase the mass flow rate of the engine. As for diesel fuel, since this engine is mechanically fuel injected by using the pressure difference and pushrod mechanism, it is hard to exactly determine the flow rate of diesel engine. But by using manual calculation, the mass of flow rate is calculated by measuring the volume difference from the diesel tank for certain amount of time. This will give the reading for the mass flow rate of the diesel fuel. As for hydrogen measurement, supplement of hydrogen was done by using electronic flow meter device OMEGA brand.

First case expressed an experimental set up for diesel and hydrogen mixture with water injection combustion process taken place at 20º CA (Crank angle) after top dead center. In other word, it can be explained better in which addition of hydrogen at 30ml/sec and water mist will be injected into diesel fuel combustion during the intake valve of diesel engine opening at 20º Crank angle after top dead center but will end in different period of crank angle. End process of hydrogen addition is taken place after crank angle travel at 20º and similarly happens to water addition as well. Next, the second case expressed can be explained in detailed as start of injection (SOI) of hydrogen and water was taken place at 20º of crank angle (CA) after top dead center. In other word, addition of hydrogen at 30ml/sec and water is injected into diesel combustion during intake valve of diesel engine opening at 20º crank angle but it stopped in different period in which hydrogen stop injected is taken place after crank angle travel at 20º and end process of water addition stop injected after travelling 40º of crank angle. Lastly, the third case shown the addition of hydrogen in diesel alone. SOI of hydrogen is taken place during intake valve opening at 20º of crank angle after top dead center and stop after travelling 40º of crank angle period.

## III. RESULTS AND DISSCUSSION

All the performance is about comparing the performance produced by the diesel alone and with the addition of the hydrogen and lastly, with water port injection. The reason is to see whether which set up has best production of performance during combustion. The performance consisting of engine speeds, peak pressure, indicated power and thermal efficiency. Hence this chapter will cover all the mentioned result in order to see comparison between the set up.

### *A. Equivalence ratio analysis*

Figure 2 shows a graph illustration for equivalence ratio versus engine speed. The graph tells that increasing of RPM in engine operation will affect changing of equivalence ratio as well. Equivalence ratio is a dimensionless number and it can be explained that the graph trend line for all set up are pointing upward. The highest ranking is diesel alone and followed by other three which are Case 2, Case 1 and finally is Case 3 mixtures. Diesel was shown the highest equivalence ratio content even at similar RPM throughout different set up. The equivalence ratio for diesel almost similar start from 1800 to 2500 rpm reading and its start changing since RPM shoot to 2800. This is because higher increment of RPM require large opening of fuel throttle since the amount of air intake is almost similar even slightly different in air flow reading throughout all rpm thus the equivalence ratio shoot upward all of sudden. The lowest reading among the rank is Case 3 reading. This is because hydrogen itself acting as high burning rate compare to diesel. Hydrogen automatically require low usage of diesel at high RPM operation even the RPM is shoot to higher but yet the amount of diesel is increase a little, the reason behind this phenomenon is resulted by hydrogen will propagate fast evenly throughout inside cylinder compare to diesel fuel propagation.

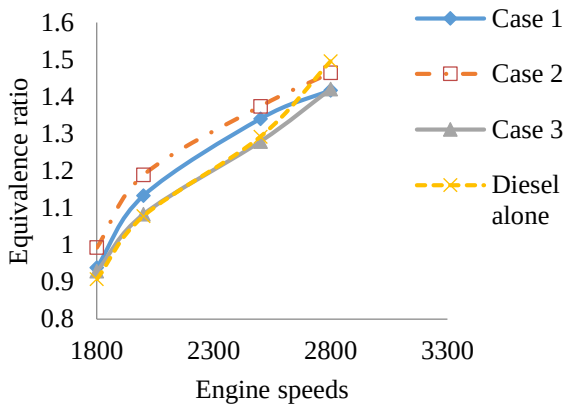



Fig. 2. Equivalence ratio against engine speeds

Peak pressure produce by every experiment is increase against equivalence ratio is shown in Figure 3. Even though the highest peak pressure was taken place on diesel and hydrogen addition experiment but graph pattern for diesel with hydrogen and diesel alone are little bit similar, the value recorded was 64.4 at Ø = 1.42 (equivalence ratio) and the value lies within range of 64~65 bar is seems normal for hydrogen addition into diesel behavior , but yet the equivalence ratio is in range of rich condition, in simple word the existence of hydrogen doesn't affect a lot on equivalence ratio compare to diesel alone but diesel fuel consumption is become lesser than diesel alone since hydrogen was applied. Back to peak pressure analysis, the amount of hydrogen supplied was 30ml/sec and crank angle opening period set for supplying hydrogen is longer enough in such way it can generate high pressure in combustion. This result follow regarding to Case 2. In addition, hydrogen is known as flammable fuel and containing high burning rate which is very sensitive to produce high combusting pressure.

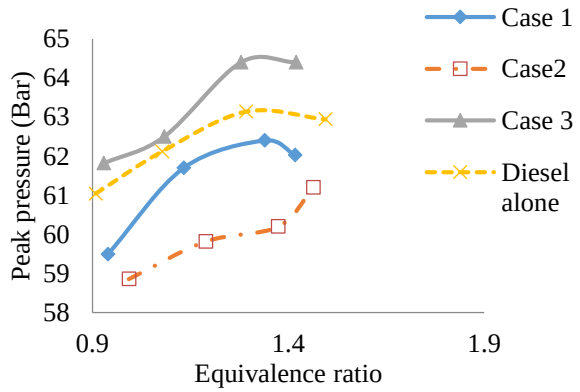



Fig. 3 Peak pressure versus equivalence ratio

Figure 4 shows the comparison between all variables with respect of equivalence ratio. This is the the indicated power comparison between all variables and to see whether the objective that have been targeted are achieved or not. The difference of reading at each can be seen significantly. Graph as shown above indicated as indicated power against equivalence ratio, this graph is very useful to compare Power produce by different equivalence ratio data. The entire graph is proportional whenever power indicated increase equivalence ratio will increase as well in simple word power will increase whenever equivalence getting toward rich condition. Here, It seems diesel and hydrogen once again recorded high Power indicated. The value of power recorded was almost 2.5 kW at 1.4 equivalence ratio compare to diesel alone that recorded 2.4 kW which is requiring 1.5 equivalence ratios. Even though both result applied within rich condition range of equivalence ratio to produce high power but Case 3 require lesser instead of diesel alone. From value above it can be explained that by introducing hydrogen in diesel combustion, it will result high pressure difference within volume displacement that will lead to large work indicated production and finally slightly increase in power production.

The lowest value recorded was power indicated produced by Case 2, the value of power indicated is higher than diesel alone produced at the same equivalence ratio but power indicated start to decrease within range of 1.2 up until to 1.4. Power indicated recorded is the lowest among those three graphs. Here, can be explained that power produced by Case 2 was inefficient when it running within this range of equivalence ratio, this result is supported by strong fact as well [32], which is introducing water in Case 2 will lead to low combustion process, this fact was afforded by simple principle of heat absorption process whereby as long there are difference of temperature taken place in combustion process, any fluid in high elevated temperature will move to lower temperature region. In addition difference of temperature will result heat transferred from high region to low temperature region. Here, the fact given has similar to excessive water addition in Case 3 will lead to low combustion process in which heat released by diesel hydrogen mixture is used by water for evaporation work, in simple work heat absorption is require most to evaporate water.

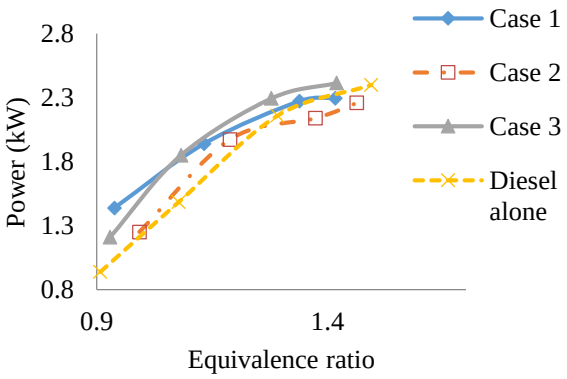



Fig. 4. $P_{indicated}$ versus equivalence ratio

Figure 5 shows indication of thermal efficiency against equivalence ratio. Every difference combustion efficiency is increased gradually follow equivalence ratio increment. Even

though all these indicated graph pattern are pointing up ward but yet thermal efficiency indicated for every graph are difference and it can be seen clearly that combustion taken place in Case 3 is the highest record compare to these three result. The graph that lies under Case 3 was followed by Case 1, Case 2 and finally was diesel alone pattern. As mention before hydrogen is containing higher burning rate of combustion even a small spark will lead to auto combust [33]. This characteristic will eventually contribute in high heat addition into combustion, due to high heat difference that will lead to high elevated in temperature of mixture in such way will affect to higher pressure production. Pressure is required mostly for determination of work indicated $W_{ci}$, the higher difference in pressure range will lead to higher in work indicate which is represented enclosed area under graph of P-V as long as pressure difference taken place at certain displacement volume there will be a work done as well thus it will lead to higher in efficiency.

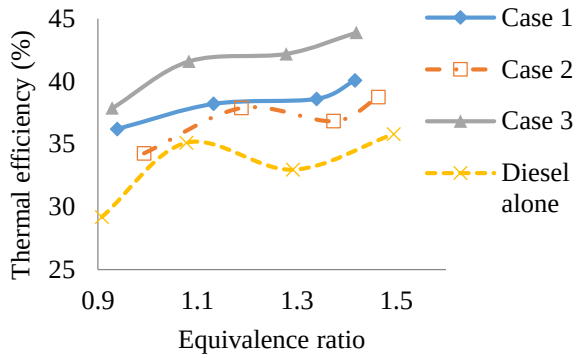



Fig. 5 Thermal efficiency versus equivalence ratio

Meanwhile, the graph illustration about $CO_2$ versus equivalence ratio in Figure 6 is pointing upwards and each of graph follow same pattern. Here, the highest percentage of carbon dioxide was taken placed at Case 1 compare to another three graph lies under it. It was recorded that Case 3 has shown an opposite result compare to Case1 which is the lowest among others three. According to the graph reading Case 1 contain high possibility of $CO_2$, the reason behind this phenomenon was introducing such excessive water in to combustion will lead to low combustion process. This incident can be supported by strong evidence which is water induction indirectly will absorb portion of heat released by diesel and hydrogen combustion to evaporate the water induction because there is huge temperature difference between diesel and hydrogen combustion and water addition Thus the heat transferred was taken place due to large gap of temperature thus it will eventually effect overall combustion and heat require for complete combustion is insufficient that will lead to high content of $CO_2$ formation.

Opposite to Case 1, Case 3 will result in different outcome which is $CO_2$ content is low instead of adding water into combustion, this result can be strongly supported by hydrogen addition in diesel combustion will result toward to complete combustion due to no existence of water to absorb heat in such way that will lead to high combustion process, in addition hydrogen itself is well known as carbon less species will reduce such amount of hydrocarbon injected for mixture combustion thus it will lead to low requirement of carbon to produce $CO_2$ formation as well. This reason can be strongly supported by Probir Kumar bose, Dines Maji journal.

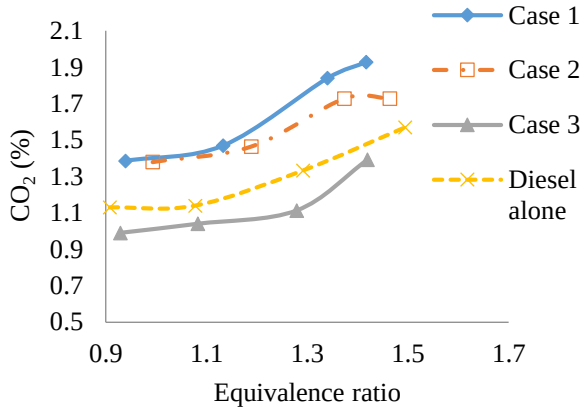



Fig. 6. $CO_2$ versus equivalence ratio

Figure 7 shows a graph illustration of Case 2. Orange color curve is highest among other three graph that lies under it graph. The rank is followed by Case 1, diesel alone and finally is Case 3. Even the content of CO for Hydrogen water is highest among other three graphs but the pattern seems pointing downward and it content is decreasing toward increment of equivalence ratio. This can be supported by evidence found in journal whereby hydrogen is exist as carbon less particle, it existence will result toward to complete and lean combustion process in simple word combustion that taken place require more hydrogen content instead of diesel. Thus hydrogen content to Carbon is getting higher in other word it will lead to total reduction of hydrocarbon content in diesel usage. But CO content is higher than diesel and hydrogen mixture can be supported by this reason whereby addition of water mist in combustion will result reduction in combustion process which is water with low energy storage will absorb some heat released by diesel and hydrogen combustion for evaporation work which will lead to incomplete combustion process.

Compared to three other graph above Case 3 recorded as the lowest value of CO content in exhaust product. This reason can be explained further where addition of hydrogen in diesel will result lean combustion [34] due to hydrogen is known as flammable fuel and containing high burning rate which is very sensitive to produce high combustion process, will result less CO content in combustion will be produced which mean most of the reactant was burnt toward to complete combustion that eventually will lead to reduction in CO content in exhaust system.

Nitrogen Oxide or $NO_x$ is a generic term for the mono-nitrogen oxides NO and $NO_2$ (nitric oxide and nitrogen

dioxide). They are produced from the reaction of nitrogen and oxygen gases in the air during combustion, especially at high temperatures. With all combustion will involve temperature and heat, the emissions of nitrogen oxide will always occur. The only differences is that how much of nitrogen oxide is being emitted into environment and atmosphere. Nitrogen oxide is hazardous to the environment because it can cause the acid rain thus this will affect the habitats and all living creature that living on this earth. Hence, all the comparison for all set ups are shown in the graph below.

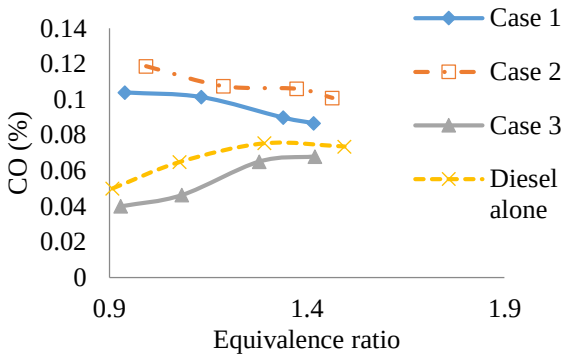



Fig. 7 CO versus equivalence ratio

Lastly, Figure 8 shows the $NO_x$ versus equivalence ratio. The highest $NO_x$ recorded taken place at Case 3 combustion followed by three other graph lies under it rank such as diesel alone, Case 1, diesel alone and finally Case 2. $NO_x$ formation is related with high temperature taken place in combustion process as long as temperature of combustion getting higher there no possible $NO_x$ formation is increasing as well. According to Case 3 combustion is top rank in $NO_x$ content, the reason is hydrogen fuel is high in burning rate combustion compare to diesel fuel, in other word hydrogen is rapid in combustion propagation which will lead to high peak pressure production in which it will result high in work indicated production, thus high contribution to heat release during combustion taken place. In other word it can simply expected that high burning rate will result large production of heat generation in such way it will lead to high temperature production. Hence, formation of $NO_x$ will be easier.

The lowest $NO_x$ formation is in diesel and hydrogen with water addition. Water is known as heat absorption component, it is useful to inject water in side diesel and hydrogen combustion whereby diesel and hydrogen mixtures will result high temperature production due to high heat release, by introducing water in diesel and hydrogen mixture it will result heat absorption by water to evaporate, this fact was supported by simple principle of heat absorption process whereby as long there are difference of temperature taken place in combustion process, any fluid in high elevated temperature will move to lower temperature region. Thus temperature of combustion is decrease which will lead to low $NO_x$ formation.

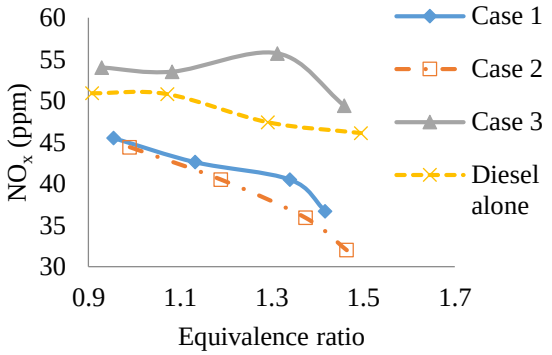



Fig. 8 $NO_x$ versus equivalence ratio

## IV. CONCLUSIONS

Diesel engine has become one of the major engine development sector in internal combustion engine industries. Many big companies have tried to improve the system of diesel engine because there are many possibilities which are beneficial can be obtained from diesel engine. with higher in term of efficiency compare to any type of engine cycle, low fuel consumption and reliability compare to with spark ignition engine, many big car companies.

The real concern for diesel engine to the world is the amount of emissions that a normal diesel engine is going to produce and release have implemented and developed diesel in varieties applications and implications such as effects to the environment, with a lot of smoke coming out from a normal diesel engine operation, the mentality of the people will start to see and think the advantages and the hazardous of the diesel engine to the environment. With much lower cost to develop, with the price of fuel is much lower compare with petrol fuel and higher durability, the development of the diesel engine should not be stopped and as engineer, sustainability of diesel should be implemented.

As for this project purpose, with the introduction of water port injection into diesel and hydrogen combustion does not affect a lot in the performance but from observation it contributes a lot in low production of $NO_x$. As conclusion in term of performance diesel hydrogen combustion generates higher in indicated power production compare to others three types. Even water injection combustion produce lower in performance but there are slightly in performance different. As far as know from the result mentioned in previous chapter, the comparison doesn't lies much on the indicated power the performance will eventually lies on thermal efficiency. Even the power produced by diesel hydrogen higher than water injection combustion but in term of efficiency water port injection produce higher than diesel alone even though power produced by diesel alone is higher instead of water port injection system. As the conclusion, by applying water port injection will lead higher percentage of fuel to complete combustion compare to diesel alone, in other word addition of

water will save a lot of fuel usage due to less incomplete combustion but high in efficiency to do work power production.

According to emissions analysis, With addition of water the in diesel and hydrogen combustion will result reduction of CO and $NO_x$ significantly. Refer to the graph shown in the previous chapter, total reduction in CO is significantly can be observed although the number of CO content in exhaust was higher instead of hydrogen and diesel combustion but the graph trend is toward reduction pattern. Addition of hydrogen is a major impact of CO reduction due to hydrogen characteristic with high burning rate and high rate of combustion propagation will lead to lean combustion but water addition will result slowing in peak pressure production. Thus, affected low in temperature and will result reduction in combustion process. Which regard to low in combustion process, heat formation is insufficient toward a complete combustion. In addition, hydrogen and water are carbonless element as well which will result less CO formation during the combustion process or in simple word absence of carbon content in water element will lead toward low in CO production.

As for $NO_x$ emission, water addition is significantly reduce $NO_x$ content in the gas exhaust. This was because water element itself acting as heat absorption during hydrogen and diesel combustion taken place. Water existence will slow down temperature production due to high rate of combustion propagation which resulting from hydrogen addition. This phenomenon is clearly related with water has low energy content that will absorb some heat from hydrogen and diesel combustion for evaporation process of water to steam. Therefore, Heat transfer process is taken place from high region of heat content to low region of heat content that will lead to temperature reduction and finally reduce content of $NO_x$ in exhaust emission.

As for conclusion, with addition of water port injection system to the diesel and hydrogen gave significant outcome especially in performance and emissions but it affect better to emission system, in which result obtained from experiment is significantly similar to other journal produced by researcher and can be used for validation purpose.

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