Study of the Performance and Emission of EFI-SI Engine Using Water Injection

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Abstract

Few studies on the effect of water addition to combustion engine have been done for the last decades on carbureted single cylinder engine. The purpose of the present research is to investigate the effect of water addition on the performance and emission of an EFI-SI, CAMPRO 1.6L four stroke cycle engine. Water in mist form was supplied to the intake manifold through the nozzle which is located after the butterfly valve at the throttle body. The water will mix with the air fuel mixture before entering into the combustion chamber. A combination of modelling simulation followed by experimental validation was carried out with and without water mist addition to examine the performance and emission produced by the engine. The simulation was carried out using GT POWER before the experimental investigation on performance and emission was carried out with various load factors at different speed within the range of 1500 rpm to 4500 rpm. Thus experimental result for the standard engine performance is used to validate the simulation model. Measurement of various parameters such as brake power, torque, volumetric efficiency, spark advance timing and the concentration of CO, NO\textsubscript{x} with water and without water addition to the engine was recorded. The experimental data obtained from the results by using the water addition method show an increase of power, torque and volumetric efficiency of the engine up to 10%. The fuel consumption is reduced about 3% to 6% when the speed is increase from 1500 rpm to 3500 rpm, then it increases up to 10% when the engine speeds up to 4500 rpm. The emission of NO\textsubscript{x} was significantly reduced, but CO does not change. The results obtained and analysed will be useful for improving the engine performance and emission for further developments.

Keywords: Compressed Natural Gas (CNG); Dedicated CNG system; Engine performance; Specific fuel consumption; Brake power; Brake mean effective pressure; Emission; Water injection; Ignition timing.

1. Introduction

Nowadays, every country is focusing on green environment implementation control strategy as the main agenda of their vision.

The internal combustion engine (ICE) (Spark Ignition (SI) and Compression Ignition (CI) engine) is the one that produces a large quantity of emission to the environment as well as to the human health. This is also reported by Malaysia Department of Environment [MDOE], (1998) where motor vehicle emissions are the leading cause of air pollution in Malaysia, and the MDOE is looking for new ways to combat the problem.

The operation of SI engine results mainly in the emission of unburnt hydrocarbon, carbon monoxide (CO) and nitrogen oxide (NO\textsubscript{x}). The higher amount of hydrocarbon and carbon monoxide come from rich mixture which does not have enough oxygen to react with all the carbon and hydrogen. The generation of NO\textsubscript{x} emissions is a function of the combustion temperature, highest near stoichiometric condition when the temperature at the peak value. And the maximum NO\textsubscript{x} emissions occur at slightly lean conditions, where the combustion temperature is high and there is an excess of oxygen to react with the nitrogen (Ganeson, 2003).

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As we know, the control strategies to reduce the emission are not only concentrating to choose the alternative fuel as an option but can explore many different ways. Nowadays a lot of car manufacturers have developed high performance engines through downsizing, which aims to increase performance per litre of displacement. Improving the performance of the existing engine with reduced fuel consumption contributes to the reduction of the emission. Various emission control strategies are available for IC engine which can reduce the emission as well as the fuel consumption of the engine.

One of the strategies to improve and reduce emission that will be discussed in this paper is the water addition to the spark ignition engine as shown in Figure 1.

Figure 1: Schematic Diagram for Water Addition to SI Engine

Technique of water addition technology either on SI engine or CI engine is nearly as old as the creation of engine itself. The techniques of water addition itself can be explained in many ways such as:

i) manifold injection or carburetion of water gasoline emulsions
ii) separate induction of water and gasoline
iii) direct cylinder injection of water
iv) manifold water vapor induction and
v) water induction into the air intake (Covey et al., 1982).

In this study, the water induction into the air intake system would be used to investigate the effect on the performance and emission produced by the engine.

2. Literature Review

Common factor that affecting the performance of the engine is detonation or knocking. This phenomenon happens due to deposit that built up on top of the piston and during combustion this deposit will burn and keep glow with a certain period. This will make the air fuel mixture self ignite before the piston reach to the TDC. Another phenomena also can be caused by the temperature of unburnt mixture exceeds the self ignition temperature of the fuel which can auto ignite occurs at various pin point location (Ganeson, 2003).

Detonation occurs when air and fuel that is ahead of the flame front ignites before the flame front arrives because it becomes overheated. Under these conditions, the combustion becomes uncontrolled and sporadic and often produces a pinging noise or a knock noise when the conditions become worse.

With the water injection, it lowers the compression temperatures through the latent heat of vaporization of the liquid water to the gaseous form. The lower temperature of compression permits increased compression ratios while avoiding pre-ignition. The low temperature water injected air/fuel or enriched O₂, air/fuel mass demands less work in the compression stroke thereby increasing overall efficiency. It also promotes increased mass flow through the engine for increased power output and efficiency (Binion, 1998).

Air pollution is a major problem in most urban areas. It is a fact that air pollution is the major problem currently facing the automobile industry. The main air pollutants from gasoline engine exhaust gas are carbon monoxide (CO), nitrogen oxides (NOₓ), carbon dioxide (CO₂), hydrocarbons (HC) and particulate matters (PM). During the combustion of gasoline with water addition, the incomplete combustion is produced. The NOₓ, CO and hydrocarbon is the most dangers to the environment and human being. Nitrogen oxides occurs in the engine exhaust is a combination of nitric oxide (NO) and nitrogen dioxide (NO₂) (Ganeson, 2003).

Nitrogen and oxygen react at relatively high temperature. Therefore, high temperatures and availability of oxygen are the two main reasons for the formation of NOₓ. The peak temperature of combustion can be
lowered by injecting water to the air fuel mixture of thus lower the formation of NO\textsubscript{x}. Water emulsion has been used to control the NO\textsubscript{x} emission that was experimented by Nicholls, (1969). He found that 10% water in gasoline caused 10% to 20% reductions in nitrogen oxide.

### 3. Methodology

#### 3.1 Engine Test Setup

A 4-stroke spark ignition “CAMPRO 1.6L IAFM” fuel injection type of engine coupled to 150 kW dynamometer was utilized in this study. Standard instrumentation was used to measure engine power, torque, injection timing, pressure of oil, barometric, intake manifold, coolant inlet, exhaust, plenum and temperature of air intake, engine oil, water coolant, exhaust as well as brake specific fuel consumption and percentage of relative humidity. Engine torque was measured via a part load test which connected at the dynamometer coupling shaft. The reason why the testing is through a part load test is due to high vacuum pressure in intake manifold is needed to assist the water mist to flow into the combustion chamber.

Firstly, the experiment is carried out to get the standard performance curve and actual parameters as an input for engine model simulation. After the model is generated, it has to be validated to make sure the accuracy of the model by comparing it with the result that we gain from the standard engine performance testing. Once the model was validated, the final goal was to use GT-Power to explore the abilities of adding the water mist to the engine system. By exploring all of the possible intake and exhaust manifold pressure, the optimum result would be chosen while trying to maximize specific quantities. The target parameters include volumetric efficiency, fuel efficiency, indicated mean effective pressure (IMEP) and others.

#### 3.1.1 Engine Specification

The testing has been done at Proton Research Center in Shah Alam. The engine that has been used is a spark ignition, electronic fuel injection system with the model of CAMPRO 1.6 IAFM (Integrated Air-Fuel Module) Proton Engine. This engine is essentially a basic DOHC CAMPRO engine equipped with a variable-length intake manifold, developed under a joint fast track programmed which began in April 2005 by EPMB, Bosch and Proton. The details of the specification are shown in table 2.

<table>
<thead>
<tr>
<th>No</th>
<th>Description</th>
<th>1.6 CAMPRO IAFM Engine</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Valve Mechanism</td>
<td>16 Valve IAFM DOHC</td>
</tr>
<tr>
<td>2.</td>
<td>Total Displacement</td>
<td>1597cc</td>
</tr>
<tr>
<td>3.</td>
<td>Bore (mm)</td>
<td>76</td>
</tr>
<tr>
<td>4.</td>
<td>Stroke (mm)</td>
<td>88</td>
</tr>
<tr>
<td>7.</td>
<td>Fuel Type</td>
<td>Multi Point Injection Petrol</td>
</tr>
<tr>
<td>8.</td>
<td>Compression Ratio</td>
<td>10</td>
</tr>
<tr>
<td>9.</td>
<td>Horse Power</td>
<td>110Hp(82kW) @ 6500rpm</td>
</tr>
<tr>
<td>10.</td>
<td>Torque</td>
<td>148 Nm @ 4000rpm</td>
</tr>
</tbody>
</table>
3.1.2 Data Acquisition System

The engine test bed is linked to the desktop computer for complete data acquisition and control. All the parameters will be displayed on a monitor as well as viewing a graph for the performance test. The schematic diagram in figure 2, shows the whole experimental test rig set up.

![Figure 2: Experimental Test Rig Facilities](image)

3.1.3 Engine Measurement

In this experiment, the SAE J1349 standard has been used. Besides of the experimental procedure is explained, the SAE J1349 is also specify various ways to include the engine's internal losses, and therefore presents a more accurate indication of engine power.

The standard CAMPRO IAFM engine testing was first conducted under several part load condition with variable engine speed started from 1000 rpm up to 4500 rpm at normal operating conditions without water mist addition. The engine was fixed at constant load factor started from 0.3, 0.4, 0.5 and 0.6 with wide open throttle position and engine speed is set to keep it increasing. This test was repeated by the advance of the ignition timing with the increasing of engine speed. During the testing, the data for engine torque, brake specific fuel consumption, throttle position, exhaust temperature, plenum temperature, air intake temperature, fuel mass flow rate, barometric pressure, ignition timing etc. has been recorded.

The final results were acquired from the average of two stable and continuously measured values, which do not vary by more than 2%. All the data recorded were used for modelling validation and comparison with the engine testing which use without water mist and with water mist addition. Then the performance test was repeated as similar as testing the standard engine without the water addition but this time the water addition device has been installed.

The data were recorded as similar with the standard engine performance testing for comparison purposes.

3.2 Engine Emission Test and Measurement

The engine gas analyser is used for measuring the exhaust-gas components CO, HC, CO$_2$, O$_2$ and NO (NO can be retrofitted) which connected to the end of tail exhaust pipe. The A/F ratio lambda calculation is based on the measured exhaust-gas values. The non-dispersive infrared method (NDIR non-dispersive infrared spectroscopy) is used for the measurement of CO, CO$_2$ and HC percentages. The oxygen content is determined by an electro-chemical acting sensor.

3.2.1 Air Fuel Ratio Measurement

The gas analyser bases its A/F ratio lambda measurement on the measured concentration of HC, CO, CO$_2$ and O$_2$. An exact oxygen-content measurement is vital for the lambda calculation. The value calculation is based on the Brettschneider formula:
3.2.2 Oxygen Measurement

The gas analyzer is equipped with an O\textsubscript{2} sensor. The O\textsubscript{2} sensor is screwed into the rear side of the VPSM (Vehicle Power Supply Control Module) at the location specified for it. The O\textsubscript{2} sensor is a part subject to wear. Oxygen measurement is automatically compared with the atmospheric oxygen of 20.9 % by volume and is required for the lambda calculation (Robert Bosch, 2007). After all the above operation has been completed, connect the gas analyzer probe to the end of the engine tail pipe and start to measure the emission without water addition added to the system, as shown in figure 3.12. Start the engine and slowly increase the engine speed started from 1500 rpm till 6000 rpm. The testing need to do several times to ensure that the result obtained is more accurate and reliable. The system will record all the data through the computer. From the result obtained, and then analysed to confirm the data measurement is close to actual reading for the internal four stroke SI-EFI engine with catalytic converter.

4. Results and discussion

4.1 Simulated Engine Model

The entire step by step that has been discussed above are used to make a complete model of the engine as shown in below figure 3. The complete model shown is referring to the original CAMPRO engine without adding the mist of water in to it.

Figure 3: Complete Standard Engine GT-Power Model
4.2 Validation of GT POWER Model and Experimental Measurement Without Water Addition

After the simulation run on complete model, the data measured from the experiment, is to be used that make GT-Power graph as close as possible to the final experimental results shown in below figure 4.

![Figure 4: Comparisons of GT Power Modelling with Experimental Result On Base Engine](image)

There are difficulties to make the simulation graph as close as possible to the experimental result. This is due to the simulation run without the fuel energy losses by the engine. The way to make it as close as possible is to adjust the fuel burn rate of the engine. The relative error between the measured data of the experiment and the GT-Power model are present as follows:

![Relative Error Graph](image)

From the relative error above, the GT Power simulation of the engine can be considered almost 90% accurate.

4.3 Reliability of Water Addition in the Simulated Model

After all the component of water addition has been placed to project file base on Standard GT POWER model, then run the simulation. The adjustment has been made to the mass flow rate of the water till its shows either the performance is towards positive or negative result. The comparison is based on simulation models and the experimental result with water addition into the system. From figure 5, shows that the simulation and the experimental works cannot get as close to experimental result because of the mass flow rate that has been used during the simulation are not consistent.

![Figure 5: Simulation Versus Experimental With Water Addition](image)
4.4 Performance of Standard Engine without and with Water Addition

Several testing parameters have been done to get the performance of the engine. The testing is run under constant load test of 0.3, 0.4, 0.5, 0.6 factor condition which is wide open throttle is maintain and increasing gradually the speed of the engine started from 1500 rpm to 4500 rpm. All the data and results of engine testing which use a water addition and standard engine without water addition have been recorded to facilitate analysis and discussion which will be explained in the following step.

4.4.1 Power and Torque

Test was done to determine the maximum torque increase with adding the water mist into the engine.

![Figure 6: Torque vs Engine Speed at Various Load Condition](image)

Compared to standard engine without water addition, engine with water addition at load factor 0.3, 0.5 and 0.6 produces a bit increasing of power and torque started at 1500 rpm till 3250 rpm. The increasing engine performance of the engine with water addition is mainly due to high volumetric efficiency of the dissociation of water converted into hydrogen and oxygen. Figure 6 shows that the engine operation with water addition produced on the average torque approximately 10.0% to 14.0%, respectively, compared to that of standard engine (without water addition).

The graph in figure 6 also shows that the torque keeps reducing started from approximately 3250 rpm till 4500 rpm. From the experiment the volumetric efficiency also keep reduce. This is due to when high speed the vacuum suction inside the intake manifold were reduce and this will reduce the amount of water to get into the intake manifold.

4.4.2 Fuel Consumption

The reduction of brake specific fuel consumption shows the overall performance of an engine. It shows that with the high torque produces by the engine, its use less fuel consumption.

This experiment is to get the fuel consumption rate with an experiment with and without adding water mist to the system. During both of the experiment the throttle angle is fix by varying the load to the engine according to the various speed started from 1500 rpm to 4500 rpm.

From the figure 7, shows that the b.f.s.c somehow reduce dramatically for the testing with load 0.3 with water addition and the other load factor looks a bit reduce with and without water addition to the engine. The less fuel consumption about 3% to 6% was obtained started at 1500 rpm up to 3000 rpm. It also indicate that increasing in engine torque with water addition shows the fuel consumption keep increasing after the speed reach more than 3500 rpm.
4.4.3 Torque with and without Adjustment of Spark Timing

Spark timing is considering the correct timing of the spark plug to ignite the air fuel mixture in the combustion chamber. J.A Harrington (1982) reported that the power output of the engine, with and without water added, therefore depend strongly on spark timing setting relative to MBT.

An experiment has been conducted with an adjustment of the degree for the spark plug to ignite. With the engine with multipoint injection used, the controlling is being done by electronically control by specific control device. The advances of the ignition timing are approximately 6 degree every time the speed of the engine increasing gradually (1500 rpm, 2000 rpm, 3000 rpm, 3500 rpm, 4000 rpm and 4500 rpm). Figure 8 shows the effect of the advances of ignition timing to the engine with adding water addition to the system.

The comparison is focused on standard ignition timing and advances ignition timing with water addition to the engine. From the figure 8, shows that the advance of ignition timing is not give any effect to the engine performance with adding the water mist to the system. The reason for the above is the equivalent ratio between the water and the air fuel mixture is the same without and with the advance spark. So, it is actually not given any improvement to the power output of the engine. This is supported by Gunnerman (1992), says that the combustible fuel is exploded by the high voltage spark, which helps to crack the water molecule into hydrogen and oxygen which are in turn exploded to not only give a cleaner burn but also to add considerable thrust to the piston.
4.5 Emission of Standard Engine without and with Adding Water Mist

An experiment for exhaust gas emission has been done by using the Bosch gas analyser in recording the data of the emission produced by the engine. The experiment is being done under certain speed started with 1000 rpm, 1500 rpm, 2000 rpm, 2500 rpm, 3000 rpm, 3500 rpm, 4000 rpm, 4500 rpm and 5000 rpm. The testing is being done for both water and without water mist addition to the engine.

4.5.1 Effect of Water Addition on Nitric Oxide Emission

The variation of nitric oxide concentration at the engine exhaust with and without water addition is given in figure 9.

![NO Versus Engine Speed](image)

Figure 9: NO vs Engine Speed

The results show that the concentration of NO for with water addition is lower than without water addition to SI engine with no load operating condition. It shows that when the engine speed keeps increasing the formation of NO is increasing. When the engine speed increase, it produce high temperature which allowed the formation of NO\(_x\). This is supported by V. Ganeson(2003) which high temperatures and availability of oxygen are the two main reasons for the formation of NO\(_x\). When the proper amount of oxygen is available, the higher the peak combustion temperature, the more is NO formed. Therefore, with water addition, it would reduce the peak combustion temperature in the combustion chamber thus reduce the formation of NO\(_x\).

4.5.2 Effect of Water Addition on Carbon Monoxide Emission

The results of CO emissions with water addition is lower than without water addition, SI engine with no load operating condition shows in figure 10.

![CO Versus Engine Speed](image)

Figure 10: CO vs Engine Speed
The results show that with water addition to SI engine are not much affected. As we known, CO is a product of incomplete combustion due to insufficient amount of air in the air fuel mixture or insufficient time in the cycle for completion of combustion.

5. Conclusion
The contribution of this research can be summarized as follows:

i) Developed simulation model for EFI SI CAMPRO 1,6 L 4-stroke cycle engine with/without water addition.
ii) Validated simulation model through experimental investigation.
iii) The result has shown up to 10% increase of power, torque and volumetric efficiency using water addition into the engine.
iv) There was a decrease of fuel consumption by 3% to 6% when engine runs from 1500 rpm to 3500 rpm using water addition.
v) NO\textsubscript{x} emission was significantly reduced using water addition into the engine but there was no change of CO emission.

Overall result indicates that water addition leads to an increase of the performance of the engine and a reduction of the emission produced by the engine.

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Reference


