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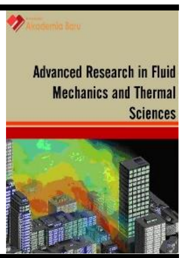

Engine Characteristics Analysis of Turbocharged Spark Ignition Engine with Water Injection Charge Air Cooling

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ABSTRACT

This paper presents the effect of engine performance by water injection charged air cooling. Water was injected into the intake manifold with different flowrate in a turbocharged spark ignition engine. The simulation was done on a validated engine modelling using GT-Power simulation that was based on a 1.6L turbocharged CamPro CFE engine. Two injectors were used to inject the water into the intake manifold. The addition of water injection shows potential to improve the engine operation characteristics. Improvement of brake torque as much as 19% and brake power as much as 10% have proven that the charged air cooling has improved the turbocharged engine. In this this study, the charged air intake raises the air density in the combustion chamber and has improved the brake specific fuel consumption as much as 23%. With the introduction of water to the upstream of the engine operation, the cooling effect does assist the engine to improve.

1. Introduction

In a turbocharged engine, air intake temperature is increased after the compression process. A higher air intake temperature will produce engine knocking that is caused by the fuel self-ignition. Therefore, the air intake is cooled before it enters the combustion chamber to avoid the engine's knocking and to increase the air density [1]. The charged air cooling will reduce the engine knocking and increase air density. Therefore, more oxygen enters the combustion chamber and the fuel combustion becomes more efficient. In conventional system, air-to-air cooling system is used [2]. However, air-to-air cooling system requires larger spaces in the engine compartment. Thus, a compact water-to-air cooling system which has a higher overall heat transfer coefficient is a better option [3]. However, water-to-air cooling system is complicated to build. Two automotive manufacturers, Volkswagen and Audi; are well known of using water-to-air cooling system in their powertrain system. Audi 1.2L TSFI engine for example, the charge air cooling is shared with engine

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cooling system in two different circuit flow. They are connected and disconnected by non-return valve and flow restrictor [4]. Sankar *et al*., has proved that water-to-air intercooler was more effective compared to air-to-air intercooler. Water has higher coefficient in heat transfer compared to cold air [3].

1.1 Water Injection

In 1940's, most of the warplane used for world war II were using supercharged gasoline engine. The war planes were facing the engine's knocking problem [5]. The application of heat exchanger for the cooling system is not practical because of the weight addition and the part is exposed. Rothrock *et al*., used water as a cooling agent to minimize engine knocking. The application has improved the intake air by reducing the temperature, increase the air density and higher combustion efficiency was achieved. Thus, the warplane was able to fly higher and less smoke was produced from the aircraft exhaust. Boretti also reported that water injection reduced the occurrence of knocking in turbocharged spark ignition engines. The usage of port water injection in Formula one engine is very effective to control knocking and exhaust gas temperature to the turbine. Injection of water upstream proved to lower the combustion temperature and limit the knocking tendency [6]. Study done by Breda *et al*., on the water and ethanol mixture injection into the GDI engine has shown how the intake cooling effect by different types of cooling agent influences the knocking occurrence in engine operation. The study analyzes the best mixture to avoid knocking and found out injecting pure water can lead to lowering the knocking tendency [7]. Turbocharged engine has higher density of intake air, thus it will give higher pressure and temperature with higher temperature the tendency of knocking is high. This will give a problem if the engine increases the torque and power. Recently, researchers have used the water injection method that was proposed by Rothrock *et al*., as their reference of study. Tauzia *et al*., the engine performance with water injection and compared with the Exhaust Gas Recirculation in the naturally aspirated (NA) engine [8]. The study found that the NOx emissions is improve as much as 50%. However, the study is tested to the NA engine and the exhaust pressure amount of exhaust gas expelled is different to compared with turbocharged engine. Most of the performance criteria for the water injection system is to study the improvement of the emission level [8-12]. The studies show that the HC is decrease as much as 5%, the $CO2$ is improved as much as 3% and the NOx is improved as much as 34%. Subramanian et al., reports that the NOx can be improves as much as 70% without any loss in brake thermal efficiency [13]. Turbocharged engine has higher combustion rate than NA engine [6]. Water injection is reported capable to reduce the in-cylinder temperature and help improves the engine characteristics and improves capability for the engine to perform [8]. Although the study shows an improvement towards the emissions result, it is performs on the compression ignition engines. The value is varies to spark ignition due to amount of carbon in the fuel mixture is completely different.

1.2 Engine Characteristics

Water injection does improve the power output of an engine. Most testing done on water injection provide the result for engine power. Arabaci has done a trial and experiment on a different type of engine and shows brake power increase as much as 10% [11]. This shows that temperature decrement will provide better engine operation. By improving the engine temperature, detonation or knocking occurrence also being reduces and this results in improved engine power. However, this study has been done on six stroke engine that specifically design for engine operation with water injection stroke. Berni *et al*., [14] found that by injecting water into the combustion the in cylinder pressure is decrease but the indicated power is increase as much as 2%. The in cylinder pressure give the engine ability to the engine to drive as the piston was force in the power stroke. Higher in cylinder pressure indicates the higher capability of the engine to overcome force inside the cylinder [15]. Kim *et al.*, found that the in-cylinder pressure were increase with the introduction of water injection in low speed. The study shows that below 3000rpm the in-cylinder pressure increase to provide more torque to the engine [16]. According to Busuttil *et al.*, the intake temperature change by injecting water in the combustion effect the engine torque by as much as 7% [17]. Higher in-cylinder pressure obtained by the engine produced higher torque. High pressure in the cylinder operation will give more power to rotate the crankshaft. Water injection helps engine operate with better efficiency [18].

Brake specific fuel consumption (BSFC) is the measured value of the total amount of fuel used to generate 1kW of brake power. The improvement of brake power in engine operation with water injection is linked to the increase of in-cylinder pressure. Wu *et al.*, found that higher in-cylinder temperature delivered by higher engine load will lead to higher vapour temperature, and improves the working capacity of the water vapour, and improves the MEP. However, the optimal thermal efficiency remains the same under different engine load due to the fact that fuel consumption is also increased under higher engine loads [19]. In the other hand, Sahin *et al.*, obtain the diverse result where BSFC decreased by 4% and effective efficiency increased approximately 4% at 3500rpm with loads. The water addition into air did not show any significant change in the BSFC and effective efficiency of this engine at selected engine loads and speeds [20]. Lower BSFC as much as 30% achieve by Bozza *et al.*, in low engine speed around 2500rpm [21]. Cinar *et al.*, also reported specific fuel consumption and volumetric efficiency decrease with higher intake cooling rate [22]. The decrease in BSFC has been reported when water injection used in compression ignition engine. However, in spark ignition engine BSFC is increase mainly due to the amount of intake air increment.

2. Methodology

2.1 Engine Modelling

Simulations performed for a modelled 1.6 L engine with turbo charging is used. Specification of this engine is given in Table 1. The engine was modelled in GT-POWER software based on the model developed by Ismail et al. [23]. Engine model was validated by comparing the data to the published engine data. The model shows an output of the engine torque with squares data residuals of 99%. Data comparison of the engine model and the published industrial data is shown in Figure 1. The engine parameters to be studied are brake power, brake torque, volumetric efficiency and brake specific fuel consumption (BSFC). The base engine model will be used to examine engine characteristic improvements made by the water injection. In all experiments, simulation runs with different engine speed between 1000rpm and 6500rpm with intervals of 500rpm.

Table 1
Proton 1.6L CamPro CFE engine specifications

Combustion system	4-stroke, in-line, gasoline PFI
Capacity	1.6 litres
Compression ratio	9.0
Bore x stroke	76mm x 86mm
Induction system	Single-stage turbocharger
Maximum torque	205 Nm @ 2000-4000 rpm
Maximum power	103 kW @ 5000 rpm
Intake cam profile	≤ 220° (duration) / 7.51 mm (valve lift)
Exhaust cam profile	2° BTDC @ 0.15 mm lift

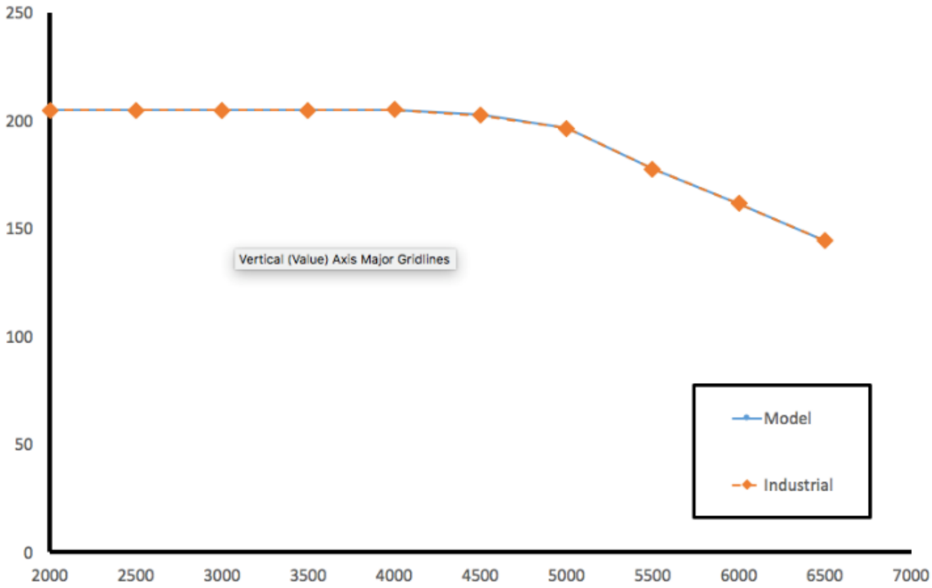

Fig. 1. Torque data comparisons of engine model and Industrial Proton 1.6L CamPro CFE data

2.2 Water Injection Modelling

The simulation gives a good foundation on expected output for water injection by varying water injection rate and location. Experiments can be carried out for various water injection rates at constant load and engine speed to observe the change in engine performance. This simulation result will show the relationship between water/fuel mass ratios to the engine performance. Engine performance is expected to increase as the water to fuel mass ratio increases. Water will be injected using injector to the intake system. The injector will inject water continuously without any control as shown in Figure 2.

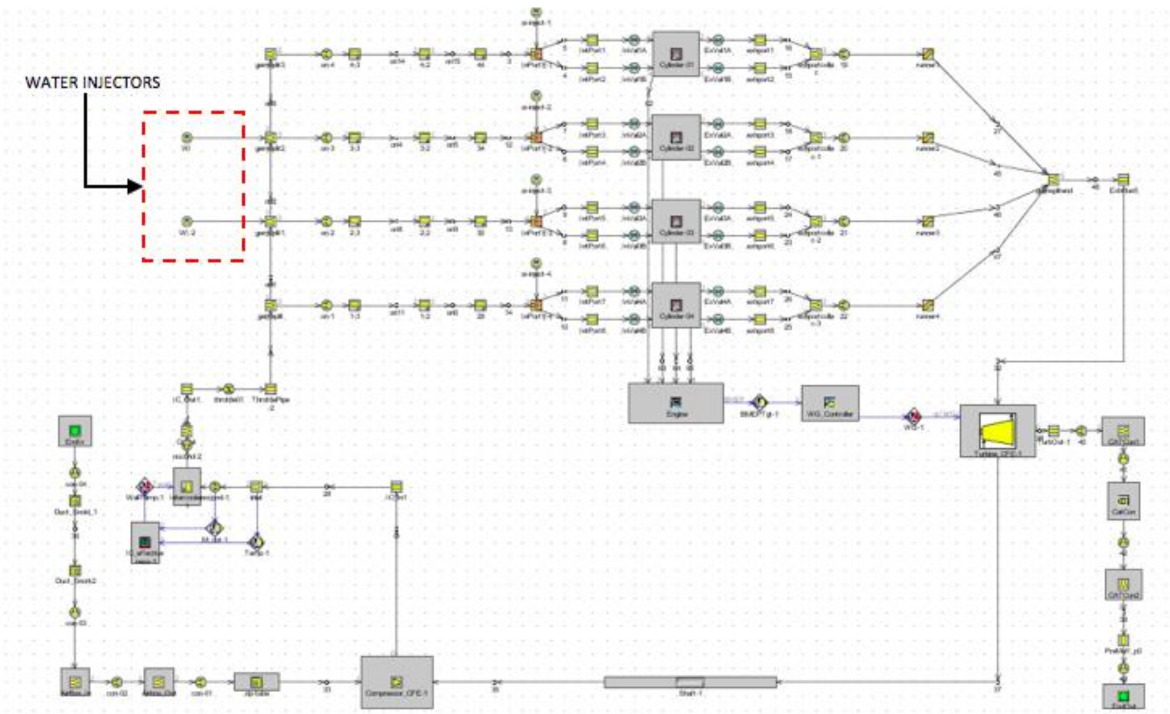

Fig. 2. Proton 1.6L CamPro CFE engine model with water injection

The red marking shows the water injector being added to the model. Injector is being added to the intake run of the model. Two injectors with mass flowrate function are used for this experiment. Different flowrates are used for this injectors are 1g/s to 20g/s with 1g/s interval. The fluid of the injector was change to H2O vapour with the ambient temperature. The injector will inject water vapour from the start of the simulation till the end. This will prove how water vapour will affect the engine operation for every loads and engine speed.

3. Results and Discussions

3.1 Brake Torque and Brake Power

Cooled air intake is desirable for turbocharged engine. This engine will experience changes in either way. Figure 3 shows the engine torque generated by the engine in the simulation. This analysis was done by taking the differences of 5 g/s water injection rate to perceive the pattern of the injection. Engine torque improves with the increment of water injection rate per injector. Increase of engine torque raised to maximum with 12 g/s flowrate by 19.6% from the maximum torque generated by the engine without water injection. Water injection rate higher than 12 g/s per-injector proved not to give any improvement to the brake torque. As recorded in the Figure 3, higher the injection rate, the lower brake torque achieved. Lower RPM with additional water injection gives negative result to brake torque. This negative value is produced by calculation in the simulation that reflects to the engine operation not generating any energy to run the engine.

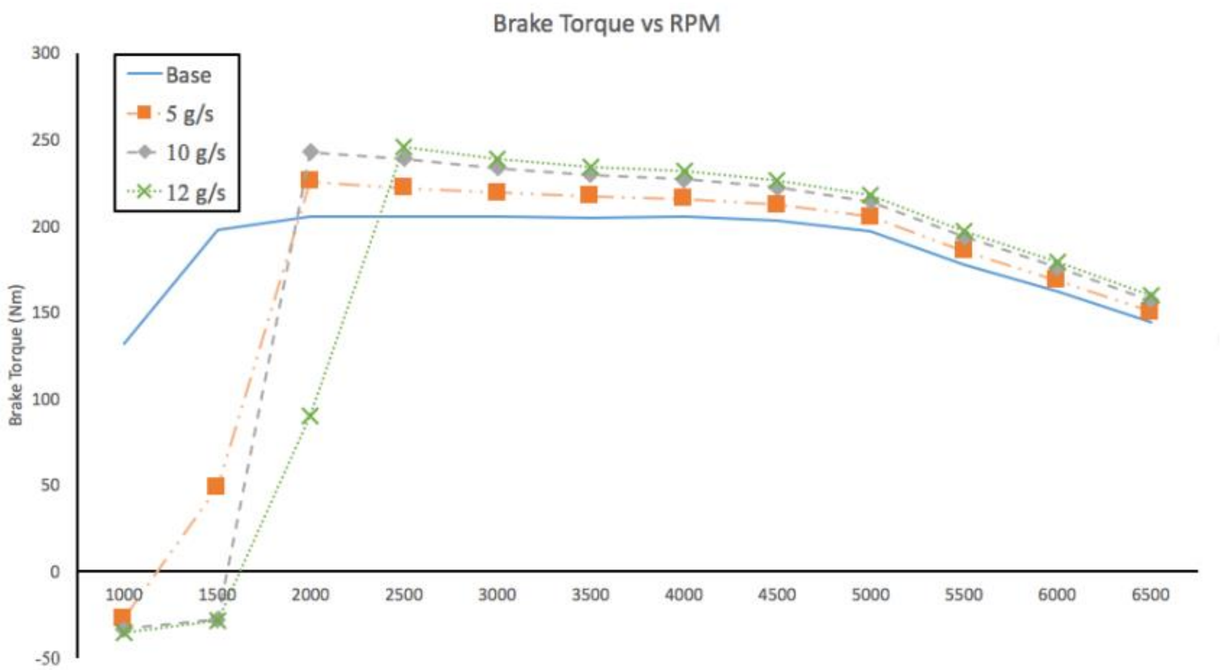

Fig. 3. Brake torque data comparisons of different water injection rate

Brake power achievement in the GT-power simulation is shown in Figure 4. Highest brake power achieved is 113.89 kW at 5000 RPM compared to the brake power achieved without water injection is 102.78kW at 5000 RPM. Brake power improves 10.8% with the comparison of the engine without water injection.

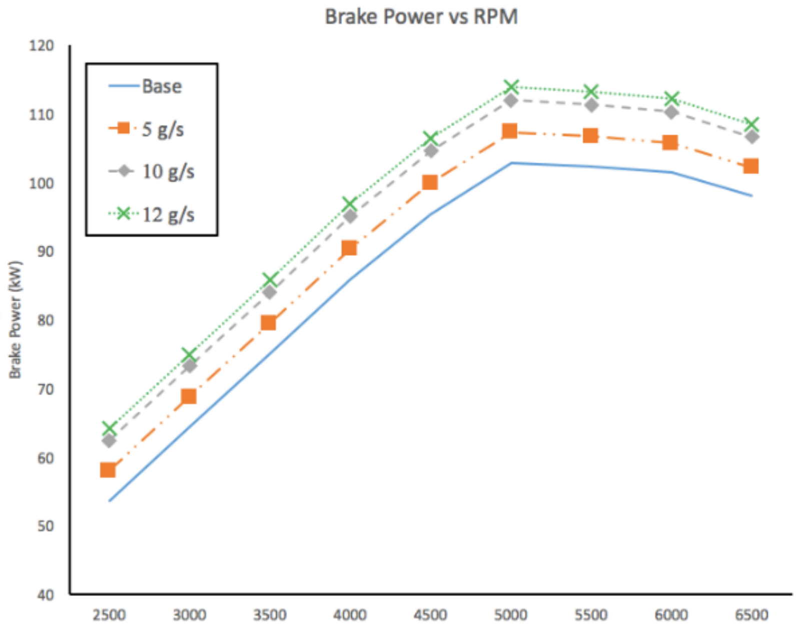

Fig. 4. Brake power data comparisons of different water injection rate

Water injection has made the condition in the combustion chamber reliable for the combustion process by lowering the operating temperature. Changes in operating temperature could be relate to other operational characteristics changes. Brake mean effective pressure of the engine increases with the increase of water injection rate as shown in Figure 5. Cylinder pressure increment generates supplementary torque to the engine.

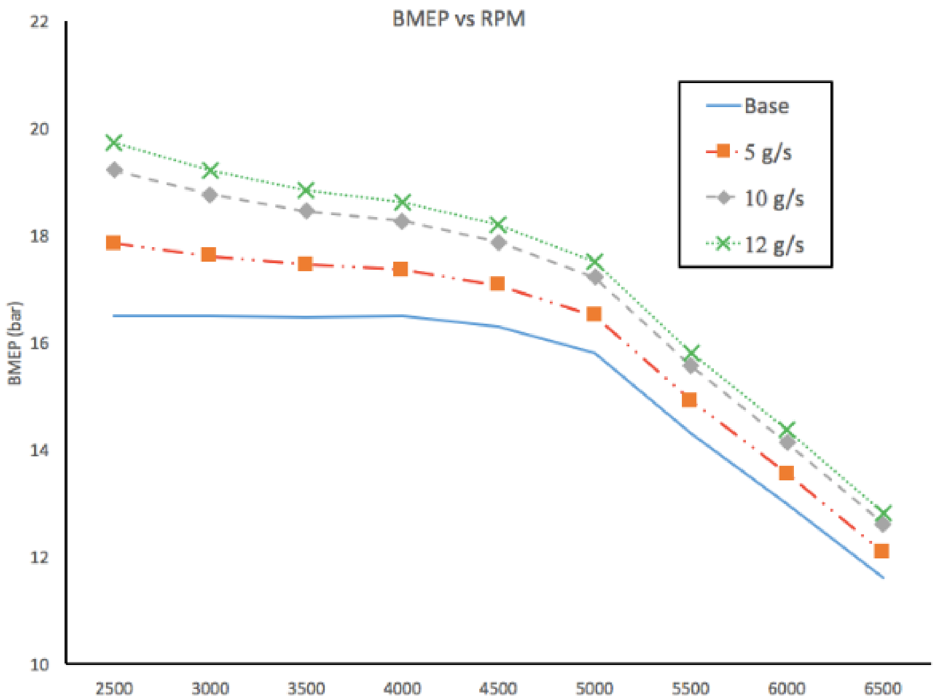

Fig. 5. BMEP data comparisons of different water injection rate

Torque improvement in water injection shown by Pressure-Volume diagram in Figure 6. This improvement effects the power and torque output of the engine. Engine speed affects the engine thermal coefficient; temperature rises with the increase of engine speed. Thus lower engine speed will have lower temperature and vice versa. It is difficult to generate torque with low RPM after the addition of water vapour to the combustion process. Combustion process in simulation is based on thermodynamic calculation. With the additional of water vapour injected into the combustion chamber, water content is higher than the air-to-fuel mixture in the combustion chamber. Stoichiometric reaction cannot be achieved here.

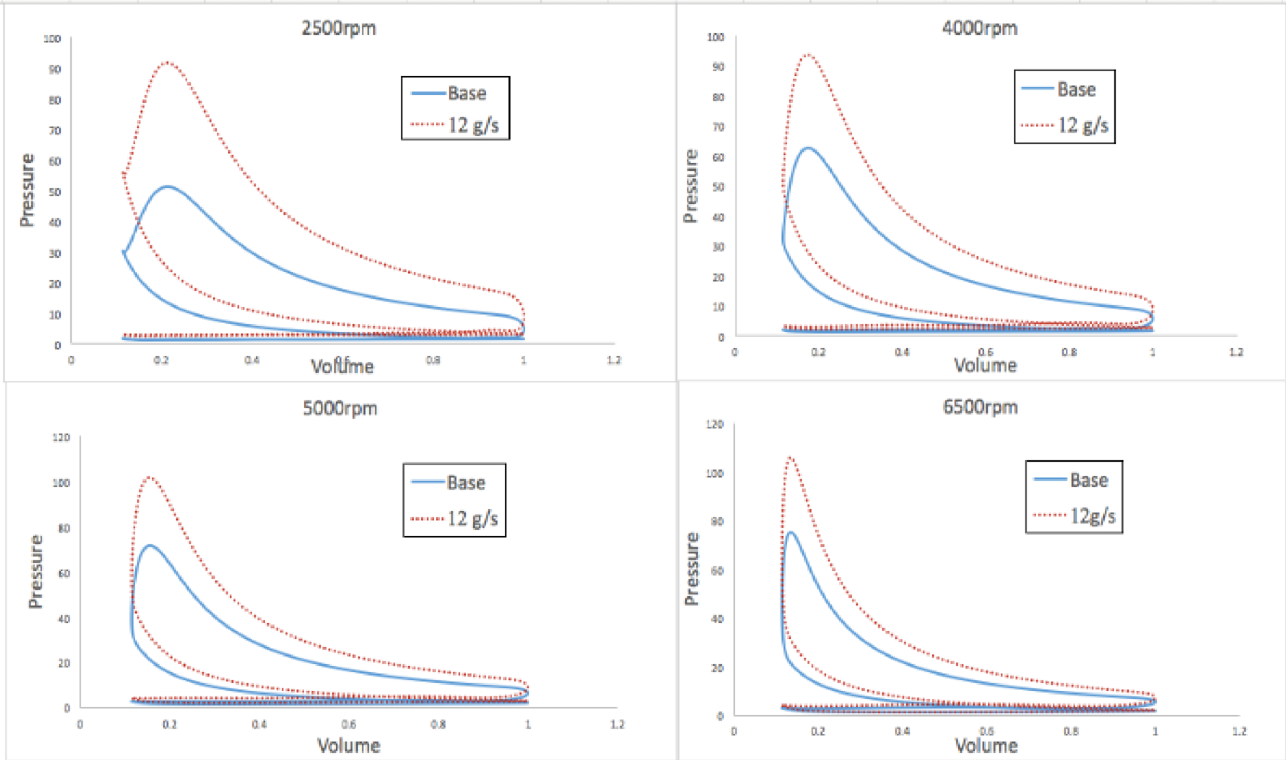

Fig. 6. P-V diagram differences for base model and 12 g/s water injection

3.2 Volumetric Efficiency

Volumetric efficiency indicates the amount of power output of the engine as compare to the amount of induces mass that is changes in the engine process. The induced mass in this study is the mixture of air, fuel and water. It is also known as breathing capacity of the engine where it is given by the ratio for the induced air volume into the engine to the cylinder swept volume. Figure 7 shows the volumetric efficiency for the baseline engine is decreased as the engine speed is increased. Base model produced highest volumetric efficiency of 1.48 at 3000rpm. Highest volumetric efficiency produced in water injection model is 2.38 at 2500rpm with the injection rate of 12 g/s. Increment of 61% of air volume process in the engine compared to the based model. This is because the amount of theoretical induced masses is increased as the engine revolution is increased. The Figure 7 also shows that the volumetric efficiency is increased as the mass flow rate of the water injection is increased. The volumetric efficiency is increased because the actual induced mass is increased.

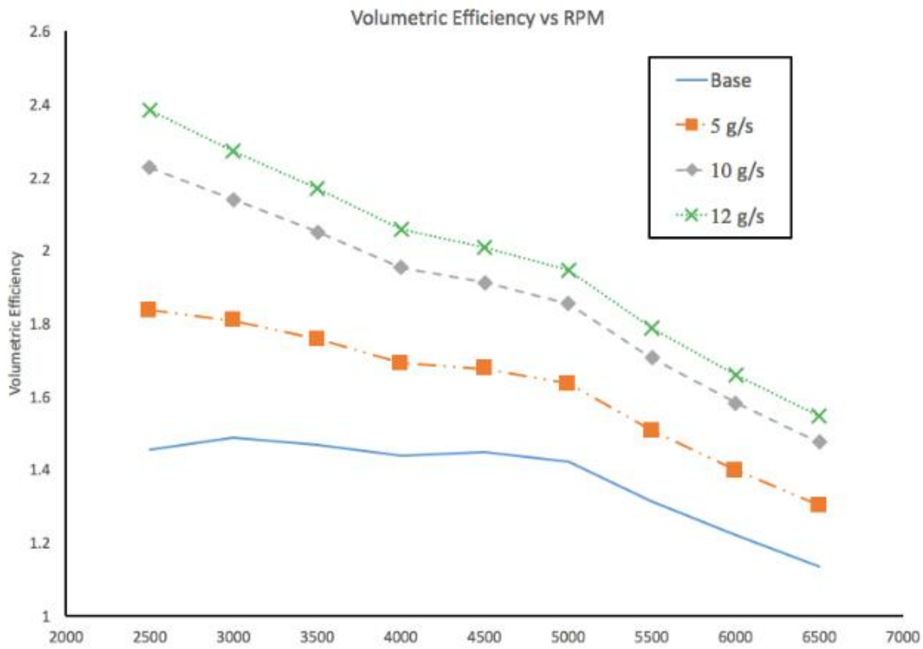

Fig. 7. Volumetric efficiency data comparisons of different water injection rate

3.3 Brake Specific Fuel Consumption

The brake specific fuel consumption (BSFC) is the ratio of the amount of fuel used to the brake power output of the engine. The larger the value, the more fuel is used to produce 1kW of brake power. The BSFC measures how the engine used the fuel to produces the power effectively. In general, the BSFC is high at the low RPM, it decreases as the engine speed is increased until it achieved its minimum BSFC value; and the BSFC will increase as the engine speed peaked at higher speed. This trend can be seen clearly in Figure 8 for the baseline engine. The similar trend is also observes for the water injected modelling.

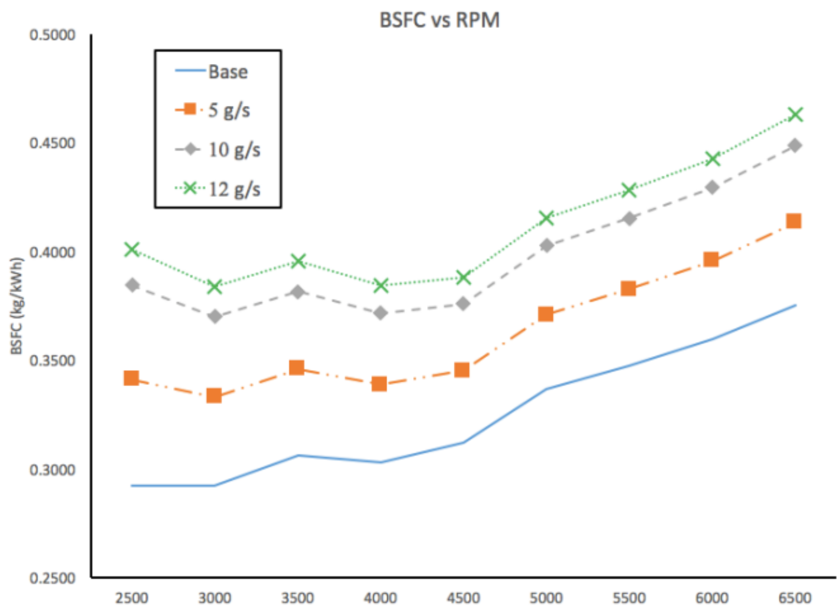

Fig. 8. Brake specific fuel consumptions data comparisons of different water injection rate

The Figure 8 also shows the BSFC is increased as the water injection is increase. Base model produced highest BSFC of 0.3755kg/kWh at 6500rpm. Highest BSFC produced in water injection model is 0.4629 kg/kWh at 6500rpm with the injection rate of 12 g/s. Increment of 23.3% from the base engine model at the same engine speed. This is due to the increased of the induced mass into the engine cause more fuel is used to mixed with the air.

4. Conclusions

In this study the effects for the addition of water into intake air on engine performance characteristics were investigated experimentally in GT-Power simulation. Brake torque of the engine is increased significantly with the addition of water into the intake. This is due to the changes in the combustion process that is led by changes in-cylinder pressure and increases the torque generates by the engine. Improvement in brake torque increase the brake power of the engine.

The improvement of the intake air temperature provide engine with higher amount of air in the engine process, thus brake specific fuel consumption increases to generate combustion in the cylinder. Addition of fuel is necessary to provide stoichiometric proportion to intake air and completion of combustion.

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