Water Injection for Higher Engine Performance and Lower Emissions

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Water injection for higher engine performance and lower emissions

Wei Mingrui [a, b], Nguyen Thanh Sa [a, b, c, *], Richard Fiifi Turkson [a, b, d], Liu Jinping [a, b], Guo Guanlun [a, b]

[a] Hubei Key Laboratory of Advanced Technology for Automotive Components, Wuhan University of Technology, Wuhan 430070, China
[b] Hubei Collaborative Innovation Center for Automotive Components Technology, Wuhan University of Technology, Wuhan 430070, China
[c] Faculty of Mechanical Engineering, Ho Chi Minh City University of Transport, No.2, D3 Street, Ho Chi Minh City, 70000, Viet Nam
[d] Mechanical Engineering Department, Ho Polytechnic, P. O. Box HP 217, Ho, Ghana

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A B S T R A C T

The influence of variable water injection by mass on the performance and emission characteristics of a gasoline direct injection (GDI) engine under light load conditions has been investigated and the results are presented in this paper. The study involved the injection of water into the cylinder at an angle of 640 °CA over an injection duration of 10 °CA. Gasoline was directly injected into the cylinder with a fixed injection timing duration starting from 660 °CA to 680 °CA and determined the flow rate of fuel. The results indicated that a 15% water injection by mass used together with fuel gave the best engine performance due to the increase in the indicated mean effective pressure and efficiency resulting from the cooling of certain parts of engine. Water injection also demonstrated a decrease in the NOx emissions (ppm), as well as soot emissions.

1. Introduction

The higher thermal efficiencies attained by an internal combustion engines could be linked to the use of higher compression ratios. However, the use of high compression ratios leads to higher combustion temperatures and creates conducive conditions for the formation of nitrogen oxide (NOx) emissions. Many studies have shown that the formation of NOx increases as the compression ratio increases [4,16]. For a gasoline engine, the increase in compression ratio, would lead to the formation of NOx emissions because of the near-stoichiometric air–fuel ratio used to ensure that the conversion efficiency of the catalytic converter used for converting NOx emissions remains fairly high [2].

Additionally, the higher compression ratios employed by internal combustion engines leads to higher temperature at the latter stages of the compression stroke and a higher local temperature at the earlier stage in the combustion and expansion processes, resulting in a rapid NOx reaction rate. Minimizing NOx formation via gasoline direct injection is well-known, and has been studied by many researchers [7,11,13,21]. The method of introducing a water injection system would be one of the perfect solutions to reduce NOx formation [18,23]. The thermal-dissociation process of water will form hydroxide and hydrogen at high temperature, which absorbs the heat during combustion [20]. The water not only absorbs the heat of intake gas for decreasing the temperature, but also to provides oxygen for burning the fuel. The injected water also reduces the local temperature of the combustion flame and leads to lower NOx emissions.

Fundamentally, water injection in the spark-ignition (SI) engine helps in controlling the temperature and pressure of the combustion process. Hence, this method is useful for controlling unwanted emissions. An improvement in the volumetric efficiency of an engine and its power output may also be achieved via water injection technology. Water or steam injection systems have been used in gas turbine engines since the last century [14]. In reality, its application in internal combustion engine running on conventional fossil-based petroleum fuels is rare. Moreover, a water injection system is also considered as cheaper and simpler solution for improving the power output of an SI engine.

* Corresponding author. Hubei Key Laboratory of Advanced Technology for Automotive Components, Wuhan University of Technology, Wuhan 430070, China. Tel.: +86 159 2724 6606.
E-mail address: nguyenthanhsa@gmail.com (N. Thanh Sa).

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The effect of water injection on the performance of an SI engine with hydrogen as fuel was investigated by [18]. The emission related problems and the effects of injected water into the cylinder of an engine on air–fuel mixture and combustion were studied and discussed the study. The experimental engine had a single cylinder and four (4) valves, and was manufactured by the Ford Motor Company. The study [18] concluded that water injection was a better technique for reducing NOx emissions. At high load, water injection was delayed and prolonged the combustion phase, which required an advanced spark timing setting in order to maintain its power output. Furthermore, Gadallah et al. [12] implemented a similar study on a hydrogen fueled direct injection SI engine in combination with the use of a water injection system. A water injector was installed adjacent to a spark plug on a single cylinder engine with the amount of injected water ranging from 4 to 14 mg/cycle using different compression ratios. The study demonstrated that water injection during the latter stages of the compression stroke improved the indicated thermal efficiency and reduced NOx emissions.

A study [10] based on a single cylinder experimental engine used two kinds of fuel: pure gasoline and 35% volume butanol–gasoline blend + 1% H2O addition. The experiment covered two operational modes with full and partial loads at 6500 rpm and 8500 rpm, respectively. The results demonstrated that engine performance, brake specific fuel consumption (BSFC), CO and HC emissions of the dual fuel were better than those of the pure gasoline under the test conditions considered. In another study [17] the effects of hydrous ethanol (with a high water content up to 40%) on the performance and emissions of a small spark ignition engine for a generator was investigated. The result indicated that CO, HC and NOx emissions after the catalytic converter were lower than the EPA limit for the model year 2011, with 5% water content in ethanol, a constant engine speed of 3600 rpm and a stoichiometric air–fuel ratio. The study also indicated that there was an overall decrease in efficiency and NOx emissions as opposed to an increase in the brake specific fuel consumption (BSFC), HC, CO, formaldehyde and acetaldehyde emissions by increasing the water content in the cylinder at constant load. For 16% of water, the NO emissions could be reduced by 30% and the engine worked normally with a gasoline–alcohol fuel spray containing up to 30% ethanol and 16% water [6].

Wu et al. [26] presented a novel concept for combining the water injection process with an oxygen-fueled internal combustion engine cycle for enhancing thermal efficiency. The water was injected into the cylinder after being heated by passing it through the engine coolant and exhaust gas systems. Heat waste stored in exhaust gas was recovered for doing work and the achievement higher thermal efficiency. Calculated results showed that the thermal efficiency reached 53% and 67% when the water injection temperature was 120 °C and 200 °C, respectively. Moreover, the indicated thermal efficiency increased from 32.1% to 41.5% under similar test conditions with an increase in both engine load and water injection mass.

The water injection technique also has been applied for many years for controlling NOx emissions in compression ignition engines. Kohketsu et al. [15] focused on the effect of NOx and PM emission in traditional diesel engines by using stratified fuel-water sprays. Using water injection in combination with EGR, Euro V emission levels could be achieved by heavy duty engines [22]. In addition, this system is also used to increase the working stability under higher compression ratios [17].

Boretti [3] used water injection in combination with turbocharging, with ethanol as a fuel to explore the possibility of reducing the tendency to detonate, increasing the charge efficiency, and controlling the temperature of gases flowing to turbine. The possibility of the engine using higher compression ratios and boost pressures was also investigated by a study reported by Cesur et al. [5] and involved investigations on an original engine in combination with water injection under selected operating conditions. Together with water, steam was injected into the engine. The optimum steam ratio in comparison with the fuel mass was fixed at 20%, with the investigation focusing on the performance and emission parameters. The presence of water injected into the cylinder may improve atomization and mixing which leads to increase in the combustion efficiency and, in effect, higher engine output [9,24].

In this investigation, simulations were carried out to analyze the effect of water injection on the performance and emissions of a gasoline direct injection engine. The major objective was to determine the best water mass in comparison with fuel mass for better engine performance and emission control. Moreover, water was added as absorbent which could potentially help to control the peak temperature during combustion. The vaporization of water is expected to reduce the temperature of the gas charge at the latter stages of the compression stroke. The vaporized water also had the potential of decreasing the concentrations of both oxygen and nitrogen. The ignition delay and combustion duration using water injection was also changed, with its influence studied and discussed.

2. Study procedure

The engine model had an axisymmetric cylinder with the inlet and exhaust valves located about the cylinder axis. To obtain a flow field and combustion characteristics, the ensemble-average for differential form of continuity equations, momentum equations, energy equations were solved with the appropriate boundary conditions. The finite volume method was employed for numerical solving of the governing equations to the relevant boundary conditions. The upwind technique was employed to discretize the convective terms. The computer terms were developed by using the SIMPLE algorithm. Turbulent flow conditions were considered. The standard k-ε turbulence model for fluid flow, turbulent combustion and spray model were utilized.

Fame engine plus had been employed for producing 3D hexahedral cells for engine moving mesh, which involved the intake port and valves, the cylinder head, the combustion chamber, the exhaust port and valves. The number of cells was about 168,498 at top dead centre (TDC) position and around 436,286 cells at bottom dead centre (BDC) position; while about half of the cells of the computational mesh around the valves and combustion chamber were concentrated to obtain accurate results.

An important consideration of engine simulation is computational time. In this work, the required CPU time for generating the moving mesh from 360 °CA of the intake stroke to 1080 °CA of the exhaust stroke was around 43 h and around 48 h for simulating the engine processes at an engine speed of 2000 rpm on an 3.4 CPU RAM 8 GB computer.

The simulation was started from 360 °CA at the top dead centre of the intake stroke and finished at 1080 °CA of the exhaust stroke. The inlet mass flow rate, intake temperature, outlet pressure, and the cylinder head temperature, were used as boundary conditions based on available AVL data. The initial pressure was fixed at 120 kPa while an initial temperature of 1014 K was used as the initial conditions. An initial density of 1.19 kg/m^3 of gas was used with the assumption that the working fluid was fresh air for the simulation process. The initial value of the turbulent kinetic energy *k* was set equal to 5% of the kinetic energy and the turbulence length scale was assumed to 0.001 m.

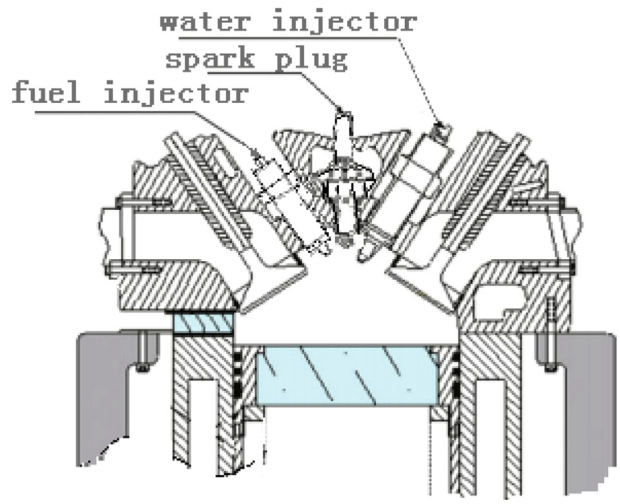

Fig. 1. Schematic representation of engine model for numerical investigation.

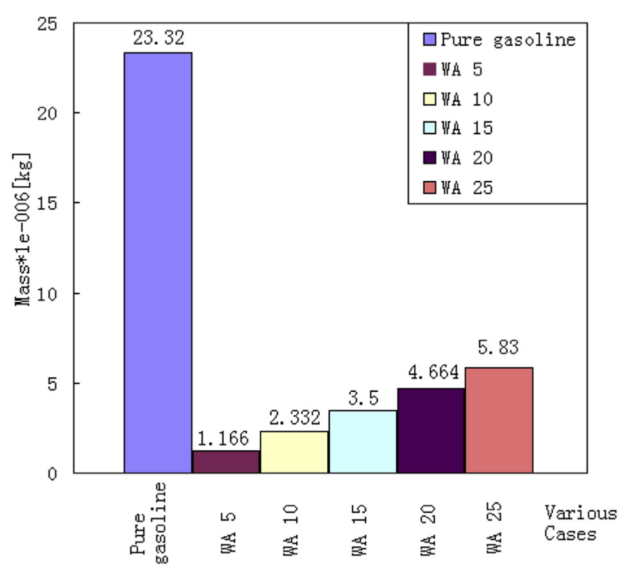

Fig. 2. The gasoline mass and different water addition ratios per a cycle for various cases.

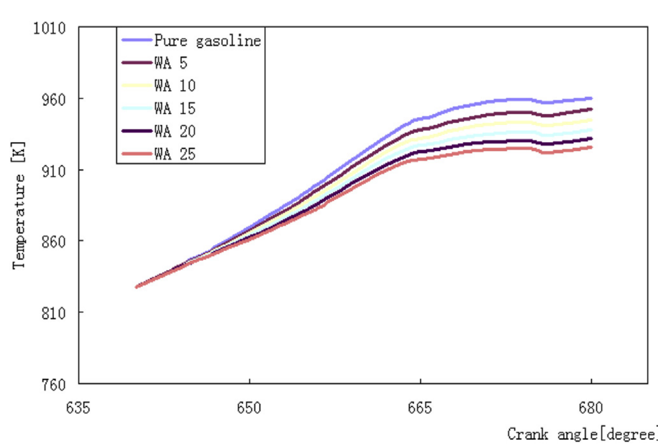

Fig. 3. The effect of water injection on the in-cylinder temperature of the suction gas, during the latter part of the compression stroke.

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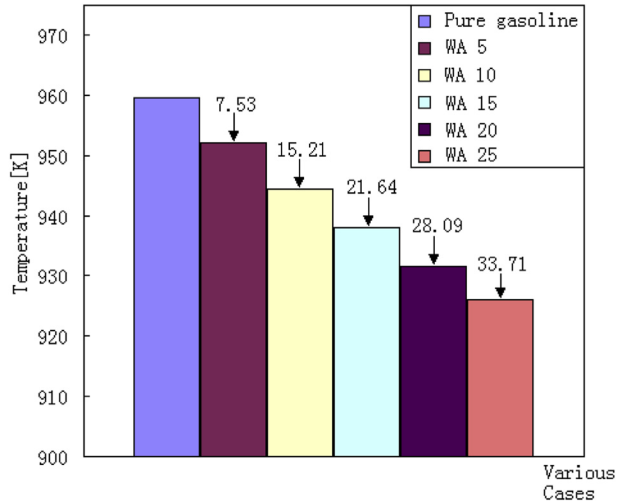

Fig. 4. The effect of water injection on the in-cylinder temperature of the suction gas at the end of fuel injection (680 °CA).

AVL Fire was used as the program for the simulation. For the combustion model, the Eddy Break-up Model was used; and for NO formation, the Original Heywood Model. The Eddy Break-up model has been used in many studies about combustion engineering and it was considered as the typical example of the mixed-is-burnt combustion model. This combustion model assumed that the chemical reactions are completed at the moment of mixing, so that turbulent mixing completely controls the reaction rate.

The gasoline direct injection (GDI) engine model was used with gasoline as a fuel, employing a compression ratio of 13:1. The simulations were carried out at an engine speed of 2000 rpm. Fuel was injected into the cylinder beginning at 660 °CA for an injection duration of 20 °CA. The water injection system worked in a similar manner to a fuel injection system only that it injected water instead of gasoline. The water injector sprayed water into the compressed air before fuel injection at 640 °CA with the duration for water injection ending at 650 °CA. The study applied different cases of water addition in the order of 5% (WA 5), 10% (WA 10), 15% (WA 15), 20% (WA 20), and 25% (WA 25) in comparison with fuel mass, with the hope of observing the changes in gas suction temperature before ignition, pressure and temperature of combustion, and other emissions parameters.

Water was injected into the cylinder in quantities that could affect engine performance and chemical behaviors in combustion process. The water injector was used with the desire to cool the suction charge that distributed is chamber, and over the surfaces of certain engine parts or water injector location to prevent overheating, depending on the structure of engine. This study used a water injector with the main purpose of cooling intake gas during the compression stroke to observe in-cylinder changes and associated emissions. Hence, water and fuel injectors were placed opposite each other in relation to cylinder axis as illustrated in Fig. 1.

3. Results and discussion

After supplying combustible charge or motive fluid to the engine, water injection could have a cooling effect on such a charge or motive fluid and could lead to an increase in the effective octane number, ultimately resulting in an improved anti-knock resistance (anti-

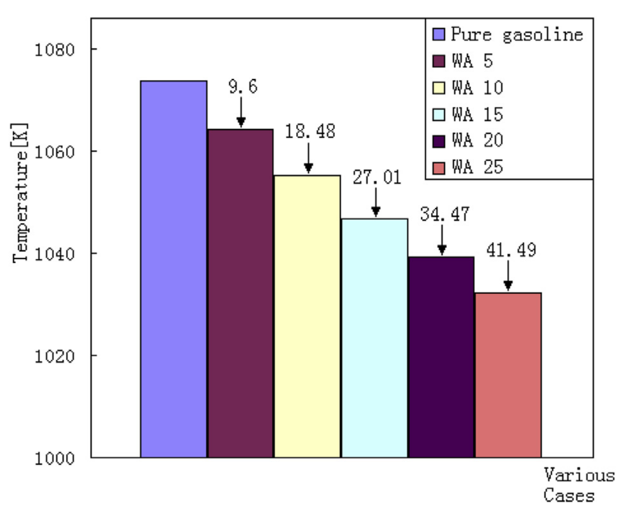

Fig. 5. The effect water injection on the in-cylinder temperature for a fixed ignition timing angle (700 °CA).

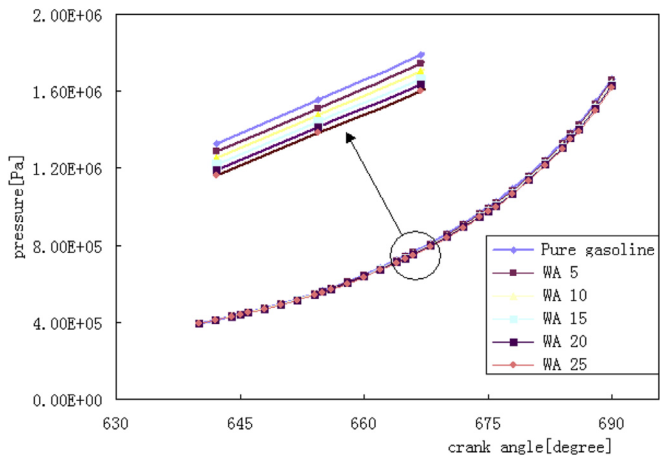

Fig. 6. The change in in-cylinder pressure after water injection.

detonation ability) of the combustible mixture. The effects of sprayed water into the cylinder of the engine model used are discussed in the subsequent sections (Fig. 2)

3.1. Effects on the anti-detonation and via charge cooling

As the water droplets vaporized by absorbing the heat from compressed air, they are converted into high pressure steam. The evaporation of water in small liquid droplets may absorb the heat which decreases the average temperature of suction gas. At the same time, it reduces compression pressure. Hence, the initial injection of water not only facilitates the cooling of the air but significantly also increases its density, allowing more fresh air to enter the cylinder (Fig. 3).

Although water was injected into the cylinder at 640 °CA, water evaporation was slower compared with gasoline. This reduced the temperature significantly beyond 660 °CA. With the presence of water (up to 25% WA) in cylinder, the average temperature of compressed air at the end of fuel injection dropped to about 33.71 K compared with a temperature of 41.49 K at the time of ignition for pure gasoline, as shown in Figs. 4 and 5.

The water injection significantly cooled the charge gas in the GDI engine or air–fuel mixture in an MPI engine and increases the density of air in each case. Hence, higher engine output can be reached with an increase in the fresh-air mass that enters the cylinder. The gains in power output is possible due to the more complete combustion facilitated by increase in the quantity of air by mass. Additionally, engines with higher compression ratios or boost pressures have to support higher octane number fuels as a requirement for anti-detonation. For engines equipped with turbochargers or superchargers, in which the intake air compressed before entering the cylinder, the suction air temperature at the latter part of the compression stroke is higher. This is one of the enabling conditions for detonation. The combination of water injection and boost pressure could be acceptable in this case due to the greater benefits derived from the cooling effects of vaporized water.

Moreover, an engine with a normal compression ratio can also be run on a low octane number fuel in combination with water injection. Water injection can also be applied for cooling of the compressed air leading to an improvement in volumetric efficiency, power output and brake specific fuel consumption, for an increase in the compression ratio.

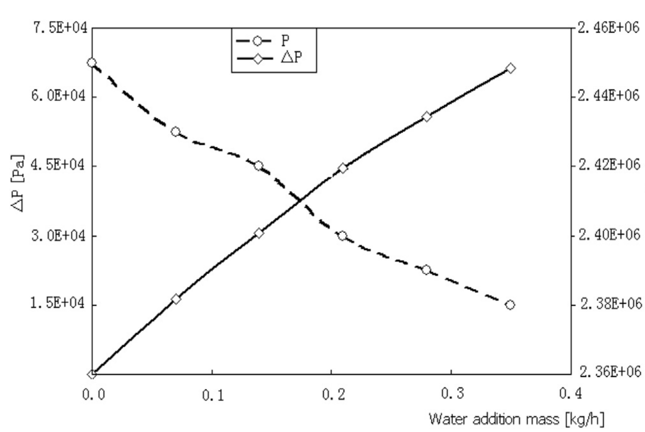

Fig. 7. The effect of injected water on in-cylinder pressure. ΔP: Pressure decrease and P: in-cylinder pressure with different water addition ratios.

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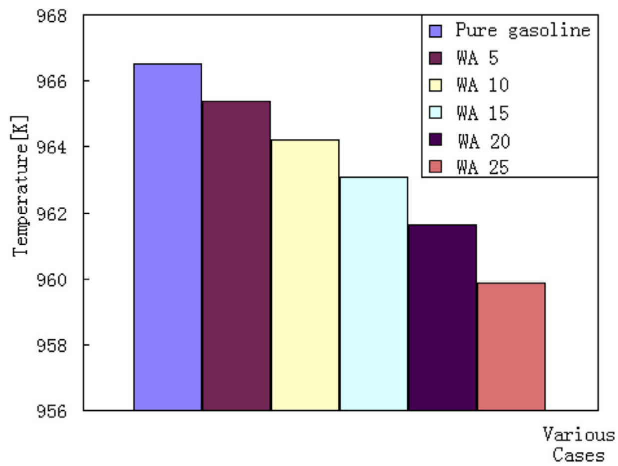

Fig. 8. The comparison of combustion chamber temperatures for different injected water quantities.

3.2. *The effect of water injection on the work done during the compression stroke*

As the injected water injected vaporizes it conducts the required latent heat from the combustible charge injected into the cylinder leading to a decrease in temperature and in-cylinder pressure. Furthermore, the decrease in the in-cylinder pressure at the end of the compression stroke is useful for improving the engine efficiency as a consequence of the decrease compression work. Fig. 6 shows the change in in-cylinder pressure with crank angle for the various water injection proportions. From Fig. 6 it is evident that the highest in-cylinder pressure was achieved using pure gasoline while there was a decreasing in-cylinder pressure as the quantity of injected water was increased.

When water is injected into the intake airflow towards the end of the compression stroke, it becomes heated due to the high temperature of the compressed air in the cylinder. The inert water vapor absorbs part of the heat released and, in effect, lowers the in-cylinder pressure instantaneously. The water addition at suitable times may be used to control in-cylinder pressure.

The vaporized water could lead to increase in pressure due to the phase change. In this situation, the pressure decreases linearly with the amount of injected water as illustrated in Fig. 7. A higher quantity of injected water into the cylinder will cause more heat absorption and pressure decrease as a result. The reduction in pressure is not only helpful for reducing the compression work, but also helps in reducing the suction gas losses resulting from blow-by past the piston rings, especially for engines with high compression ratios. However, the injected water into cylinder along with air–fuel mixture can also be taken through piston rings more or less, which could have deteriorating effects on the oil lubrication properties. This problem needs to be considered in detail under different operating conditions via extensive engine testing.

3.3. *Water injection for cooling certain parts of the engine*

The operation of an internal combustion engine is based on the theory of converting the burning of fuel into useful power. However, the percentage of fuel energy converted into effective work in the federal test protocol (FTP)-75 engine cycle is only 10.4% [8]. A thermal energy

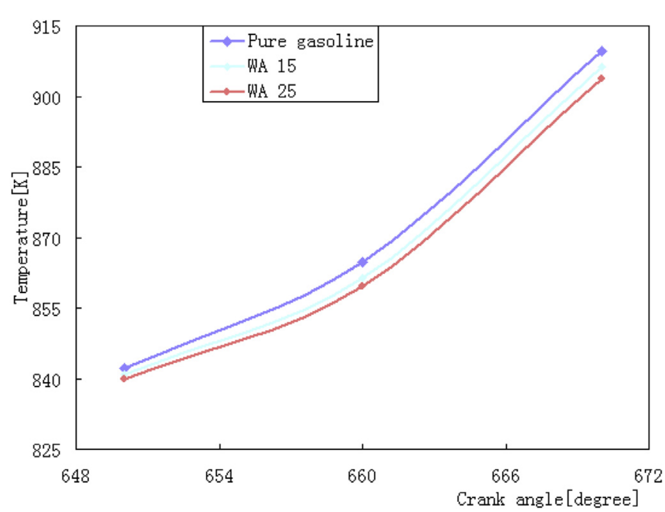

Fig. 9. The effect of water injection on the cooling of exhaust valves.

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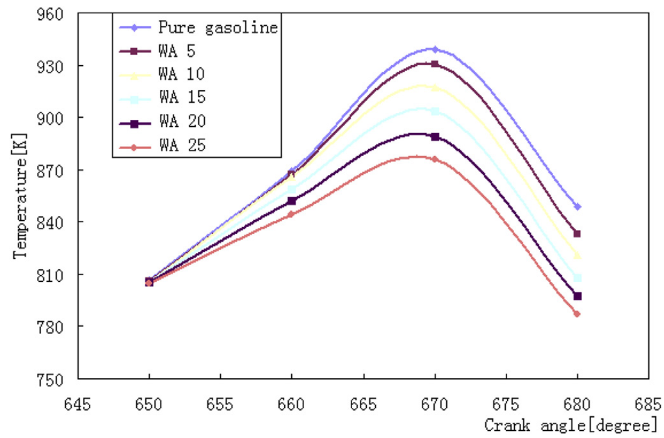

Fig. 10. The effect of water injection on the temperature of the piston crown.

of 27.7% is lost to the exhaust gases, while the remaining 61.9% is lost to friction, coolant, and others. Recovering of the lost heat for reuse is one of the main aspects of engine design and optimization. The energy expended in heating engine parts such as piston, combustion chamber, and exhaust valves is further evidence of heat loss. The lost energy by heat transfer is highest during combustion stroke in which maximum temperatures are generated. The second in the descending order is the exhaust stroke followed by the compression stroke.

Water is one of the naturally existing substances with a high capacity of heat absorption (approximately 2260 kJ/kg). It can be seen in Figs. 8 and 9 that the average temperature of exhaust valves and combustion chamber decreased as the injected water quantity increased. The reason for this temperature drop may be caused by the cooling water which helps in reducing the temperature of the fresh air on the surface of these parts compared with the case of pure gasoline case.

As the water-fuel ratio increases, the average temperature of the piston crown during the compression stroke is lowered compared to that of pure gasoline operation. The results showed that the heat loss through the piston also decreased as the water to fuel mass ratio increased, as illustrated in Figs. 10 and 11.

In this regard, water injection reduces the temperature at the latter part of the compression stroke, and also prevents the overheating of cylinder, exhaust valves and combustion chamber. By using water injection with 25% of fuel mass, the temperature could be decreased more than 50 K, 9 K, and 6 K for the piston crown, exhaust valves and combustion chamber respectively. The reduction in temperature for the piston crown is the most effective because of the direction of injected water. The quantity of injected water within the combustion chamber nearly touches the top surface of piston before it is compressed until the spark is introduced to initiate combustion. Fig. 12 is an illustration of the significant effect of water injection on resulting in the decrease in temperature of the piston crown.

Just after injecting the water, the temperature of fresh air in different cases did not change much due to the comparatively slower water evaporation rate in relation to the crank shaft rotational speed. A dramatic change occurs at the end of fuel injection. At 670 °CA, the temperature of the piston crown decreases with an increase in in-cylinder pressure. This is mainly due to the presence of fuel on the surface of piston crown.

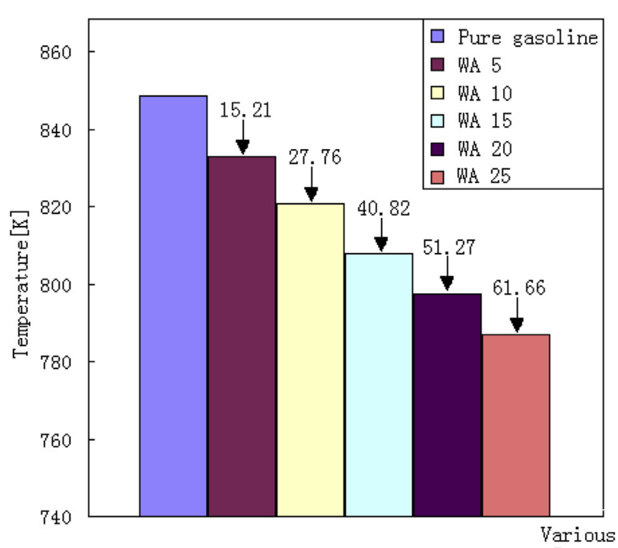

Fig. 11. Different temperatures for piston crown at 700°CA.

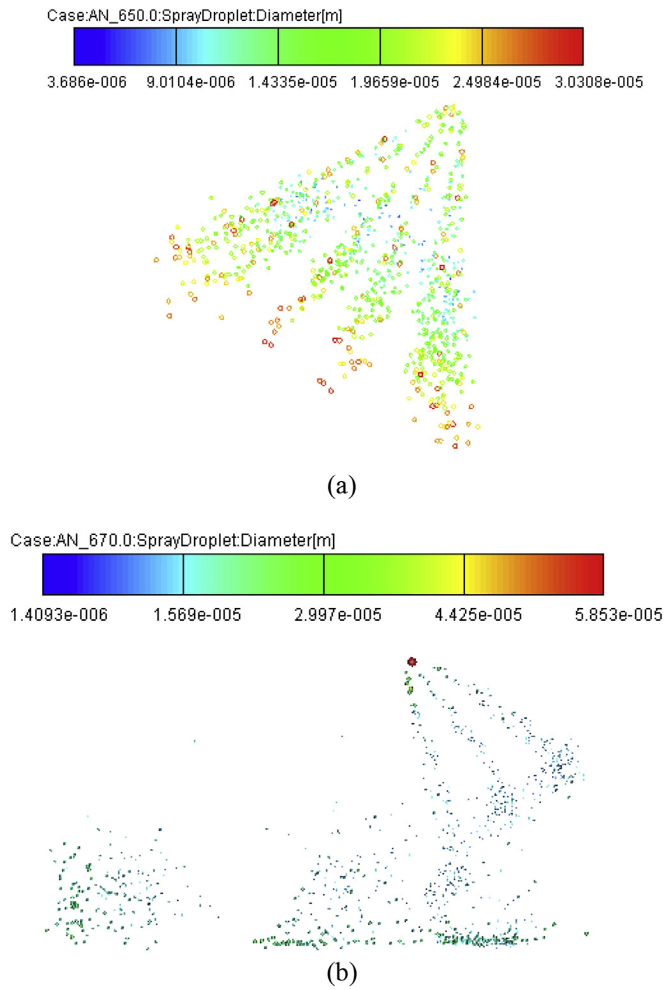

Fig. 12. The illustration for water and fuel spray nearly touching the crown of piston. (a) The direction of injected water towards the piston crown (b) The direction of gasoline fuel towards the piston crown.

The temperatures of the combustion chamber and exhaust valves decreased no more than that of piston crown with the direction of the injected water. However, the temperature changes in exhaust valves and combustion chamber depended on the direction of water injected, and determined the efficiency of cooling. In this study, the temperatures of exhaust valves and combustion chamber decreased by 9 K and 6 K, respectively, compared with the case of pure gasoline. In reality, the above temperatures could be decreased much further by the application of vortex charge technologies such as mixture plate, longer manifold length, and especially the shape of piston crown.

The greatest benefit of water injection is an increase in the knock resistance by the cooling of overheated hot spots in the combustion chamber, especially for engines with high compression ratios. Water injection is significant for increasing the conversion efficiency of changing heat energy to pressure within cylinder of an engine leading directly to a lower heat transfer to the cylinder walls.

3.4. *Temperature during the combustion stroke*

In this work, the Eddy-breakup model was used for the combustion model, and the turbulence flame conditions also utilized. The ignition timing was set at 700 °CA. The calculations for different cases were carried out under the same conditions. With the initiation of combustion, the change in temperature was used as an indication of progressive combustion (Fig. 13).

As mentioned earlier, the latent heat required to convert the injected water to vapor is absorbed from the combustible charge. The resulting steam comparatively increases the in-cylinder pressure in relation to the use of pure gasoline. This increase in in-cylinder pressure due to the expansion of the steam formed could be leveraged for doing more work during the expansion stroke. However, a large quantity of injected water is not always useful at this stage. While the amount of injected water was 15% for maximum in-cylinder pressure, maximum in-cylinder temperature is achieved by injecting 10% of water by mass. Furthermore, 25% of water injection was not the most effective for improved power output due to the lower temperature at the latter stage of the compression stroke as illustrated in Fig. 15.

The injected water into the cylinder has an influence on the temperature, the turbulence of the water spray, the speed of evaporation of fuel and the mixture of fuel with fresh air, ultimately affecting the flame speed and burning time. As illustrated in Fig. 16, the injected water delays the combustion because ignition delay increases with the chemical-reaction rates being reduced by the lower temperatures.

The effects of injected water on the ignition delay and combustion duration are shown in Fig. 16. The ignition delay here is defined as a function of the maximum temperature points on the temperature curves shown in Fig. 16. As expected, both the ignition delay and the

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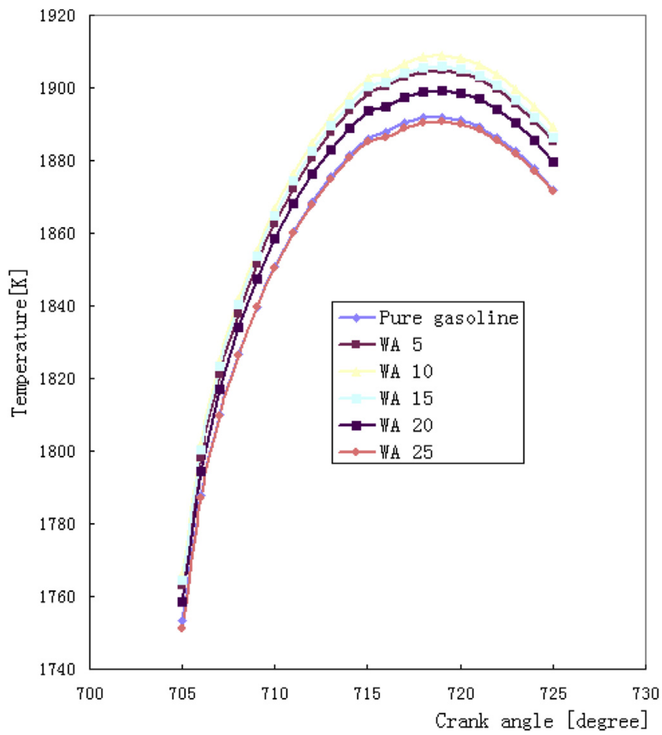

Fig. 13. Comparison of in-cylinder temperatures with respect to various water-fuel ratios.

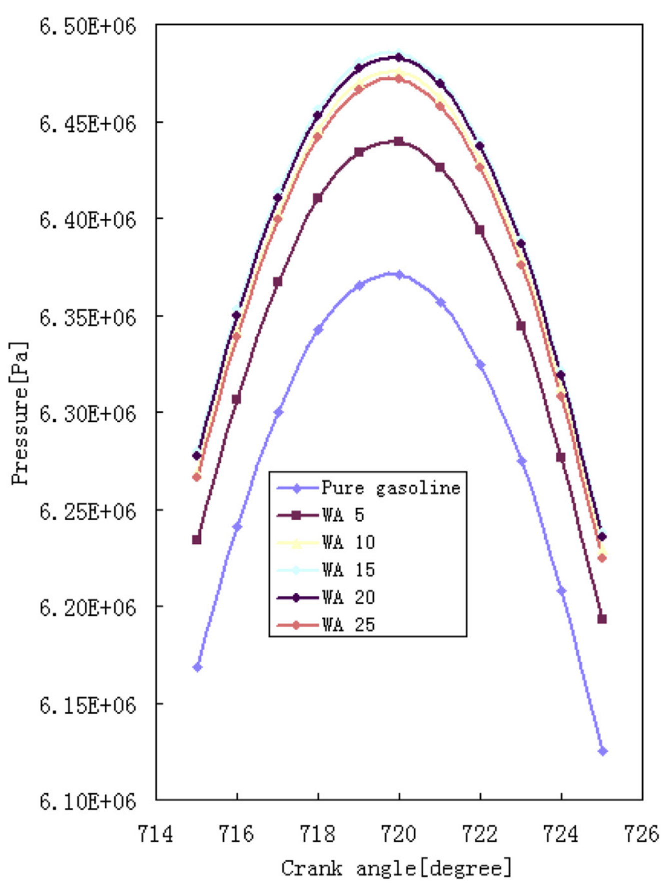

Fig. 14. In-cylinder pressure for the different cases of water injection and pure gasoline.

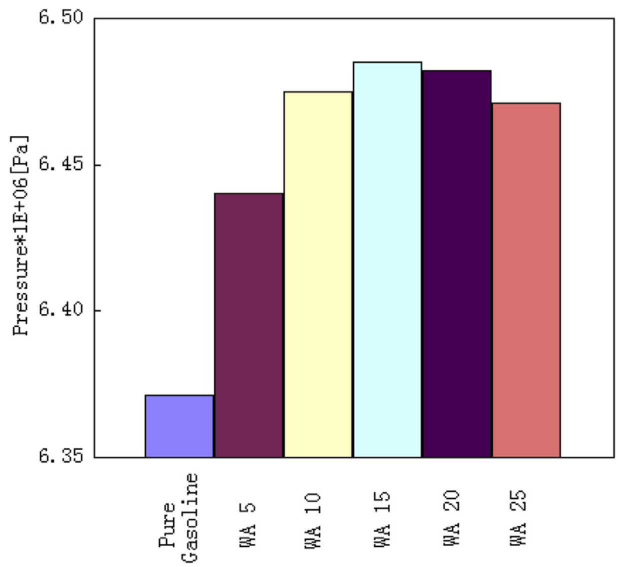

Fig. 15. The maximum in-cylinder pressure for the different cases of water injection and pure gasoline.

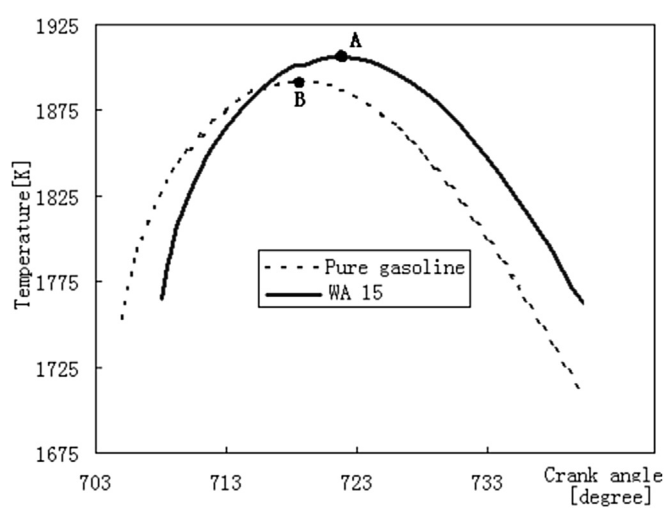

Fig. 16. The effect of water injection on the maximum temperature points between the pure gasoline case and a 15% water injection.

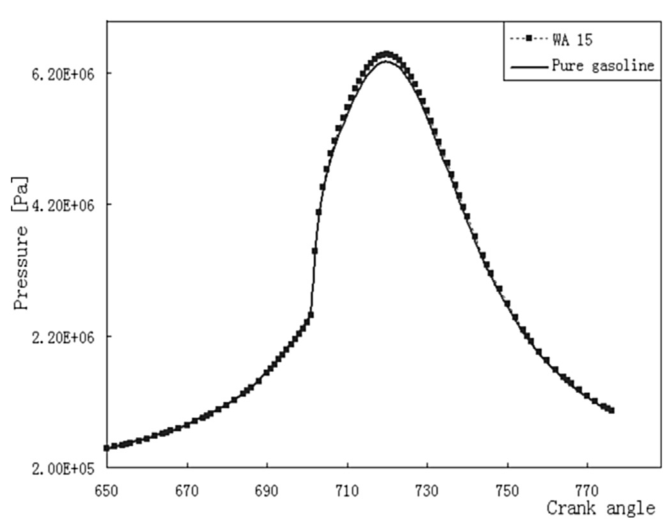

Fig. 17. Indicated mean effective pressure for 15% water injection compared with the pure gasoline case.

Table 1
Theoretical thermal efficiencies for gasoline and the different water injection proportions.

Items	Theoretical thermal efficiency
Pure gasoline	0.2675
WA 5	0.2712
WA 10	0.2739
WA 15	0.2765
WA 20	0.2751
WA 25	0.2746

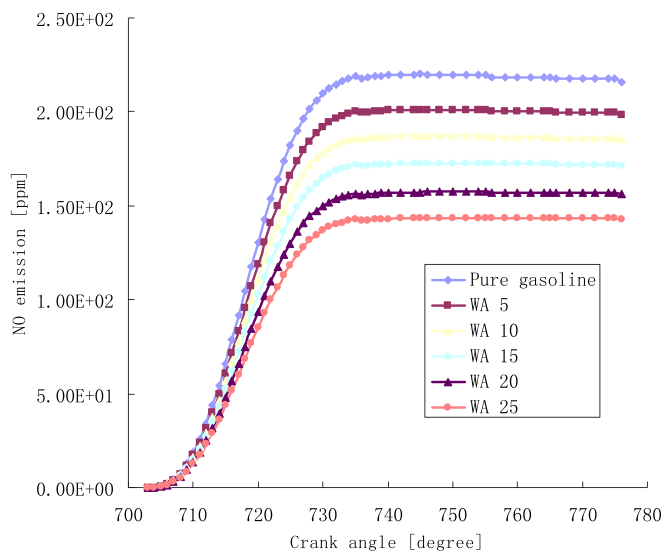

Fig. 18. NO emissions for the various cases of water injection and the pure gasoline case.

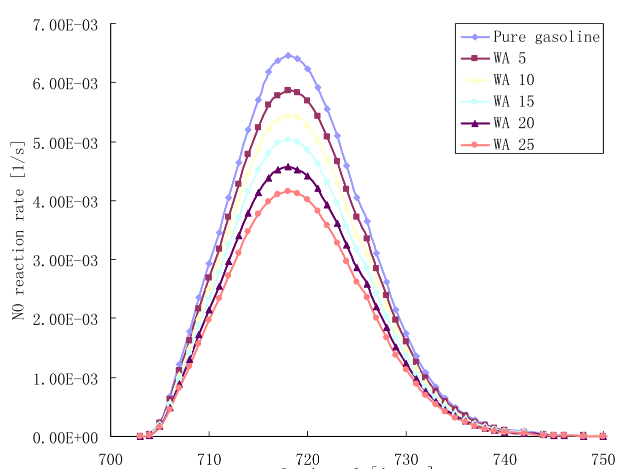

Fig. 19. Different reaction rates for the various water injection rates and pure gasoline.

maximum temperature points indicate a slower combustion rate with water injection. The maximum temperature point was delayed by about 2–3 °CA as illustrated in Fig. 16 with points B and A representing pure gasoline and 15% of water injection (Fig. 17).

Water injection is also expected to achieve higher performance as demonstrated in other studies involving compression-ignition and gas turbine engines [22,25]. In the current study, a higher quantity of water by mass was useful for cooling while a 15% of water addition to the fuel mass gave the highest in-cylinder pressure as shown in Figs. 14 and 16. The amount of injected water for each engine could be different depending on the engine design, purpose, performance requirements or anti-knock resistance.

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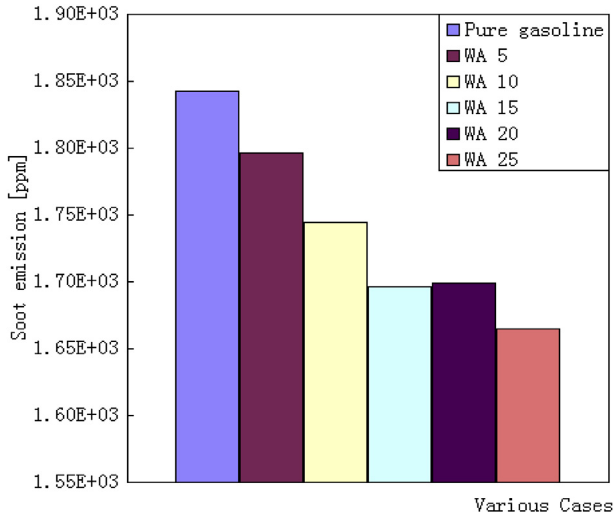

Fig. 20. Soot emissions in exhaust gas with various water injection ratios in comparison with pure gasoline.

The theoretical efficiencies for gasoline and the different levels of water injection are shown in Table 1. It could be seen from the table that the highest thermal efficiency is not necessarily achieved by injecting the highest quantity of water (25% by mass). There was only a slight difference between the theoretical thermal efficiency for pure gasoline and the water injection cases.

3.5. NOx emissions

The exhaust gas emissions from the tail pipe of vehicles make a significant contribution to environmental pollution. Nowadays, the optimization and improvement in engine performance could take one of the following forms: improving the volumetric efficiency of for a higher engine power output or adjusting engine input parameters in a manner that keeps the exhaust gas emissions within the stipulated limits. The NO formation in the combustion chamber of an engine can be described by the extended Zeldovich mechanism. The oxidation reactions of nitrogen occur with an air–fuel mixture near the stoichiometric regions and the catalysis at high temperature. The formation equations of NO from nitrogen molecule are as follows:

$$O + N_2 = NO + N \tag{1}$$

$$N + O_2 = NO + O \tag{2}$$

$$N + OH = NO + H \tag{3}$$

This section will focus on exhaust gas emission for the various water-fuel ratios. Fig. 18 shows the comparison of the in-cylinder NO mass with respect to the various water-fuel ratios. It was evident that the NO formation rate strongly depended on peak temperature and combustion duration at peak temperature in the cylinder. Therefore, when the water is injected into cylinder, peak temperatures decreased compared to that of the pure gasoline case. As can be seen from the Fig. 18, water injection leads to a reduced NO emissions. The NO emission

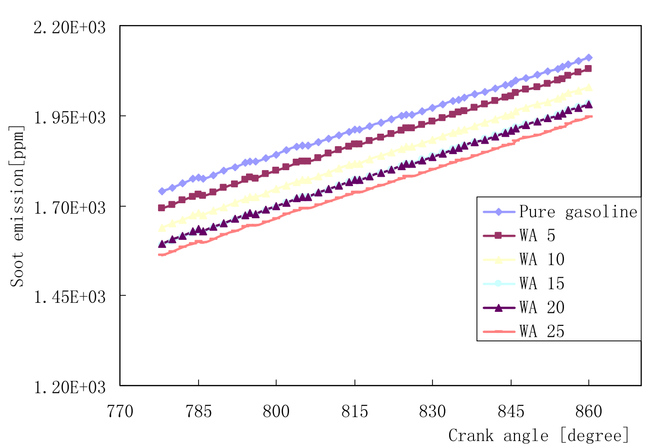

Fig. 21. The mean soot emissions for the various cases.

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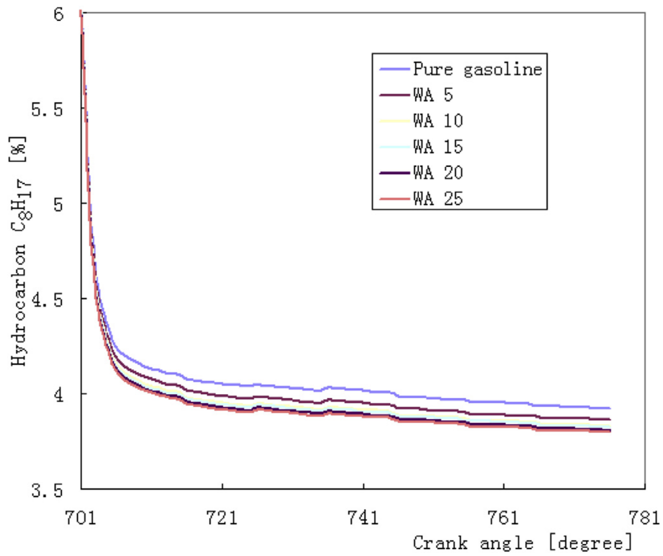

Fig. 22. The hydrocarbon concentration in exhaust due to the presence of water.

was 9.0E-06 ppm for the pure gasoline case as a standard condition, while the NO mass was 5.8E-06 ppm at 25% of water injection by mass. The reductions in NO emissions for water injection in comparison with the pure gasoline case was approximately 8.5%, 14.7%, 21.4%, 28.3%, 34.6% at 5% for 10%, 15%, 20% and 25% of water injection mass, respectively.

As Fig. 18 shown, the NO emissions can be decreased for the various water injection ratios. The higher the quantity of injected water into the cylinder was the lower the NO emissions. A water injection of 25% added to the fuel mass can be used for achieving a decrease of 34.6% NO in comparison with the case of pure gasoline. However, this quantity of water by mass is not totally useful for achieving high in-cylinder pressure. The main reason for this positive decrease in NO emission is that the absorption of latent heat by the injected water decreased the combustion temperature. Combustion takes place in regions that are characterized by lower local temperatures leading to reduced reaction rates for nitrogen oxidations as illustrated in Fig. 19.

Due to injected water into the combustion chamber during the combustion stroke, the reaction rate for NO formation was decreased although at the beginning and ending point of the reaction rate for nitrogen oxidation were similar to that of pure gasoline as can be seen in Fig. 19.

3.6. Soot emission

Under high temperature conditions and in fuel-rich regions, hydrocarbon fuels show a strong tendency to form soot. Usually, most of the soot formed in the early stages of the combustion process is depleted due to oxidation in oxygen-rich regions. Particle oxidation mainly

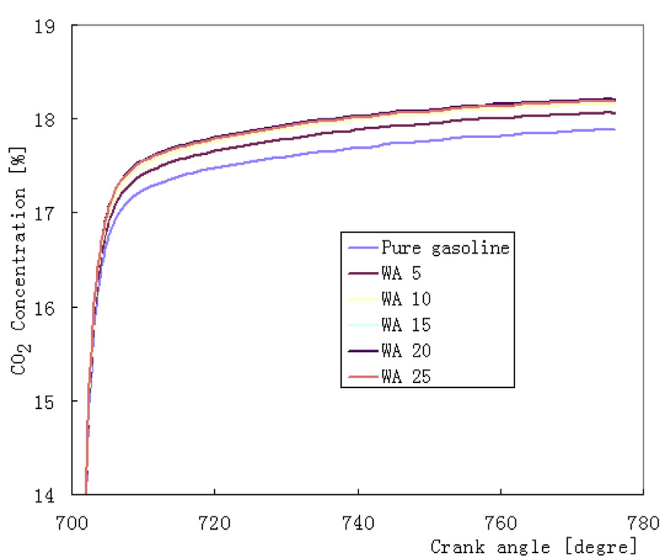

Fig. 23. The CO_2 concentration in exhaust gas with water injection rates.

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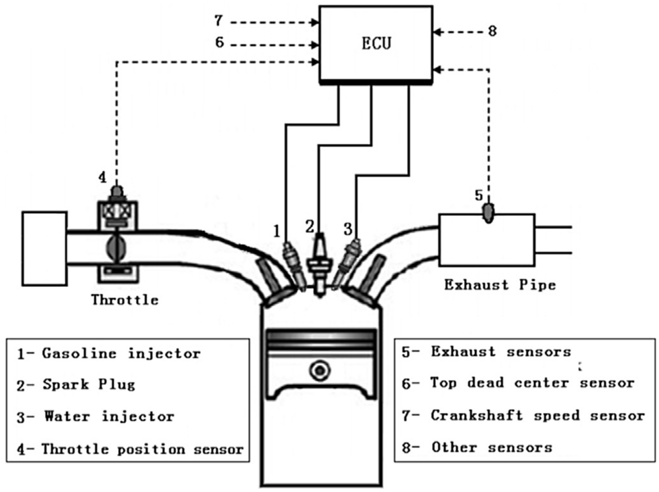

Fig. 24. A schematic for water injection system integration with ECU.

occurs with the carbonaceous particles on the catalyst at high temperature. The formation of particulates involves a large number of chemical and physical processes.

In the formation of particulates, there are many parameters that can affect to the process. The commonly important parameters can be listed such as the local air–fuel ratio (C–H ratio and/or C–O ratio), temperature, reaction time and pressure.

The effects of pressure and reaction time on soot formation were neglected in this study because the changes of in-cylinder pressure were similar between pure gasoline and the water injection cases. By using water injection, burning took place at lower temperatures, and was the main reason for the soot emission reductions as illustrated in Figs. 20 and 21.

By applying water injection, the steam should be decomposed into hydrogen and oxygen at high temperature during the combustion stroke. Oxygen atoms were used for fuel oxidization, especially in rich-mixture regions. The concentrations of OH and O radicals are increased. This results in a higher oxidation rate. Therefore, the concentrations of the polycyclic aromatic hydrocarbons and the amount of soot emissions are reduced dramatically.

Consequently, hydrocarbon (HC) emissions were decreased due to a more complete combustion (see Fig. 22) while more CO_2 was created as illustrated in Fig. 23. HC and CO_2 concentrations in the cylinder were slightly affected while the NO emissions were dramatically reduced because of the presence of water.

On the whole, water injection is a very effective strategy for reducing NOx emissions, promoting complete combustion and for controlling combustion knock. However, the compatibility of prolonged usage of water in the cylinder has to be studied in detail as water vapor could lead to changes in the combustion process. Water vapors could also weaken the strength of the air–fuel mixture, prolonging the combustion duration and ultimately affecting emission control. Modern engines use electronic control units (ECU) for controlling fuel and spark ignition timing. It is necessary for water injection to be controlled by the ECU. This way, ECU could adjust the spark ignition timing and the injected fuel mass once the water injection system is activated. By this means, a programming for water injection control should be an integral part of ECU design or used with other electronic module that is connected to the ECU. The following (Fig. 24) illustrates how a water injection system could be integrated into the fuel and ignition systems of an engine.

Water vapor in cylinder may have an effect on corrosion resistance and the lubrication properties of an engine. The engine lubrication system for an engine employing the use of a water injection system, operating under high pressure has to be considered in detail. This problem could be solved by using a mixture of water and alcohol (approximately 50/50), with trace amounts of water soluble oil. The injected water provides cools the cylinder the associated parts with the alcohol (which is combustible) serving as an anti-freezing agent, while the oil provides some lubrication and helps in resisting corrosion.

4. Conclusions

The effects of different water injection ratios on the performance and emissions of a gasoline engine have been investigated. The various water mass ratios were injected directly into the cylinder at the latter part of the compression stroke. The optimum water ratio was determined as 15% for a given fuel mass in terms of engine performance and emissions (including NO, CO_2, HC and soot). The results were compared with those obtained for the pure gasoline case. It was seen that the mean indicated pressure in cylinder at combustion stroke increased leading to an increase in power output. Similarly, the NO emissions were decreased by 34.6% on the average.

The important effect of direct water injection was the reduction of inlet temperature as a direct consequence of water vaporization, which resulted in a large decrease in in-cylinder temperature at the latter stages of the compression stroke. Water injection was helpful for improving the anti-detonation properties of the fuel, higher performance in the form of higher compression ratios. Using water injection could also permit the use of fuel with lower octane number ratings.

Water injection is also a perfect solution for obtaining high power densities when used in combination with boost pressure systems for turbocharged engines. Water injection is a simple but very efficient way of reducing the engine's tendency to detonate when the intake gas is compressed by the turbocharger.

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Water injection does not only improve the power output of an engine, but also improves the fuel economy by careful design in of the engine [1,19]. The use of water in the cylinder has to be studied in detail at different engine speed and load conditions. By experimental studies, the aspects such as the effect of water vapor on the combustion process integrated with the fuel metering and spark timing control system of the engine needs further research. Once these problems are dealt with, the system could be applied to engines for the purpose of emission reduction and improved power output as well as downsizing of the engine for further reduction in emissions.

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