Impact of water inoculation in the intake pipe on the emission characteristics and performance of the gasoline engine

Abdullatif H. Bashiri[a] and Ahmed S. Hassan[a,*]

[a] *Mechanical Engineering Department, Faculty of Engineering, Jazan University, Jazan, 25142, KSA*

* Ahmed S. Hassan; *E-mail: ashassan7@yahoo.com,*

Abstract:

This study examines the effect of inoculation of water and air into the intake pipe on the performance of the spark-ignition engine and the temperature of the exhaust gas as well as on the air pollution due to the nitrogen oxide emissions in the engine exhaust. The current pilot study was conducted on a four-stroke, single-cylinder petrol engine at different speeds and with different quantities of water inoculation. The water was inoculated through nozzles installed on the engine intake pipe at different flow rates to the gasoline fuel ranging from 0 to 1.5. The water was inoculated through nozzles installed on the engine intake pipe. The engine has been tested at various speeds ranging from 3,600 rpm to 6,600 rpm. Under different operating conditions of the engine, the temperature of the exhaust gases from the engine and oxide emissions were measured. Both the laboratory and theoretical studies showed that increasing the ratio of water inoculation to the consumed fuel reduces the temperature of exhaust gases exiting from the engine by about 16.7%, and reduces emissions by about 60%. Thus, reducing the temperature of the exhaust gas, and the increased efficiency of the engine is due to the stimulation of inoculated water to complete the fire. The experimental results showed that increasing the water inoculation by up to 1.5% of the engine fuel mass flow rate (about 10% of the engine air mass flow rate) reduced nitrogen oxides by about 20% due to the increased vapor energy from the vaporization of the injected water.

Key words*: two-stroke engine, water injection, spraying, exhaust gas recirculation.*

1. INTRODUCTION

It is well-known that for the highest efficiency of the gasoline engine, complete combustion within the combustion chamber is necessary. One of the final products of this complete combustion is water besides carbon dioxide. This means water actually exists inside the combustion chamber during the complete combustion processes. Numerous recent researches (Mostafa et al. 2021, Sharafoddini and Habibi 2020, Kotob et al. 2020, Ankit and Mallikarjuna 2019a, Ankit and Mallikarjuna 2019b, Ankit 2018, Saravanan 2015, Cesur et al. 2013, Ashok et al. 2017, Shameer and Ramesh 2018, Berni et al. 2015, Breda et al. 2015, Boretti 2013 and Totala at al. 2013) confirm the presence of some water inside the combustion chamber during the combustion process, turning into steam and serving as a powerful catalyst for this combustion. Studies have tended to add a certain amount of water to the mixture of air and fuel entering the engine to improve the volumetric efficiency of the combustion chamber and thus improve the performance of the engine in addition to reducing the temperature of exhaust gases and reducing the NOx, i.e., the residual water vapor inside the combustion chamber combines with the amount of water injected at high temperatures and transforms into superheated steam, providing extra heat to the engine. In contrast, some researchers (Worm 2017, Abdullah et al. 2014, Ghazal 2019 and Gonca 2014) mentioned that the water vapor in the indoor air reduces the speed of the flame front and requires the advancement of the spark to ensure maximum energy and engine efficiency. Saravanan (2015) conducted laboratory experiments on a diesel engine and added water vapor with exhaust gas recycling and showed that nitrogen oxides (NOx) and smoke emissions could be controlled by adding water vapor to the engine inlet gas. The effect of different vapor injection rates on a gasoline engine performance was tested (Cesur et al. 2013) theoretically and in the laboratory, and the results show that adding water to the inlet of the engine increases its torque and efficiency by up to 4.65% at 3200 rpm, reduces specific fuel consumption by 6.44% at 2000 rpm, decreases NO emissions by 40% at 2800 rpm.

Berni et al. (2015) mentioned that the injection of water inside the combustion chamber of an internal combustion engine is an excellent method of decreasing the combustion temperature by absorbing a great amount of heat from the combustion chamber and cooling the elements of the engine and preventing it from shock, thus increasing engine long-life. Breda et al. (2015) studied the effect of water injection on the performance and emission reduction of an internal combustion engine coupled to a turbocharger and observed a decrease in intake gas temperature, improving engine power and fuel efficiency. Laboratory experiments were conducted (Worm 2017) on a four-cylinder compression ignition engine, and water was injected into the intake manifold, and the marks displayed that adding water to the intake pipe increases the volumetric efficiency of the combustion chamber and reduces the blow start, which in turn allows for more optimal combustion stages, and enhances engine brake power by about 5.5%. On the other hand, Babu et al. (2015) stated that adding a water spray to the intake manifold directly after the throttle flap not only affects the density of air entering the combustion chamber but also reduces exit gas emissions and reduces heat loss, which increases the vapor expansion process. Also, the addition of water into gasoline fuels (Sahin et al. 2014) with higher octane ratings can increase engine performance and decrease NOx emissions in the exhaust gas. Lanfazame and Brusca (2003) measured a decrease in pressure action when running experiments on a single-cylinder CFR engine with water inoculation and stated that water injection represents a novel method for avoiding detonation and controlling the formation of nitrogen oxides in gasoline engines. Also, two injectors were also used in the spark-ignition engine; one for controlling fuel injection and the other for direct water injection (Mingrui et al. 2017, Soyelmez et al. 2013, Mingrui et al. 2016 and Waukesha Engine Division 1980), increasing the full-load thermal efficiency by up to 35%. However, in burning process inside the gasoline engine combustion chamber, nitric oxide is typically existing in greater concentration in exhaust gas related to nitrogen dioxide. Further, the thermal nitric oxide creation has a central role over extra tools of nitric oxide creation. Usually this reaction will happen at temperatures higher than 1800 K and the speed of this reaction doubles with increasing temperature (Brusca et al. 2019). That is when the combustion temperature echelons are lesser owing to the growth in heat aptitude, fewer nitrogen oxide is occurred. Another positive result of water inoculation is the dynamic cooling of the inhaled charge and thus the reduction in the temperature of the mixture at the end of the compression process which reduces knocking in the engine, allowing for an increase in compression ratio with increased efficiency and reduced fuel consumption (Arruga et al. 2017).

From the above review, it can be confirmed that the injection of water into the cylinder of the gasoline engine reduces emissions, soot, and nitrogen oxides, and this would lead to the possibility of a higher compression ratio in the engine due to the reduction of engine strokes and thus reduce the rate of fuel consumption in spark-ignition engines. However, in fact, the interpretation of water injection inside the cylinders of a gasoline engine is a very complex process, and it is believed that the precise aspects of it are not clearly understood, such as the interaction of the water spray inside the cylinder and the spatial distribution of water vapor, as well as the effect on the spread of the flame is rarely accurately described and reported in research. Laboratory limitations as a result of experimental. In this article, a laboratory and theoretical study are undertaken to analyze the effects of water injection on spark-ignition engine performance as well as emission.

2. Exprimental work

In the present experimental work, to reduce pollution and heat emissions, thermal stresses, and knock from internal combustion engines, laboratory experiments were performed by spraying water with air/fuel mixture into the gasoline engine in the direction of the inlet port.

2.1. Experimental apparatus

Several experimental tests were performed on a four-stroke single spark-ignition engine to study the possibility of improving engine performance, exhaust gas temperature and air pollution as a result of spraying water into to the air and fuel mixture entering the engine. The suction port of the currently tested engine is equipped with a spray device connected to a small water pump. The spray system is designed with an intermittent or pulsed injection system, and spray nozzles are installed in a suitable extension of the suction tube at a small distance before the inlet valve. Figure 1 shows the test rig of the gasoline-tested engine: a self-contained unit with an air-cooled 7kW/4,000 rpm eddy current dynamometer. A wide range of engines may be used, and Cussons offers models covering two/four stroke, air/water cooling and spark/compression ignition.

These engines can accept a cylinder pressure transducer and crank angle encoder. (See P8005 electronic engine indicating [PV] system). In the present experimental work, several thermometers and thermocouples have been used to measure different temperatures. The engine has been tested at various speeds ranging from 6,600 rpm to 3,600 rpm. The intake suction is prepared with water spouts to consent the rate of water inoculation to be exact. Gasoline was filled into the carburetor via a typical jet. The adjustment of the fuel and water stream amounts in the machine was made by varying the gasoline skull and water source pressure correspondingly (in the range of 0.5 to 2 MPa) and by regulating the backflow of water to the intake of the pump, by means of a well indicator regulator. Throughout the experiment, data on machine torque, brake gasoline ingestion, throttle position, exhaust temperature, laboratory temperature, air suction temperature, gasoline mass flow rate, air pressure, and ignition time were tested. Dissimilar water injector nozzles with different diameters of 0.2, 0.3 and 0.4 mm were used in addition to using no water at all.

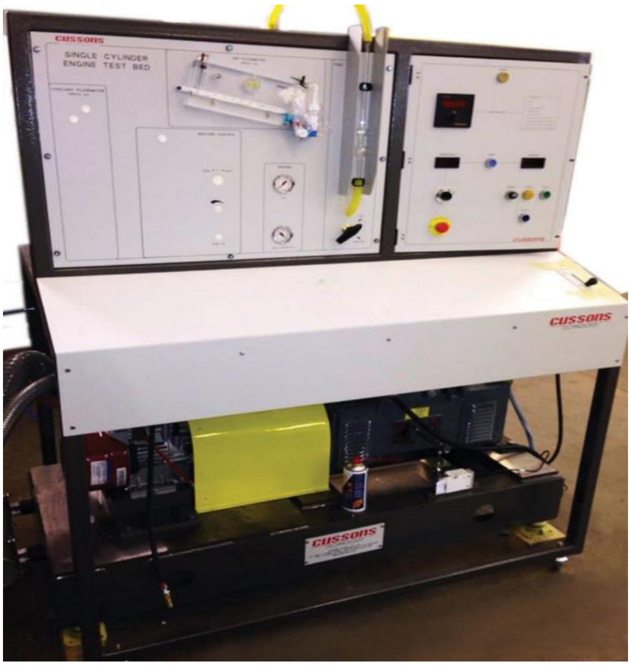

Figure 1. Gasoline engine test facility.

2.2. Experimental results and discussion

Figure 2 shows the experimental results on a single-cylinder spark-ignition engine at various speeds of 3600 rpm, 4600 rpm, 5600 rpm and 6600 rpm. It shows the engine exhaust gas temperature at the above-mentioned speeds with different water pollination rates starting from zero water/fuel ratio (without water injection) to a maximum water/fuel ratio of 1.5. Obviously, the figure presents a decrease in the engine exhaust temperature with an increase in the water-to-fuel ratio. Moreover, the exhaust engine temperature gradually decreases with increasing engine speed, which can be experienced more at higher engine speeds, as shown in the figure. At water-to-fuel ratio pollination of 0.21, the engine gives approximately the same exit temperature of 215^{o}C by decreasing ranges from

12.5% to 5%. At the maximum water-to-fuel ratio of pollination of 1.5, the maximum decrease in the spark-ignition engine exhaust temperature reaches to 16.7% due to the decrease of combustion temperature.

These results confirm that the water dispersed with the air entering the gasoline engine from the intake pipe contains significant heat energy when evaporating inside the combustion chamber, i.e., when the water is pollinated through the engine intake manifold, it takes an amount of heat that is transferred from the head of the hot room and this leads to the evaporation of water and reduces the gasoline charge that the engine consumes and thus the intake charge becomes denser (higher volumetric efficiency) and also has a lower inclination for roads.

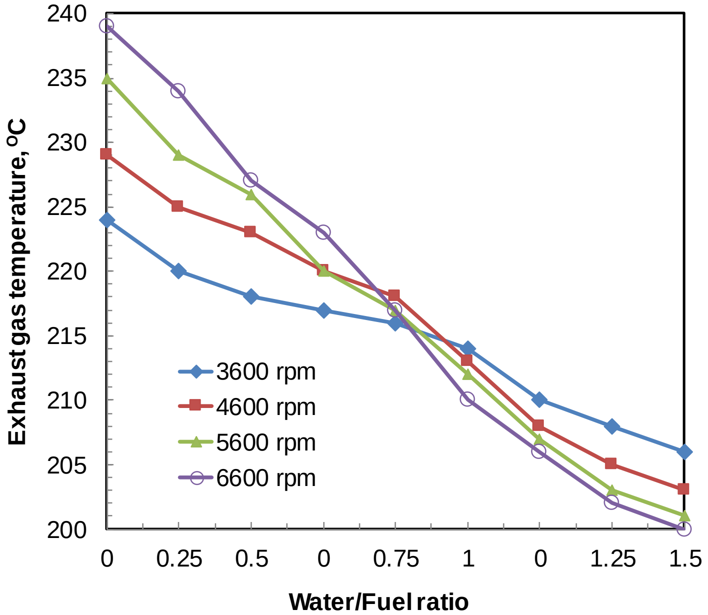

Figure 2. Effect of the ratio of water inoculation to gasoline on exhaust temperature

To assess the effects of water inoculation on nitric oxide emissions, NOx were measured during the variable water-to-gasoline mass flow rate tests and plotted as points in the figure. A comparison with the theoretical model of Lanfazame (2003) was done and is represented as a full line in the figure and shows a good agreement. Fig. 3 shows the effects of increased water to gasoline ratio on reduced NOx emissions. On the other hand, Fig. 3 emphasizes and shows the effect of water injection (Totala et al. 2013) on emissions of NOx to the water-to-fuel ratio. Note that Lanfazame's (2003) theoretical work on NOx emissions is consistent with the current experimental work of engine exhaust temperature, and current experimental results acknowledge that water inoculation of the intake engine may reduce the temperature, thereby reducing nitrogen oxides in the engine. Moreover, the present experimental results indicate that water inoculation is a method of avoiding detonation and controlling the formation of NOx in internal combustion engines. Water pollination reduces NOx emissions by exactly 7% for every 10% of water added to the fuel. However, only the water in the combustion chamber evaporates completely, and the process of evaporation in the intake air is not completed.

As a result, it will hit the cylinder walls, causing the lubricant to shatter and damage the engine, so the next pilot study will examine the injection of steam instead of water. That is spraying the water into a gasoline engine will improve the engine performance and will certainly reduce exhaust temperature and hence heat emission rates. It also reduces pollution and warming, thus helping to maintain a healthy environment. Also, from Fig. 3, it can be concluded that inoculation at the water to gasoline ratio of 1.5 decreases the NOx productions by about 60%, i.e., the burning space of the spark-ignition engine is cooled by inoculation of water or having low water temperature inside the chamber. This result confirmed the laboratory results of response through a decrease in the exhaust gas temperature by water inoculation, which can be seen in Fig. 2, where, the temperature of the exhaust gas decreases almost linearly with the increase in the water to feed the mass flow rate with a decrease of approximately 16.7 % as the rate of water flow to the fuel changes from 0 to 1.5.

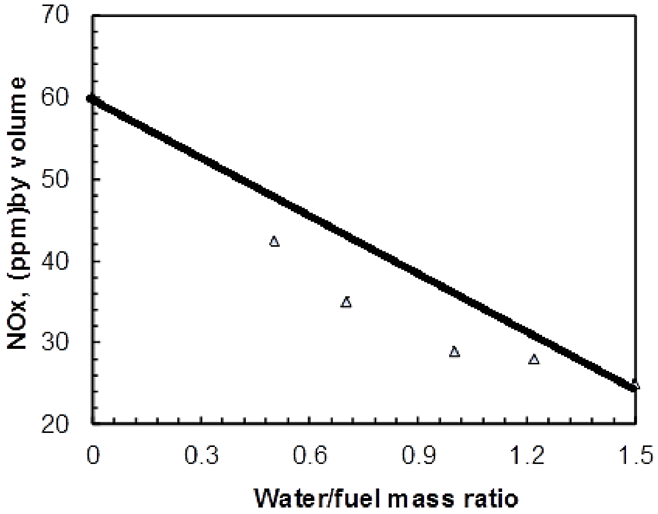

Figure 3. Effect of the ratio of water inoculation to gasoline on the NOx

3. Theoritical work

To investigate the effect of water inoculation with fuel to the spark-ignition engine on the octane number, theoretically, the Waukesha model (1980) was considered. If the water inoculation equivalent specific volume is named as V_W, the gasoline specific volume as V_g, the specific volume of the mixture of gasoline and water as V_{Wg}, and the gasoline concentration as x, then, the density of gasoline and water mixture is as follows:

$$1/ V_{wg} = x/V_w + (1-x)/V \quad (1)$$

The mass friction of water inoculation can be written as follows:

$$y_w = m_w / (m_w + m_g) = \{1+(V_w/V_g) [(1-x)/x]\} \quad (2)$$

The effect of increasing the percentage of injected water, which converts to steam inside the combustion chamber, relative to gasoline on the octane number was studied using different combinations of base gasoline and a different flow rate of water to fuel from 0 to 1.5. On the other hand, the complete combustion in a spark-ignition engine requires that the air-to-fuel ratio be equal to the stoichiometric ratio, and the self-ignition process inside the combustion chamber governs the chemical composition of the gasoline-air mixture and water vapor, its density and temperature. Therefore, the process of inoculating steam into the combustion chamber by inoculating some water into the engine intake to change the proportion of stoichiometric fuel air can change the heat transfer rate and gas temperature. To study the effect of water inoculation into a gasoline engine, the quantity of water inoculated is typically measured by means of mutable water-gasoline ratio. The ratio between the mass flow of water and gasoline in a specific working point is set as follows:

$$Y= m_w/ m_g \quad (3)$$

And the discharge of heat in the gasoline engine combustion chamber is as follows:

$$Q= m_m Cv \Delta T \quad (4)$$

where m_m is the mass of in-cylinder custody, Cv is the specific heat capacity of the in-cylinder custody, and ΔT is the temperature growth owing to ignition.

Rendering to Equ. (2), the growth of the heat ability of the combination of water and gasoline reasons to a lesser in the drain temperature.

The combination mass of water inoculation (m_W) and gasoline (mg) can be estimated from the temperature drop due to the enthalpy of the vaporization of water from the subsequent equation:

$$m_w.\Delta h_{ev} = m_{ch}.Cp.\Delta T_{ch} \tag{5}$$

where m_{ch} is mass of intake air, ΔT_{ch} is the custody air temperature decrease and Cp is the specific heat capacity at constant pressure.

If it is supposed that the mole fraction of the H_2O vapor in the fuel mixture that enters the combustion chamber is defined as y,

y= [number of moles of water (nH_2O) / (number of moles of water plus fuel (H_2O + fuel C_8H_{18})].

where nH_2O is the mole fraction of the water vapor and nC_8H_{18} are the mole fractions of isooctane and water mixture. According to [25], the correlation equation with water injection can be written as follows:

$$\gamma[(1-y)C_8H_8 + yH_2O] + [12.5(1-y)][O_2 + 3.76N_2] = C_8H_8(\gamma-1)(1-y) + 8CO_2(1-y) + H_2O[\gamma y + 9(1-y)] + N_2[12.5(1-y)] \tag{6}$$

On the other hand, the proportion of burnt mass during the burning process can be written as follows:

$$\emptyset_b = \frac{mb}{m} = 1 - e^{ln(1.001)(\frac{\theta-\theta s}{\Delta\theta s})^n} \tag{7}$$

Where θ and θs are the specific internal energy for burnt and unburnt mixtures, respectively.

Aimed at spark-ignition engines at instantaneous time delay, τ the induction time can be written as follows:

$$\int_{t=0}^{t_i} dt/\tau = 1 \tag{8}$$

Using equation (3) it is possible to detect the initiation of knocks:

$$\tau = C1e^{\frac{C2}{T}}/P^{C3} \tag{9}$$

Where D1, D2, and D3 are constants equals, C1=17.68(ON/100)3.402, C2 =3800 and C3 =1.7.

The ignition delay or so-called inti detonation in a compression ignition engine can be written:

$$\tau = 17.68(ON/100)^{3.402}\ P^{-1.7}exp(3800/T) \tag{10}$$

Fig. 4 shows the effect of increasing in water inoculation relative to gasoline on the exhaust gas temperature. The figure evidently shows a severe drop in exhaust gas temperature with an increase in the water inoculation to gasoline ratio. Fig. 5 shows the effect of water inoculation relative to gasoline on the octane number. It is observed in this figure that increasing the water inoculation to fuel ratio almost linearly increases the octane number. It was also noted in this diagram that the higher the water-to-fuel flow ratio, the higher the octane number. The figure also shows that a linear increase is obtained with each mixture. A single exact theoretical equation has been distinct to linearly associate the growth in octane number with the water-to-fuel ratio as reported in the overhead balance (Brusca et al. 2019).

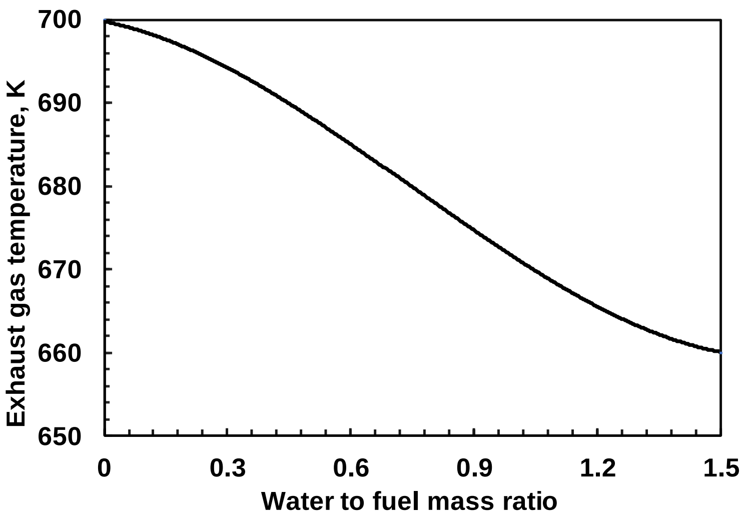

Figure 4. Effect of water-to-fuel ratio on the exhaust gas temperature

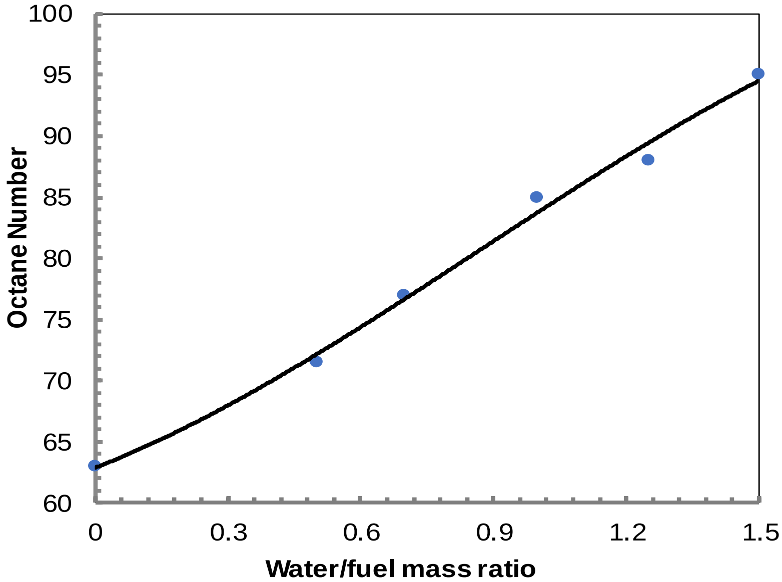

Figure 5. Effect of water-to-fuel ratio on the octane number

The instantaneous balance of burning capacity (V) is the classified as (Hoppe et al. 2016):

$$V(\theta) = (\pi b^2/4)\{s/(r_c-1) + [l_c + a - a\cos\theta - (l_c^2 - a^2\sin^2\theta)^{1/2}]\} \quad (11)$$

where, b=cylinder dia., s= stroke lc =connecting rod length rc=compression ratio, and θ=crank angle.

$$A(\theta) = (\pi b/2)\{b + s[l_c + a - a\cos\theta - (l_c^2 - a^2\sin^2\theta)^{1/2}]\} \quad (12)$$

The pressure prediction model is derived from the first law of thermodynamics. It is also the instantaneous pressure inside the combustion chamber at a given crank angle. The subsequent pressure will be rummage-sale to deduce the temperature inside the combustion chamber.

$$dP/d\theta = (1/V)\{(\gamma-1)[Q_{in}\,df/d\theta - hA/6Ne(T_g - T_w)] - (P/V)\,dV/d\theta\} \quad (13)$$

where γ is the specific heat relation, Qin is the complete heat input, h is the coefficient heat relocation inside the burning chamber, f is burned mass portion, the burning efficiency is ηc, Tw and Tg are the temperatures of the cylinder wall and the gas inside it respectively.

With corrected air-to-fuel ratio (A/F) c, and inferior heating rate (LHR) can be written as follows:

$$Q_{in} = \eta_c\, m_{in} LHR/[1+(A/F)_c] \tag{14}$$

The gas temperature inside the combustion cylinder is evaluated as follows:

$$T_g = PVMaM_f[(1+A/R_c)/(M_a+MfA/R_c)]/Rm_m \tag{15}$$

Where m_m is total mass of the injected petrol and the water inoculation, M_a is the air molecular weight (28.97 kg/kmol), M_f is the petrol molecular weight (101.21 kg/kmol, (Ferguson and Kirkpatrick 2016)).

On the otherwise, to detect influence of water inoculation on the knocking of spark ignition engine, assuming that the knowing occurs when the actual time has been under maximum temperature that equivalent to the dynamically shaped induction time for that collection. The beginning of the knocking or detonation phenomena will be happening at maximum pressure inside the burning space:

$$\int_{t_0}^{t_{det.}} \frac{1}{\tau}\, dt = 1 \tag{16}$$

As a function of the start and finish of the burning angles, Equ. (16) can be written as:

$$\int_{t_0}^{t_{Pmax}} \frac{P^{C3}}{C1 \cdot e^{\frac{C2}{T}}}\, dt \le 1 \tag{17}$$

But, the burning of steady operation can be expressed as:

$$\frac{30}{\pi \cdot n} \int_{\varphi_0}^{\varphi_{Pmax}} \frac{P^{C3}}{C1 \cdot e^{\frac{C2}{T}}}\, d\varphi \le 1 \tag{18}$$

By using Equ. (18), the detected knocking can be written as:

$$I_{det.} = \frac{30}{\pi \cdot n} \int_{\varphi_0}^{\varphi_{Pmax}} \frac{P^{C3}}{C1 \cdot e^{\frac{C2}{T}}}\, d\varphi \tag{19}$$

On other side the non-knocking condition can expressed as:

$$I_{det.} = \frac{1}{n} \int_{\varphi_0}^{\varphi_{Pmax}} \frac{P^{C3}}{C1 \cdot e^{\frac{C2}{T}}} \le \frac{\pi}{30} \cdot A \tag{20}$$

Where n is the engine speed, C1, C2, C3 are constants, P_{max} is the crank angle at burning peak pressure.

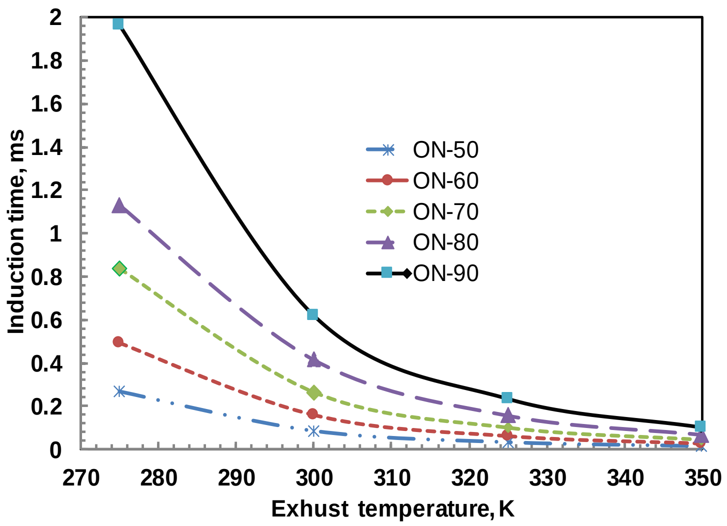

Figure 6. Effect of exhaust temperature on the induction time.

Fig. 6 shows the effect of exhaust temperature on the induction time at different petrol octane number. It is clear from the figure that decrease the exhaust engine temperature decreases the induction time due to water inoculation. This figure clearly shows the increase in induction time with the decrease in the engine exhaust gas temperature and the higher the percentage of octane in the fuel, this effect is more pronounced. This explains that injection of water into the combustion chamber is the main reason for reducing the exhaust gas temperature, which in turn led to an increase in induction time, that leads to an improvement in combustion process and the hole of engine efficiency. Figure 6 confirmed by the decrease in the measured exhaust gas temperature with increasing the water inoculation (see Fig.1).

From the previous three figures, it is possible to summarize and emphasize that decreasing the gasoline engine exhaust gas temperature, which must have happened due to the injection of water through the engine intake manifold, reduces the induction time, which makes the engine in the complete faraway of reducing knock. As can be seen, the exhaust gas temperature decreases almost linearly with the water-to-fuel mass flow rate with a decrease of approximately 6% as the fuel-to-water mass flow rate changes from 0 to 1.5.

Fig. 7 shows also the effect of pressure on the induction time of a gasoline engine. The figure indicates that increasing the pressure inside the combustion chamber decreases the induction, and this effect increases with a decrease in combustion temperature. Fig. 8 shows the effect of octane numbers on the induction time at different temperatures. The figure shows that as the octane number of gasoline increases, the induction time increases, and this effect increases as the temperature decreases, which indicates that the exhaust temperature and NOx will decrease.

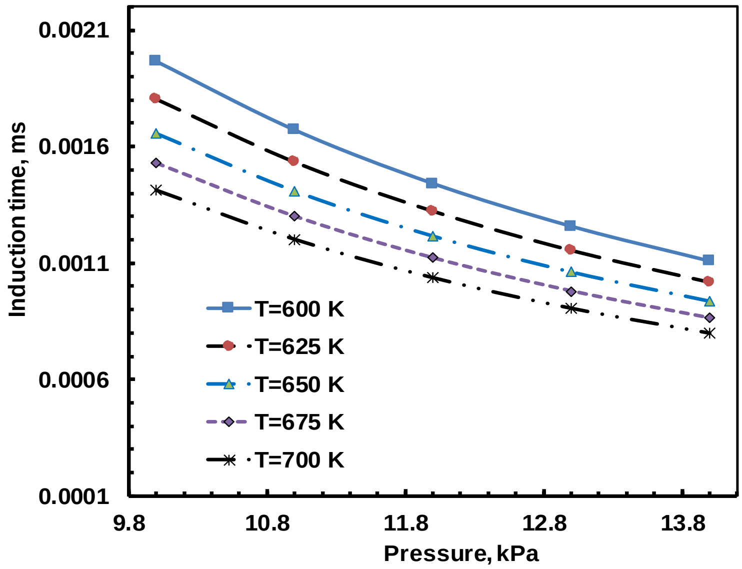

Figure 7. Effect of pressure cylinder on the induction time

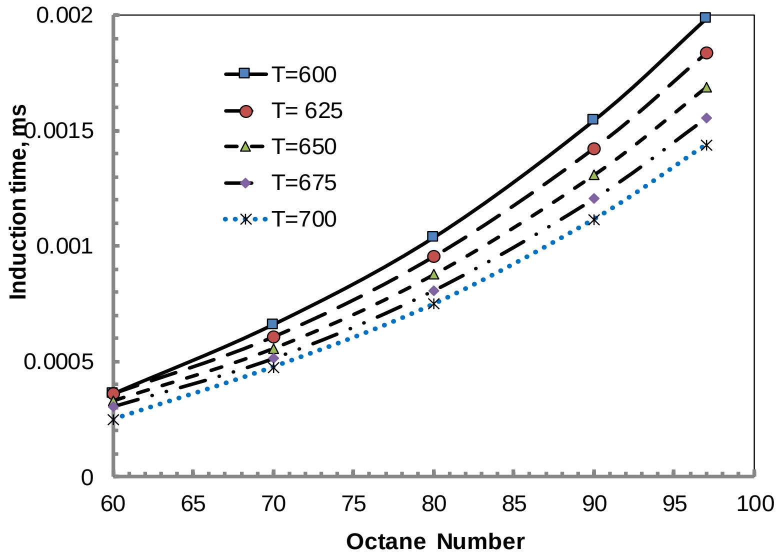

Figure 8. Effect of induction time (ms) on octane number

Fig. 9 shows a comparison between the pressures inside the burning chamber at different crank angles in the two cases of with and without water inoculation. The maximum pressure with water inoculation is lower than that without by about 0.5%, leading to good combustion efficiency and hence good engine efficiency. The maximum pressure with water inoculation occurs at a crank angle of 20 degrees while without water inoculation it occurs at 24 degrees, meaning that the combustion starts earlier with water injection than without water inoculation due to increase of mixture density.

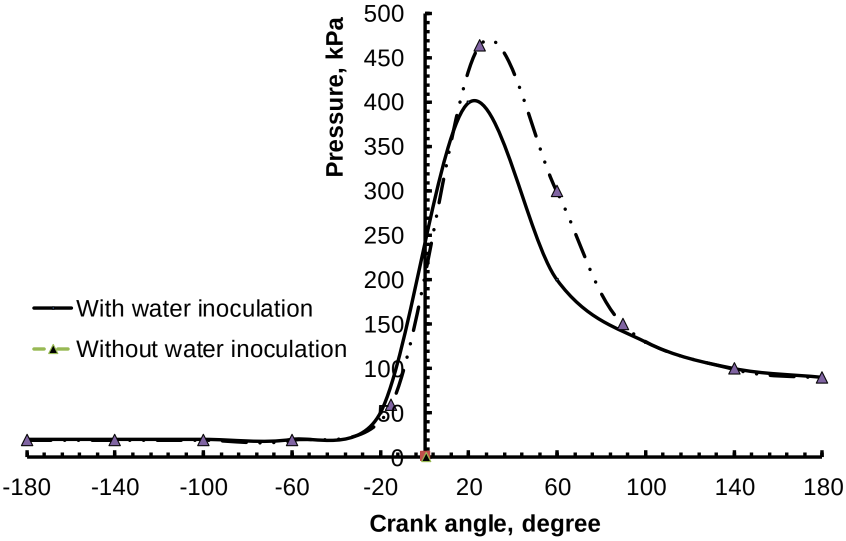

Figure 9. Effect of water inoculation on the pressure inside the cylinder

Fig. 10 shows the result of inoculating a quantity of water into the inlet of the spark-ignition engine on the temperatures inside the burning chamber and compares the results obtained without injecting water into the engine. As shown in the figure, when the water was inoculated into the intake pipe of the spark-ignition engine, the temperature in the cylinder was reduced by about 7% due to the reduction of nitrogen oxide emissions by about 50% resulting in lower maximum cylinder temperature, as mapped in Fig. 2 of the present experimental work. These results are consistent with Chintala and Subramanian reporting a 37% reduction in nitrogen oxide emissions when water was injected into the dual-fuel engine (Chintala and Subramanian 2014). On the other side, the delay period for the maximum cylinder pressure when performing the water injection was increased, due to a decrease in the temperature of the entering mixture of air inoculated with water.

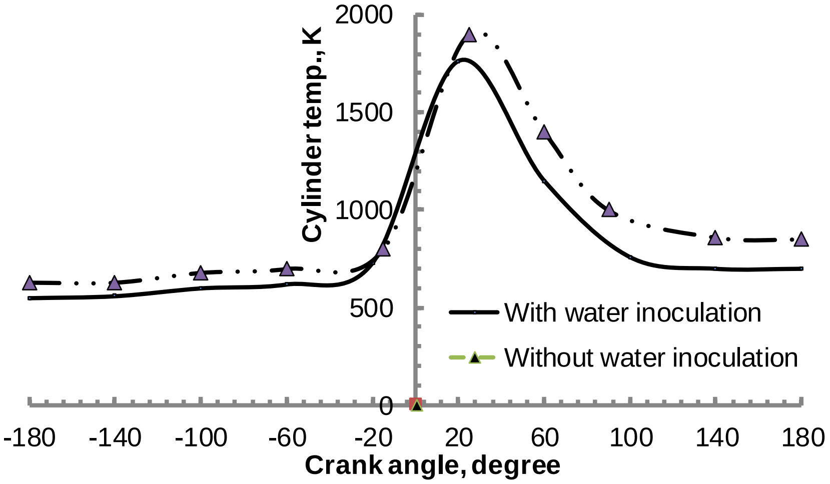

Figure 10. Effect of water inoculation on the temperature inside the cylinder

Conclusion

In this paper, laboratory and theoretical studies were undertaken to find out the effect of water inoculation in the intake inlet of the gasoline engine, which is converted into steam inside the combustion chamber, on the temperature of the waste gases and emissions of nitrogen oxides as well as on the rate of fuel consumption. A single-cylinder spark-ignition engine of four-stroke test bed was equipped with the equipment necessary for measuring the rate of fuel consumption, temperatures, pressure, power, engine speed, and temperatures of the exhaust gases, in addition to the exhaust gases carbon dioxide and nitrogen. Also, a water inoculation device equipped with a nebulizer was designed to work with the cycles of the aforementioned gasoline engine, and it could control the amount of water pumped into the inlet of the spark-ignition engine, ranging from zero to 1.5 of the actual average fuel consumption of the engine. The laboratory study showed that the injection of water with air into the inlet of the spark-ignition engine led to a decrease in both the temperature of the exhaust gases leaving the engine and the carbon ratios with improvement rates of up to 50%, and this was confirmed by the theoretical analyses. This research was identical to the results of some previously published research consistent with these circumstances. The study in this research confirmed that the inoculation of water with air into the combustion chamber of a gasoline engine reduces thermal emissions, environmental pollution, and fuel consumption, as well as improving the overall efficiency of the engine.

Nomenclature

NOx	Nitrogen Oxides
rpm	Revelation per minute
CFR	Cooperative Fuel Research
PV	Photovoltaic
V_w	The water inoculation equivalent specific volume [m^3/kg]
V_g	The gasoline specific volume [m^3/kg]
V_{wg}	The specific volume of the mixture of gasoline and water [m^3/kg]
y_w	The mass friction of water inoculation [kg]
m_m	The mass of in-cylinder custody [Kg]
C_v	The specific heat capacity of the in-cylinder custody [J/kg.^{o}C]
□T	The temperature growth owing to ignition [^{o}K]
m_w	The mass of water inoculation [Kg]
m_g	The mass of gasoline [Kg]
□T_{ch}	The custody air temperature decrease [^{o}K]
C_p	The specific heat capacity at constant pressure [J/kg.^{o}C]
θ	The specific internal energy for burnt [J]
θ_S	The specific internal energy un-burnt mixtures[J]

τ	The induction time [time]
V	The instantaneous balance of burning capacity [j/^{o}k]
b	Cylinder diameter [cm]
s	Stroke
l_c	Connecting rod length [cm]
r_c	Compression ratio
θ	Crank angle [^{0}]
□	The specific heat relation [J/kg.^{o}C]
Q_{in}	The complete heat input [J/mm]
h	The coefficient heat relocation inside the burning chamber [W/m^{2}.^{0}k]
f	The burned mass portion [kg]
η_c	The burning efficiency
T_w	The temperatures of the cylinder wall [^{o}K]
T_g	The temperatures of the gas inside the cylinder wall [^{o}K]
$(A/F)c$	The corrected air-to-fuel ratio
LHR	The inferior heating rate
m_m	The total mass of the injected petrol and the water inoculation [kg]
M_a	The air molecular weight [kg/kmol]
M_f	The petrol molecular weight [kg/kmol]
P_{max}	The crank angle at burning peak pressure [MPa]

References

Abdullah NR, Shahruddin NS, Mamat R, Ihsan Mamat AM, Zulkifli A., "Effects of air intake pressure on the engine performance, fuel economy and exhaust emissions of a small gasoline engine", Journal of Mechanical Engineering and Sciences, 6:949-58, 2014.

Ankit A Raut, and Mallikarjuna, J M., " Effects of direct water injection and injector configurations on performance and emission characteristics of a gasoline direct injection engine: A computational fluid dynamics analysis, International Journal of Engine Research, 2019.

Ankit A Raut, and Mallikarjuna, J M., " Effects of water injector spray Angle and Injector orientation on emission and performance of a GDI Engine - A CFD Analysis", International Journal of Engine Research, 2019.

Ankit A Raut, "Effect of water injection and spatial distribution on combustion, emission and performance of GDI Engine-A CFD Analysis", International Powertrains, Fuels & Lubricants Me, 2018.

Arruga H, Scholl F, Kettner M, Amad O, Klaissle M, B Giménez4, "Effect of intake manifold water injection on a natural gas spark ignition engine: an experimental study", 4th International Conference on Mechanical Engineering Research (ICMER2017), IOP Conf. Series: Materials Science and Engineering 257-012029, 2017.

Ashok B, Nanthagopal K, Thundil Karuppa Raj R., "Influence of injection timing and exhaust gas recirculation of a calophyllum inophyllum methyl ester fuelled CI engine", Fuel Process Technol; 167: 18–30, 2017.

Babu, A.R., Amba Prasad Rao G., and T., Hari Prasad, "Direct injection of water mist in an intake manifold spark ignition engine", International Journal of Automotive and Mechanical Engineering (IJAME), Vol. 12, pp. 2809-2819, 2015.

Berni F., Breda S., Lugli M., Cantore G., "A numerical investigation on the potentials of water injection to increase knock resistance and reduce fuel consumption in highly downsized GDI engines", Energy Procedia, 81, 826–835, 2015.

Breda S., Berni F., D'Adamo A., Testa F., Severi E., "Effects on knock intensity and specific fuel consumption of port water/methanol injection in a turbocharged GDI engine: Comparative analysis", Energy Procedia, 82, 96–102, 2015.

Boretti A., "Water injection in directly injected turbocharged spark ignition engine", Applied Thermal Engineering, 52 (1), 62–68, 2013.

Brusca S, Galvagno A, Lanfazame R., Mauro S., Messina M., "Fuels with low octane number: water injection as knock control method", 2405-8440/Ó2019, 15, 2019.

Cesur Idris, Adnan Parlak, Vezir Ayhan, Barıs¸ Boru, Guven Gonca, "The effects of electronic controlled steam injection on spark ignition engine", Journal of Applied Thermal Engineering 55, pp. 61-68, 2013.

Ferguson C. R. and A. Kirkpatrick, Internal Combustion Engine: Applied Thermosciences, Willey, Chichester, 2016.

Chintala V., Subramanian K.A., "Hydrogen energy share improvement along with NOx (oxides of nitrogen) emission reduction in a hydrogen dual-fuel compression ignition engine using water injection", Energy Convers. Manag. 83, 249–259, 2014.

Ghazal Osama H., "Combustion analysis of hydrogen-diesel dual fuel engine with water injection technique", Case Studies in Thermal Engineering 13- 100380, 2019.

Gonca Guven, "Investigation of the effects of steam injection on performance and NO emissions of a diesel engine running with ethanol-diesel blend", Energy Conversion and Management 77, 450–457, 2014.

Hoppe F, Thewes M, Baumgarten H and Dohmen J, "Water injection for gasoline engines", Potentials, challenges, and solutions, International Journal of Engine Research ,17, 86-96, 2016.

Kotob M., Lu T., and Wahid S., "Experimental Study of Direct Water Injection Effect on NOx Reduction from the Gas Fuel", J. of Adv. Res. Fluid Mech. Therm. Sci., 76(3), 92–108, 2020.

Lanfazame S., Brusca, R., "Water Injection in IC – SI Engines to Control Detonation and to Reduce Pollutant Emissions", JSAE 20030140, SAE -01-1912, University of Catania, 2003.

Mingrui Wei, Thanh Sa Nguyen, Richard Fiifi Turkson, Guanlun Guo and Jinping Liu و "The Effect of Water Injection on the Control of In-Cylinder Pressure and Enhanced Power Output in a Four-Stroke Spark-Ignition Engine", www.mdpi.com/journal/sustainability, 2016.

Mingrui Wei, Nguyen Thanh Sa, Richard Fii, Turkson, F., Liu Jinping, Guo Guanlun, "Water injection for higher engine performance and lower emissions", Journal of the energy institute, Vol. 90, 2, pp 285-299, 2017

Mostafa R., Tianfeng L., and Seddik S., "Experimental Comparison Between Steam and Water Tilt-Angle Injection Effects on NOx Reduction from the Gaseous Flame", J. of Energy, 25575-25585, 2021.

Sahin Zehra, Mustafa Tuti and Orhan Durgun, "Experimental investigation of the effects of water adding to the intake air on the engine performance and exhaust emissions in a DI automotive diesel engine", Fuel, 115, 884–895, 2014.

Saravanan S., "Effect of EGR at advanced injection timing on combustion characteristics of diesel engine", Alexandria Engineering Journal; 54: pp. 339–342, 2015.

Sharafoddini R., and Habibi M., "Numerical Study of Water Vapor Injection in the Combustion Chamber to Reduce Gas Turbine Fuel Consumption", J. of Appl. Fluid Mech., 1047-1054, 2020.

Shameer Mohamed P and Ramesh K., "Assessment on the consequences of injection timing and injection pressure on combustion characteristics of sustainable biodiesel fuelled engine", Renew Sust Energy Rev; 81: 45–61, 2018.

Soyelmez Sait M. and Hakan Ozcan, "Water Injection Effects on the Performance of Four-Cylinder, LPG Fuelled SI engine", Faculty of Engineering, Department of Mechanical Engineering, Ondokuz Mayıs University, Samsun, Turkey, Vol. 2, 1, 2013.

Totala N.B., Pratyush, Hussain A., Tajkhan M., Siddharth, "Performance analysis of 4-stroke single cylinder SI engine and preheating gasoline and Injecting 50% volume/volume water Methanol mixture in carburetor, Indian Journal of Applied Research, 3 (7), 293-296, 2013.

Waukesha Engine Division, "The Waukesha CFR fuel research engine", an international historic mechanical engineering landmarkthe Waukesha, Bulletin, 1980.

Worm Jeremy, "The impact of water injection on Spark ignition engine performance under high load operation", A doctoral thesis, Mechanical Engineering-Engineering Mechanics, Michigan technological university, 2017