Enhancement of the two-stroke engine performance by spraying a quantity of water or recycling part of the exhaust gas to the intake manifold

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Abstract:

Water injection and exhaust gas recirculation in two-stroke engines is a modern ships technique studied in literature to improve engine performance and reduce nitrogen oxides. Therefore, further investigation on the application of water injection and gas recycling to the engine suction port is essential to indicate the proportions and effect of each of them, such as percentages of fuel consumption and the extent of its impact on pollution. The study was conducted to inject a quantity of water and recycle a portion of the exhaust gas with the main engine charge at the intake to improve performance and reduce pollution. The exhaust gas amount needed by the engine was circulated, and the water spray rate ranged from 0 to 35 of the amount of fuel was used. The water droplets were mixed by a blower installed before the intake port of a two-stroke single-cylinder diesel engine at a rate starting from zero to 35% as a percentage of fuel consumption. The test decreases the exhaust gas temperature as well as a deficiency of nitrogen oxide. This improvement was increased by increasing the water spray rate to 30% due to the energy generated from the unburned mixture and water vapor, which led to a decrease in the drain gas hotness. The rate of improvement in engine capacity reached 12%, the waste gas temperature decreased to about 16%, and the air pollution rate was reduced by 20% through recycling due to exhaust gas..

***Keywords**: two-stroke engine, water injection, spraying, exhaust gas recirculation*

1. Introduction

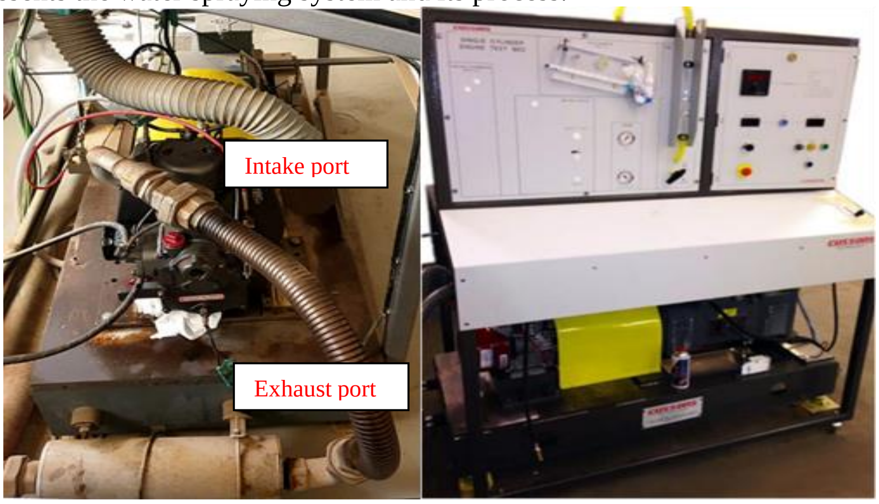
Most ships in the world use two-stroke petrol or diesel engines to generate energy, substantial commercial ships. Exhaust gas circulation was tested on the world's largest marine two-stroke engine, 4UE-X3, and the results confirmed the reduction of nitrogen oxides (NOx) in the engine (Masahiko et al, 2013). The two-stroke engine is simpler in combination than the four-stroke engine because it has no valves, camshaft, or lubrication system and gives a capacity close to twice the capacity of a four-stroke engine (Xinyan and Hua, 2019). A two-stroke engine works in any direction, even if it is upside down due to the absence of lubrication and the lack of lubrication leakage (Xinyan and Hua, 2019). Exhaust gas recirculation systems were added (Sokratis and Gerasimos, 2020) with a four-stroke diesel engine. It reduced emissions of nitrogen oxides in the engine by approximately 73%, with an improvement in the engine brake specific consumption by 9.9% at 100% load. Also, (Ji et al. 2019) summarized that recycling the exhaust gas in addition to humidifying the air entering the two-stroke diesel engine by injecting water with fuel lead to a reduction in nitrogen oxide emissions by 30%. Increased water concentration to a ratio of 2:1 water mass to fuel improved engine fuel consumption was observed (Nielsen et al. 2015). Besides, many types of recent research (Guven et al. 2017, Shyam et al. 2015, Worm 2017, Kettner et al. 2016 and Zehra et al. 2014) have confirmed that spraying water into the engine combustion chambers reduces environmental pollution and improves the efficiency of engines. Besides spraying of water, exhaust gas recycling gives enhancement of engine performance (Wei et al. 2017, Mingrui et al. 2016, Madhavan et al. 2017, Woschni and Jan 2016, Ghazal 2019 and Babu1 et al. 2015).

Based on the literature, many experiments on internal combustion engines using water injection showed many interesting and proven effects. However, they have many differences, such as the methods used with these experiments and the different effects of the devices used. The agreement was noted in summaries and results regarding the decrease in nitrogen oxides and carbon dioxide emissions, but with different impact ratios. The results also revealed that the timing of water injection significantly affects the evaporation of water. Earlier injection leads to better evaporation and a decrease in the tendency to form wetting on the walls. Therefore, the present work focuses on exhaust gas recirculation and water spraying on two-stroke engine performance characteristics. In the previously published research, the effect of adding water or steam to internal combustion engines as the exhaust gases circulate together has not been precisely established. How much improvement will occur in engine performance, how much reduction of the exhaust temperature will occur, and a decrease in heat secretion amounts of contamination to the milieu, and how much improvement in global warming will be with known values.

2. Experimental Work

Experiments were conducted in the internal combustion lab, mechanical engineering department, Jazan University, KSA, on a two-stroke single cylinder petrol engine test facility. Fig. 1 illustrates the present test apparatus containing means for measuring engine speed, torque, power, temperature and pressure, and exhaust gas analyzer device. The test device is equipped with a water spray blower with a valve to control the amount of water that is sprayed with the charge of fuel and air consumed at the suction port. It is also equipped with a tube and valve to recycle part of the exhaust gas according to the required amount. In addition, the test platform contains a stand-alone unit for measuring eddy current dynamics of 7 kW / 4000 rpm, air-cooled and, can replace any engine for testing whether in four or two-stroke type, including gasoline or diesel, air/water cooling, spark ignition/compression. The engine has been tested at various speeds ranging from 1500 rpm to 3600 rpm. The quantities of fuel, the amount of water injected, and the rate of exhaust gases circulated are controlled by valves attached to each of them. The exhaust temperature readings, the laboratory temperature, the air intake temperature, the mass flow rate of gasoline, water, air, and exhaust gas are recorded.

Fig. 3 shows the effect of adding water with air and some of the circulating exhaust gas to the amount of spent fuel on the efficiency of the two-stroke engine at different air-to-fuel ratios from 11.5 to 16.5. The exhaust gas recirculation rate (mass fraction) was calculated as defined in (Sokratis and Gerasimos, 2020). It is clear from the figure that as the percentage of added water increases, the engine's efficiency significantly improves, reaching 12% at 30% of the water injection to fuel percentage. The engine efficiency is increased with an increase in the air/fuel ratio. This results from turning water into steam and generating thermal energy, the engine's efficiency increased by 30%. Fig. 4 shows the effect of an spraying amount of water estimated at 30% as a percentage of the engine's fuel consumption into the combustion chamber on engine NOx. The figure shows that the percentage of pollution decreases with water spraying into the combustion chamber by about 20% at engine speeds from 2000 rpm to 2750 rpm, and this effect decreases at low and high speeds. That is, spraying water to engine intake decreases the NOx with high-efficiency operating speeds due to the lowest specific consumption of the engine. Fig.2 represents the water spraying system and its process.



Two stroke engine

Fig. 1: Two stroke gasoline engine test facility.

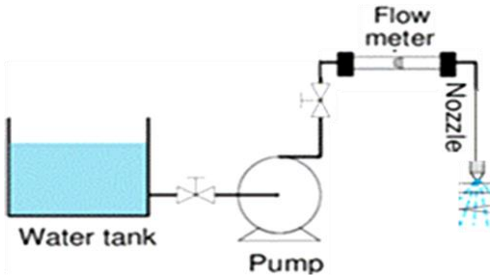


Fig. 2: Water spraying system.

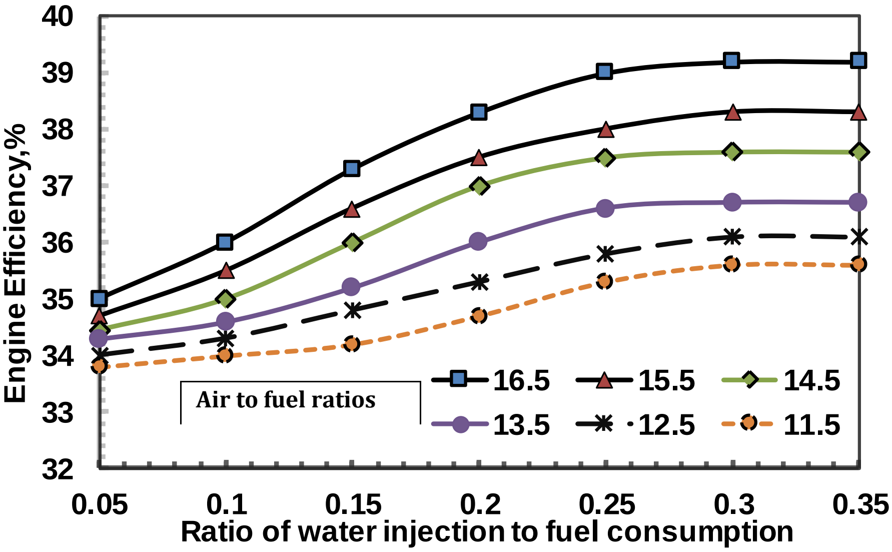


Fig.3: Effect of water injection on two stroke engine efficiency.

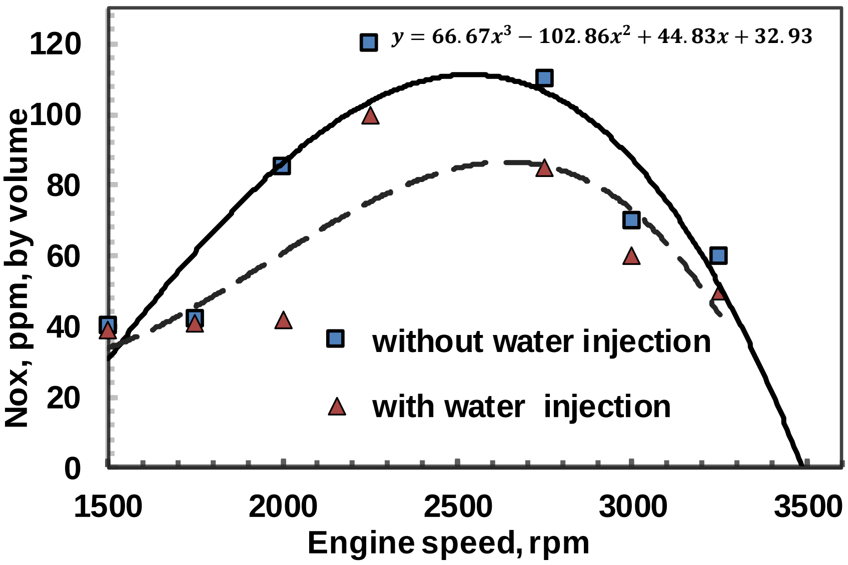


Fig.4: Effect of water injection on the engine NOx.

Fig. 5 represents the effect of adding mass of spray water as a percentage of the spent fuel on the exhaust gas temperature exiting at different engine speeds, ranging from 1500 rpm to 3500 rpm. The figure clearly shows that adding water to the engine's intake pipe decreases the exhaust gas temperature by about 100 ºC or about 16% of the engine exhaust temperature at speeds of 2000 rpm, 2500 rpm, 3000rpm, and 3500rpm. This effect may decrease at the low engine speed and becomes about 15% at an engine speed of 1500 rpm. Also, an increase in water injection decreases the engine exhaust temperature until 0.3 of fuel consumption. Likewise, by increasing the percentage of water spraying higher than 30%, the exhaust gas cooling does not increase more. That indicates that this percentage is sufficient to give the highest thermal energy in the combustion chamber.

Fig. 6 shows the effect of injecting water with the air entering the engine through the intake manifold with a rotating part of the exhaust gas. It is remarked that the volume of air pollution resulting from combustion decreases by increasing the water spraying rates of up to 30% of the fuel consumed in the engine, and by increasing it than this percentage, the effect, which is represented by vertical columns. The study compares the effect of water addition on operational exhaust emissions to the theoretical research results of Lanfazame (1999), where a magnificent agreement in the results was observed. Fig.6 represents the natural result because the spraying water into the combustion chamber leads to a decrease in temperature and a better scavenging action, thus reducing the percentage of specific carbon emissions and pollution in the environment. That confirms that adding water to the fuel is a catalyst to evaporate the water in the combustion chamber. The engine brake-specific fuel consumption was measured without and with spraying water into the charge inlet as represented in Fig. 7 at different speeds. It shows that spraying water at a rate of more than 30% leads to a decrease in engine brake-specific consumption. It is due to an increase in the intake of fumigation and a decrease in heat loss through the combustion chamber walls.

The present results emphasized previously published results that adding an amount of water or recycling part of the exhaust gas through the intake port of two-stroke engines enhances engine performance and reduces exhaust temperature and emission rates. This result of converting water inside the combustion chamber into thermal energy increases the combustion energy of the fuel; additionally, the circulating exhaust gas is further combusted. The injection of water into the combustion chamber cools the combustion chamber, which leads to the ignition speed due to the fuel heating value with an increase in the water content in the fuel. The water in the droplets is evaporated first. The enthalpy value of water evaporation is less than that of the fuel combustion in an engine ignition by pressure when there is no spraying with water.

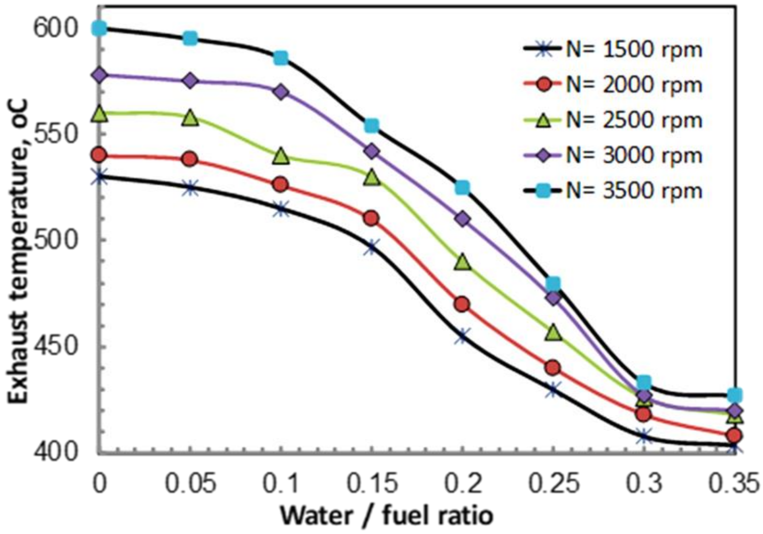


Fig.5: Effect of water injection on the engine exhaust temperature.

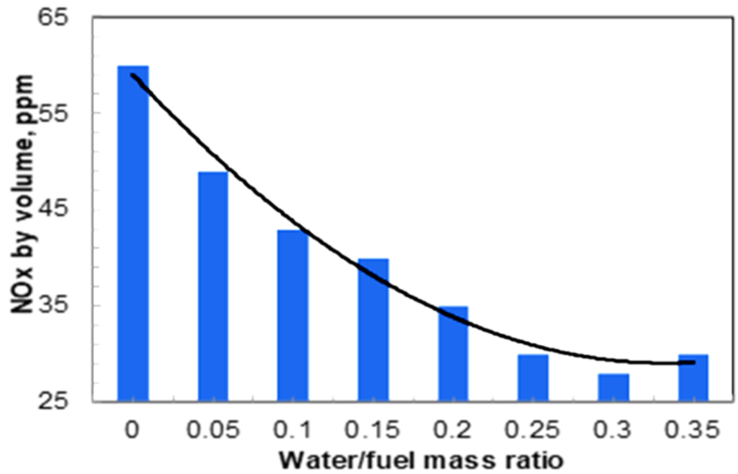


Fig.6: Effect of water injection on the engine Nox

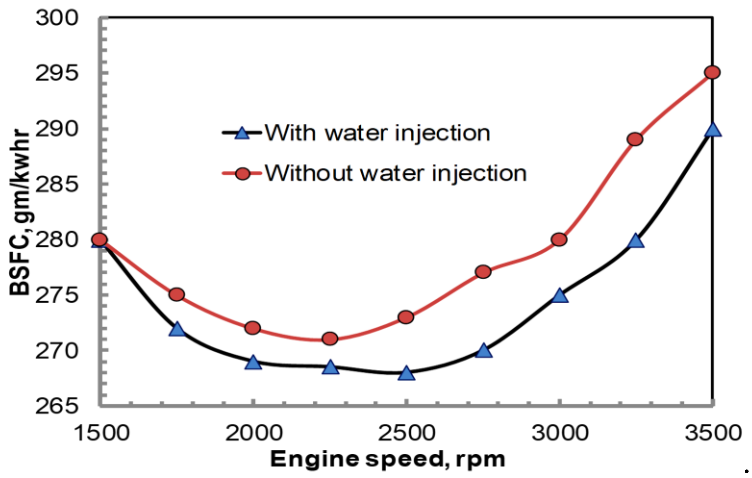


Fig. 7: Effect of water injection on engine brake specific fuel consumption.

3. Theoretical work:

Most of the published research on spraying water into the engine intake port is based on experimental results. Thus, it is considered somewhat insufficient to confirm the density of the fresh mixture, the optimal amount of water that should be sprayed into the intake pipe, and its effect on engine efficiency and polluting emissions, including greenhouse gases, nitrogen oxides, and fine particles. In this theoretical analysis, the effect of water spraying or increasing the density of the fresh inhaled mixture on engine performance and environmental pollution can be studied. It was conducted using an algebraic model of mass-energy balance equations, which relates the density of the fresh mixture at the suction point to the intake system data and the surrounding areas of pressure and temperature. The theoretical analysis results better explain the effect of this process in reducing the exhaust gas temperature. That is because it is known that spraying water into the intake pipe entrance increases the surrounding humidity of the mixture entering the engine instead of having dry air and an intake manifold at a relatively high temperature.

When the water sprays into the pipe or the engine intake pipe, the water evaporates and mixes with the engine cylinder's fresh charge. Thus, an increase in the mixture's density observed, and as a result of the effect of thermal evaporation, the temperature decreases. Thus, increasing the engine's mechanical strength leads to a decrease in the mechanical strength required for the compression stroke, where the gas to be compressed at the beginning is at a lower temperature. Also, the density of the mixture is increased, and at a lower temperature at the end of the compression stroke, the combustion heat is released. Thus, the possibility of road phenomenon decreases. The octane number is increased (Brun et al. 1944 and Lappas 1996). On the contrary, it was mentioned (Kim et al. 2016) that the water injection inlet of the engine inlet is counter or opponent to the exhaust gas recirculation technology. For these and other reasons, the effect of water spraying with exhaust gas recycling is studied through suction and intake of the engine to see the extent of its impact on the engine performance.

To calculate the total mass flow rate that enters into the intake port of the engine, it will be the sum of the gas mass with fresh air consumed, the mass of gas being recycled, and the mass of water that is sprayed, that will be written as follows: $\dot{m}$

$$\dot{m}_{ti} = \dot{m}_{ff} + \dot{m}_{fair} + \dot{m}_{gr} + \dot{m}_{w} = \dot{m}_{dfm} + \dot{m}_{wi} + \dot{m}_{gr} \quad (1)$$

where $\dot{m}$ is the mass flow rate, the subscripts, $_{ti}$ means total inter, $_{ff}$ = fresh fuel, $_{fair}$= fresh air, $_{gr}$ = gas recirculation, $_{dfm}$ = dry air, and $_{w}$ = water spraying, $_{i}$ = inter. The air-to-fuel ratio (AFR) can be defined as the ratio of the dry air mass flow rate to the fuel consumed, so the mass of air is:

$$\dot{m}_{a} = \dot{m}_{f} * AFR \quad (2)$$

Using Eq. (2), the dry fresh mixture flow rate, $\dot{m}_{dfm}$ can be written as:

$$\dot{m}_{dfm} = \varphi\, \dot{m}_{ff} + \dot{m}_{fai} + \gamma\, \dot{m}_{gr} = \dot{m}_{ff} (\varphi + \gamma + AFR) \quad (3)$$

where ϕ and γ are factors those equal to unity if the fuel is mixed with air in the fresh mixture before the intake, or equal to zero otherwise. For the case of air humidity, ω, the ratio of the water vapor mass, ended the dry air one [20], using ω instead of a mass fraction Eq. (3) rearranged to:

$$\omega_i = \dot{m}_{\omega,i} / \dot{m}_{dfm} = \dot{m}_{\omega,i} / [\dot{m}_{ff} (\varphi + \gamma + AFR)] \quad (4)$$

The same steps and sequence were taken to complete the analysis with the decrease in the temperature of the combustion chamber and the exhaust gas out of the engine by researchers (Vaudrey, 2019 and Kim et al. 2016) with Eq. (4) after adding a new term for the mass flow rate of recycling the exhaust gas besides to mass flow rate of the water injection and with the mixture entering the intake hole of the engine. This relationship gives the magnitude of the decrease in temperatures, ΔT, as a function of the rate of water injection and exhaust gas recirculation and the fuel consumed to the engine:

$$\Delta T=(C_{pvap}T_i+C_{pEGR}T_i+\alpha_{EGR}+\alpha_w)WFR/[(\phi+AFR)\cdot(Cp,_{dfm}+\omega_1\cdot C_{p,vap}).(C_{pvap}WFR)] \quad (5)$$

Where α_w is the water specific enthalpy of vaporization at intake temperature T_i, α_{EGR} is the exhaust gas recirculation specific enthalpy.

Fig. 8 shows the effect of spraying water or rotating part of the exhaust gas with the shipment of fuel and air to the engine separately or simultaneously on the amount of decrease in engine temperature, practically and theoretically. It shows that spraying water gives the most significant effect of a decrease in engine temperatures, and the most considerable effect is at 30% of the fuel consumed. The top two curves in fig. 8 show a good match between the laboratory and theoretical results, which gave about 28% decrease in exhaust gas temperatures compared to the results without spraying water, and that at 0.3 of spent fuel, and this percentage decreases when a smaller amount of water is sprayed to the entrance of the intake pipe. Also, it obvious in the figure that recycling a portion of the exhaust gas only to the intake pipe entrance with the charge consumed in the engine gives a more negligible effect than spraying water, up to a temperature decrease of 17% and matches to some extent between laboratory results and theoretical analysis. In contrast, in spraying water, besides rotating part of the exhaust gas together, the effect will be less in reducing the engine temperature. As a result, the reverse action of the exhaust gases with the spraying of water may lead to the loss of a large part of the evaporation energy of the water injected into the inlet, which agrees with Lappas (Lappas 1996). The exhaust gas temperature and the combustion temperatures are decreased with an increase in water injection due to the heat generated by the evaporation of water inside the combustion chamber. As a result of the disintegration of water during the evaporation process, the latent heat of hydrogen increases with an increase in the water injection ratio. This effect was decreased with EGR when added with water injection. Water injection becomes more effective in saving fuel consumption than when the water injected together with EGR. These results confirm that the water contains a large amount of evaporative heat that results when water is sprayed into the engine's intake pipe with the spent shipment of fuel and air. This, in turn, reduces this charge entering the engine and becomes denser or has higher volumetric efficiency. As a result, it gives the engine a better efficiency due to spraying this water into the intake pipe. Spraying water with exhaust gas circulation eliminates the benefits of a denser intake charge, resulting in a weaker engine efficiency than just spraying water.

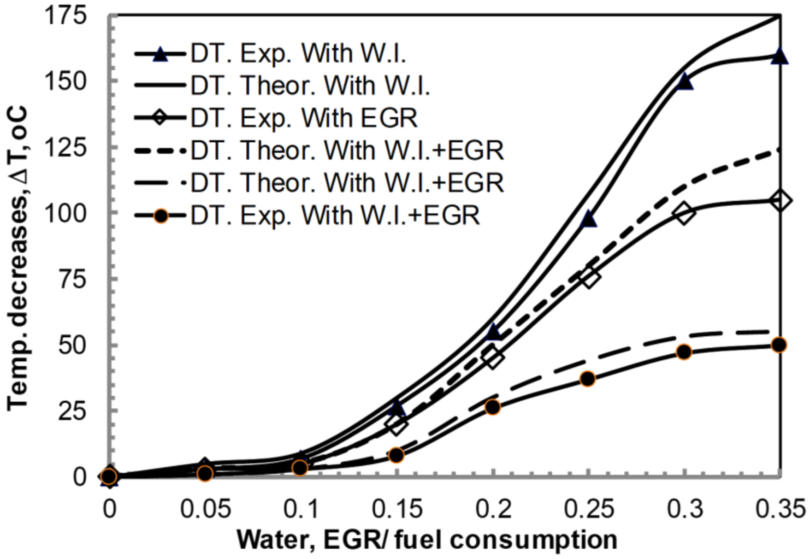


Fig.8: Effect of water injection, exhaust gas recirculation on temperature decreases.

On the other hand, to study the effect of spraying water at the intake hatch with the mixture entering the engine, the extended Zeldovich model (Ghazal, 2019) was used to calculate NOx emissions using the formulas listed below.

$$O + N_2 = NO + N \quad (6)$$

$$N + O_2 = NO + O \quad (7)$$

$$N + OH = NO + H \quad (8)$$

Also, to be able to explore the start of the knocking in the combustion chamber of the engine, models that know the occurrence of knocking using the GT-Power symbol and others [23 and 24] as a function of the crank angle have been used, which are represented as follows:

$$KI=10000\psi * \phi_f(\alpha)\,(V_{TDC}/V(\alpha))\, e^{-60000/T(\alpha)} * max(0,\ 1-(1-\Phi(\alpha)))(I_{ave}(\alpha)/I_{k-ref}I_{k-corr}) \quad (9)$$

Where: KI is the initiation of knock, ϕ_f is the unburned fuel percentage in the cylinder, ψ is the detention key, V_{TDC}, V_{BDC} are the cylinder volumes at the top and bottom dead centers respectively, T is the temperature of unburned gas (K), Φ is the unburned region equivalence ratio, I_{ave}, I_{K-corr} and I_{k-ref} are the integral time of detonation, initiation time integral correlation factor and the average end gas zones.

Because of the knock must occur inside the combustion chamber at the maximum pressure, the expression (Lappas 1996) can be written as a function of the beginning and end of the combustion angles in case of non-violation as follows

$$I_{det.} = \frac{30}{\pi \cdot n}\int_{\varphi_0}^{\varphi_{Pmax}} \frac{P^{C3}}{C1\cdot e^{\frac{C2}{T}}}\,d\varphi \quad (10)$$

And the ignition delay or so-called inti detonation in the spark-ignition engine can be written as:

$$\tau = 17.68(ON/100)^{3.402}\,P^{-1.7}\,exp(3800/T) \quad (11)$$

The thermal energy generated as a result of spraying the water into the intake port with the entry of a mixture of air and fuel into the engine, the models introduced by Woschni (2016), Ghazal (2019), and Soyhan (2009) were rearranged and used for the current engine data for non-knocking condition is:

$$H_{ewi} = \frac{m_{wi}\,LHV_{wi}}{m_{wi}.LHV_{wI} + m_f.LHV_f} + \frac{AC_1(T_g - T_{wall})P^{0.8}}{T^{0.5}D^{0.2}}[C_2U_P + \frac{C_3T_SV(p-p_m)}{(P_SV_S)}]^{0.8} \quad (12)$$

Where the subscript $_{ewi}$ is related to the engine with water injection, A is cylinder area, C_1 C_2 C_3 are Woschni cycle coefficients, P, T, V, D are the combustion chamber pressure, temperature, volume, and diameter, respectively. U, is the piston mean speed; T_s, P_s, and V_s are the temperature, pressure and the cylinder gas volume of the combustion chamber at the start of the burning process; P_m= pouring cylinder pressure. When knock does not occur, the knock index Eq. (9) becomes zero. Otherwise, the value of the knock index will be reported. Also, when knock occurs, the knock probability is reported as 100%, and when knock does not occur, the probability is 0%. The increase of water flow mass resulted in decreased pressure rise rate and reduced engine knock probability, engine vibration, and increased engine stability. Fig. 9 shows a significant decrease in all carbon oxides and nitrogen emissions by increasing the rate of water spraying, and later, controlling emissions from the engine. That is consistent with the present laboratory results of a decrease in temperature by increasing water spraying entering the intake pipe. The NOx emissions limit is reached around 50% for a water mass of 0.3 spent fuel and also from carbon monoxide. Fig. 9 explains the decrease in NOx or gas emission with an increase in the water injection. It emphasizes the decreasing knock and or exhaust gas temperature and increases in octane numbers, increasing the percentage of water injection. The NOx in gasoline and diesel engines decreased as the steam was injected due to the temperature decrease in the combustion chamber. [note that Excel sheet and commercial code have been used in the present solution].

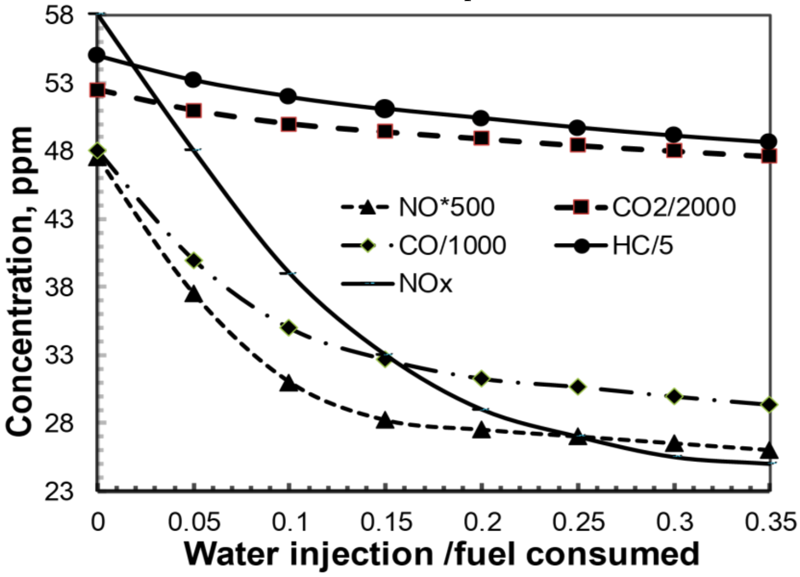


Fig.9: Effect of water injection on engine emissions.

4. Conclusions

Many researchers have published that injecting water into the combustion chamber of internal combustion engines, whether gasoline or diesel, four or two strokes, leads to improved engine efficiency and reduces pollution rates. Also, they disagree on the quality and quantity of improvement, especially the laboratory ones. This confirms the need for more research, especially those studying the effect of this on two-stroke engines, to confirm the ratio of spraying water inside the combustion chambers to the fuel consumption rate in the engine and the amount of exhaust gas that can be recycled. Impact on engine efficiency reduced pollution rates and actual application to large ship engines according to the amount of fuel that can be saved.

The effect of water injection with some exhaust gas recirculating through the engine intake manifold on NOx emissions, engine specific fuel consumption and efficiency has been studied experimentally and theoretically in a two-stroke single-cylinder engine. The results showed improved engine efficiency and fuel consumption by about 30%, decreased the percentage of NOx with the waste gas by about 20%, and reduced the exhaust gas temperature by about 16%. As a result, the increase in the density of the fresh mixture due to the evaporation of liquid water in the intake manifold. The experimental results showed improved engine efficiency by about 20% with 30% water injection to fuel, 20% - 30% reduction in nitrogen oxide emission, and 16% reduction in exhaust temperature. Also, the engine brake specific consumption decreased by 30%. That resulted in a decrease in the pressure inside the combustion chamber, leading to suppress engine knock.

Nomenclature

AFR	air-to-fuel ratio of the dry fresh mixture, , kJ/kgK
$Cp,_{dfm}$	specific heat of exhaust gas recirculated, kJ/kgK
C_{PEGR}	specific heat of exhaust gas recirculated, kJ/kgK
C_{pvap}	specific heat of evaporated water, kJ/kgK
H_2	hydrogen
I_{det}	integral time of detonation
KI	initiation of knock
$\dot{m}_a$	mass flow rate of dray air, kg/s
$\dot{m}_{dfm}$	mass flow rate of the dry fresh mixture, kg/s
$\dot{m}_f$	mass flow rate of fuel, kg/s
$\dot{m}_{fair}$	mass flow rate of the fresh air, kg/s
$\dot{m}_{ff}$	mass flow rate of the fresh fuel, kg/s
$\dot{m}_{gr}$	mass of gas being recycled, kg/s
$\dot{m}_{ti}$	total mass flow rate that enters into the intake port of the engine, kg/s
$\dot{m}_w$	mass of water that is sprayed, kg/s
N_2	nitrogen
O	oxygen
T	temperature, ^oC
T_i	intake temperature
ΔT	decrease in temperatures, ^oC
V_{BDC},	cylinder volumes at the bottom dead centers
V_{TDC}	cylinder volumes at top dead centers
α_{EGR}	specific enthalpy of the exhaust gas recirculation.
α_w	specific enthalpy of water vaporization
ϕ_f	unburned fuel percentage in the cylinder
Φ	unburned region equivalence ratio
ψ	detention key
ϕ and γ	factors
τ	ignition delay or so-called inti detonation in the spark-ignition engine
ω	air humidity

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