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EXPERIMENTAL INVESTIGATION OF THE EFFECTS OF WATER ADDING INTO THE INTAKE AIR ON THE ENGINE PERFORMANCE AND EXHAUST EMISSIONS IN A SPARK-IGNITION ENGINE

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Abstract: In the present study, the effects of water addition into intake air (WAIA) on the engine performance and exhaust emissions have been investigated experimentally in an automotive spark-ignition engine (SIE) which is used in Renault Clio vehicles. Experiments have been performed for (3, 6, 9 and 12) % (by vol.) water ratios (WRs) at different engine speeds and different loads. Selected engine speeds were (3000, 4000 5000, and 6000) rpms. 6000 rpm is the maximum speed of this engine. Selected loads were (100, 90, 80, 70, 60, and 50) Nm for (3000, 4000, and 5000) rpms and were (80, 75, 70, 65 and 65) Nm for 6000 rpm, respectively. The test results showed that WAIA decreases significantly brake specific fuel consumption (BSFC) at (3000, 4000, and 5000) rpms, but it increases BSFC at 6000 rpm. The maximum reduction ratios of BSFC at (3000, 4000, and 5000) rpms have been attained at the levels of 28.27 % for 5.60 % WR, 4.160 for 2.67 % WR and 7.19 % for 9.00 % WR, respectively. WAIA generally decreases nitrogen oxides (NO_x) and total hydrocarbon (HC) emissions at all of the selected operating conditions. At (3000, 4000, 5000 and 6000) rpms, the maximum reduction ratios of NO_x have been reached at the levels of 37.80 % for 8.67 % WR, 58.21 % for 12.18 WR, 57.80 % for 12.17 WR and 66.17% for 12.12.WR, respectively. Approximately 9.40 % decrement in HC was achieved by WAIA at the selected engine speeds. Carbon monoxide (CO) emission decreases by applying WAIA at 3000 rpm whereas it generally increases at (4000 and 5000) rpms. Unlike other engine speeds, WAIA increases CO emission significantly at 6000 rpm. Approximately 9 % WR yields the best results for engine performance and exhaust emissions at all of the selected operating conditions.
Keywords: Spark ignition engine, Water addition into intake air, Engine characteristics, Exhaust emissions

BİR BENZİN MOTORUNDA EMME HAVASINA SU EKLENMESİNİN MOTOR PERFORMANSINA VE EGZOZ EMİSYONLARINA ETKİLERİNİN DENEYSEL OLARAK İNCELENMESİ

Özet: Sunulan çalışmada, buji ateşlemeli bir otomobil motorunda (Renault Clio) emme havasına su eklenmesinin (EHSE) motor performansı ve egzoz emisyonları üzerindeki etkileri deneysel olarak incelenmiştir. Deneyler; dört farklı motor devrinde ve % (3, 6, 9 ve 12, hacimsel oran) gibi dört farklı su oranında gerçekleştirilmiştir. Her motor devri için 6 faklı yükleme durumu seçilmiştir. Ayrıca motorun maksimum devri 6000 d/d için 5 tane yük değeri seçilmiştir. Çalışma sonunda; EHSE ile özgül yakıt tüketiminin (ÖYT) (3000, 4000 ve 5000) d/d için azaldığı belirlenmiştir. (3000, 4000 ve 5000) d/d devir sayılarında ÖYT'nde bulunan maksimum azalma oranları sırasıyla % 5.60 su oranında % 28.27, % 2.67 su oranında % 4.160 ve % 9.0 su oranında % 7.19 düzeyinde olduğu belirlenmiştir. Bununla birlikte; ÖYT, 6000 d/d devir sayısında EHSE ile artmıştır. EHSE ile, NO_x'lerin ve HC'lerin ise seçilen tüm çalışma koşullarında genel olarak azaldığı görülmüştür. (3000, 4000, 5000 ve 6000) d/d devir sayılarında; NO_x'lerde elde edilen maksimum azalma oranları sırasıyla, % 8.67 su oranında % 37.80, % 12.18 su oranında % 58.21 ve % 12.17 su oranında % 57.80 % 12.12 su oranında % 66.17düzeylerinde olmuştur. Aynı devir sayıları için EHSE ile HC'lerde ortalama % 9.40 düzeyinde azalma sağlanmıştır. EHSE ile; 3000 d/d devir sayısında CO emisyonunu azalmasına karşın, (4000 ve 5000) d/d'da CO emisyonu genel olarak artmıştır. 6000 d/d devir sayısında ise CO oranları EHSE ile önemli ölçüde artmıştır. Bu çalışmada deneysel verilerin değerlendirilmesi sonunda, hem motor karakteristikleri ve hem de egzoz emisyonları açısından yaklaşık % 9 su oranının en iyi su oranı olduğu belirlenmiştir.
Anahtar Kelimeler: Buji ateşlemeli motor, Emme havasına su püskürtme, Motor karakteristikleri, Egzoz emisyonu

NOMENCLATURE

be, BSFC	Brake spesific fuel consumption (kg/kWh)
CO	Carbon monoxide (vol.%)
HC	Total hydrocarbons (ppm)
Ne	Effective power (kW)
NG	Neat gasoline
NOx	Oxides of nitrogen (ppm)
SIE	Spark ignition engine
Te	Exhaust temperature (K)
WAIA	Water adding into the intake air
WR	Water ratio
α	Excess air coefficient

INRODUCTION

It is known from the media and relevant literature that the use of diesel cars in the capitals of some European countries and the major metropolitan cities will be banned after 2020 due to increased environmental pollution (Şahin et al., 2017). In addition, the use of spark-ignition engines (SIEs) would become the most widespread solution for hybrid vehicles, which is considered to be the solution of the near future. However, the vehicles used on highways are noted to be the major emission contributor to the environment, which is dangerous to human health. For this reason, scientists, politicians and automotive companies have been working intensively to reduce environmental pollution nowadays (Nguyen and Wu, 2009; Awad et al., 2018; Bozza et al., 2016).

In this context, many different studies are carried out on the SIEs ((Nguyen and Wu, 2009; Awad et al., 2018; Bozza et al., 2016). The use of different alternative fuels, (Awad et al., 2018; Deng et al., 2018; Li et al., 2018; Wang et al., 2018) and water addition (Nguyen and Wu, 2009; Bozza et al., 2016; Worm, 2017; Wilson, 2011; Mingrui et al., 2017, Tiryaki, 2008) can be given as examples of these studies, and the numbers of these studies have been increased in recent years. Using of many alternative fuels and additives, especially alcohols, and also water in SIEs have shown promising results for engine performance and exhaust emissions (Awad et al., 2018; Li et al., 2018; Arabacı et al., 2015). However, since the use of water in SIEs was examined in the present study, the literature review on water addition in SIEs was briefly presented below.

It is known that the studies on water addition in engines began in the 1950s. The use of water into SIEs has been researched for many years to improve the engine in various ways, including: to increase power output, to boost efficiency, to lower NOx and CO emissions, to cool the engine and to reduce knock by increasing the octane number (Nguyen and Wu, 2009; Bozza et al., 2016; Worm, 2017; Wilson, 2011; Mingrui et al., 2017). However, it is stated that HC generally increased in some of the water adding studies (Wilson, 2011; Nguyen and Wu, 2009), but it decreased in the other studies (Mingrui et al., 2017; Valentino et al., 2017, Fan et al., 2021; Osama et al., 2019; Babu et al., 2015). In the relevant literature, water addition is applied in SIEs by three different methods. These are use of direct water–gasoline (fuel) emulsion, water injection into the cylinder by using a separate injector and adding/injecting water into the intake manifold (WAIA) (Wilson, 2011; Tiryaki, 2008; Tiryaki and Durgun, 2010). The water–gasoline emulsion method has been applied lesser than other techniques in SIEs (Nguyen and Wu, 2009; Peters and Stebar, 1976). This method has been usually used in diesel engines (Fahd et al, 2013, Subramanian, 2011). Other water injection methods (port and direct water injection) have been widely investigated by different researchers in SIEs, and the number of these studies has increased in recent years. Some examples of these studies applying the above-mentioned methods are briefly presented in the following paragraphs.

Nguyen and Wu (2009) performed experimental research on the effects of water-gasoline emulsions on engine performance and emissions in a SIE. They found that for 13.23 air-fuel ratio (AFR), 5% and 10% water-gasoline emulsion slightly increase engine torque; otherwise, 15% water-gasoline emulsion decreases. Also, their results showed that water-gasoline emulsions create good reductions in NO_x and CO emissions near the stoichiometric AFR while increases in HC emission occurs. Mingrui et al. (2017) investigated the influence of variable water injection (WI) on the performance and emission characteristics of a gasoline direct injection engine under light load conditions. In this study, water was directly injected into the cylinder by using a different injector. Their results showed that 15% water injection gave the best engine performance. Also, they found that WI decreased NO_x emissions as well as soot emission. Martin Böhm and colleagues (Böhm *et al.*, 2016), who work for BMW, examined the water injection into the combustion chamber in a 1.5 L three-cylinder SIE. In this study, a water-gasoline mixture is injected into the cylinder by using an adapted injection system. Their results show that water injection decreases particulate and CO/HC emissions and BSFC. Fan et al. (2021), investigated port water injection technique in a three-cylinder direct-injection SIE. They explained that adding water to the intake air of gasoline engines could efficiently advance the combustion phase by enhancing the anti-knock capability of the engine and significantly improving thermal efficiency. In this study, they obtained 3.4%–16.7% improvements in the brake-thermal efficiency under different engine operating conditions. Merola et al. (2020), studied water injection effects on engine performance and exhaust emissions in a single-cylinder SIE. In this research, engine performance was found to exhibit a slightly decreasing trend when increasing the injected water quantity in three steps, at 10, 20 and 30% of the mass flow of gasoline. Here, CO emission did not change largely with the water ratio, while NO_x decreased up to 35% for the highest water-fuel ratio.

From the above given literature, it can be seen that the results of these methods are different from each other. The same method may give different results for different engines. However, by applying all three water adding methods in SIEs, it has been determined that in-cylinder temperatures and NO_x are decreased and the knock resistance is increased (Nguyen and Wu, 2009; Bozza *et al.*, 2016; Worm, 2017; Wilson, 2011; Mingrui *et al.*, 2017; Tiryaki, 2008; Tiryaki and Durgun, 2010). Water using research have been usually carried out in SIE by applying one of these methods. However, the number of studies on the use of water in SIE is less than diesel engines. In addition, selected operating conditions such as engine load, water ratio and engine speed are limited in the water use research for SIEs given in the literature. Therefore, in this study, the effects of the four different WAIA on engine performance and exhaust emissions are investigated experimentally under six different loads at four different engine speeds in an automotive SIE. The experiments were carried out in an automotive SIE currently used in motor vehicles, is very important for providing new information to the industry. In addition, the performing of water adding tests at 6000 rpm, which is higher than nominal engine speed, may contribute some extra information to the literature from a different point of view.

EXPERIMENTAL STUDY

Engine and Experimental Set-up

Experiments for neat gasoline (NG) and water adding into the intake air (WAIA) were conducted in an automotive SIE (Renault Clio). In the present study, water at different ratios has been added into intake air by an adapted variable main jet carburettor placed on the inlet manifold of the engine. The main technical specifications of the engine were given in Table 1 and the schematic diagram of the test system used is presented in Figure 1. The test bed was produced by Cussons. Here, loading was done by a water brake, and the brake moment was measured electronically. Exhaust gases were measured by using an exhaust gas analyzer (MDS 450, AVL). The measurement ranges and uncertainties of the exhaust gas analyzer and test system were given in Table 2.

Table 1. Main technical specifications of the test engine.

Engine	Renault Clio
Number of cylinder	4
Displacement	1.4 L
Stroke and bore	79.5; 70 mm
Compression ratio	9.5
Fuel injection system	Multi point port injection
Maximum power	55 kW @ 5800 rpm
Maximum torque	114 Nm @ 4250 rpm

Test Procedure

In the present study, tests were carried out at (3000, 4000 5000 and 6000) rpms engine speeds and for approximately 3 %, 6 %, 9 %, and 12 % (by vol.) WRs. Also, six different loads of (100, 90, 80, 70, 60, and 50) Nm were selected for 3000, 4000 and 5000 rpms. But at 6000 rpm, five different loads such as (80, 75, 70, 65, and 60) Nm were chosen. Firstly, NG tests were conducted as NG values were required to compare with that of water addition. After NG tests were completed, the adapted carburettor was mounted on the intake manifold of the engine. Figure 1 presents the technical view of the adapted carburettor. Information about the adapted carburettor was given authors' previous studies (Şahin *et al.*, 2014; Şahin *et al.*, 2015). In addition, to introduce water into intake air and to measure the amount of the added water, a small water tank, a scaled glass bulb, and a flexible pipe were used and the water adding unit is shown in Figure 1. Any other change on the experimental system and engine was not done. The main steps of the experiments are briefly given in the following paragraph.

Table 2. Technical specifications of exhaust gas analyser (MDS 450, AVL) and test system

Parameter	Measurement Range	Accuracy
CO (%)	(0-15)	± (0.02-0.03) %
CO2 (%)	(0-20)	± 0.3 %
HC (ppm)	(0-3000)	± 4 ppm
O2 (%)	(0-25)	± 0.02 %
NOx (ppm)	(0-5000)	± 5 ppm
Excess air coefficient (α)	0-9.999	α is calculated from CO, CO2, HC ve O2
Engine speed (rpm)	Max: 7500	± 5 %
Torque (Nm)	Max: 280	± 5 %

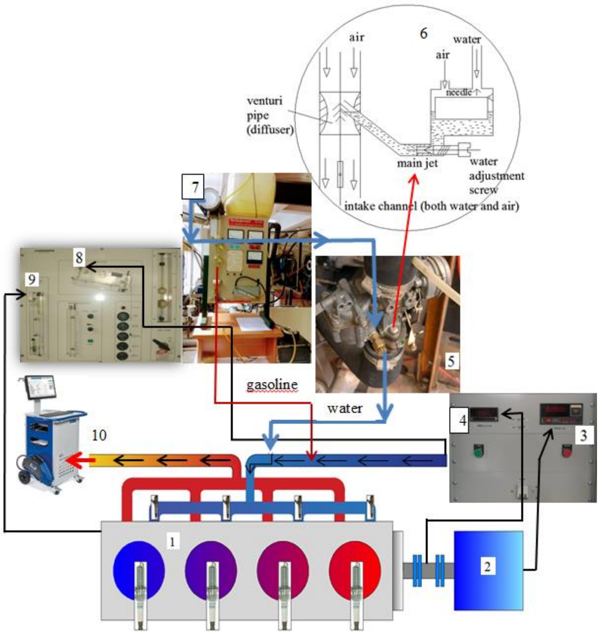


Figure 1. Experimental system. 1-Engine (Renault Clio), 2-Load unit, 3-Torque, 4- Engine speed, 5- Adapted carburettor, 6- Technical drawing of the adapted carburettor, 7- Water tank, 8- Air measurement manometer, 9- Coolant flow meter, 10-Exhaust gas analyzer

The test engine was run for approximately (20-30) minutes before tests, and when the temperature of cooling water becomes (70 ±5) °C, that is steady-state conditions were reached, experiments for NG and various WRs have been carried out. For example, at 3000 rpm, firstly, the engine load was adjusted as 100 Nm. Then, the mean jet opening of the carburettor was adjusted to the 1st opening, which gives ~3 % WR. After approximately ~3 % WR tests were carried out for loading moments between (100-50) Nm; by reducing the engine load at 10 Nm steps and simultaneously adjusting gas throttle levels suitably to obtained constant 3000 rpm. Thus, ~3 % WR tests under six different engine loads were performed. After that, for obtaining ~6 % WR, the main jet opening of the carburettor was adjusted to the 2nd opening, and this opening was again retained fixed at the same 3000 rpm. Thus, tests for ~6 % WR were carried out under the above selected six different engine loads. Then, the similar experimental procedure for approximately (~9 % and ~12 %) WRs at 3000 rpm was performed. The similar tests were performed for the same loads and same WRs at (4000, 5000 and 6000) rpms. Calculation of the engine performance parameters, such as effective power, total fuel consumption, BSFC etc. by using experimental values is given briefly in the following paragraphs. Detailed information can be found in the reference (Durgun, 2018; Durgun, 1990).

$$N_e(kW) = \frac{0.1013}{1000} \cdot \frac{T_b \cdot \omega}{P_0} \cdot \sqrt{T_0/293} \cdot X_{hum} \quad (1)$$

$$B(kg/h) = \frac{\Delta m}{\Delta t} = \frac{(\Delta V \cdot \rho) \cdot 3600}{\Delta t \cdot 10^6} \quad (2)$$

$$b_e(kg/kWh) = \frac{B}{N_e} \quad (3)$$

In Eq.1; T_b (Nm) and ω (r/s) are brake torque and angular velocity, respectively. P_0 (MPa) and T_0 (K) are ambient air pressure and ambient air temperatures, respectively. X_{hum} is the humidity correction factor. In Eq. 2; ΔV is the volume of consumed gasoline, Δt (s) is the duration of consumption of ΔV volume (50 mL) of gasoline, ρ (kg/m^3) is the density of gasoline.

Here, from the experimental results by applying the error analysis to the measured or derived values (Holman, 2001), uncertainties for effective power and BSFC were computed and it is determined that they took values at the interval of (0.365-1.486) % and (0.995-5.445) %, respectively. Thus, it can be said that these uncertainties are within acceptable limits.

Some of the results obtained from the experimental study are presented in the following section. Here, the variation ratios of BSFC and exhaust emissions in respect of NG were also calculated. For example, variation ratio of BSFC was computed as follows:

$$\frac{\Delta b_e}{b_e} \cdot 100\ [\%] = \left[\left(b_{e,WAIA} - b_{e,NG}\right)/b_{e,NG}\right] \cdot 100 \quad (4)$$

where $b_{e,WAIA}$ and $b_{e,NG}$ are BSFC values for water addition and neat gasoline, respectively.

RESULTS AND DISCUSSION

In this section, the effects of four different WRs on effective power, BSFC, exhaust emissions such as CO, NO_x and HC, excess air coefficient and exhaust temperature (T_e) of this automotive SIE at different loads and engine speeds are presented by comparing with NG. Figures 2 (a-b)-Figures 18 (a-b) present the variation and VRs of effective power, BSFC, CO, NO_x, HC versus WRs under six different loads at (3000, 4000, and 5000) rpms and under five loads at 6000 rpm, respectively. Also, the effects of WAIA on excess air coefficient (α) are shown in Figures 19 (a-d) at selected above engine speeds. Besides, T_e values at (4000, 5000, and 6000) rpms are shown in Figures 20 (a-c). Due to an arising technical problem in the thermocouple when performing experiments at 3000 rpm, T_e values could not be measured.

The effects of WAIA on effective power and BSFC

Figure 2 (a-f) shows the variations and VRs of effective power versus to WRs under different loads at 3000, 4000, 5000 and 6000 rpms, respectively. As can be seen from these figures, WAIA has little influence on effective power. From Figures 2 (a-d), it is observed that the effective power increases at 3000 and 4000 rpm with the addition of water. However, as can be seen in Figures 2 (e-h) that the effective power decreases with the addition of water at 5000 and 6000 rpms. The variation ratios in effective power are very small and they take place within the error limits. Babu et al. (2015) were studied the effects of water mist injected directly into an intake manifold of an SIE. In this study, it has been found that the maximum torque increases by 10%-14% when different water mist is injected into the engine. The improvements in engine performance were explained as follows by these authors. The used water dissociated into molecules of hydrogen and oxygen that assists combustion in the combustion chamber. This may improve engine torque. In the present study, it is thought that the WAIA has created similar effects. Besides, Arabacı et al. (2015) the effects of the water injection quantity and injection advance on engine performance and exhaust emissions were investigated in a six-stroke SIE. In this study, water was injected directly into the cylinder by using a different water injector. They found that brake power was increased 10% by water injection.

Figure 3 (a-b) show the variations and VRs of BSFC versus to WRs under (100, 90, 80, 70, 60, and 50) Nm loads at 3000 rpm, respectively. It is observed that WAIA decreases BSFC at all of the selected operating conditions. From these figures, it can be seen that the reductions ratios in BSFC generally continue up to (5-9) % WRs, but the reductions ratios in BSFC begin to decrease after these WRs. The obtained maximum decrease ratio of BSFC is 28.27% for 6.6% WR at 3000 rpm. Figure 4 (a-b) show the variations and VRs of BSFC versus WRs under (100, 90, 80, 70, 60, and 50) Nm loads at 4000 rpm. It is observed that WAIA generally decreases BSFC at this engine speed. However, BSFC increases for 5.45 % and 9.37 % WRs, but it decreases for 3.05 % and 12.18 % WRs under 100 Nm. As shown in Figure 4 (a-b), BSFC reduces under the other selected loads; on the other hand, the decrease ratios in BSFC are low at high WR such as 12%. The attained maximum decrease ratio of BSFC is 4.16% for 2.67% WR at 4000 rpm.

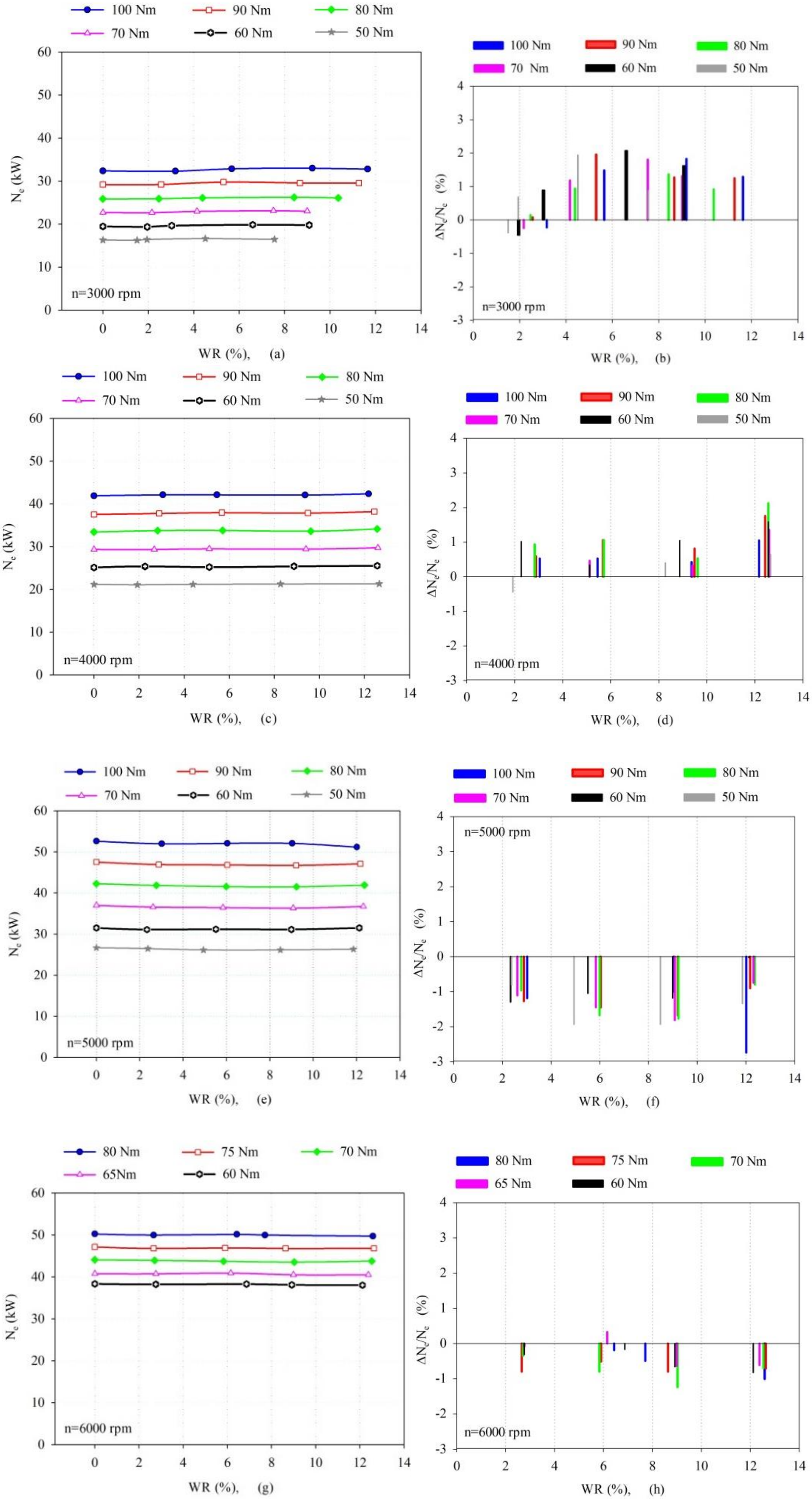


Figure 2 (a-h). Variations and VRs of effective power versus different WRs under different loads at 3000, 4000, 5000 and 6000 rpm, respectively

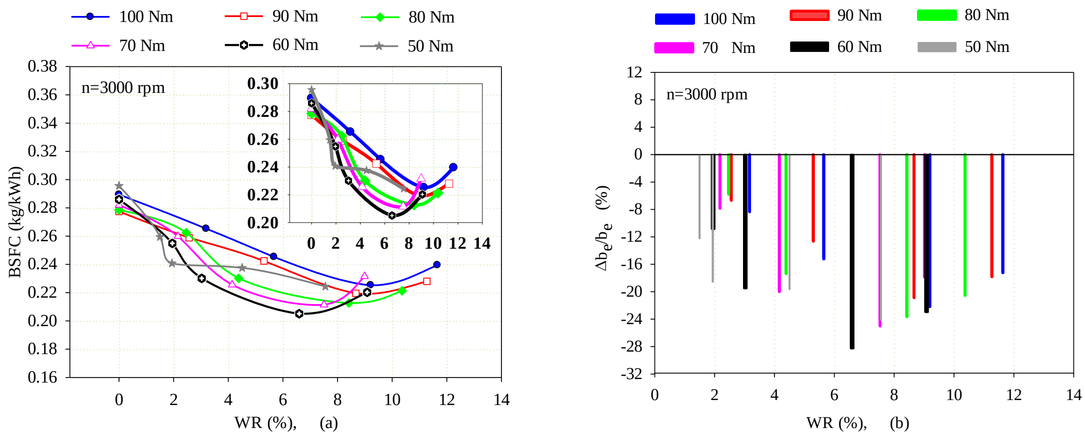


Figure 3 (a-b). Variations and VRs of BSFC versus different WRs under six different loads at 3000 rpm, respectively

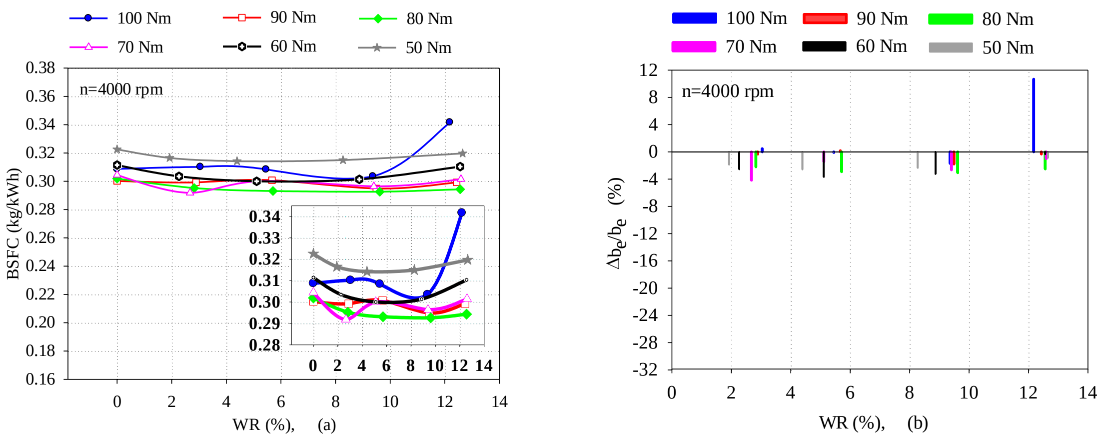


Figure 4 (a-b). Variations and VRs of BSFC versus different WRs under six different loads at 4000 rpm, respectively

Figure 5 (a-b) shows the variations and VRs of BSFC versus WRs under (100, 90, 80, 70, 60, and 50) Nm loads at 5000 rpm. It is observed from the figures that WAIA generally decreases BSFC at all of the selected operating conditions. However, BSFC increases for approximately 12 % WRs under 100 Nm and 90 Nm loads. The obtained maximum decrease ratio of BSFC is 7.19% for 9.03% WR at 5000 rpm.

Figure 6 (a-b) shows the variations and VRs of BSFC versus WRs under (80, 75, 70, 65, and 60) Nm loads at 6000 rpm. Unlike to the other engine speeds, WAIA generally increases BSFC at 6000 rpm. This speed is higher than the nominal speed of the experimental engine. For this reason, the expected beneficial effect of water adding did not occur at 6000 rpm, because of higher mechanical losses and smaller combustion duration. At this engine speed, for (6-8) % WRs, the increase ratios of BSFC are lower at low loads in which the engine is less forced. Similar results have also been reported by the earlier researcher (Worm, 2017; Wilson, 2011; Böhm et al., 2016; Fan et al., 2021; Rocha et al., 2021). Martin Böhm and colleagues (Böhm et al., 2016) examined the water injection into the combustion chamber in an SIE. In this study, it was stated that by adding water, BSFC decreased significantly, and 23% decrement ratio in BSFC was determined for 35% WR.

The following interpretations can be made by considering the reduction of BSFC. As water has a very high latent heat of vaporization, evaporating of the added water during intake and compression processes could reduce the cylinder temperature and pressure values. The reduction in pressure values is not only helpful for reducing the compression work but also helps in reducing the suction gas losses resulting from blow-by pass to the piston rings. It is also thought that the charge cooling effect of water addition might also increase volumetric efficiency. Furthermore, the addition of water improves the combustion process, thus increasing the combustion rate of the fuel and enhancing the knocking tendency of the engine. The above effects are thought to contribute to the improvement of BSFC (Wilson, 2011; Worm, 2017; Mingrui *et al.*, 2017; Tiryaki, 2008, Tiryaki and Durgun, 2010).

The effects of WAIA on exhaust emissions

Figure 7 (a-b) shows the variations and VRs of CO emission versus WRs under six different loads at 3000 rpm, respectively. It is observed from these figures that WAIA decreases CO emission at all of the selected operating conditions at this engine speed. As can be seen in Figure 7 (a-b) that as the water addition ratios into the intake air increase, the ratios of reduction in CO emission increase. The obtained maximum decrease ratio of CO emission is 11.65% for 10.5% WR at this engine speed. It can be seen in Figure 19a that WAIA increases the air excess coefficient, which results in improving the combustion process and reducing of the CO emission (Heywood, 1988; Nguyen and Wu, 2009). However, as shown in Figures 8(a-b) and Figures 9(a-b) that WAIA generally increases the CO emission at 4000 and 5000 rpms. CO emission decreases for about (2-3) % WRs at 4000 rpm. However, after these WRs, CO emission has started to increase. At 5000 rpm, CO emission generally increases for selected WRs, but the increasing ratios in CO emission have remained below 10%. Reductions of CO emission have been achieved for 12% WR under some loads. As can be shown in Figures 10 (a-b), WAIA increases CO emission significantly at 6000 rpm, which is higher than that of the nominal speed of this engine, As shown in Figures 19 (b-d) that excess air coefficients reduce with WAIA at (4000, 5000, and 6000) rpms. In this condition, combustion occurs in the richer mixture, which could increase CO emission. Similar results have been reported in the literature (Harrigton,1982; Babu et al., 2015; Nguyen and Wu, 2009, Osama et al., 2019).

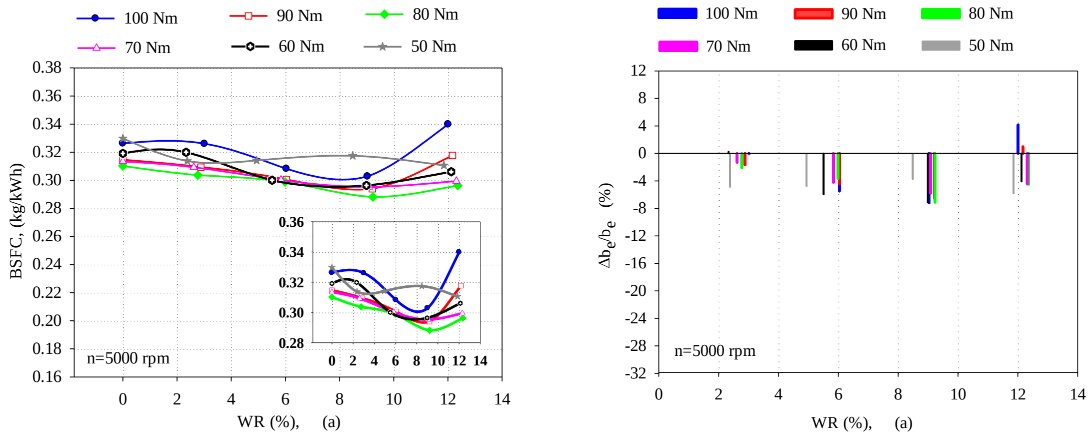


Figure 5 (a-b). Variations and VRs of BSFC versus different WRs under five different loads at 5000 rpm, respectively

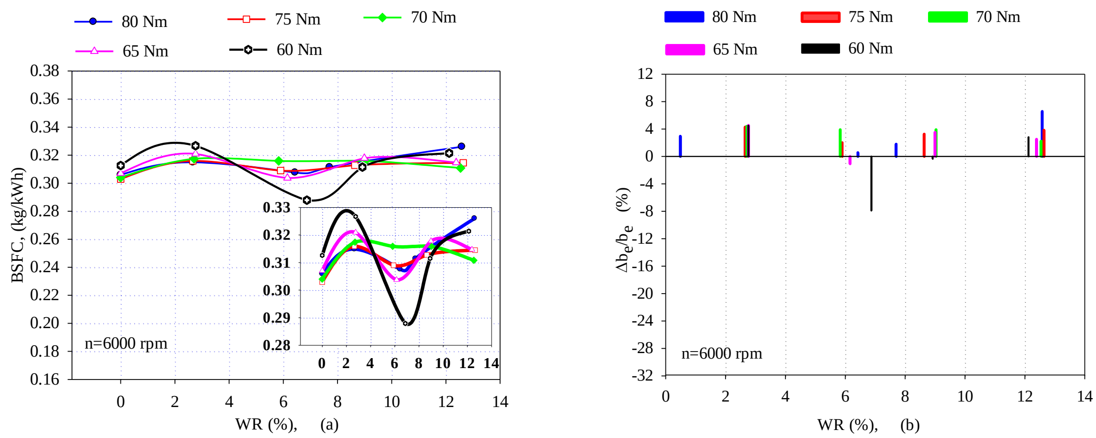


Figure 6 (a-b). Variations and VRs of BSFC versus different WRs under five different loads at 6000 rpm, respectively

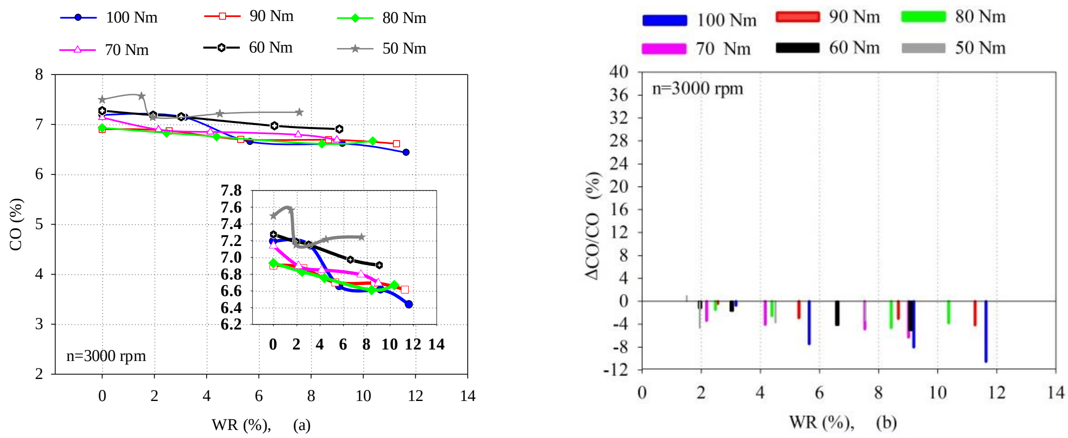


Figure 7 (a-b). Variations and VRs of CO emission versus different WRs under six different loads at 3000 rpm, respectively

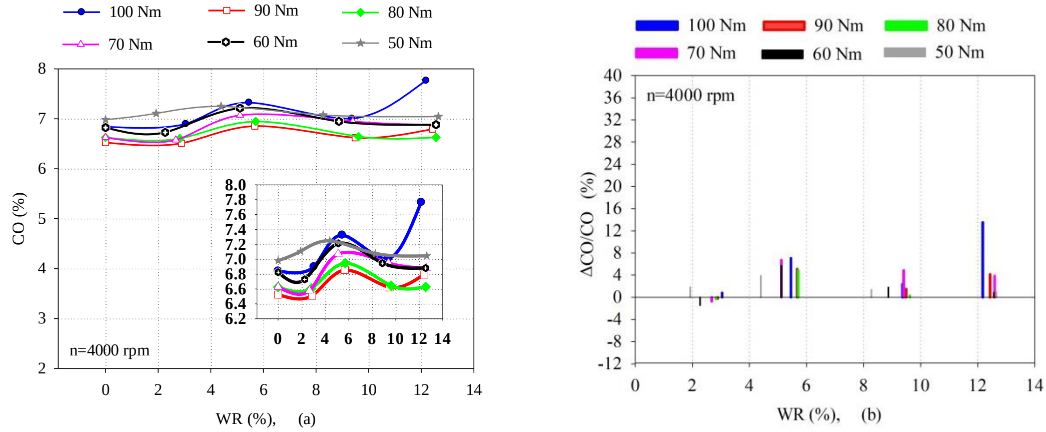


Figure 8 (a-b). Variations and VRs of CO emission versus different WRs under six different loads at 4000 rpm, respectively

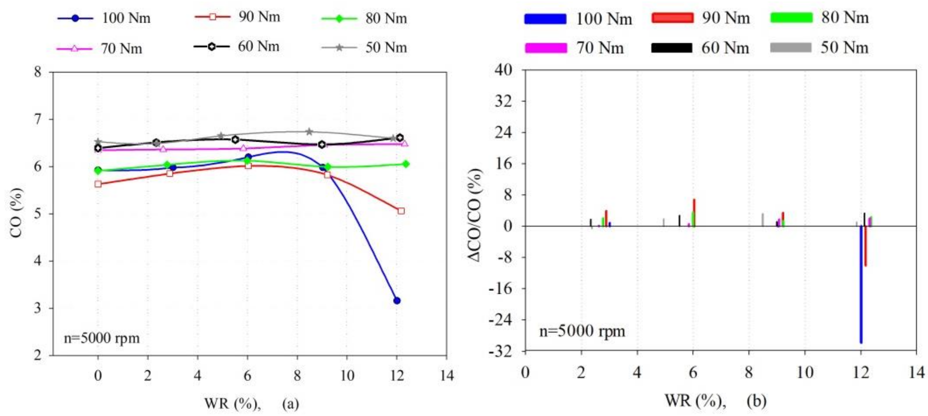


Figure 9 (a-b). Variations and VRs of CO emission versus different WRs under six different loads at 5000 rpm, respectively

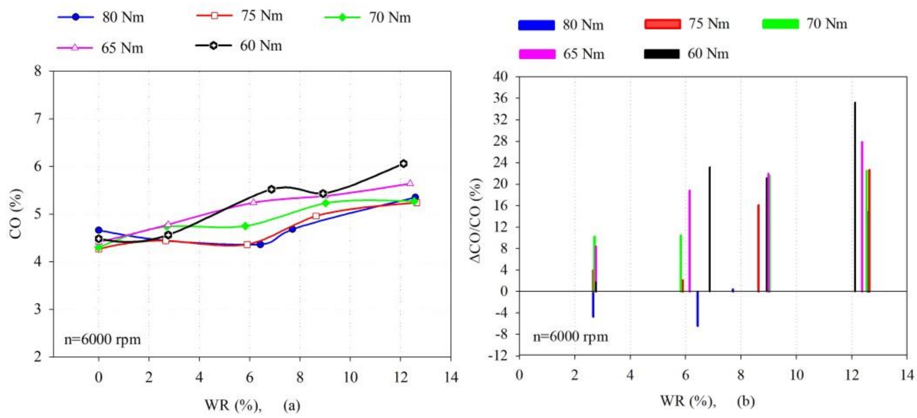


Figure 10 (a-b). Variations and VRs of CO emission versus different WRs under five different loads at 6000 rpm, respectively.

The effects of WAIA on NO_x emissions are presented in Figure 11(a-b), 12(a-b), 13(a-b) and 14(a-b) at (3000, 4000, 5000, and 6000) rpms, respectively. As expected, WAIA decreases the NO_x emissions significantly at most of the selected working conditions. Figures 11 (a-b) show the variations and VRs of NO_x emissions versus WRs under (100, 90, 80, 70, 60, and 50) Nm loads at 3000 rpm, respectively. It could be observed that WAIA increases NO_x emissions at low WRs, such as approximately 3%. However, after this ratio, NO_x emissions are decreased significantly with WRs. The obtained maximum decrease ratio of NO_x emissions reaches to 37.81% for 8.67% WR under 90 Nm load at 3000 rpm.

Figures 12 (a-b) present the variations and VRs of NOx emissions versus WRs under (100, 90, 80, 70, 60, and 50) Nm loads at 4000 rpm. At this engine speed, NOx emissions decrease significantly at all of the selected operating conditions. The obtained maximum decrease ratio of NOx becomes 58.21% for 12.18% WR under 100 Nm load. It is observed that although there NOx emissions increase somewhat at some water ratios at (5000 and 6000) rpm, NOx emissions decrease significantly in general. The decrease ratios in NOx emissions for 12% WR are more prominent than that of low WRs at these engine speeds. The obtained maximum decrease ratios of NOx emissions are 57.80% for 12.17% WR under 90 Nm and 66.17% for 12.12 WR under 60 Nm at (5000 and 6000) rpm, respectively.

Similar results have been found in the literature (Nguyen et al, 2009; Babu et al., 2015; Mingrui et al., 2017). Nguyen et al. investigated the effects of water-gasoline emulsions in an automotive SIE, and they found that NOx emissions have been decreased approximately 35.0% by 5% water concentration. Mingrui et al. studied the effects of direct water injection into the cylinder by using different injectors on engine performance and exhaust emissions in a SIE. In this study, the optimum water ratio was determined as 15%. Also, they found that NO emissions were decreased up to 34.6% on average with the water use.

As well from the relevant literature (Heywood, 1988) that, the formation of NO_x emissions depends on the level of maximum temperature and excess air coefficient of the engine. As can be seen in Figures 19 (a-d), Figures 20 (a-c) that WAIA generally decreases excess air coefficient, and it increases the exhaust temperature slightly at all of the selected operating conditions. For this reason, it could be said that excess air coefficient reduction is more dominant than that of exhaust temperature in reducing NO_x formation. Although the exhaust temperature values are higher than that of NG, it is thought that there are lower local combustion zones leading to reduced reaction rates for NO_x in the combustion chamber (Mingrui et al., 2017; Wilson, 2011; Worm, 2017).

HC emissions are formed mainly due to the incomplete combustion of fuel and the quenching effect at the cylinder wall (Galloni et al., 2016; Feng et al., 2015). Also, HC emissions formation depends on engine operating conditions and fuel properties to some extent (Feng et al., 2015).

As shown in Figure 15 (a-b), 16 (a-b), 17 (a-b), and 18(a-b), the WAIA generally decrease HC emissions formation at all of the selected operating conditions. Figures 15 (a-b) depict that HC emissions decrease with increasing WRs at 3000 rpm. The reduction ratios in HC emissions at high loads are more prominent than that of lower loads. It is thought that higher cylinder temperatures at high loads have an improving effect on the reduction of HC emissions. The obtained maximum decrease ratio of HC emissions becomes 27.34% for 11.27% WR under 90 Nm at this engine speed. At (4000 and 5000) rpms, HC emissions decrease approximately 6% and 9% WRs, but they increase about 3% and 12% WRs. It is thought that for (6 and 9) % WRs, the combustion phase could be improved, which reduces HC emissions. The wall quenching effect may be more dominant for 12% WR due to lower temperatures because of the cooling effect of water. The obtained maximum decrease ratio in HC emissions reaches to 32.80% for 9.37 % WR under 100, Nm and 30.30 for 9.03% WS under 100 Nm at 4000 and 5000 rpms, respectively. WAIA also decreases HC emissions at 6000 rpm. At this engine speed, an average 15.13% reduction has been obtained in HC emissions.

In the present study, it is observed that WAIA generally decreases HC emissions at the selected engine speeds. It could be thought that water adding into intake air may cause subsequent burning, which results in the reduction of HC emissions during the expansion process. Besides, it can be said that the low quenching effect at the cylinder wall, especially at high loads, contributes to the decrease of HC formation. Similar results have been reported in the literature (Mingrui et al., 2017; Valentino et al., 2017, Fan et al., 2021; Osama et al., 2019; Babu et al., 2015; Arabacı et al., 2015). Mingrui et al. (2017) have explained the reduction of HC as follows. By applying water injection, the steam should be decomposed into hydrogen and oxygen at high temperatures during the combustion stroke. Thus, 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 hydrocarbons are reduced dramatically. However, in the existing literature, there are also studies in which it was stated that HC emissions increase with the water adding (Wilson, 2011; Nguyen and Wu, 2009).

The effects of WAIA on excess air coefficient and exhaust temperature

As shown in Figure 19a, WAIA decreases excess air coefficient at 3000 rpm; on the other hand, it increases excess air coefficient values at all of the other selected engine speeds. It is well known from the literature that the excess air coefficient is one of the most important combustion parameters that gives us useful information about the combustion process (Heywood, 1988; Durgun, 2018). As explained above, at 3000 rpm the combustion is become lean because of increasing excess air coefficient values, considerable reduction of BSFC and CO emission. At (4000 and 5000) rpms, excess air coefficient values decrease slightly with WAIA. These reductions are below of 2%. Therefore, as WAIA improves combustion at these engine speeds, BSFC has decreased, and CO emission has also decreased at (5 and 9) % water ratios. At 6000 rpm, BSFC and CO emission increase significantly as the increase ratios of excess air coefficients take higher values by the effect WAIA. It should not be forgotten that the reduction of excess air coefficient has an improving effect on the formation of NO_x emissions (Heywood, 1988).

As shown in Figure 20 (a-c) that WAIA generally increase exhaust temperature at all of the selected engine operating condition. At 4000 rpm, the exhaust temperature decreases for ~12% WR, but it increases for other lower WRs. The increase ratios in exhaust temperature values have remained below of 4% during this engine speed. At 5000 rpm, the exhaust temperature increases for approximately (9 and 12) % WRs and under full load (100 Nm). Exhaust temperature slightly increases at these WRs under other lower loads. For (3 and 6) % WRs, the exhaust temperature has decreased under some loads and contrarily has increased under some loads. However, increases and decreases in exhaust temperature values have not been very high at 5000 rpm.

At 6000 rpm, the exhaust temperature increases significantly at all of the selected operating conditions. As seen in Figure 19d, the engine has operated in rich conditions for WAIA at this engine speed. This might increase the exhaust temperature.

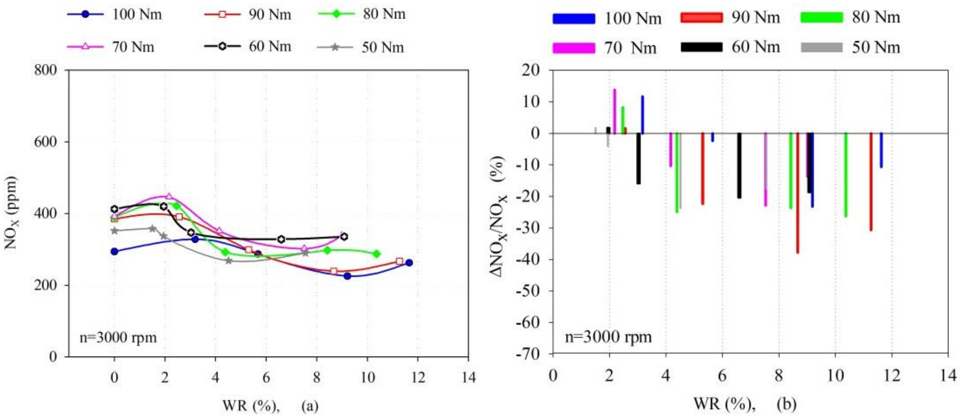


Figure 11 (a-b). Variations and VRs of NO_x emissions versus different WRs under five different loads at 3000 rpm, respectively.

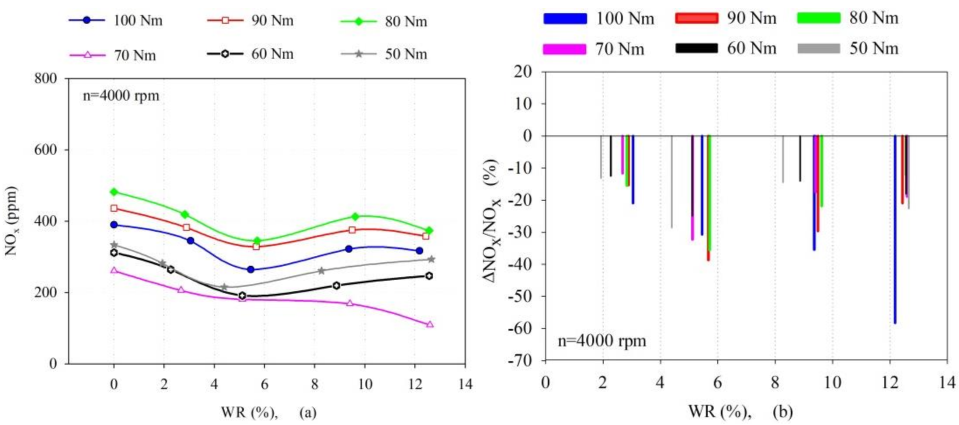


Figure 12(a-b). Variations and VRs of NO_x emissions versus different WRs under five different loads at 4000 rpm, respectively.

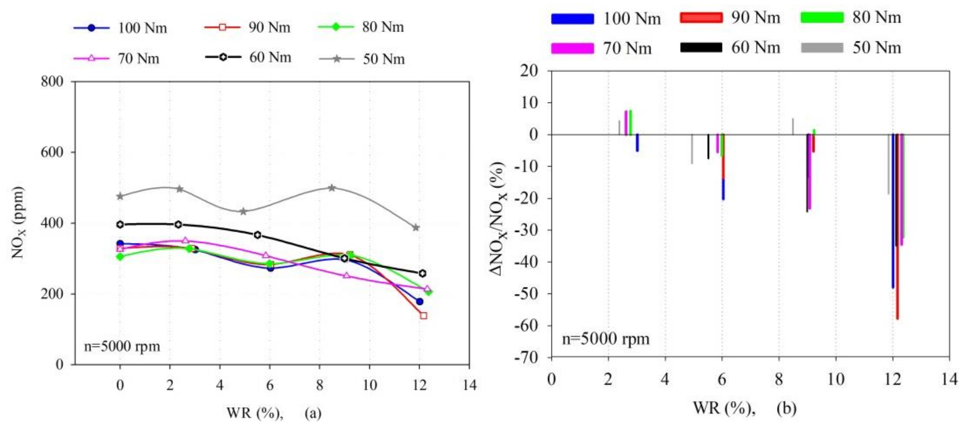


Figure 13 (a-b). Variations and VRs of NO_x emissions versus different WRs under five different loads at 5000 rpm, respectively.

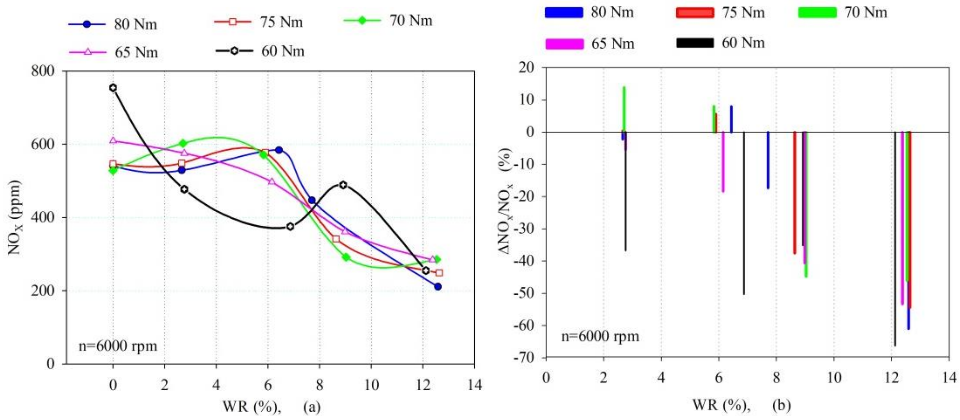


Figure 14 (a-b). Variations and VRs of NO_x emissions versus different WRs under five different loads at 6000 rpm, respectively.

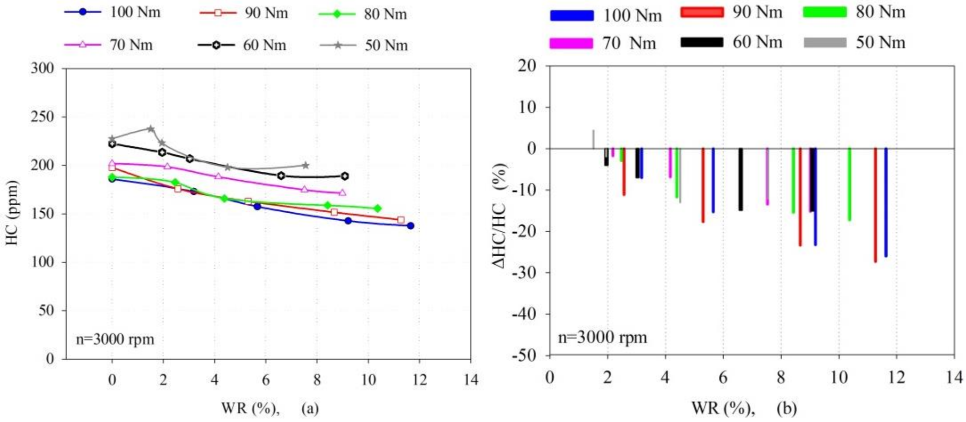


Figure 15 (a-b). Variations and VRs of HC emissions versus different WRs under five different loads at 3000 rpm, respectively.

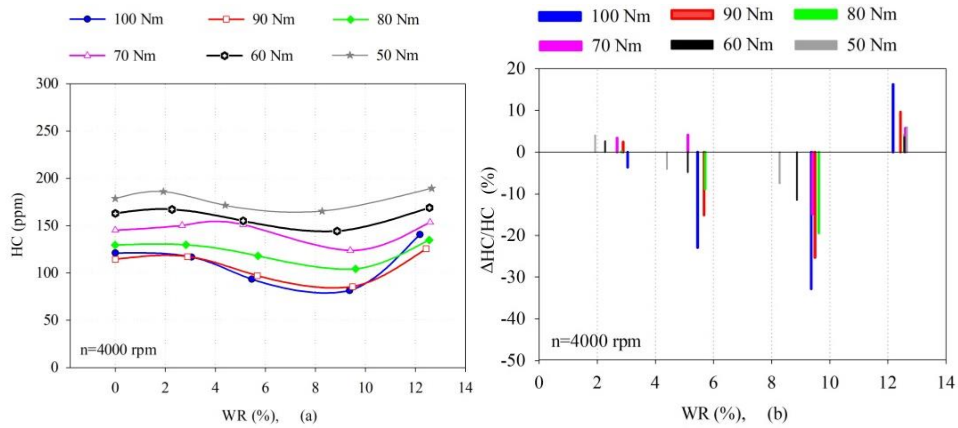


Figure 16 (a-b). Variations and VRs of HC emissions versus different WRs under five different loads at 4000 rpm, respectively.

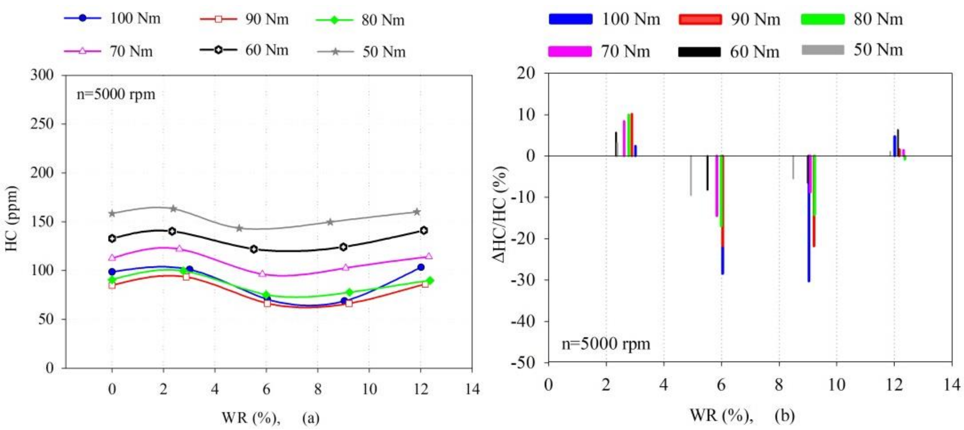


Figure 17 (a-b). Variations and VRs of HC emissions versus different WRs under five different loads at 5000 rpm, respectively.

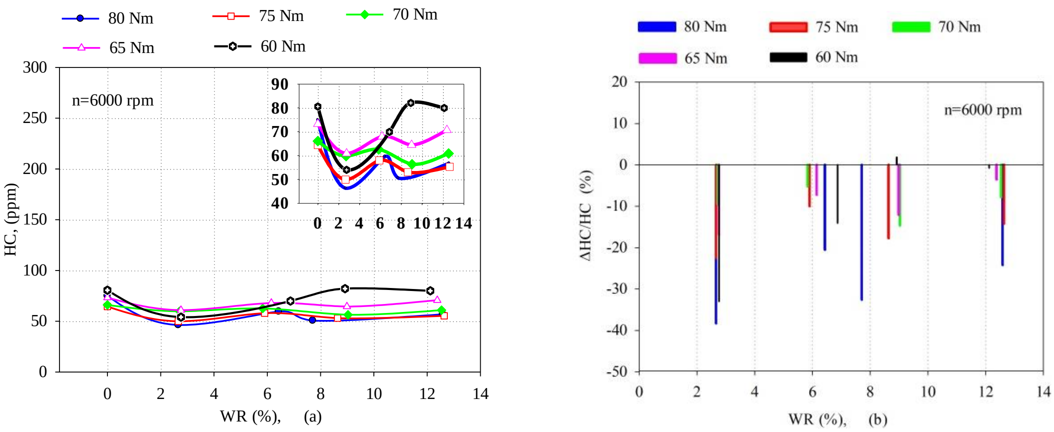


Figure 18 (a-b). Variations and VRs of HC emissions versus different WRs under five different loads at 6000 rpm, respectively.

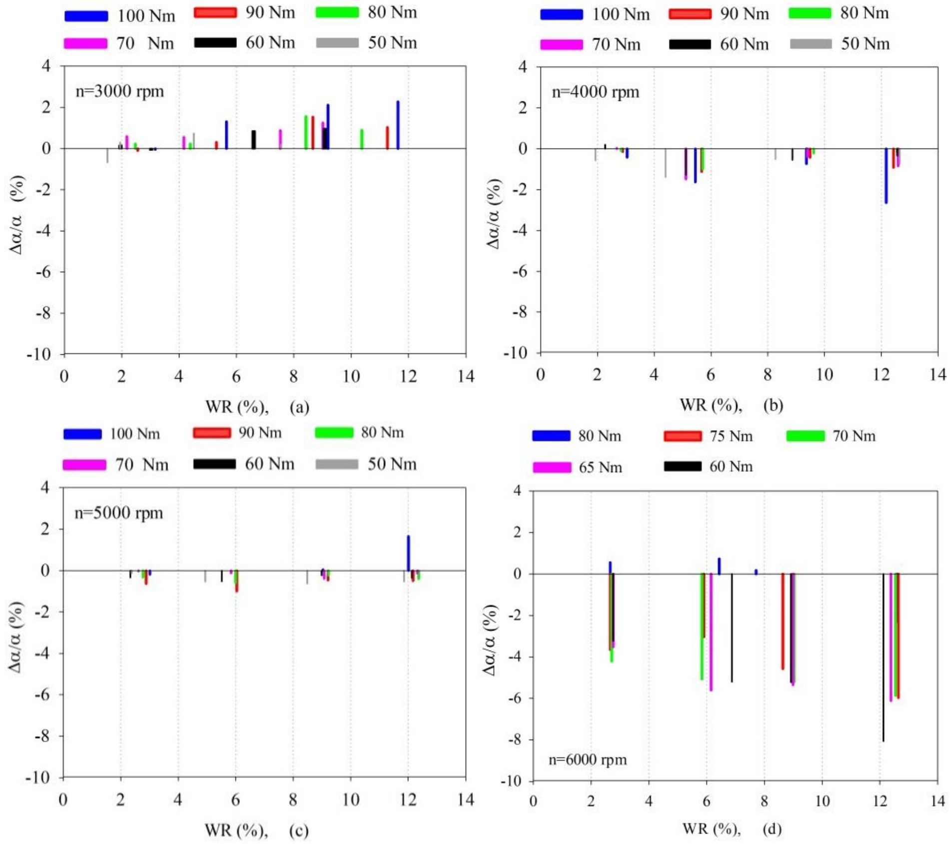
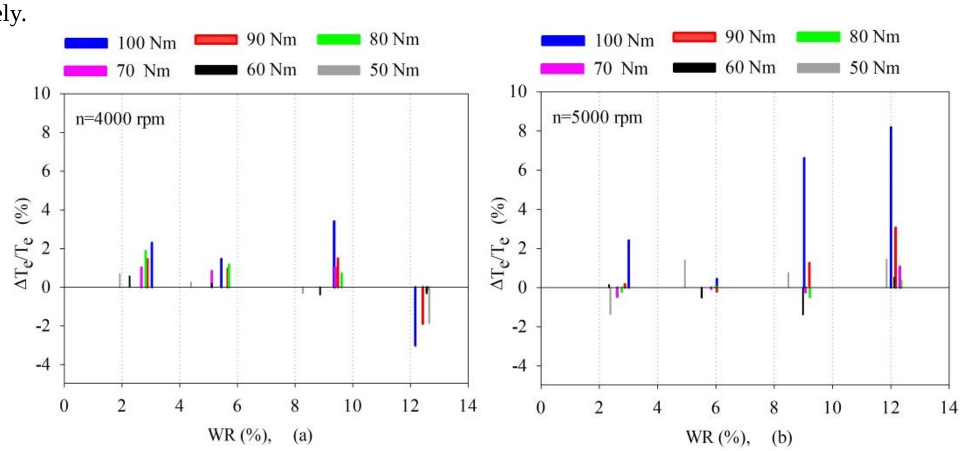


Figure 19 (a-d). VRs of excess air coefficient values versus different WRs under different loads at 3000, 4000, 5000, and 6000 rpm, respectively.



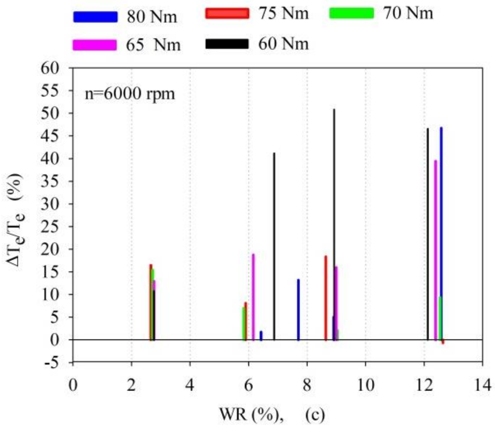


Figure 20 (a-c). VRs of exhaust temperature versus different WRs under different loads at 3000, 4000, 5000, and 6000 rpm, respectively

CONCLUSIONS

In this study, the effects of water addition to intake air on BSFC and emission characteristics were investigated experimentally and compared with that of NG in an automotive SIE. By evaluating of the experimental results, the obtained results can be summarized as follows:

-The water addition into the intake air has little effect on the engine brake effective power at all selected operating conditions.

-The water addition into the intake air decreases the BSFC under selected six different loads at (3000, 4000 and, 5000) rpms. The obtained maximum decrease ratios of BSFC are 28.27% for 6.6% WR at 3000 rpm, 4.16% for 2.67%WR at 4000 rpm and 7.19% for 9.03% WR at 5000 rpm, respectively. Unlike at the other engine speeds, the water addition into the intake air generally increases BSFC at 6000 rpm.

-CO emission decreases by applying water adding into intake air at 3000 rpm whereas it generally increases at (4000 and 5000) rpms. At 6000 rpm, the water addition into the intake air has increased CO emission significantly. The excess air coefficient decrease at (4000, 5000, and 6000) rpms, but it increases at 3000 rpm. Although the excess air coefficient reduction is desirable for NO_x formation, it has a worsening effect on the CO formation and BSFC.

-The water addition into the intake air decreases NOx under all of the selected six different loads at (3000, 4000, 5000, and 6000) rpms. The obtained maximum decrease ratios of NO_x are 37.81 % for 8.67% WR, 58.21 for 12.18% WR and 57.80 for 12.12 WR, and 66.17% for 12.12.WR at (3000, 4000, 5000, and 6000) rpms.

-The water addition into the intake air generally decreases HC emissions under all of the selected six different loads at 3000, 4000, 5000 and 6000 rpms. The obtained maximum decrease ratios of HC emissions are 27.34 % for 11.27% WR, 32.80% for 9.37% WR, 30.30 for 9.03% and 38.30% for 2.66 WR at (3000, 4000, 5000, and 6000) rpms.

-The water addition into the intake air exhibits a general tendency to increase the exhaust temperature. It is thought that the increase in the exhaust temperature could be caused by subsequent combustion, which could be occurred by the effect of the water addition during the expansion stroke.

-As a result, it was determined that 9% is the most suitable water ratio in terms of both BSFC and exhaust emissions for this experiment engine. At this WR, BSFC, NO_x and HC values are significantly reduced without any significant deterioration in effective power and CO emissions.

-Adding a suitable amount of water into intake air by using an adapted carburettor or an electronically controlled water injection system could improve considerably of any SIEs performance, BSFC and exhaust emission.

-To obtain general results, more experiments must be done. Also, computer-aided engine combustion and any cycle models must be developed.

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