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Research Article

Comparison of the Effects of Hydrogen and Hydroxygen Additions and Oxygen Enrichment on the Emission Characteristics of EF7 Engine

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ABSTRACT

In this study, the effects of hydrogen and hydroxygen additions and oxygen enrichment on the emission characteristics of a gasoline engine (EF7) were investigated and compared with each other. The simulation was launched by GT-Power at different engine speeds with 5 % to 15 % volume fractions for both of oxygen and hydrogen enrichment and 4.5 % to 9 % volume fractions of hydroxygen addition in the intake gas, respectively. In addition, the model was validated by experimental data. The results showed that CO emission decreased from 11 % to 28 % in the hydrogen-enrichment condition. Moreover, carbon monoxide production was reduced from 28 % to 42 % for hydroxygen addition, and this pollutant emission experienced a reduction of 51 % to 67 % for oxygen enrichment. According to the results, HC emission decreased up to 13% in the hydrogen-enriched air condition, and it was reduced from 30 % to 43 % during hydroxygen addition. In addition, HC emission experienced maximum reduction of 47 % to 68 % during oxygen addition. On the other hand, there was an opposite trend for NOx emission. It was observed that NOx emission increased by around 40 % and 75 % for hydrogen and hydroxygen enrichment, respectively. Moreover, nitrogen oxides enhanced 2 to 5 times during oxygen enrichment, compared to that in the normal condition of the engine. Results showed that 15 % oxygen enrichment and 9 % hydroxygen enrichment had significant effect on the reduction of HC and CO emissions, and oxygen enrichment had greater effect on the rise of NOx emissions than hydrogen and hydroxygen additions.

1. INTRODUCTION

Due to limited fossil fuel reserves, energy demands, and environmental problems, the improvement of the performance and emission parameters of the SI engines have received much attention in recent years. The addition of oxygen, as a combustion promoter, can improve the combustion process of the engines during fuel-air mixing [1]. Oxygen can facilitate complete combustion of the fuel-air mixtures in lean conditions. These conditions help improve the thermal efficiency of engines [2]. Hydrogen as an alternative and clean fuel can be used in spark-ignition engines [3, 4]. In comparison with gasoline, hydrogen performs lower burning energy and shortened combustion, causing smooth combustion in lean conditions and exhaust losses [5, 6]. However, according to the energy density of hydrogen, which is lower than that of gasoline, the power output of engine running with hydrogen is lower at high loads [7]. Hydrogen is a renewable and clean energy source that can be used in engines [4] and does not produce greenhouse gases from the engines [8]. Hydrogen can be used in vehicles through fuel cells and hydrogen-fuelled engines [9]. The application of hydrogen in engines can modify some combustion problems, e.g., cold wall quenching and poor mixing [5]. The mixture of hydrogen and oxygen with a constant hydrogen-to-oxygen molar ratio of 2:1 is called hydroxygen. A water electrolysis hydrogen generator can provide the hydrogen-oxygen blends (hydroxygen) for vehicles. In addition, in a number of studies, oxygen and hydrogen have been premixed before injecting into the combustion chamber. These studies are reviewed below.

Karagöz et al. [10] studied the effect of the oxygen-hydrogen mixture addition on emissions and performance characteristics of a gasoline engine. They used H_2/O_2 gas mixture generated by an electrolyzer as a secondary fuel in SI engine. They observed a significant improvement of emission characteristics with the slight addition of H_2 to the fuel mixture. They also observed an increase in NO_x emissions with hydrogen addition. In another study [8], the effects of hydroxygen enrichment on the performance and emissions of a gasoline engine under idle operating conditions were investigated. According to the results of this study, THC and CO emissions were reduced, while NO_x emissions with hydrogen addition increased in idle operating conditions.

Ma et al. [11] performed an experimental study to investigate the influence of various hydrogen ratios in hydrogen-enriched CNG fuels on the performance and emission characteristics of SI CNG engine. Their results indicated a significant decrease in CO and CH_4 with H_2 addition. In addition, NO_x emissions were improved by optimizing the ignition timing. Moreover, brake power and cylinder pressure decreased by the addition of excess hydrogen. Wang et al. [12] studied the effect of hydroxygen addition on the performance of an SI engine equipped with an individual injection system. They used hydroxygen (H_2O_2) in the tests with concentrations of 0 %, 2 %, and 4 % of the total volume of the intake gas. The results showed that BTE and BMEP of the hydroxygen-blended gasoline engine were higher than those of hydrogen-blended gasoline engines in lean conditions. Despite an increase in NO_x emissions after

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the H_2O_2 addition, HC and CO emissions were reduced by hydroxygen enrichment. In another study, Wang et al. [13] evaluated the effect of different hydrogen concentrations in hydroxygen on the performance of an SI engine. A control unit was also used to control the spark and injection timing. They found an improvement in the thermal efficiency at higher H_2 fraction in hydroxygen. Moreover, the brake power and particulate emissions decreased by increasing H_2 hydrogen concentration in hydroxygen. Diéguez et al. [14] performed an empirical study on the emission and performance parameters of an SI engine running with hydrogen-methane mixtures. They used low methane concentrations in their experiments. According to the results, a high air-to-fuel ratio reduced the performance while increasing specific NO_x emissions. They also indicated that NO_x emissions decreased with increasing the methane percentage.

Salimi et al. [9] studied the effects of mixture richness, spark, and valve timing on the performance and emission of a hydrogen-fuelled engine by a thermodynamic model. Their two-zone, quasi-dimensional model was validated by test data. They observed a maximum NO_x concentration at a fuel-to-air equivalence ratio of 0.8 for the hydrogen engine. Their results also showed the need for spark advance in the engine fuelled with hydrogen due to the little advance of the hydrogen flame speed.

Ghazal [15] modeled an SI engine. The results showed that the addition of hydrogen to the fuel caused a reduction in BSFC for both port and direct injection systems. The results indicated that the performance and emissions of the engine were improved by the addition of hydrogen to methane.

In another research, Karagöz et al. [16] conducted an experimental study on the performance characteristics of an SI engine with water injection and addition of hydroxygen. According to the literature, NO_x production significantly increases with hydroxygen addition. The results showed that the brake power and BSEC improved with hydroxygen addition. Moreover, CO and THC emissions decreased with hydroxygen addition. In addition, water injection improved NO_x emissions produced with $H_2 + O_2$ addition.

Karagöz et al. [17] investigated the influence of hydrogen addition on the combustion characteristics, CO, THC, smoke, and NO_x emissions and performance of a CI engine. The authors reported a significant improvement in CO and smoke emissions with a higher percentage of hydrogen. However, THC emissions increased slightly; NO_x emissions significantly increased with an addition of 53 % hydrogen as compared to pure diesel fuel. According to the results, maximum in-cylinder pressure values also increased by hydrogen enrichment, compared to pure diesel fuel.

Karagöz et al. [18] investigated the combustion characteristics, emissions, and performance of a diesel engine by the addition of hydrogen and methane. The results showed that CO and THC emissions increased with gas injection in respect of neat diesel fuel. However, the performance parameters improved when only methane fuel was used in diesel fuel.

Baskar and Senthilkumar [19] studied the influence of oxygen enrichment on emission and performance parameters of a diesel engine by the addition of oxygen in the intake air. The results showed that thermal efficiency and brake specific fuel consumption improved. Moreover, the unburned HC, CO, and smoke level decreased with oxygen enrichment; however, NOx emissions increased because of the higher combustion temperature condition.

Nidhi and Subramanian [20] investigated the effect of oxygen enrichments on the performance, emission, and combustion parameters of an SI engine by methanol fuel blends. The results showed that the BTE enhanced by 9.9 % and 20.5 % with the amount of 38.7 % and 60.4 % oxygen enrichment, respectively. Moreover, there was a significant increase in peak pressure and cumulative heat release with the 60.4 % oxygen enrichment, compared to base oxygen amount. CO and HC emissions underwent reduction rates of 49 % and 31 % with the highest oxygen enrichment. Although NOx emission enhanced 1.1 times with an oxygen amount of 39 %, it reduced by around 31 % with the highest amount of oxygen enrichment. The results of this study indicated that the application of methanol in the engine with the highest amount of oxygen enrichment improved NOx, CO, HC emission and thermal efficiency.

According to the literature, there are few studies on the use of SI engine simulation models to investigate the effect of hydrogen, hydroxygen, and oxygen enrichment on the emission and performance characteristics of engines. In this paper, an engine model was developed by GT-POWER software to predict and compare emission characteristics (HC, CO, and NO_x) of a four-cylinder SI engine (EF7) with hydrogen, hydroxygen, and oxygen enrichment at 1000, 2000, 3000, 4000, 5000, and 6000 rpm engine speeds.

2. METHODS

Modeling was performed by GT-Power software at different engine speeds (1000, 2000, 3000, 4000, 5000, and 6000 rpm). Various volume fractions of the enrichment (5 to 15 % hydrogen and 4.5 to 9 % hydroxygen) were selected according to previous pieces of research to study HC, CO, and NO_x emissions of the engine at full engine load. The engine modeled in this study is a four-cylinder spark-ignition engine (EF7). The specifications of the SI engine are shown in Table 1.

Table 1. Engine specifications.

Engine type	Gasoline EF7
Cylinder number	4
Stroke(mm)	85
Bore(mm)	78.5
Compression ratio	11.2:1
Power (kW/rpm)	85/6000
Torque (N.m/rpm)	155/4000
Fuel System	Multi-point fuel injection

2.1. Modeling

The simulation of combustion rate is based on burn rate according to the selected combustion model in GT-POWER. There are two available combustion models: non-predictive and predictive models. The non-predictive combustion model used in this research considers a function based on crank angle and burn rate without considering the cylinder conditions. In the modeling of the SI engine, the Wiebe function was applied to consider the burn rate. Moreover, the heat transfer from the piston to the cylinder wall was calculated based on Woschni's model.

The input data in this model include the geometry of the cylinder, spark timing, air flow, and fuel properties. Besides, hydrogen-to-oxygen with a mole ratio of 2:1, called standard hydroxygen ($2H_2/O_2$), was used in simulations for hydroxygen predictions. Oxygen, hydrogen, and hydroxygen volume fraction in the intake are considered as follows:

$$\alpha = \frac{[V_{O_2}]}{[V_{O_2}+V_{air}]} \times 100 \tag{1}$$

$$\beta = \frac{[V_{H_2}]}{[V_{H_2}+V_{air}]} \times 100 \tag{2}$$

$$\gamma = \frac{[V_{H_2}+V_{O_2}]}{[V_{H_2}+V_{O_2}+V_{air}]} \times 100 \tag{3}$$

$$\lambda = \frac{(0.21V_{air}+V_{O_2})\rho_{O_2}}{(V_{H_2}\rho_{H_2}OF_{st,H_2}+m_{gas}OF_{st,gas})} \tag{4}$$

$$Ef = V_{H_2} \times \rho_{H_2} \times LHV_{H_2} + m_{gas} \times LHV_{gas} \tag{5}$$

In Eqs. (1) to (5), α, β, γ are the volume fractions of oxygen, hydrogen, and standard hydroxygen in the intake air in normal conditions; λ and E_f represent the excess oxygen ratio and flow rate of fuel energy, respectively; V_{H_2}, V_{O_2}, and V_{air} are the hydrogen, oxygen, and air volume flow rates, respectively; ρ_{H_2} and ρ_{O_2} show hydrogen and oxygen densities in normal conditions; m_{gas} is the gasoline mass flow rate in g/min; OF_{st,H_2} and $OF_{st,gas}$ are the stoichiometric oxygen-to-fuel ratios of hydrogen and gasoline that are 8 and 3.6, respectively; LHV_{gas} and LHV_{H_2} are the lower heating values of gasoline and hydrogen equal to 44 MJ/kg and 120 MJ/kg, respectively.

In the standard conditions, the volume fraction of air in the intake is 21 % O_2 and 79 % N_2. Therefore, for 5 % oxygen, 5 % hydrogen, and 4.5 % hydroxygen enrichment, the O_2 volume fraction in the intake will be 24.8 %, 0.2 %, and 21.5 %, respectively.

GT-POWER has the capability to calculate HC, CO, and NO_x concentrations. In each emissions prediction, the predicted cylinder pressure profile and burn rate can be used for emission predictions [21]. For calculating HC emissions, GT-POWER uses a 2-plate quenching model with a kinetic model after the flame is quenched. The fuel and air mixture re-entering before the end of combustion will be burned according to the combustion model, and any mixture that re-enters after the end of combustion will be burned according to a kinetic model.

The kinetic HC calculation is based on the following rate equation:

$$\text{HC + Air => Products} \tag{6}$$

$$k_{HC} = A \times 10^{12} \times [HC][O_2] \times e^{\frac{-19000B}{T}} \tag{7}$$

where k_{HC}=rate constant, A=pre-exponent multiplier, B=activation temperature multiplier, T=temperature, [HC]=Volume concentration of HC, $[O_2]$=volume concentration of O_2.

Moreover, the CO calculation is based on the following mechanism and is developed for homogenous combustion as follows:

$$CO + OH = CO_2 + H \tag{8}$$

$$k_{CO} = A * 6.76 * 10^7 * e^{\frac{T}{1102B}} \tag{9}$$

where k_{CO}=rate constant, A=pre-exponent multiplier, B=activation temperature multiplier, T=temperature.

The main source for nitric oxide in internal combustion engines is thermal NO, which forms due to the dissociation of air nitrogen during combustion. The NO_x emissions are predicted by using the Extended Zeldovich mechanism as the reactions can be presented in the following lines:

$$N_2 + O \Leftrightarrow NO + N \tag{10}$$

$$N + O_2 \Leftrightarrow NO + O \tag{11}$$

$$N + OH \Leftrightarrow NO + H \tag{12}$$

$$k_1 = F_1 * 7.6 * 10^{10} * e^{\frac{-38000A_1}{T_b}} \tag{13}$$

$$k_2 = F_2 * 6.4 * 10^6 * T_b * e^{\frac{-3150A_2}{T_b}} \tag{14}$$

$$k_2 = F_3 * 4.1 * 10^{10} \tag{15}$$

where k_1, k_2, k_3=rate constants, $F_1=N_2$ oxidation rate multiplier, F_2=N oxidation rate multiplier, F_3=OH reduction rate multiplier, $A_1=N_2$ oxidation activation temperature multiplier, A_2=N oxidation activation temperature multiplier, T_b=burned sub-zone temperature (K).

Figure 1 shows the EF7 engine model based on the SI engine data.

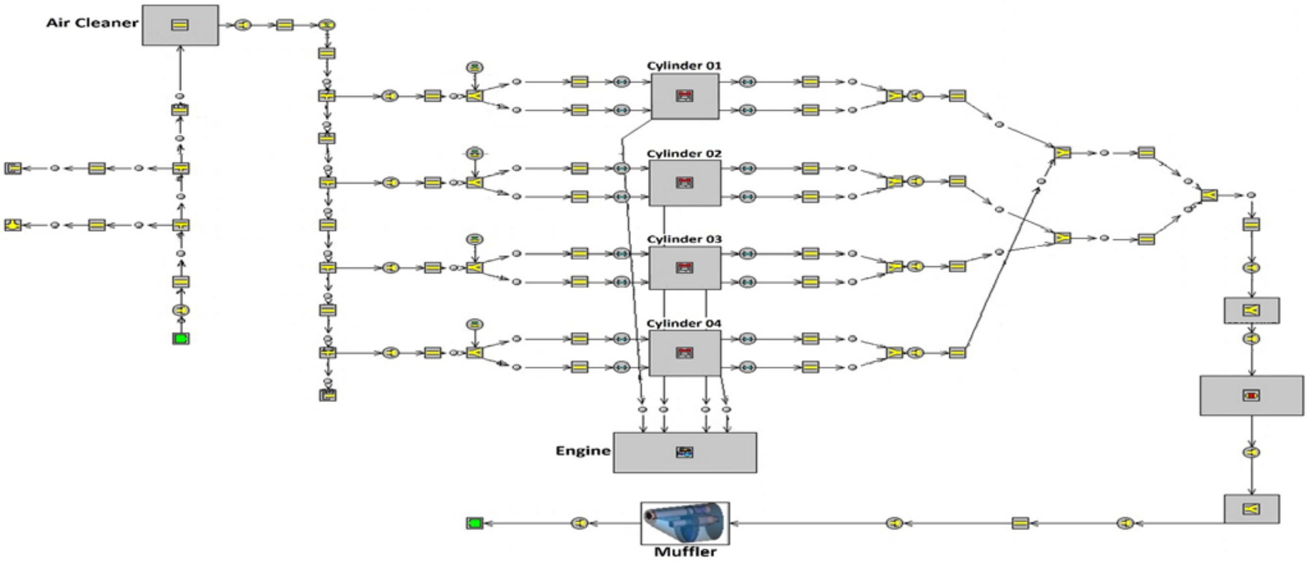

Figure 1. The EF7 engine model.

2.2. Model validation

In this research, the accuracy of the numerical model was verified and validated by comparing the model results with experimental data on the NOx emissions for the naturally aspirated engine. AVL gas analyzer (DIGAS 4000) was used to measure NO_x emissions. As shown in Figure 2, the model and experimental data are in good agreement together, confirming the accuracy of the employed model. Table 2 shows the specifications of the gas analyzer.

Table 2. The specifications of the gas analyzer.

Variable	Range of measurements	Resolution
CO	0–10 vol.%	±0.01 (vol. %)
HC	0–20,000 ppm	±1 (ppm)
NOx	0–5000 ppm	±1 (ppm)

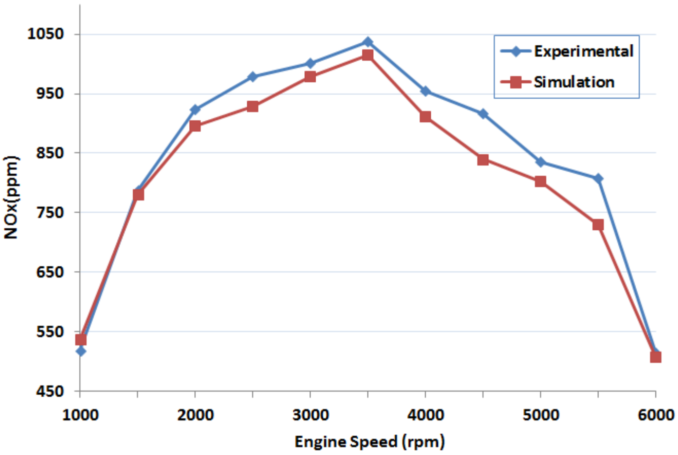

Figure 2. The values of NOx emission at various engine speeds based on experimental and model data.

3. RESULTS AND DISCUSSION

3.1. Effect of hydrogen-enriched air on CO emission

Figure 3 shows CO emissions in both normal and hydrogen-enriched air conditions (5 to 15 % by volume) at various engine RPMs. It can be seen that CO emissions increased by hydrogen enrichment, especially at higher engine speeds. Since hydrogen contains no carbon atom, the carbon monoxide will be lower when hydrogen is added to gasoline [8]. Furthermore, the higher heating value of hydrogen, compared to gasoline, causes a high in-cylinder temperature and, thereby, the enhanced oxidation reaction rate facilities the reduction of CO emissions [22]. According to the results, CO emissions decreased from 11 % to 28 % in the hydrogen-enriched condition. The large amounts of CO emissions were produced at higher engine speeds due to a reduction in volumetric efficiency at engine speeds more than 4000 RPM. This combustion condition causes a considerable increase in CO emissions [23].

3.2. Effect of hydrogen-enriched air on HC emission

Figure 4 illustrates the variation of HC emissions versus engine speed in normal and hydrogen-enriched air conditions. The results showed that the HC emission decreased with hydrogen enrichment. This can be explained by the fact that the formation of unburned hydrocarbon is related to the chemical equilibrium. Hence, the hydrogen addition causes a gradual decrease in C content as a key factor in reducing HC production at a constant oxygen-to-fuel ratio [8, 24]. Moreover, the hydrogen enrichment causes a higher cylinder temperature that results in decreased HC emissions during the combustion process [24]. According to the results, HC emissions decreased dramatically at medium and high engine speeds. This could result from a lower cylinder temperature that prevents the reduction of HC emissions at lower engine speeds. Based on the results, HC emission decreased up to 13 % with hydrogen enrichment.

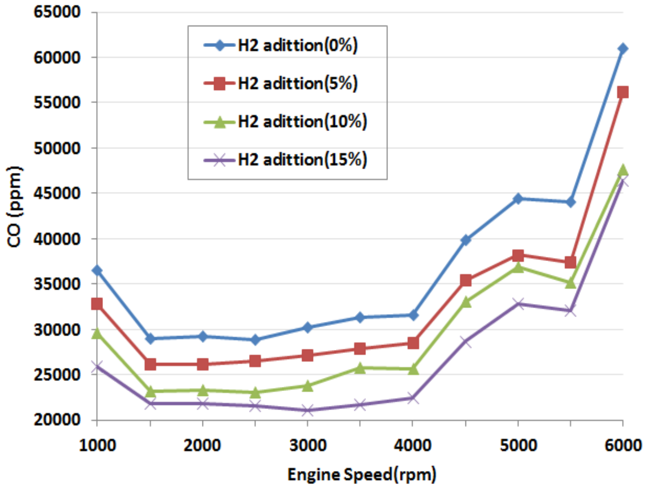

Figure 3. Effect of hydrogen-enriched air on CO emission at various engine speeds.

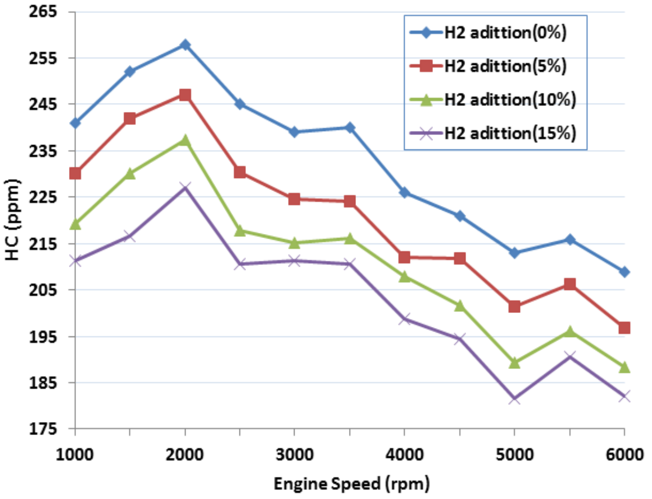

Figure 4. Effect of hydrogen-enriched air on HC emission at various engine speeds.

3.3. Effect of hydrogen-enriched air on NOx emission

Figure 5 shows the variation of NO_x emissions versus engine speed in normal and hydrogen-enriched air conditions. The results showed that NO_x emissions were enhanced with hydrogen addition due to the higher heating value of hydrogen than that of gasoline, resulting in increasing the cylinder temperature; therefore, higher nitrogen oxides are simulated according to the Extended Zeldovich mechanism [25]. It was observed that NO_x emission increased by 40 % with hydrogen enrichment. According to the results, maximum NO_x emissions were produced at medium engine speeds due to the highest air-to-fuel ratio at these RPMs that led to excess air and oxygen and formation of NO_x emissions [23].

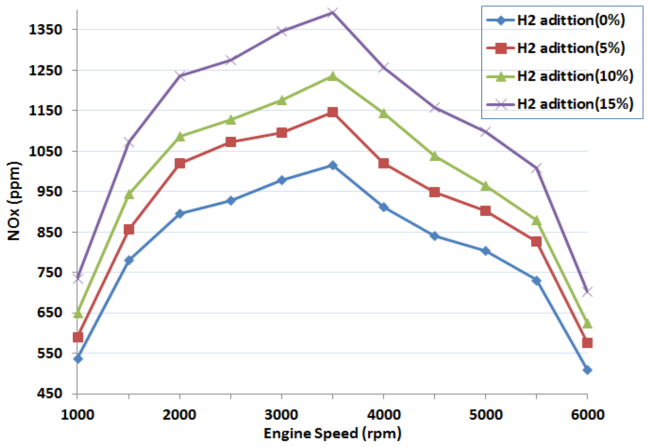

Figure 5. Effect of hydrogen-enriched air on NOx emission at various engine speeds.

3.4. Effect of hydroxygen-enriched air on CO emission

Figure 6 shows CO emission values in normal and hydroxygen-enriched (4.5 % to 9 % volume fractions of intake air) conditions at various engine speeds. It can be seen that CO emissions decrease significantly by increasing hydroxygen fraction in the total intake gas. Moreover, the results showed that hydroxygen addition was more effective in reducing carbon monoxide than hydrogen enrichment. The reason for this is that the excess air ratio will be higher in the engine intake manifold by using hydroxygen; thereby, the higher oxygen molecules in hydroxygen could oxidize carbon monoxide into carbon dioxide [13, 16]. The results indicated that the carbon monoxide production decreased from 28 % to 42 % with hydroxygen enrichment. According to the results, CO emissions increased at higher engine speeds due to a reduction in engine volumetric efficiency that caused incomplete combustion in the engine [23].

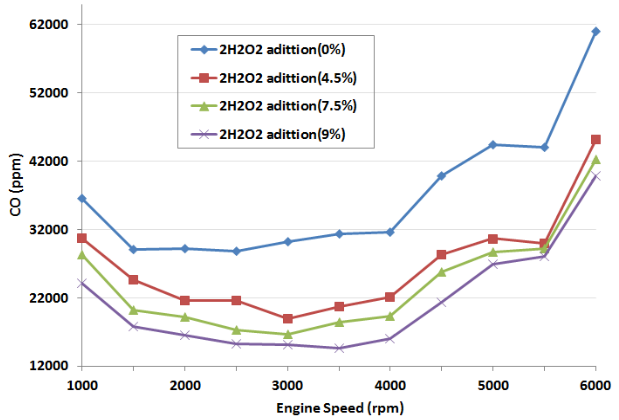

Figure 6. Effect of hydroxygen-enriched air on CO emission at various engine speeds.

3.5. Effect of hydroxygen-enriched air on HC emission

Figure 7 shows the variation of HC emissions versus engine speed in normal and hydroxygen-enriched air conditions. According to the results, HC emissions decrease during hydroxygen enrichment. This can be related to the decreased C-atom of gasoline and replacement by hydrogen atoms that help reduce HC emissions [8, 24]. On the other hand, the higher heating value of hydrogen than that of gasoline causes an increase in the cylinder temperature after hydrogen enrichment; therefore, the calculated HC is reduced [2, 12]. Based on Eq. (4), hydroxygen enrichment results in the increased oxygen content, leading to the improvement of the combustion condition and reduction of HC emissions [12, 24].

Although engine speed has no significant effect on HC emissions in the hydroxygen-enriched condition, HC emission increases at lower engine speeds than that at higher engine speeds. It could be due to cold wall quenching and lower combustion chamber temperature at lower engine speeds [23]. According to the results, HC emissions decreased from 30 % to 43 % under the hydrogen-enriched air condition.

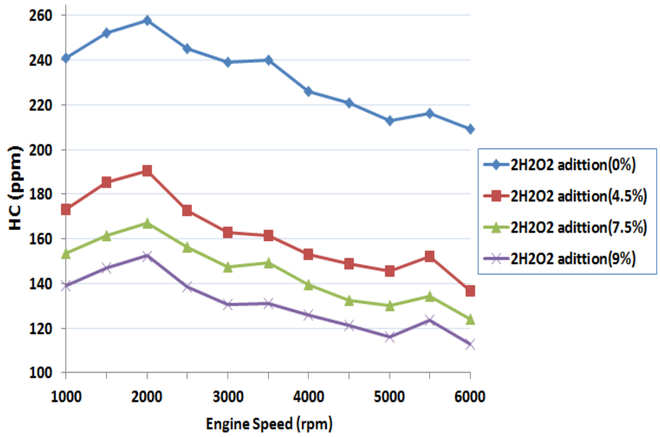

Figure 7. Effect of hydroxygen-enriched air on HC emission at various engine speeds.

3.6. Effect of hydroxygen-enriched air on NOx emission

Figure 8 indicates NO_x emissions values versus RPM in the hydroxygen-enriched condition. As the figure shows, NO_x emissions were enhanced after hydroxygen addition due to the high cylinder temperature. According to the thermodynamic equilibrium, the formation of NO_x emissions will be enhanced with an increase in combustion temperature under hydroxygen additions [8, 24]. Moreover, according to Eq. (4), hydroxygen supplies more oxygen molecules that enhance NO_x formation; therefore, the emission of nitrogen oxides is higher in hydroxygen-enriched conditions than that of the hydrogen enriched-air engine [24]. Besides, similar to hydrogen addition, the maximum NO_x emission is observed at medium engine RPMs. This could be related to the pick combustion temperature and the maximum volumetric efficiency of the engine that occur at these engine speeds [23]. According to the results, NO_x emissions increase by about 75 % with hydroxygen enrichment.

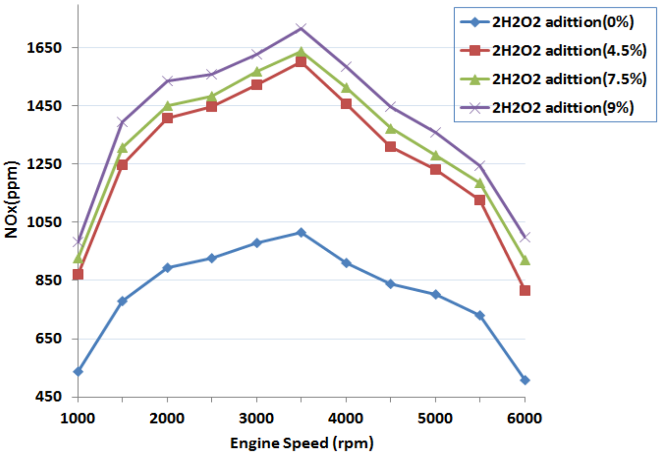

Figure 8. Effect of hydroxygen-enriched air on NOx emission at various engine speeds.

3.7. Effect of oxygen-enriched air on CO emission

Figure 9 shows CO emission variations in both normal and oxygen-enriched air conditions (5 to 15 % by volume) at various engine speeds. According to the figure, CO emissions decreased by oxygen enrichment. This could be related to the increase of oxygen fraction in the intake gas, leading to greater CO_2 production instead of CO emissions [19, 20]. According to the results, CO emissions decreased from 51 % to 67 % under the oxygen-enriched condition. The results indicated that the large amounts of CO emissions were produced at higher engine speeds because of the reducing volumetric efficiency of the engine at higher RPMs. This situation affects combustion conditions and reduces CO_2 production [23].

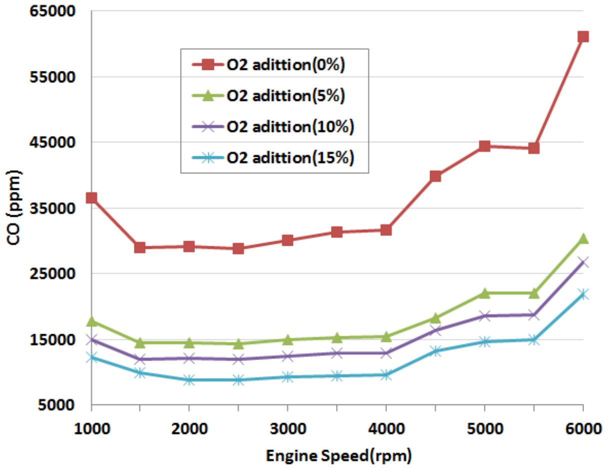

Figure 9. Effect of oxygen-enriched air on CO emission at various engine speeds.

3.8. Effect of oxygen-enriched air on HC emission

Figure 10 shows HC emission values versus RPMs in the oxygen-enriched condition. The results indicated the HC emissions decreased after oxygen additions. According to Eq. (4), oxygen enrichment results in a higher excess oxygen ratio. This causes a better combustion condition and reduces HC emissions [12, 19, 24]. Unlike CO emissions, HC emissions decreased by increasing engine speeds, because the increased cylinder temperature at higher engine speeds helps reduce HC emissions during the combustion process [23]. According to the results, HC emissions approximately decreased from 47 % to 68 % by oxygen enrichment.

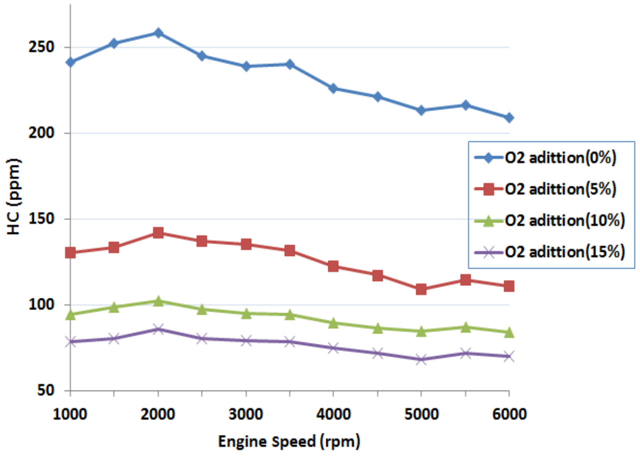

Figure 10. Effect of oxygen-enriched air on HC emission at various engine speeds.

3.9. Effect of oxygen-enriched air on NOx emission

The variation of NO_x emission versus engine speed is demonstrated in Figure 11 in normal and oxygen-enriched air conditions. As the figure demonstrates, NO_x emissions increased with oxygen enrichment because of the increased in-cylinder temperature that causes higher NO_x emissions based on the Zeldovich mechanism [24]. Moreover, the higher oxygen concentration in the intake air as a result of oxygen addition leads to high thermal NO formation rates [19, 20].

Besides, similar to hydrogen and hydroxygen additions, maximum NO_x emission occurs at medium engine speeds. This could be attributed to the pick combustion temperature and maximum volumetric efficiency of the engine that occur at these RPMs [23]. According to the results, the volume of NO_x emissions increased 2 to 5 times under the oxygen-enriched, rather than normal, conditions.

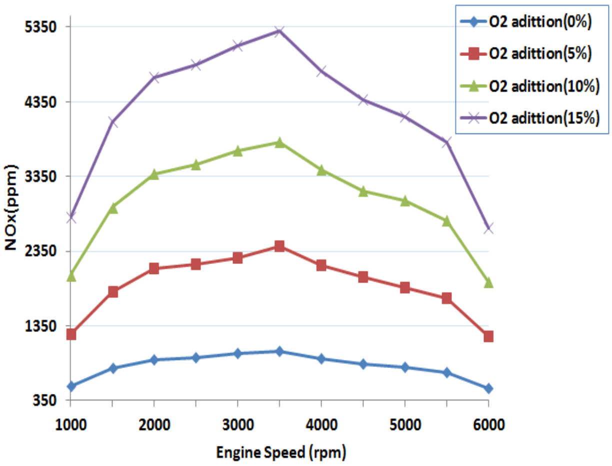

Figure 11. Effect of oxygen-enriched air on NOx emission at various engine speeds.

4. CONCLUSIONS

In this research, the effects of hydrogen and hydroxygen and oxygen additions on the emissions of an SI engine at various speeds were investigated and compared together by GT-Power modeling. The main conclusions are listed below:

a) HC and CO emissions decreased in all volume fractions of oxygen, hydrogen, and hydrooxygen enrichment.

b) NO_x emissions increased with the addition of oxygen, hydrogen, and hydroxygen.

c) CO emissions increased at higher engine speeds because of a reduction in the engine volumetric efficiency and incomplete combustion of fuel at higher speeds.

d) HC emissions increased at medium and high engine speeds as compared to lower engine speeds. It could be due to cold wall quenching and lower temperature of the combustion chamber. Moreover, the effect of hydrogen addition on unburned hydrocarbon emissions was not significant at lower engine speeds.

e) According to the results, engine speed had no significant effect on HC emissions under oxygen- and hydroxygen-enriched conditions.

f) The results implied that hydroxygen addition was more effective in reducing HC and CO emissions than hydrogen enrichment.

g) The results showed that the NO_x production under oxygen and hydroxygen enrichment was higher than that under the hydrogen-enriched air condition. This is because the oxygen

and hydroxygen enrichment provides more oxygen content and leads to the greater reduction of NO_x emission.
h) It was found that 15 % oxygen and 9 % hydroxygen enrichment had a significant effect on the reduction of carbon monoxide and unburned hydrocarbon emissions.
k) Oxygen enrichment had more effect on the rising of NO_x formation than hydrogen and hydroxygen addition due to the key role of excess oxygen in NO_x formation.

5. ACKNOWLEDGEMENT

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REFERENCES

1. Uykur, C., Henshaw, P.F., Ting, D.S.K. and Barron, R.M., "Effects of addition of electrolysis products on methane/air premixed laminar combustion", ***International Journal of Hydrogen Energy***, Vol. 26, No. 3, (2001), 265-273. (https://doi.org/10.1016/S0360-3199(00)00068-9).
2. D'Andrea, T., Henshaw, P.F. and Ting, D.S.K., "The addition of hydrogen to a gasoline-fuelled SI engine", ***International Journal of Hydrogen Energy***, Vol. 29, No. 14, (2004), 1541-1552. (https://doi.org/10.1016/j.ijhydene.2004.02.002).
3. Ball, M. and Wietschel, M., "The future of hydrogen–Opportunities and challenges", ***International Journal of Hydrogen Energy***, Vol. 34, No. 2, (2009), 615-627. (https://doi.org/10.1016/j.ijhydene.2008.11.014).
4. Veziro>lu, T.N. and Barbir, F., "Hydrogen: The wonder fuel", ***International Journal of Hydrogen Energy***, Vol. 17, No. 6, (1992), 391-404. (https://doi.org/10.1016/0360-3199(92)90183-W).
5. Kahraman, E., Cihangir Ozcanlı, S. and Ozerdem, B., "An experimental study on performance and emission characteristics of a hydrogen fuelled spark ignition engine", ***International Journal of Hydrogen Energy***, Vol. 32, No. 12, (2007), 2066-2072. (https://doi.org/10.1016/ j.ijhydene.2006.08.023).
6. Ma, F., He, Y., Deng, J., Jiang, L., Naeve, N. and Wang, M., "Idle characteristics of a hydrogen fueled SI engine", ***International Journal of Hydrogen Energy***, Vol. 36, No. 7, (2011), 4454-4460. (https://doi.org/10.1016/j.ijhydene.2010.12.121).
7. Sadiq Al-Baghdadi, M.A.R., "Effect of compression ratio, equivalence ratio and engine speed on the performance and emission characteristics of a spark ignition engine using hydrogen as a fuel", ***Renewable Energy***, Vol. 29, No. 15, (2004), 2245-2260. (https://doi.org/ 10.1016/j.renene.2004.04.002).
8. Karagöz, Y., Sandalcı, T. and Dalkılıç, A.S., "Effects of hydrogen and oxygen enrichment on performance and emissions of an SI engine under idle operating condition", ***International Journal of Hydrogen Energy***, Vol. 40, No. 28, (2015), 8607-8619. (https://doi.org/ 10.1016/j.ijhydene.2015.05.006).
9. Salimi, F., Shamekhi, A.H. and Pourkhesalian, A.M., "Role of mixture richness, spark and valve timing in hydrogen-fuelled engine performance and emission", ***International Journal of Hydrogen Energy***, Vol. 34, No. 9, (2009), 3922-3929. (https://doi.org/10.1016/ j.ijhydene.2009.02.077).
10. Karagöz, Y., Yuca, N., Sandalcı, T. and Dalkılıç, A.S., "Effect of hydrogen and oxygen addition as a mixture on emissions and performance characteristics of a gasoline engine", ***International Journal of Hydrogen Energy***, Vol. 40, No. 28, (2015), 8750-8760. (https://doi.org/ 10.1016/j.ijhydene.2015.05.039).
11. Ma, F., Wang, M., Jiang, L., Deng, J., Chen, R. and Naeve, N., "Performance and emission characteristics of a turbocharged spark-ignition hydrogen-enriched compressed natural gas engine under wide open throttle operating conditions", ***International Journal of Hydrogen Energy***, Vol. 35, No. 22, (2010), 12502-12509. (https://doi.org/ 10.1016/j.ijhydene.2010.08.053).
12. Wang, S., Ji, C., Zhang, J. and Zhang, B., "Improving the performance of a gasoline engine with the addition of hydrogen–oxygen mixtures", ***International Journal of Hydrogen Energy***, Vol. 36, No. 17, (2011), 11164-11173. (https://doi.org/10.1016/j.ijhydene.2011.05.138).
13. Wang, S., Ji, C., Zhang, B. and Liu, X., "Performance of a hydroxygen-blended gasoline engine at different hydrogen volume fractions in the hydroxygen", ***International Journal of Hydrogen Energy***, Vol. 37, No. 17, (2012), 13209-13218, (https://doi.org/10.1016/j.ijhydene. 2012.03.072).
14. Diéguez, P.M., Urroz, J.C., Marcelino-Sádaba, S., Pérez-Ezcurdia, A., Benito-Amurrio, M. and Sáinz, D., "Experimental study of the performance and emission characteristics of an adapted commercial four-cylinder spark ignition engine running on hydrogen–methane mixtures", ***Applied Energy***, Vol. 113, (2014), 1068-1076. (https://doi.org/10.1016/ j.apenergy.2013.08.063).
15. Ghazal, O.H., "A comparative evaluation of the performance of different fuel induction techniques for blends hydrogen–methane SI engine", ***International Journal of Hydrogen Energy***, Vol. 38, No. 16, (2013), 6848-6856. (https://doi.org/10.1016/j.ijhydene.2013.03.090).
16. Karagöz, Y., Yüksek, L., Sandalcı, T. and Dalkılıç, A.S., "An experimental investigation on the performance characteristics of a hydroxygen enriched gasoline engine with water injection", ***International Journal of Hydrogen Energy***, Vol. 40, No. 1, (2015), 692-702. (https://doi.org/10.1016/j.ijhydene.2014.11.013).
17. Karagöz, Y., Güler, İ., Sandalcı, T., Yüksek, L. and Dalkılıç, A.S., "Effect of hydrogen enrichment on combustion characteristics, emissions and performance of a diesel engine", ***International Journal of Hydrogen Energy***, Vol. 41, No. 1, (2016), 656-665. (https://doi.org/10.1016/j.ijhydene.2015.09.064).
18. Karagöz, Y., Güler, İ., Sandalcı ,T., Yüksek, L., Dalkılıç, A.S. and Wongwises, S., "Effects of hydrogen and methane addition on combustion characteristics, emissions, and performance of a CI engine", ***International Journal of Hydrogen Energy***, Vol. 41, No. 2, (2016), 1313-1325. (https://doi.org/10.1016/j.ijhydene.2015.11.112).
19. Baskar, P. and Senthilkumar, A., "Effects of oxygen enriched combustion on pollution and performance characteristics of a diesel engine", ***Engineering Science and Technology, an International Journal***, Vol. 19, No. 1, (2016), 438-443. (https://doi.org/ 10.1016/j.jestch.2015.08.011).
20. Nidhi, Subramanian, K.A., "Experimental investigation on effects of oxygen enriched air on performance, combustion and emission characteristics of a methanol fuelled spark ignition engine", ***Applied Thermal Engineering***, Vol. 147, (2018), 501-508. (https://doi.org/ 10.1016/j.applthermaleng.2018.10.066).
21. Technologies G., GT-Power Engine Performance Application Manual, (2009).
22. Wang, S., Ji, C., Zhang, M. and Zhang, B., "Reducing the idle speed of a spark-ignited gasoline engine with hydrogen addition", ***International Journal of Hydrogen Energy***, Vol. 35, No. 19, (2010), 10580-10588. (https://doi.org/10.1016/j.ijhydene.2010.08.002).
23. Pulkrabek, W.W., Engineering fundamentals of the internal combustion engine, Prentice Hall, New Jersey, United States, (1997).
24. Wang, S., Ji, C., Zhang, J. and Zhang, B., "Comparison of the performance of a spark-ignited gasoline engine blended with hydrogen and hydrogen–oxygen mixtures", ***Energy***, Vol. 36, No. 10, (2011), 5832-5837. (https://doi.org/10.1016/j.energy.2011.08.042).
25. Budzianowski, W.M. and Miller, R., "Towards improvements in thermal efficiency and reduced harmful emissions of combustion processes by using recirculation of heat and mass: A review", ***Recent Patents on Mechanical Engineering***, Vol. 2, No. 3, (2009), 228-239. (https://doi.org/10.2174/1874477X10902030228).