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The Effect of Hydrogen on Performance of Internal Combustion Engine Fueled by Compressed Natural Gas

Fouad Alwan Saleh[1], Abdulrahman Shakir Mahmood[2*], Mohammed Kadhim Allawi[3] Ali Khalid Shaker Al-Sayyab[4]

[1]Mechanical Engineering Department, College of Engineering, Mustansiriyah University, Baghdad, Iraq
[2]Environment Research Center, University of Technology– Iraq, Alsina'a street, 10066 Baghdad, Iraq
[3]Department of Mechanical Power Engineering, Baghdad-Technical Engineering College, Middle Technical University, Baghdad, Iraq
[4]Department of Mechanical Engineering and Construction, Universitat Jaume I, Campus de Riu Sec s/n, 12071 Castellón de la Plana, Spain

*Email: Abdulrahman.S.Mahmood@uotechnology.edu.iq

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Abstract

The natural gas can readily serve as the replacement fuel for internal combustion engines. This work tested the SI engine when running on a hydrogen-enriched compressed natural gas (CNG) mixture. The modelling has been implemented at a range of engine speeds from 1000 to 5500 rpm with a full load, direct injection, and a spark-ignited engine with a compression ratio of 10. Engine performance influences were examined, especially regarding brake power, brake thermal efficiency (BTE), and brake specific fuel consumption (BSFC), in addition to the combustion characteristics like cylinder temperature and pressure. A Lotus Engine Simulation program was used for analyzing and modeling. The results demonstrated that the best performance and combustion characteristics were with mixtures that have increased in the H_2 percentage. The results show that the brake power and BTE increased, and the BSFC decreased with the increase of hydrogen in the mixture. It was found that the brake power and BTE increased by 2% and 21% for HCNG 25, and the best reduction in BSFC was 6% for HCNG 20 compared to the CNG. It was also observed that maximum cylinder pressure (Pmax) and temperature (Tmax) increase with increasing percentage of H_2 in the mixture.

Keywords: Combustion Characteristics; Hydrogen; Lotus Simulation Tools; Natural Gas; Performance

1. Introduction

The worsening air pollution and the increasing oil prices pushed authors and engine manufacturers to look for gasoline-based fuel to enhance engine performance and reduce emissions. Methane, or natural gas, is suitable because it is relatively low-cost, partially clean, and easy to access. Methane has become a substitute fuel for engines for a long time. Hydrogen has the potential to replace gasoline. Hydrogen is a clean fuel with a wider flammability range [1], [2]. Moreover, hydrogen features a high flame speed and auto-ignition temperature [3]. Many works have already used the addition of various gaseous and Alcohol fuels to gasoline to have better engine performance and cleaner emissions [4]. In terms of using natural gas (NG) in internal combustion engines, these include three main methods, namely compressed natural gas (CNG) [5], liquefied natural gas (LNG) [6], [7], and CNG enriched with hydrogen (HCNG) [8], [9]. Nguyen et al. [10] Experimentally examined the SI engine performance fueled by CNG. They noticed that as the engine was run on CNG, the BSEC was higher by 14% while the engine brake power decreased by 19%. Lee et al. [11] investigated the impact of utilizing CNG to run an SI engine as an alternative fuel instead of gasoline on thermal efficiency at a full load. For them, improved thermal efficiency was noticed when the CNG was used as the fuel, and this was because of the CNG's higher-octane number than gasoline. The compression ratio (CR) influence on the combustion and performance of an SI engine working by the mixture of gasoline and CNG was examined experimentally by [12]. At the engine CR (12), it was observed that an intense knock and the indicating mean effective pressure (IMEP) was 7 bars when running with gasoline fuel. At the same time, no knocking was noticed on the engine running with CNG, even at CR 16. They reported running the engine with CNG fuel could work more efficiently, even at CR 16. Cheenkachorn et al. [13] examined the impact of adding LNG into a heavy-duty diesel engine for dual-fuel operation. LNG was the main fuel source, ignited by a tiny quantity of pilot-injected diesel spray, which auto-ignited the NG-air blend. They discovered that the CO_2 and NOx emissions were lower than the pure diesel; however, the CO and HC emissions were higher. The effect of compression ratio (CR) and natural gas composition were experimentally investigated on the characteristics of the SI engine performance and combustion fueled by the LNG [14]**.** They discovered that the cylinder pressures increased as the CR increased while peak combustion pressure decreased with longer combustion duration [15]. They noticed that BTE increases with longer combustion time, and the BSFC decreases with the CR increase. Thus, they reported that LNG has a slightly higher laminar flame speed due to the higher concentration of ethane in it.

On the other hand, some works added hydrogen (H_2) in different percentages with the natural gas (HCNG). A comparative work on the SI engine performance using CNG and a mixture of CNG with hydrogen of different ratios from 0% to 100% was carried out [16]. They discovered that the best performance was achieved with the 30% hydrogen in blends (HCNG 30%) compared to the CNG and other HCNG blends. Wongwuttanasatian et al. [17] experimentally verified the SI engine performance operating on HCNG15, HCNG20, and HCNG30 mixtures (with 15%, 20%, and 30% hydrogen content) and compared it with the engine on pure CNG. Compared with that of pure CNG, it was observed that the BSFC decreased for the engines operated by HCNG. In terms of the hydrogen percentage impact in the mixture, they reported that the torque and brake power of the engine reduced as the hydrogen percentage was increased from 15 to 30%. In addition, the thermal efficiency for the pure CNG, HCNG15, HCNG20, and HCNG30 were 21.59, 22.31, 23.20, and 23.75%, respectively. The impact of adding hydrogen to the CNG on SI engines' performance and combustion characteristics was examined numerically by [18]**.** They observed that the highest BTE, the most significant power output, and the lowest BSFC of the engine were obtained for the 20HCNG mixture (i.e., 20% hydrogen addition). They found that the torque values were 4.60, 4.51, 4.42, 4.34, and 4.25 Nm for HCNG20, HCNG15, HCNG10, and HCNG5 mixtures. For the HCNG20 blend, the peak cylinder pressure and temperature were reduced by 5.2% and 5.9% compared with CNG. The main objective of the present work is to provide a new academic addition to the field of the use of HCNG as an alternative fuel for the operation of SI engine-type internal combustion engines. In addition, the work's originality lies in using the Lotus program to determine the characteristics of different ratios of compressed natural gas and hydrogen (HCNG) and examine their effect on the performance of the SI engine.

2. Modeling Setup and Test Procedure

2.1. Engine Specifications

The current modeling used a Spark-ignition engine, gasoline fuel, four-cylinder, four-stroke, and turbocharged intake type. Details of the Spark Ignition are illustrated in Table 1 and Fig. 1. These engine specifications are utilized to build the engine model in the Lotus Engine Simulation (LES) program.

Table 1: Features of the model engine

No.	Part Name	Value	No.	Part Name	Value
1	Cylinder	4	**8**	IVO	15.0 BTDC
2	Stroke	4	**9**	IVC	60 ABDC
3	Bore	76 mm	**10**	EVO	40.0 BBDC
4	Stroke Length	82.6 mm	**11**	EVC	20 ATDC
5	Compression Ratio	10	**12**	MP	125/5500
6	Fuel System	Direct injection	**13**	MT	230/1950-4500
7	Con-Rod Length	130 mm	**14**	Intake type	Turbocharged

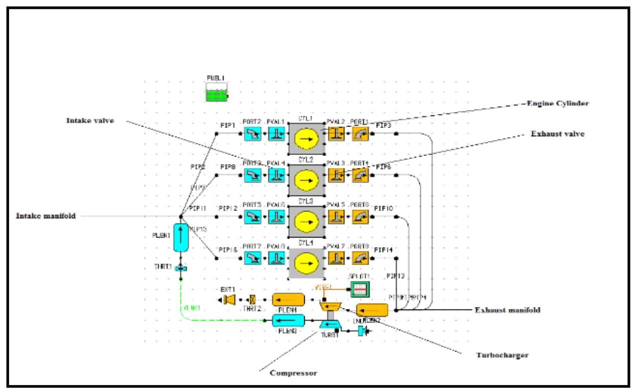

Figure 1: Engine model by LOTUS engineering software

2.2. Engine Properties and Model

The work focuses on analyzing a variety of carefully selected HCNG mixtures, which include the following mixtures: 100% CNG [CNG], 95% CNG + 5% H_2 [HCNG5], 90% CNG + 10% H_2 [HCNG10], 85% CNG + 15% H_2 [HCNG15], 80% CNG + 20% H_2 [HCNG20], and 75% CNG + 25% H_2 [HCNG25]. The properties of these (CNG) and (HCNG) mixtures are documented in Table 2. Simulations were performed using a single-zone combustion model of a spark technology internal combustion engine in the Lotus Engine Simulation (LES) calculation program. This programmer simulates the operation of an internal combustion engine, providing information about various operational parameters of a spark engine in reaction to various gas mixtures, and will be verified theoretically in a detailed step-by-step manner. Table 2 shows the basic program that requires entering gas and hydrogen fuel characterizing data into the LES program.

Table 2: Properties of the CNG and HCNG blends

Properties	CNG	HCNG 5	HCNG 10	HCNG 15	HCNG 20	HCNG 25
Calorific Value (kJ/kg)	46810	47240	47710	48255	48800	49345
Density (kg/m^3)	0.748	0.715	0.682	0.6485	0.615	0.5815
Stoichiometric A/F	16.64	16.74	16.86	16.99	17.12	17.25

2.3 Mathematical Model for Engine Performance

A simplistic model that applies the fundamental concepts of heat engine thermodynamics can represent engine performance simulation. Engine performance can be calculated using equations (1) to (7).

$$BP = (2\pi T \times N)/(60 \times 1000) \quad (1)$$

$$\eta bth = (\text{Brake Power (BP)})/(\text{Heat input from fuel Qin} \quad (2)$$

$$VE = (\text{Actual air intake})/(\text{Maximum possible air intake}) \quad (3)$$

$$T = (\text{Brake Power (BP)X 60})/(2\pi \times \text{Engine Speed}) \quad (4)$$

$$BSFC = \text{Fuel flow rate/brake power} \quad (5)$$

$$\eta\ mech = (\text{Brake Power }))/\text{Indicated Power} \quad (6)$$

$$BMEP = BP/(\text{Displacement Volume} \times \text{ no. of Cylinders} \times N) \quad (7)$$

3. Results and Discussion

Initially, the behavior of the Model validation Lotus software application in determining the performance of the SI engine was verified using the previously used method by [19], [20].

Fig. 2 shows engine brake thermal efficiency results over various engine speeds (1000–5500 rpm) for different H_2 blends. At high speeds, the level of thermal energy efficiency of the engine brake increases with the proportion of hydrogen in the mixture. Still, rapidly, due to the appearance of turbulence, the highest values of thermal energy efficiency are achieved even with mixtures with low proportions of hydrogen. At the same time, minimum efficiency values (CNG) are used at all speeds. Thus, an increase in the engine brake thermal energy efficiency was observed for the HCNG 25 mixture by 2% compared to the CNG mixture.

Fig. 3 illustrates the brake power for CNG and mixtures of CNG with hydrogen versus the engine speed. It can be seen from Fig. 3 that the maximum brake power value is obtained as (138 to 140 kW) at (HCNG20 and HCNG25) at an engine speed of 5500 rpm. Moreover, the minimum power values are generally fueled by pure CNG. However, the increase in the brake power of HCNG 25 was 21% more than that of using only CNG.

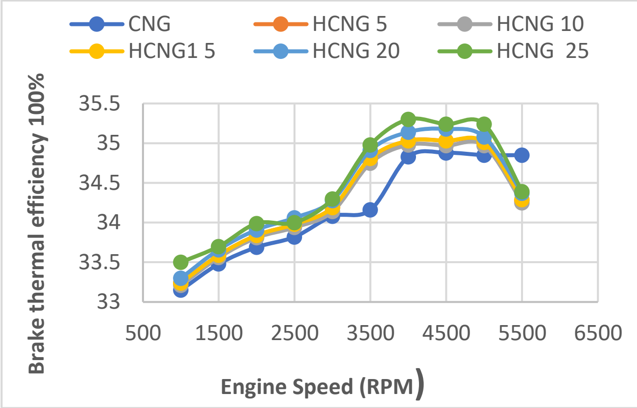

Figure 2: Variation in Brake thermal efficiency versus engine speed at different blending ratios of hydrogen

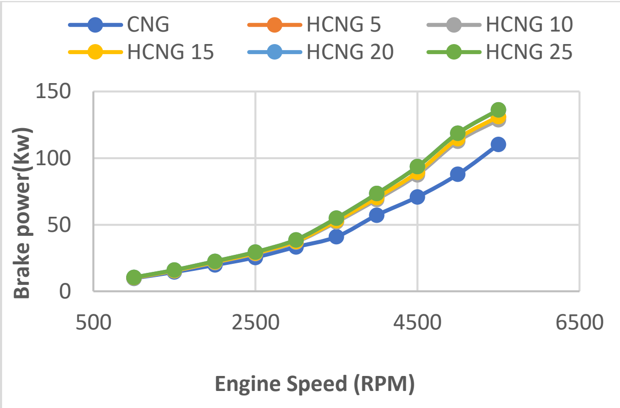

Figure 3: Variation in Brake power versus engine speed at different blending ratios of hydrogen

Fig. 4 shows the behavior of the Brake specific fuel consumption versus different blending ratios of hydrogen with varying engine speeds. The overall (BSFC) trend shows a sharp increase in fuel consumption at 1000 rpm and a decrease at a higher speed. When the engine operates at (HCNG 20 and HCNG 25) and speed engine range (1000 to 5500 rpm), a definite drop in BSFC values can be seen due to complete combustion of the natural gas. Meanwhile, the (BSFC) decreased with increased hydrogen blending ratios and fueled CNG pure at all speeds. The best BSFC reduction was obtained with the HCNG 20 mixture, where the BSFC decreased by 6% compared to CNG.

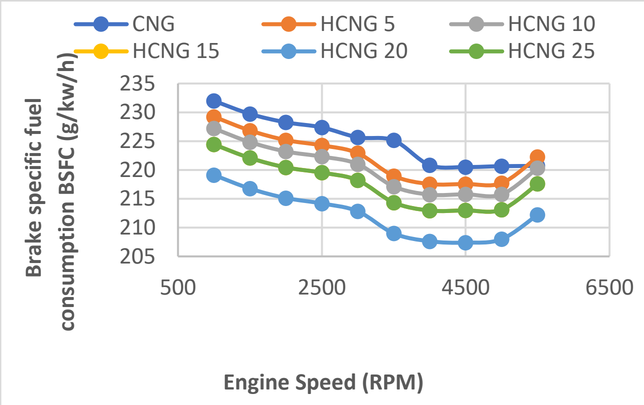

Figure 4: Variation in BSFC versus engine speed at different blending ratios of hydrogen

Fig. 5 and Fig.6 show the maximum cylinder gas pressure (P max) and maximum average gas temperature (T max), respectively, in the engine operating mode at 1000 rpm versus hydrogen fractions. It is observed that Pmax and Tmax follow similar behavior with different hydrogen fractions. Increasing the proportion of excess air results in lower Pmax and higher Tmax values, while rapid combustion enables heat release within a smaller cylinder volume and reduces heat loss to the coolant, which could raise Pmax and Tmax values. The combined effects of these two factors reduce the amounts of Pmax and Tmax by increasing hydrogen fractions when they are less than the absolute value and improve them by increasing hydrogen fractions above this value. A steady increase in pressure (0 to 60 bar) and temperature (400 to 2500 K) is also observed during check engine speeds (1000 rpm) when the engine is operating with a higher ratio of HCNG blends, raising the pressure and temperature values.

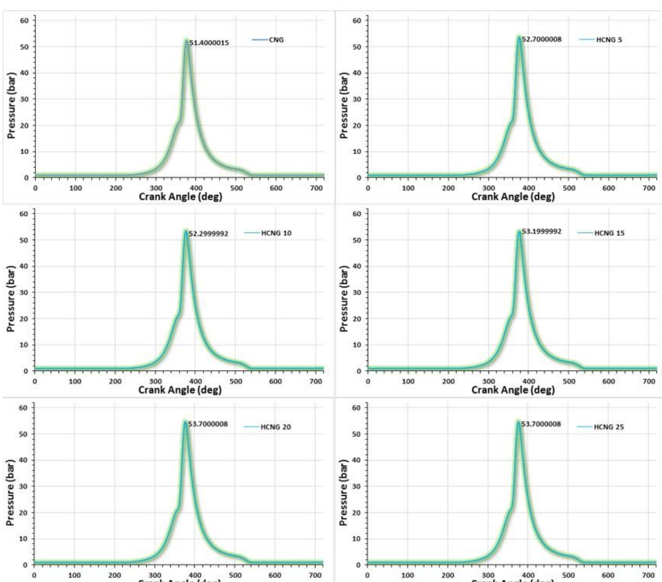

Figure 5: Pressure vs crank angle for different blending ratios of hydrogen at 1000 rpm

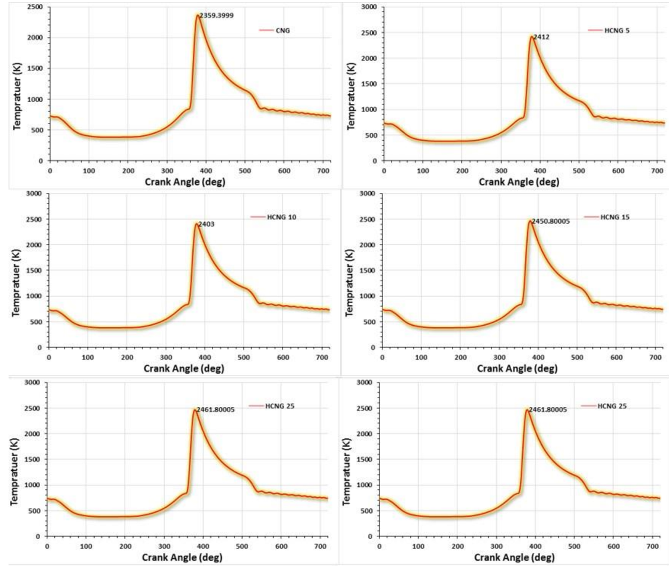

Figure 6: Temperature vs crank angle for different blending ratios of hydrogen at 1000 rpm

Fig. 7 shows the engine brake thermal efficiency results at varying speeds and with different H_2 mixtures. The contour drawings in this figure show that the maximum thermal energy efficiency (BTE) value was obtained (28.18%) at 5000 rpm, using HCNG20 and HCNG25 mixtures. In general, a decrease in the thermal energy efficiency of engine braking is observed with a reduction in the proportion of hydrogen in the fuel mixture, which pure CNG powers. Fig. 8 shows the results of (BSFC) at different engine speeds and for different H_2 blends. As can be seen from these figure's contour plots, the minimum (BSFC) of about (261g/kw/h) is obtained at 5000 rpm, fueled by (HCNG20 and HCNG25). The value of (BSFC) decreased at low speeds and increased at higher speeds under the different colors, as shown in the contour color plot. Generally, it is noted that there is an increase in the (BSFC) with a decreasing hydrogen percentage in fuel and fueled by CNG pure.

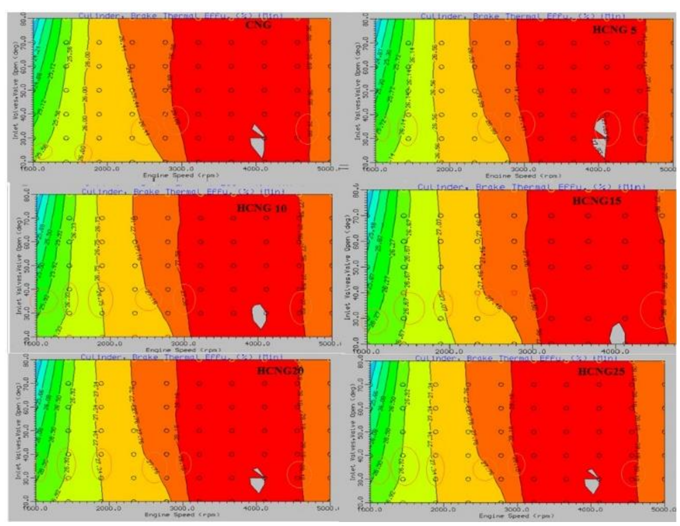

Figure 7: Brake thermal efficiency contours vs. different speeds at different blending ratios of hydrogen

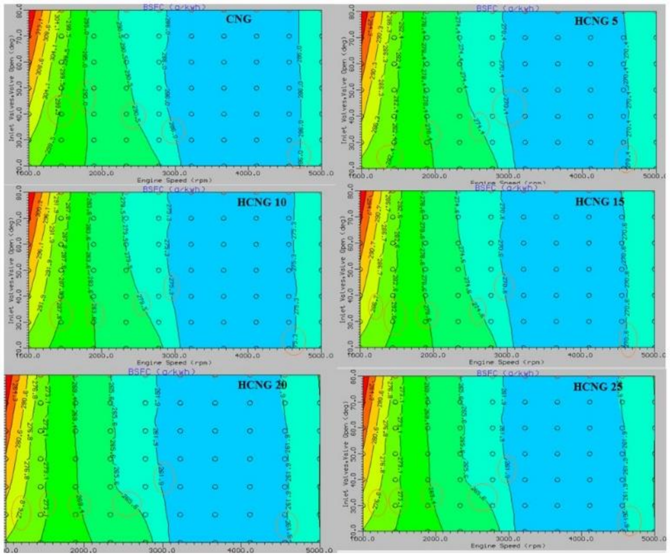

Figure 8: BSFC contours vs. different speeds at different blending ratios of hydrogen

Fig. 9 shows the maximum cylinder gas pressure contours for different H_2 blends with engine speeds. The value of (Pmax) increased by higher engine speeds. By examining engine speeds (1000 to 5500 rpm), the pressure on the piston is about (18 to 130 bar). It can be seen that the pressure rate for both (HCNG20 and HCNG25) is currently inclined to a higher value of pressure compared to other values of H_2 blends throughout the engine speeds. Finally, it can be concluded that if the engine is running at low levels of the fuel mixture (mixtures of natural gas with hydrogen), the generated pressure is reduced, and the pressure rate increases as the mixing ratios of the fuel increase.

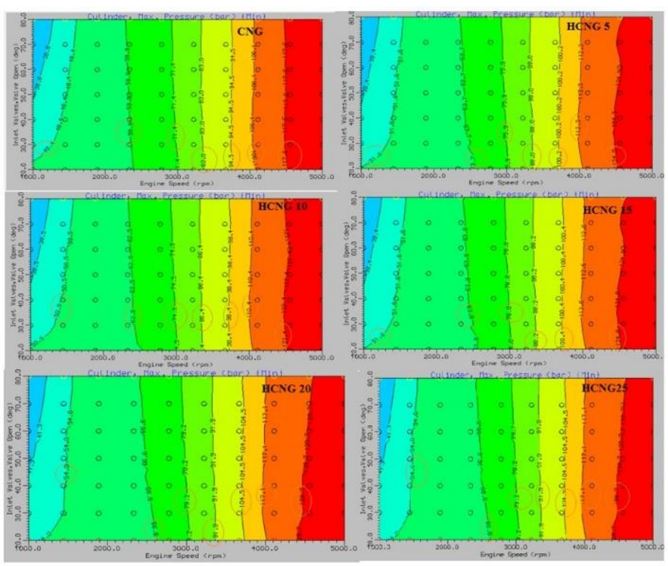

Figure 9: Cylinder gas pressure contours vs. different speeds at different blending ratios of hydrogen

Fig. 10 shows the BP results at various engine speeds and hydrogen mixtures. The contour plot shows that the maximum brake power (BP) value is achieved at around 130.4 kW at 5000 rpm when using fuel mixtures (HCNG20 and HCNG25). The value of (BP) decreased at low speeds and increased at higher speeds under the different colors, as shown in the contour color plot. In general, it is found that there is an increase in brake power (BP) with an increase in the proportion of hydrogen in the fuel and a decrease in it when using a mixture of reduced hydrogen and pure CNG.

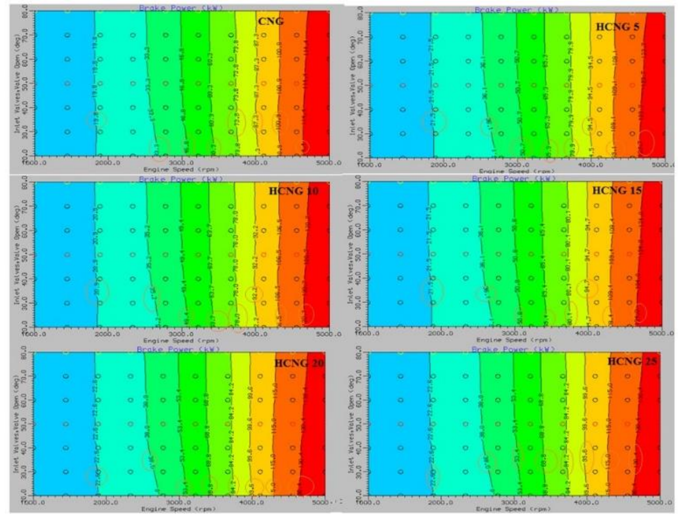

Figure 10: Break power contours vs. different speeds at different blending ratios of hydrogen

4. Conclusions

The performance and combustion characteristics of the direct injection spark-ignited engine fueled with natural gas-hydrogen blends were examined. The results showed that the thermal efficiency improved with increasing hydrogen blending ratios, and the braking power improved with increasing hydrogen blending ratios. In addition, the brake specific fuel consumption (BSFC) improved with increasing hydrogen blending ratios, while the BSFC increased with decreasing hydrogen percentage in the fuel used with pure CNG. Also, increased pressure and temperature of the cylinder gas were observed with increasing hydrogen blending ratios.

Nomenclatures

BP	Brake Power
BSFC	Brake-Specific Fuel Consumption
BTE	Brake Thermal Efficiency
CI	Compression Ignition
CNG	Compressed Natural Gas
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CR	Compression Ratio
DF	Diesel Fuel
EVC	Exhaust Valve Closes
EVO	Exhaust Valve Opens
HC	Hydrocarbon
IVC	Inlet Valve Closes
IVO	Inlet Valve Opens
LNG	Liquefied Natural Gas
MP	Max power (Kw)/speed (rpm)
MT	Max torque (Nm)/speed (rpm)

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Conflict of interest

The authors declare that they have no competing interests.

Author Contribution Statement

Fouad Alwan Saleh found the problem statement.

Abdulrahman Shakir Mahmood and Mohammed Kadhim Allawi were responsible for preparing the Material, collecting data, and Investigating the numerical program.

All authors discussed the results and contributed to the final manuscript.

References

[1] C. Satheeshkumar, T. Mohammed Shekoor, "Evaluation of emission characteristics of hydrogen as a boosting fuel in a four-stroke single cylinder gasoline engine," *International Journal of Engineering Research & Technology (IJERT),* vol. 3, no. 10, pp. 151-154, Oct. 2014. https://www.ijert.org/evaluation-of-emission-characteristics-of-hydrogen-as-a-boosting-fuel-in-a-four-stroke-single-cylinder-gasoline-engine

[2] R. D. Gandhi, "Use of hydrogen in an internal combustion engine," *International Journal of Engineering and Technical Research (IJETR*), vol. 3, no. 2, pp.207-216, Apr. 2015. https://www.erpublication.org/published_paper/IJETR031380.pdf

[3] S. Yousufuddin, S. N. Mehdi, and M. Masood, "Performance and combustion characteristics of a hydrogen− ethanol-fuelled engine," *Energy & Fuels*, vol. 22, no. 5, pp.3355-3362, June 2008. https://doi.org/10.1021/ef800309b.

[4] E. Nakova, S. Iliev, and K. Hadjiev, "Impact of Isopropanol Addition on Engine Performance and Emissions," *Engineering Proceeding, the Proceedings of International Conference on Electronics, Engineering Physics and Earth Science (EEPES 2024*, vol. 32, pp. 44–44, Aug. 2024, doi: https://doi.org/10.3390/engproc2024070044.

[5] M. I. Khan, T. Yasmin, and A. Shakoor, "Technical overview of compressed natural gas (CNG) as a transportation fuel," *Renewable and Sustainable Energy Reviews*, vol. 51, pp.785-797, Nov. 2015. https://doi.org/10.1016/j.rser.2015.06.053

[6] S. Pfoser, O. Schauer, and Y. Costa, "Acceptance of LNG as an alternative fuel: Determinants and policy implications," *Energy Policy*, vol. 120, pp. 259–267, Sep. 2018. https://doi.org/10.1016/j.enpol.2018.05.046

[7] Z. Zhang, P. Jia, G. Zhong, J. Liang, and G. Li, "Numerical study of exhaust reforming characteristics on hydrogen production for a marine engine fueled with LNG," *Applied Thermal Engineering*, vol. 124, pp. 241–249, Sep. 2017. https://doi.org/10.1016/j.applthermaleng.2017.06.012

[8] R. K. Mehra, H. Duan, R. Juknelevičius, F. Ma, and J. Li, "Progress in hydrogen enriched compressed natural gas (HCNG) internal combustion engines - a comprehensive review," *Renewable and Sustainable Energy Reviews*, vol. 80, pp. 1458–1498, Dec. 2017. https://doi.org/10.1016/j.rser.2017.05.061

[9] X. Duan, Y. Liu, J. Liu, M. C. Lai, M. Jansons, G. Guo, S. Zhang, and Q. Tang, "Experimental and numerical investigation of the effects of low-pressure, high-pressure and internal EGR configurations on the performance, combustion, and emission characteristics in a hydrogen-enriched heavy-duty lean-burn natural gas si engine," Energy Conversion and Management, vol. 195, pp. 1319–1333, Sep. 2019. https://doi.org/10.1016/j.enconman.2019.05.059

[10] K. Nguyen Duc, V. Nguyen Duy, L. Hoang-Dinh, T. Nguyen Viet, and T. Le-Anh, "Performance and emission characteristics of a port fuel injected, spark ignition engine fueled by compressed natural gas," *Sustainable Energy Technologies and Assessments,* vol. 31, pp. 383–389, Feb. 2019. https://doi.org/10.1016/j.seta.2018.12.018

[11] J. Lee, C. Park, J. Bae, Y. Kim, S. Lee, and C. Kim, "Comparison between gasoline direct injection and compressed natural gas port fuel injection under maximum load condition," *Energy*, vol. 197, p. 117173, Apr. 2020. https://doi.org/10.1016/j.energy.2020.117173

[12] S. Sahoo and D. K. Srivastava, "Effect of compression ratio on engine knock, performance, combustion and emission characteristics of a bi-fuel CNG engine," *Energy*, vol. 233, p. 121144, Oct. 2021. https://doi.org/10.1016/j.energy.2021.121144

[13] K. Cheenkachorn, C. Poompipatpong, and C. G. Ho, "Performance and emissions of a heavy-duty diesel engine fuelled with diesel and LNG (liquid natural gas)," *Energy*, vol. 53, pp. 52–57, May 2013. https://doi.org/10.1016/j.energy.2013.02.027

[14] X. Duan, Y. Liu, M. C. Lai, G. Guo, J. Liu, Z. Chen, and B. Deng, "Effects of natural gas composition and compression ratio on the thermodynamic and combustion characteristics of a heavy-duty lean-burn SI engine fueled with liquefied natural gas," *Fuel*, vol. 254, p. 115733, Oct. 2019. https://doi.org/10.1016/j.fuel.2019.115733.

[15] M. Attallah Mashkour and A. Yaseen Ahmed, "Thermodynamic Modeling For Analysing The Performance And Emissions Of Spark-Ignition Engines," *Journal of Engineering and Sustainable Development*, vol. 24, no. 2, pp. 57–79, Mar. 2022. https://doi.org/10.31272/jeasd.24.2.5

[16] S. M. V. Sagar and A. K. Agarwal, "Experimental investigation of varying composition of HCNG on performance and combustion characteristics of a SI engine," *International Journal of Hydrogen Energy*, vol. 42, no. 18, pp. 13234–13244, May 2017. https://doi.org/10.1016/j.ijhydene.2017.03.063

[17] T. Wongwuttanasatian, S. Jankoom, and K. Velmurugan, "Experimental performance investigation of an electronic fuel injection-SI engine fuelled with HCNG (H2+ CNG) for cleaner transportation," *Sustainable Energy Technologies and Assessments*, vol. 49, p. 101733, Feb. 2022. https://doi.org/10.1016/j.seta.2021.101733

[18] A. A. Elshenawy, S. M. Abdel Razik, and M. Gad, "Numerical investigation of performance, combustion, and emission characteristics of spark-ignition engine fuelled with compressed natural gas and hydrogen," *Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering*, p.09544089231208914, Nov. 2023. https://doi.org/10.1177/09544089231208914.

[19] A. S. Fouad K. A. Mohammed S. I. Murtdha and O. S. Ahmed, "Examining the Impact of Diesel Fuel Density Variation on the Performance of Compression Ignition Engines Using the LOTUS Simulation Program," *Kexue Tongbao/Chinese Science Bulletin*, vol. 69, no. 01, pp. 923- 936, January, 2024. https://www.kexuetongbao-csb.com/article/examining-the-impact-of-diesel-fuel-density-variation-on-the-performance-of-compression-ignition-engines-using-the-lotus-simulation-program

[20] M. S. Kassim, M. K. Allawi, and H. S. S. Aljibori, "Simulation of Effect of Injection Strategies on Performance of a Spark Ignition Engine," *International Journal on Technical and Physical Problems of Engineering (IJTPE),* vol. 15, no. 54, pp. 212-217, March 2023. https://www.researchgate.net/publication/370444672