Research Article

To Analyze the Effect of HCNG on Combustion, Performance and Emissions Characteristics of a Natural Gas Engine

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Abstract: Natural gas (NG) is extensively used in automobiles and studied in spark ignition (SI) engines. NG with lean combustion has revealed the potential to enhance efficiency and decrease emissions over stoichiometric petrol engines. The ignitability and instability are the main issues of NG lean combustion. Adding hydrogen (H_2) in NG can be a solution to lean NG combustion limits. Herein, the experimental research was accomplished to analyze the effect of hydrogen blending on the combustion, emission, and performance aspects of NG EQD210N-20 engines. The engine was run at six different working conditions which are characterized by engine load, engine speed, and hydrogen fractions. The main performance parameters included heat release, mass fraction burned (MFB), power (frictional, effective, indicated), efficiency (mechanical, indicated, brake thermal), and coefficient of variation for indicated mean effective pressure (COV_{IMEP}). Hydrogen blending in NG extends the lean ignition limit, accelerates combustion, and enhances the efficiency of combustion. Hydrogen has an extensive flammability range and very low ignition energy. A blending of hydrogen in NG increases heat release rate (HRR), MFB, indicated thermal efficiency (ITE), and decreases the specific fuel consumptions and engine emissions. The findings are applicable for the optimized performance of the SI engines at a bench and commercial scales.

Received: November 15, 2021; **Accepted:** 24 December 2021; **Published:** 28 December 2021
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Citation: Ali, H.L., M.T. Hassan, M.R. Siddiqi, M. Arshad and M.M. Sharif. 2021. To analyze the effect of HCNG on combustion, performance and emissions characteristics of a natural gas engine. *Journal of Engineering and Applied Sciences,* 40(2): 110-117.
DOI: https://dx.doi.org/10.17582/journal.jeas/40.2.110.117
Keywords: SI Engine, Hydrogen, Natural Gas, Combustion, Performance, Emission

Introduction

The crude oil resources shortage and ecological pollution gradually became a very serious problem for the world. Researchers and scientists are focusing on the use of substitutional fuel for automobiles. Natural gas (NG) is gaseous fuel and the term NG is referred to as hydrocarbon-rich gas which is found in NG fields, coal beds, and oil fields (Carroll, 2010). Conventional hydrocarbon fuels play a very significant role in power production but the combustion of such fuels cause a serious environmental and ecological imbalance in the atmosphere and release CO*x*, NO*x*, and hydrocarbons emissions in the universe which have adverse effects on human health. Carbon dioxide is dangerous for the ozone layer that protects the environment from the harmful rays coming from the Sun and increases global warming. Natural gas is a suitable substitutional fuel because of its low emissions, higher-octane number, abundant reserve, and less cost. The use of NG as a fuel for engines has been studied by researchers for many years. Nowadays, NG engines are used in commercial applications.

It is the combination of various gases in which methane has major composition. The properties of an NG are presented in Table 1 (Union Gas, 2017).

Table 1: *Natural gas composition.*

Component	Formula	Composition (mole %)
Methane	CH_4	95.0
Ethane	C_2H_6	3.2
Nitrogen	N_2	1.0
Carbon dioxide	CO_2	0.5
Normal butane	C_4H_{10}	0.03
Hexanes plus	C_6H_{14}	0.01
Isobutane	C_4H_{10}	0.03
Normal pentane	C_5H_{12}	0.01
Oxygen	O_2	0.02
Isopentane	C_5H_{12}	0.01
Hydrogen	H_2	Trace-0.02

The burning of NG produces very little emissions as compared to the petrol and diesel oils because of its simple organic composition and lack of fuel vaporization. It has a higher anti-knocking ability and a high-octane number that permits the engine to drive at a larger compression ratio (CR).

NG improves thermal efficiency and power output, but it has poor lean-burn ability and very low burning velocity (Rousseau *et al*., 1999). One most alternative and operative technique is to blend the NG through fuel which shows rapid burning characteristics to overcome the slow-burning velocity of NG issues. For this purpose, hydrogen (H_2) is used in NG engines because it has numerous combustion aspects that are exclusive and valuable in improving the engine's emissions as well as efficiency (Açıkgöz *et al*., 2015; Lu *et al*., 2011). Ali *et al*. (2018) have increased the engine performance. The addition of H_2 in NG improves engine's combustion performance (Chugh *et al*., 2016) increases its thermal efficiency (Deng *et al*., 2011) increase engine performance (Kavathekar *et al*., 2021; Oni *et al*., 2021) reduces combustion duration (Singh *et al*., 2016) expands lean-burn limit, and decreases carbon dioxide emissions, and pollutants (Genovese *et al*., 2011).

In a study, Akansu *et al*. (2007) used a 4-stroke, spark-ignition 4-cylinder engine to investigate its performance through blends of hydrogen and NG. The experimentation was conducted using the CNG/H_2 (HCNG) blends with the equivalence ratios (ER) of 100/0, 90/10, 80/20, and 70/30 correspondingly. The brake thermal efficiency was improved and carbon monoxide (CO) and HC emissions were decreased with hydrogen blending. Whereas, it was observed that NO*x* emissions were increased by the adding of H_2 in the fuel blend. However, for the lean-burn ($\varphi < 0.75$) mixture, the NO*x* emissions were reduced substantially. In another similar study by Deep *et al*. (2017), the influence of H_2 blending through NG was investigated on engine performance and emissions and performances were studied. For tests, single-cylinder engines were used through a bore and stroke of 70 and 90 mm respectively. The engine has functioned at diverse ER and a uniform speed of 2000 rev/min and 24000 rev/min with the ignition of spark timing 26° before top the dead center (bTDC). The outcomes exposed that introducing hydrogen along with the NG significantly increased the BTE of the engine. It was also noted that exhaust emissions of CO*x* and HC were reduced through the rise of the ratio of H_2.

Hora and Agarwal (2015) investigated through experiments at various engine conditions to examine the hydrogen blending effect. The outcomes revealed that BTE as well as brake-specific fuel consumption (BSFC) both improved using HCNG mixture. The engine performance increases by the increased percentage of hydrogen to NG (Bauer and Forest, 2001). A 30HCNG blend showed the best performance of an engine amongst the tested compositions of HCNG mixture and no detrimental combustion characteristics were observed. The direct injection technique was utilized to improve the flame propagation speed and volumetric efficiency (Hu *et al*., 2009). Furthermore, Akansu *et al*. (2004) explored the emission properties of H_2 and CNG mixtures in IC engines and found that CO, CO_2, and HC, reduced with a rise in H_2 percentage.

In the current experimental investigation, the impact of hydrogen blending was studied on an SI six-cylinder engine through a bore and stroke of 105 mm, and 120 mm respectively. The engine was run at six dissimilar operational conditions with percentages of hydrogen included, 0%, 20%, and 40%. Hydrogen blending effect on the engine combustion, emissions, and performance characteristics was analyzed.

Materials and Methods

Experimental apparatus

In this experimental investigation, a six-cylinder inline, water-cooled spark-ignition engine Dongfeng EQD210N-20 was used. The SI engine's description is revealed in Table 2. The in cylinder of engine pressure at each angle of the crankshaft was measured by the pressure transducer. The cylinder pressure data was collected around 137 consecutive cycles. Assume that the manifold absolute pressure (MAP) equals the cylinder pressure at TDC (intake stroke), so the pressure data can be adjusted to the absolute value by shifting the first data to MAP. The in-cylinder pressure at TDC of intake stroke is a relative value and has to be converted to absolute value before calculation. The corrected pressure data was used to estimate the engine's combustions, and performance characteristics such as; in-cylinder pressure, heat release rate (HRR), power (frictional, effective, indicated), indicated mean effective pressure of coefficient of variation (COV_{IMEP}), and efficiencies (mechanical, indicated, brake thermal), and mass fraction burned (MFB). The exhaust emissions such as CO_2, NO_x, CO, and CH_4 of the engine were examined through an exhaust gas analyzer.

Table 2: *Experimental engine specifications.*

Parameters of engine	Specifications
Model	EQD210N-20
Displacement	6.234 L
No. of cylinders	6
Bore	105 mm
Compression ratio	10:1
Stroke	120 mm
Maximum Torque	620 N-m /1400 ~ 1600 rev/min
Rated Power	154 KW /2800 rev/min
Lowest SFC at full load	198 g/kWh

Engine operating conditions

The 6-cylinder inline SI water-cooled engine was run at different six various conditions shown in Table 3. For the first and last three cases the load was 120 N-m, and 350 N-m while the engine speed was 1200 rev/min, and 2000 rev/min, respectively. For the first three conditions, the engine was operated at an excess air ratio (EAR) of 1.4 whereas for the last three conditions the EAR was 1.5 respectively. The spark timings were 26 °CA bTDC and 22 °CA bTDC for the cases I-III and IV-VI respectively. Likewise, the average airflow rate was 86 kg/h in the first three cases and 351 kg/h in the last three cases respectively. The operational manifold absolute pressure (MAP) for cases I to III was 63 kPa, and for cases IV to VI, it was set at 136 kPa. On a 6-cylinder engine, all the experiments have been conducted through hydrogen percentages of 0%, 20%, 40% with natural gas.

Table 3: *Engine operating conditions.*

Sr. No	Engine speed (rev/min)	Engine load (N-m)	Hydrogen fraction (%)
Case I	1200	120	0
Case II	1200	120	20
Case III	1200	120	40
Case IV	2000	350	0
Case V	2000	350	20
Case VI	2000	350	40

Results and Discussion

Effects of HCNG on combustion

The In-cylinder pressure curve over crank angle in degree (CAD) is revealed in Figure 1. It may be noted that, with the increased percentage of hydrogen, more rapid combustion occurred that resulted in an increase of mean in-cylinder pressure. So, the increased percentage of H_2 improved the mean pressure. Maximum pressure was predicted in the case of VI with 40% volumetric substitution of hydrogen.

The heating value of the blend can be calculated through Equation 1. Table 4 represents the heating value of the HCNG mixture. Through the addition of H_2 percentage, the fuel blend heating value is rising. The HRR can be estimated through Equation 2.

$$H_{u,mix} = \left(\frac{\dot{m}_{CNG}}{\dot{m}_{CNG} + \dot{m}_{H_2}}\right) H_{u,CNG} + \left(\frac{\dot{m}_{H_2}}{\dot{m}_{CNG} + \dot{m}_{H_2}}\right) H_{u,CNG} \quad ...(1)$$

$$\frac{dQ_{ch}}{d\theta} = \frac{\gamma}{\gamma - 1} p \frac{dV}{d\theta} + \frac{1}{\gamma - 1} V \frac{dp}{d\theta} + V_{cr}\left[\frac{T'}{T_w} + \frac{T}{T_w(\gamma - 1)} + \frac{1}{bT_w}\left(\frac{(\gamma - 1)}{(\gamma' - 1)}\right)\frac{dp}{d\theta}\right] + \frac{dQ_{ht}}{d\theta} \quad ...(2)$$

$$x_i = \frac{\sum_0^i \Delta P_c^*}{\sum_0^N \Delta P_c^*} \quad ...(3)$$

The third and fourth term of Equation 2 assumes to be zero because the effect on HRR is very small. Where $dQ_{ch}/d\theta$ is the HRR (J/°CA), x_i is the fuel mixture MFB at step i, and N is the total number of combustion increments, ΔP^*_C normalized pressure rises due to combustion.

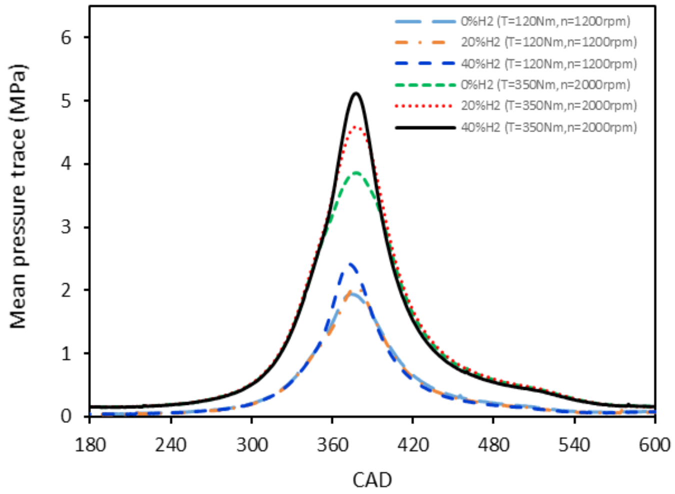

Figure 1: *Mean pressure trace over 720 °CA.*

Table 4: *Heating value (MJ/kg) of HCNG mixture.*

Percentage of hydrogen	N =1200 rpm, T= 120 N-m, EAR = 1.4	N = 2000 rpm, T= 350 N-m, EAR = 1.5
0	50	50
20	52.258	52.151
40	55.617	55.385

The variation in HRR over CAD is shown in Figure 2. The rise in HCNG leads to the development of the HRR. At 2000 rev/min the highest HRR of 66.4, 56.8, and 47.8 J/CAD are obtained at 13, 20, and 29 CAD. Similarly, values of HRR at 1200 rev/min are 27.7, 27.1, and 20 J/CAD are obtained at crank angles of 7, 13, and 10 degrees. The HRR of HCNG can be better through the adding of H_2 to NG, which offers to decrease the combustion duration. Consequently, before the power stroke, a great portion of chemical energy was discharged as heat as well as this was minor afterward burning happened.

MFB is the quantity that defines the combustion process of organic energy as a function of CAD. Figure 3 displays the variation in MFB against CAD by the RW method applied to measure the MFB inside the combustion chamber. The outcomes reveal that most of the fuel is burned from a range from 348 to 410 CA over all the selected cases, which is the region of maximum temperature and pressure.

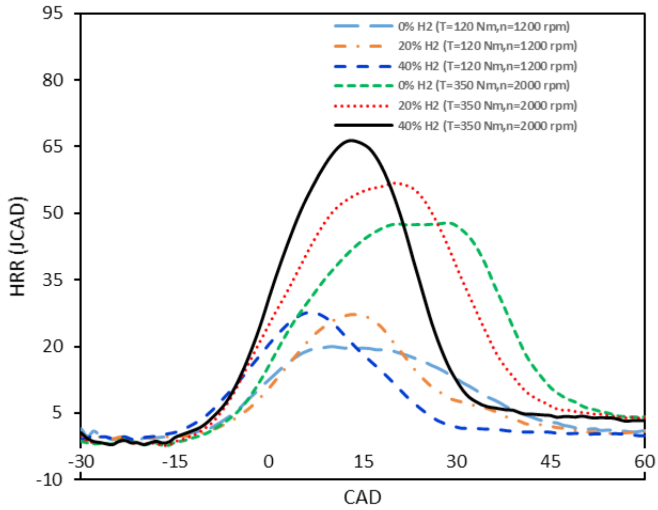

Figure 2: *Variation in HRR against CAD.*

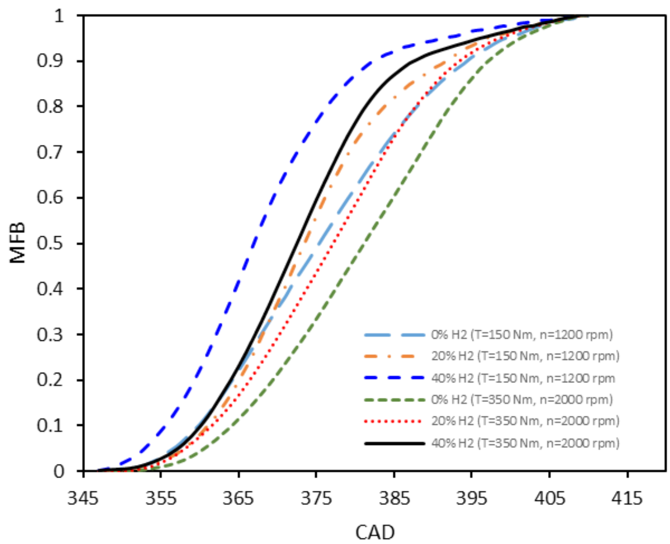

Figure 3: *Variation in MFB against CAD.*

The COV according to IMEP is used regularly to quantitatively estimate the cycle-by-cycle variation. IMEP ratio of the standard deviation to the arithmetic means in several successive engine cycles is referred to as COV_{IMEP} and can be estimated by using Equation 4.

$$COV_{IMEP} = \frac{\sigma_{IMEP}}{\mu} \times 100\% \quad ...(4)$$

$$\sigma_{IMEP} = \sqrt{\sum_{i=1}^{N} (x_i - \mu)^2 / N} \quad ...(5)$$

Where σ_{IMEP} is the IMEP standard deviation, μ is the arithmetic means, and x_i is the measured IMEP over N engine cycles. Figure 4 shows the effect of COV over HCNG ratio by adding hydrogen which results in decreasing the COV of IMEP. The smaller value of COV means better performance of the engine. For an engine running at 1200 rev/min and 2000 rev/min, the COV_{IMEP} decreases about 1.03%, and

2.03%, respectively. Hydrogen addition decreases the combustion duration that leading to improved fuel consumption, and thermal efficiency.

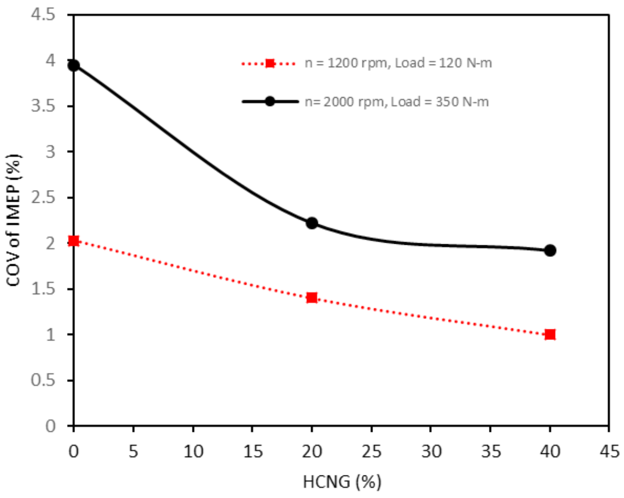

Figure 4: *Effect of HCNG on COV of IMEP.*

Effects of HCNG on performance

Thermal efficiency (TE) is a significant factor for the evaluation of an engine's general performance and economic viability. Optimizing the combustion structure or properties of fuel can lead to its development. With the addition of hydrogen, the engine BTE as well as indicated thermal efficiency (ITE) was improved at all operating conditions. The ITE and BTE with various percentages of hydrogen in the fuel are shown in Figure 5. The results show that when no hydrogen was mixed, the ITE of 31% and 36% were obtained at the engine's load of 120 N-m and 350 N-m correspondingly. The maximum ITE was attained i.e., 34% and 38% at low load (120 N-m, 1200 rev/min) and high load (2000 rev/min, 350 N-m) respectively with 20% and 40% of H_2 addition. The values of BTE of 22%, 24%, and 23% were obtained at 0%CNG, 20% H_2, and 40% H_2 respectively at low engine load (1200 rev/min).

Whereas, the highest value of BTE i.e., 30% was achieved at 20HCNG at high load. The efficiency of the engine can be enhanced by a rise in the blend burning speed. Similar results were found by different researchers such as Carroll (2010) and Tangöz *et al.* (2015).

Figure 6 display the effect of dissimilar percentages of HCNG on mechanical efficiency (ME) and specific fuel consumption (SFC). It may be noted that by the addition of H_2 in the fuel blend, the SFC was decreased. Results revealed that using 40 HCNG, at low and high load, maximum SFC was reduced that is 15.83% and 13.61%, respectively.

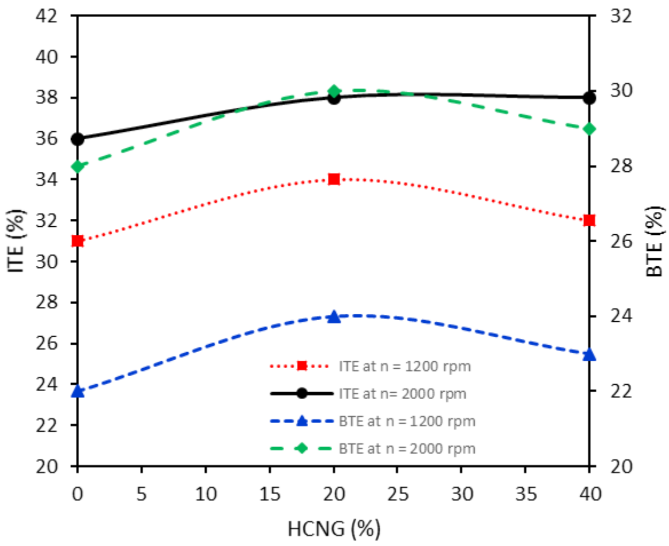

Figure 5: *Effect of HCNG on ITE and BTE.*

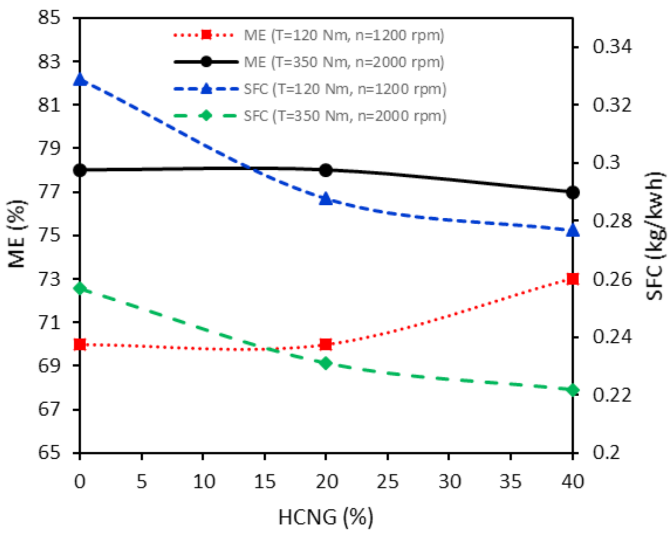

Figure 6: *Effect of HCNG on ME and SFC.*

The engine's performance parameters such as ITE, BTE, ME, SFC, I_P and B_P were calculated using Equations 6-11.

$$ITE = \frac{I_p \times 3600}{m_f \cdot CV} \quad ...(6)$$

$$BTE = \frac{B_p \times 3600}{m_f \cdot CV} \quad ...(7)$$

$$ME = \frac{B_p}{I_p} \quad ...(8)$$

$$SFC = \frac{m_f}{B_p} \quad ...(9)$$

$$I_p = \frac{IMEP \times V_s \times n \times N}{z \times 60} \quad ...(10)$$

$$B_p = \frac{2\pi NT}{60} \quad ...(11)$$

While m_f is the fuel mass supplied (kg/hr), and CV is the calorific value of fuel or mixture (kJ/kg), N is the number of revolutions (rev/min), V_s is the swept volume of the engine, *n* represents the number of cylinders, N is the engine speed, and the value of z is 2 for four-stroke engines. Where I_P and B_P are the indicated power and brake power, respectively.

Effects of HCNG on emissions

Another promising advantage of an HCNG engine over the conventional NG, diesel, or gasoline engine is its potential to reduce the level of contaminants in emissions. The addition of H_2 in NG significantly reduces the engine's emissions such as hydrocarbons (HC) and CO_2. This is due to the reduced carbon contents in the mixture of fuel, the improved calorific value of the mixture that improves the combustion process. Figure 7 reflects the effect of H_2 blending on CO, CH_4 NO*x*, and CO_2 emissions. It may be noted that emissions of NO*x* and CO rise with an increase in the H_2 ratio. When H_2 is over 20%, the higher the engine speed, resulting in more NO*x*, and CO emissions. Furthermore, the production of unburned hydrocarbons may be produced due to incomplete in-cylinder burning of the mixture.

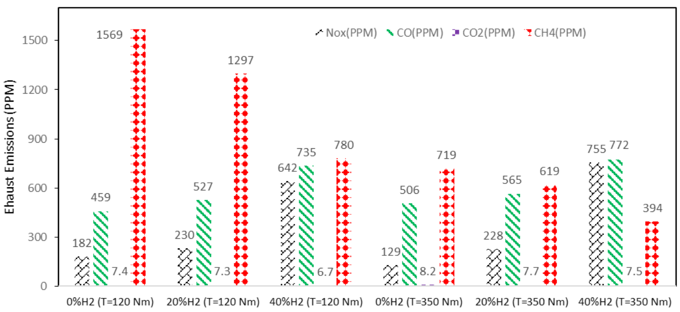

Figure 7: *Effect of HCNG on exhaust emissions (NOx, CO, CO_2, CH_4).*

However, the emissions of CO_2 and CH_4 decrease with the H_2 ratio increasing. At 40% of H_2, and an engine speed of 1200 rev/min (case-III), there was a decrease of more than 50% in CH_4 and 9.5% in engine emissions. While at an engine speed of 2000 rev/min and 40% of hydrogen (case-VI), the CH_4 and CO_2 emissions were reduced by 45.2% and 8.5% respectively. Similar results were found in an investigation using hydrogen and oxygen addition in a gasoline engine by Karagöz *et al*., (2015).

Conclusions and Recommendations

In this experimental investigation, the effect of H_2 blending with NG on the combustion, emission, and performance characteristics of the original SI NG engine was analyzed. The significant facts of conclusions are as given:

- Hydrogen gas as a fuel, has a shorter ignition delay, least ignition energy, and high laminar flame speed which offers an improved in-cylinder flame propagation process and initial flame kernel development. Therefore, in an HCNG engine decreased COV, improved and complete combustion, reduced emissions, and higher efficiency can be achieved.
- The COV under all working conditions is within the limit of 3.95 %. The COV_{IMEP} reduced around 1.03% and 2.03% at lower and higher loads respectively. It displays that with the addition of H_2 COV_{IMEP} decreases.
- The maximum BTE was achieved at both 1200 and 2000 rev/min when 20% hydrogen was blended.
- SFC increased with the addition of hydrogen 0%, 20%, and 40%. The maximum SFC i.e., 15.83% and 13.61% were achieved at 40% addition of H_2 at low and high loads respectively.
- Another significant parameter is the H_2 ratio in the fuel mixture that affects the HCNG engine's performance. A larger H_2 ratio may result in abnormal combustion such as knock, pre-ignition delay, and backfire whereas, using a low H_2 ratio, required benefits cannot be achieved completely.
- By adding hydrogen, the mixture heating value is increased.
- The CO_2 and CH_4 emissions were reduced through the addition of H_2 to the fuel mixture. At 40% H_2 and an engine speed of 1200 rev/min, the amount of CH_4 and CO_2 emissions reduced by 50.3%, and 9.5% respectively.
- From overall results, it may be concluded that the adding of hydrogen in NG is much beneficial for enhancing engine in-cylinder combustion processes, reducing emissions, and increasing the engine's overall performance.

Novelty Statement

This research addresses the challenging issue of hydrogen blending with natural gas and abnormal behavior of combustion such as knock-ing, pre-ignition, and backfire. A six-cylinder NG engine EQD210N-20 was used for contemporary research work. The hydrogen blending ratios were used as 10% HCNG, 20% HCNG, and 40% HCNG, and new design con-

Links Researchers

straints ignition timing and excess air ratios were effectively applied.

Author's Contribution

Hafiz Liaqat Ali: Proposed topic, basic study de-sign, experimental testing, and man-uscript writing.
Muhammad Tahir Hassan: Data collection, quality insurer and manuscript review.
Muftooh Ur Rehman Siddiqi: Involved in plan-ning and supervised.
Mehwish Arshad: Statistical analysis and interpretation of results.
Muhammad Mudassar Sharif: Literature review and implementa-tions referencing.

Conflict of interest
The authors have declared no conflict of interest.

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