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Investigation of SI Engine Performance Optimization and Emission Reduction Using Gasoline, CNG, and HHO Blends

Medhat Elkelawy*[1, 2], M.M. Bassuoni [3], Hagar Alm-Eldin Bastawissi [4], Saied I. Haiba [5]

[1] Mechanical engineering department, Faculty of Engineering, Pharos University in Alexandria, Alexandria, Egypt – Email medhat.elkelawy@pua.edu.eg
[2] Department of Mechanical Power Engineering, Faculty of Engineering, Tanta University, Tanta, Egypt – email: medhatelkelawy@f-eng.tanta.edu.eg
[3] Department of Mechanical Power Engineering, Faculty of Engineering, Tanta University, Tanta, Egypt – email: mahgoub.m@gmail.com
[4] Department of Mechanical Power Engineering, Faculty of Engineering, Tanta University, Tanta, Egypt – email: hagaralmeldin@f-eng.tanta.edu.eg
[5] Mechanical Power Engineering Departments, Faculty of Engineering, Tanta University, Tanta, Egypt – email: saied.haiba@f-eng.tanta.edu.eg

Corresponding author: Medhat Elkelawy, medhatelkelawy@f-eng.tanta.edu.eg

Abstract: This research addresses the environmental challenges posed by engine emissions, specifically carbon dioxide (CO2), a primary contributor to global warming. The study investigates the performance characteristics of internal combustion (SI) engines fueled by gasoline, compressed natural gas (CNG), and oxy-hydrogen gas (HHO) blends. Experiments are conducted using a Honda 4-stroke, single-cylinder, air-cooled SI engine. A fixed flow rate of HHO at 8 L/min is maintained while varying CNG concentrations from 0.5 to 2.5 L/min in 0.5 L/min increments. The setup includes an electrical loading board with ten 0.5 kW bulbs, managed by an 8 KVA Variac to control the load. Engine performance metrics assessed include brake specific fuel consumption (BSFC), brake thermal efficiency (BTE), exhaust emission factor, and exhaust gas temperature (EGT). At the optimal blend ratio of 0.5 L/min CNG, the weighted average brake thermal efficiency reached 22.47%, marking a 26.45% improvement compared to the 17.77% efficiency of gasoline alone. By integrating CNG and HHO, this work aligns with sustainability goals, as these cleaner fuels reduce carbon emissions, enhance fuel efficiency, and minimize the environmental impact. The optimized fuel blends demonstrate a strategic approach to achieving greater engine efficiency while supporting global efforts to combat climate change and promote sustainable energy solutions

Keywords: SI Engine; Gasoline/Compressed Natural Gas (CNG)/Oxy-Hydrogen Gas (HHO) blends; Engine Performance Optimization; Brake Thermal Efficiency (BTE

I. INTRODUCTION

As countries attempt to strike a balance between economic progress and the preservation of natural resources for future generations, environmental sustainability is one of the most important concerns facing the globe today [1-4]. Natural gas is essential in this situation since it is efficient and clean fuel, which can help lower harmful emissions and enhance air quality [5-10]. With their high emissions of carbon dioxide (CO2), nitrogen oxides (NOx), and particulate matter, conventional gasoline engines rank among the biggest contributors to environmental contamination. However, using natural gas as an alternate or supplemental fuel can increase these engines' efficiency and reduce their emissions [11-14]. When compared to gasoline, natural gas offers cleaner combustion characteristics, which lowers hazardous gas emissions and increases fuel economy[15-17]. Furthermore, using natural gas can lessen reliance on traditional fossil fuels, improving resource sustainability and reducing adverse environmental effects [18-22].

Fuel depletion and environmental pollution have made it more crucial than ever to improve internal combustion engine performance and emissions characteristics [23-29]. In order to improve combustion characteristics, various technologies have been created and implemented into engine fuel systems. Particularly, experimental studies have looked at how adding hydrogen affects a CNG (Compressed Natural Gas) engine's performance. The results show that adding more CNG to the blend lowers engine cyclic variance, mostly because of the shorter combustion time.

Furthermore, the addition of hydrogen enhanced combustion, which decreased emissions of CO and HC [30-33]. The findings also showed that, especially in lean and light load scenarios, adding CNG can improve engine thermal efficiency, reduce hazardous emissions, and minimize cyclic volatility. However, there are also issues with using CNG alone, like higher wear on parts like cylinder heads and valves if the engine isn't built to handle the extra heat. Additionally, the lack of lead can cause valve seat wear, and natural gas's poorer lubricating qualities can cause moving parts to wear down more quickly [34-37].

Therefore, in order to further enhance combustion and emissions performance in gasoline engines, it is important to develop and evaluate novel approaches for introducing CNG to cylinders [38-42]. With an emphasis on the financial and environmental advantages as well as the difficulties in putting this technology into practice, this study will investigate the connection between sustainability, the environment, and the use of natural gas in gasoline engines [43-47]. We'll also go over recent studies and research that show how using natural gas affects engine efficiency and dangerous gas emissions, as well as methods for making gasoline engines more environmentally friendly. Generally speaking, engine researchers use a variety of tactics to increase combustion efficiency or lower exhaust gas emissions [48-51].

In order to lower exhaust emissions, the first approach makes use of a new technology that modifies the engine somewhat. Such as recycling exhaust gases, adjusting the timing of valve opening or spark ignition, and using premixed charge compression ignition mode, among other modification approaches. Galindo et al. (2021) investigate how to optimize exhaust gas recirculation (EGR) and variable valve timing (VVT) in order to optimize the performance of a turbocharged direct-injection gasoline engine with a variable nozzle turbine (VNT). The work combines 1D engine simulations with experimental data from 25 studies to calibrate the model [52-55]. After that, 150 parametric simulations were conducted to optimize the VVT and EGR parameters in order to increase engine efficiency. The findings demonstrated that the updated VVT and EGR configurations significantly reduced fuel consumption and improved overall engine performance by reducing pumping and heat losses. The study also revealed that experimental data demonstrated that the best EGR (exhaust gas recirculation) rate was 28%, although modeling studies determined the ideal EGR rate to be 25% [56]. Elkelawy et al. (2023) investigate the effects of employing direct biodiesel injection in conjunction with diesel as a premixed charge on a CI-engine.

In order to enable the usage of biodiesel and diesel at the same time, a direct injection diesel engine had to be modified. Different combinations of diesel and biodiesel were made; diesel was mixed with air before going into the engine, while biodiesel was pumped straight into the combustion chamber. In addition to pollutants like NOx and particulate matter, performance parameters including power, torque, and fuel consumption were measured. When compared to utilizing diesel alone, the results showed that the biodiesel-diesel blend enhanced engine performance by lowering NOx and particle emissions. Furthermore, the biodiesel-diesel blend demonstrated more steady and efficient combustion, improving engine performance overall and lowering hazardous emissions [52].

The second approach is to switch from diesel to renewable energy sources such alcohols, hydrogen, algal oil, and biofuel. The performance and emissions characteristics of using biodiesel blends on a single cylinder, four-stroke diesel engine were investigated by Kasaby et al. (2013). The findings showed that B30 produced the least amount of CO, whereas B10 showed the highest BTE [57]. Abedin et al. (2016) investigated the effects of using biodiesel blends (B10 and B20) on engine performance, combustion, and emissions. They then compared their results to the engine's performance on B5 and diesel. Brake-specific fuel consumption (BSFC) rises by an average of 6% to 20% when using B5, B10, and B20 fuels. Diesel fuel produces more hydrocarbons and carbon monoxide than fuel blends B5, B10, and B20. Biodiesel mixed fuels have a 2.5%–3% higher NOX content than diesel fuels [7].According to recent studies by Abdu and Inambao (2018), ethanol and methanol have the potential to be used as an alternative fuel for SI engines because it shows significant emissions reductions when compared to pure gasoline. Torque, engine power, and fuel efficiency are generally improved by gasoline and ethanol blends, particularly when the engine is operating at a low speed [58-61]. Methanol and gasoline blends can improve brake thermal efficiency and reduce CO emissions, but they can also increase the quantity of fuel consumed for the brakes. Because the advantages of various blends vary based on the operating conditions and blend ratios, more fine-tuning is necessary.

All things considered, mixes of gasoline and alcohol are a practical means of enhancing engine performance while reducing environmental effect [62]. Kaya et al. (2021) investigated the performance, combustion, and emissions characteristics of a PCCI engine powered by pure diesel and diesel with biodiesel blended. Although it came at the expense of soot and BTE, they found that adding biodiesel decreased NOx emissions [63]. Elkelawy et al. (2022) conducted experiments to investigate the effects of using different biodiesel blends (B20, B40, B60, and B80) on the engine performance, combustion, and emissions characteristics using a single cylinder, four stroke, direct injection diesel engine running at a constant speed of 1400 rpm. It was discovered that increasing the proportion of biodiesel reduced BTE by 9.6%, CO and HC levels declined, exhaust gas temperature (EGT) decreased by 7.6%, and NOX concentration increased due to the high oxygen content of biodiesel [64-68].The effects of combining gasoline and oxy-hydrogen gas in spark-ignition engines are examined by Elkelawy et al. (2023). In the study, gasoline was pumped into the engine's air intake system along with oxy-hydrogen gas produced by electrolysis [69-71]. The results showed that adding oxy-

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hydrogen gas improved engine performance and reduced emissions by increasing combustion efficiency by 10%. Specifically, using oxy-hydrogen gas resulted in a more thorough combustion and an 18% decrease in NOX emissions, increasing fuel economy and reducing environmental impact [72-78].

Ruthvik Bathala et al. (2024) investigate the emission characteristics of gasoline-alcohol blends in motorcycles, focusing on both idle and revving conditions. According to the results of ANN modeling and experiments, some blends, such M55 and E55, significantly reduce NO and HC emissions, respectively, whereas engine speeds and higher alcohol concentrations increase CO2 emissions. The produced model shows good precision and minimal error variability. M15 to M50 for methanol-gasoline and E15 to E55 for ethanol-gasoline were the optimal mixtures for lowering emissions, according to TOPSIS. The development of a control algorithm and electronic injection system prototype is suggested by later study[79]. Sun et al. (2024) investigated the performance of a lean-burn natural gas spark ignition engine in the presence of hydrogen enrichment. It was discovered that adding hydrogen raised the combustion temperature, which enhanced flame propagation, increased NO and CO emissions, and significantly decreased HC and soot emissions[80].

The discussion above makes it evident that there has been a variety of prior research conducted on the effects of using dual fuel blends in engines on emissions characteristics, performance, and combustion. The goal of the current study is to observe the impact of adding HHO to five different CNG gasoline concentrations—"0.5-2.5 L/min CNG"—can improve Combustion process and engine performance and reduce exhaust emissions from SI engines. This study examines the effects of utilizing HHO-CNG-gasoline mixes on engine performance, emissions characteristics, and combustion of a 4-stroke, single-cylinder, air-cooled, SI engine. Additionally, the work's outcomes were applied to determine the ideal premixing ratio among the five ratios listed above, which will yield the best results when compared to the use of pure gasoline.

II. EXPERIMENTAL SET-UP

A. Introduction

Despite being the most widely used fuel in the automotive industry, gasoline still has low thermal efficiency because of its low octane number and is a limited supply, which forces researchers to concentrate on finding a more dependable substitute [81-83]. Therefore, a strategy to create multi-fuel mixes to enhance combustion and reduce emissions was developed in this work. The multi fuel blends were consisting of the gasoline itself, hydroxyl gas (HHO) and natural gas, and different concentrations of natural gas were tested to show the impact on the performance of the engine and the emissions [84-86]. This will be shown in detail in upcoming sections.

B. Measurements and Errors Analyses

In order to measure the engine's steady speed of 3000 rpm, a speed sensor was attached to the crank shaft in the current investigation [87-90]. The temperature was measured using three type K thermocouples: one at the air intake, one at the exhaust emission outlet, and one at the engine oil. The amount of intake air entering the engine is measured by an orifice system, and the pulsations produced by the suction stroke are stopped by a dampening tank. GASBOARD-5020 emission gas analyzer was used to monitor CO2, CO, O2, HC, and NO. NOX and HC were measured in parts per million, while CO2, CO, and O2 were approximated in percentage Vol [91-94]. Since it affects the measurement's limiting errors, the equipment's operating conditions and environment may affect its accuracy [95-97]. As a result, the uncertainty of the measured and computed values can be quantified using equations 1 and 2. The outcomes of the computations for the accuracy and uncertainty analysis of the different pieces of equipment are displayed in Table I.

Table I. Instrumentation features and unreliability

Instrument	Parameter	Accuracy	Range
Emission gas analyzer	CO2	± 4%	0-20%
	CO	± 1%	0-20%
	O2	± 3%	0-25%
	HC	± 5%	0-9999 ppm
	NO	± 5%	0-5000 ppm
CNG Flow meter	Gas flow meter	±1.5%	0.025 – 4 m3 /h
K-type thermocouple	Exhaust gas Temperature	±1%	0 to 800 ◦C
Gas Gauge Pressure	Gas pressure	±1.6%	0 to 2.5 bar.
Inclined manometer	Airflow rate	±2%	0–2.99 m3 /h
Graduated cylinder/stopwatch	Diesel flow meter	± 1 %	1 to 30 cm3
Load indicator	Load	±0.2%	1 to 1000 W

C. Experimental set-up

The experimental system's schematic diagram is shown in Fig. 1. Figs. 2 and 3 depict the experimental test rig from two distinct angles to assess the HONDA engine's combustion performance, which is frequently done. Additionally, the characteristics of CNG and gasoline are examined.

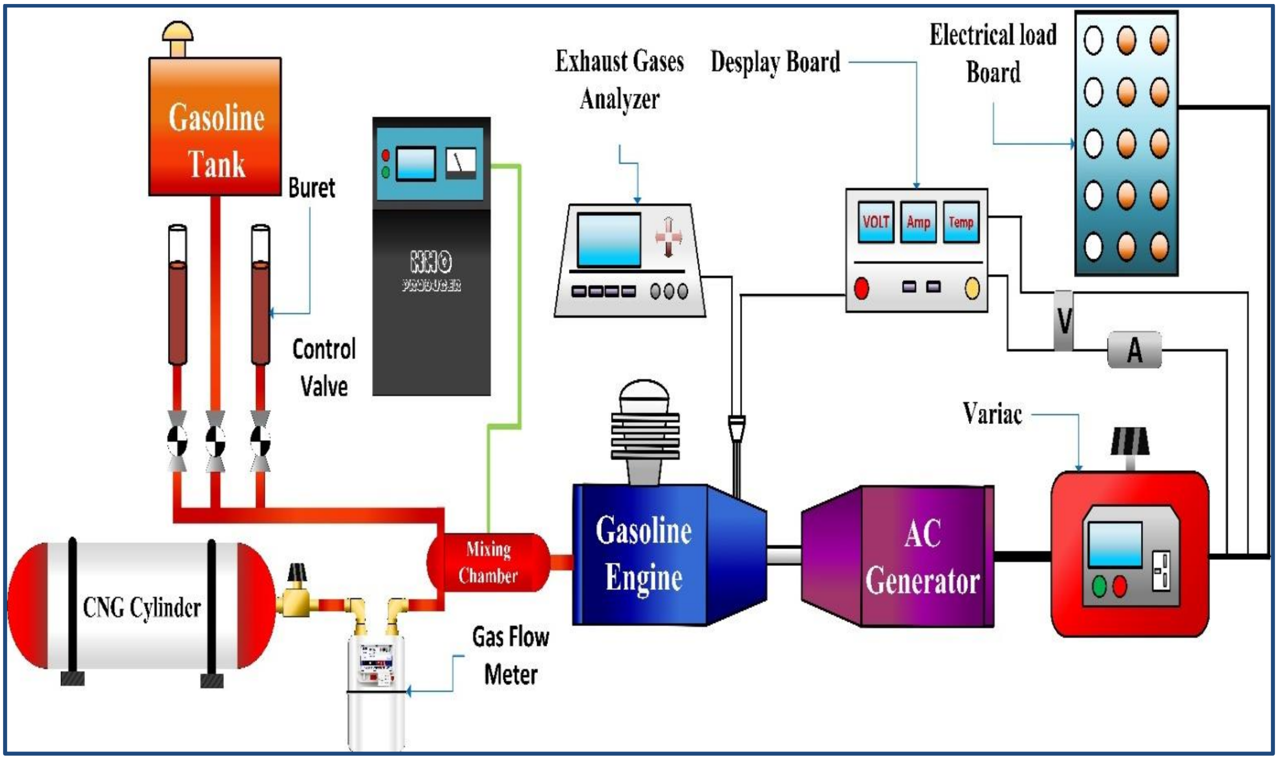

Fig. 1 Schematic diagram of experimental procedure

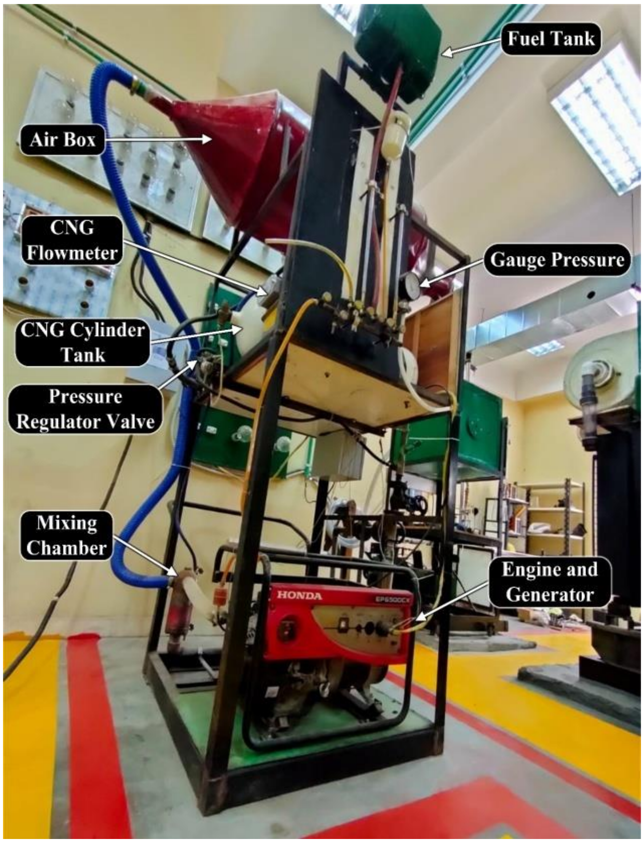

Fig. 2. test rig main view

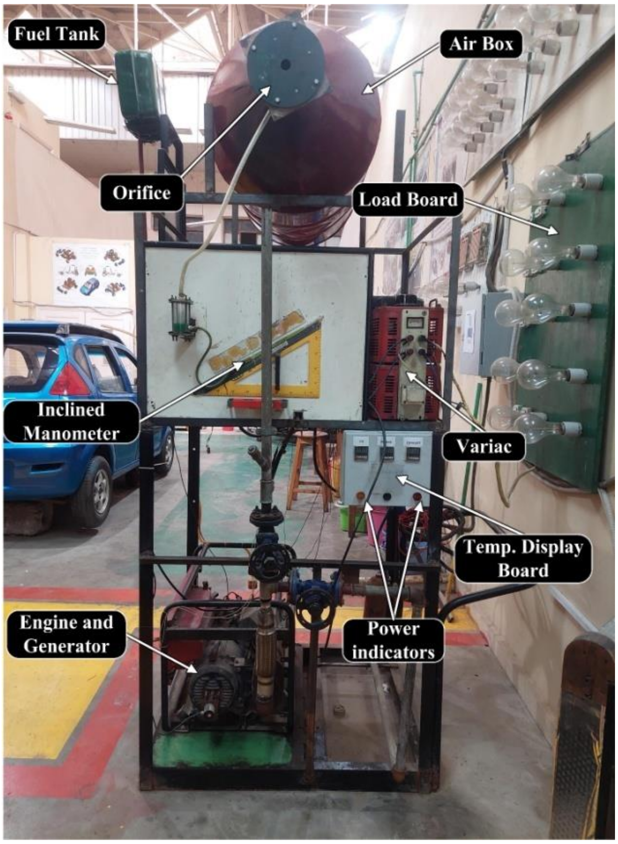

Fig. 3. test rig main view

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The engine with its generator, fuel system, and measurement devices makes up the experimental setup. For the combustion process, a four-stroke, single-cylinder, air-cooled engine is employed [98-101]. Table II lists the characteristics of the Honda commercial OHV engine and its generator.

Table II: Engine and Generator specification

Model Number	GX390
Max Alternating current Output	5.5KVA
Rated Alternating current Output	5.0KVA
Direct current Output(Generator/Charger)	8.3A
Type of generator	D-AVR
Method of Starting	Hand Cranking
Rated Frequency	50 (Hz)
Rated Voltage	240 (V)

An 8 L tank and seven gas valves to regulate the fuel flow rate make up the fuel system (Fig. 4). In the experimental work, several concentration mixtures of gasoline and CNG fuels are used [1, 102, 103]. The primary fuel in all blends is gasoline. The characteristics of the fuel utilized in the trials are listed in Table III.

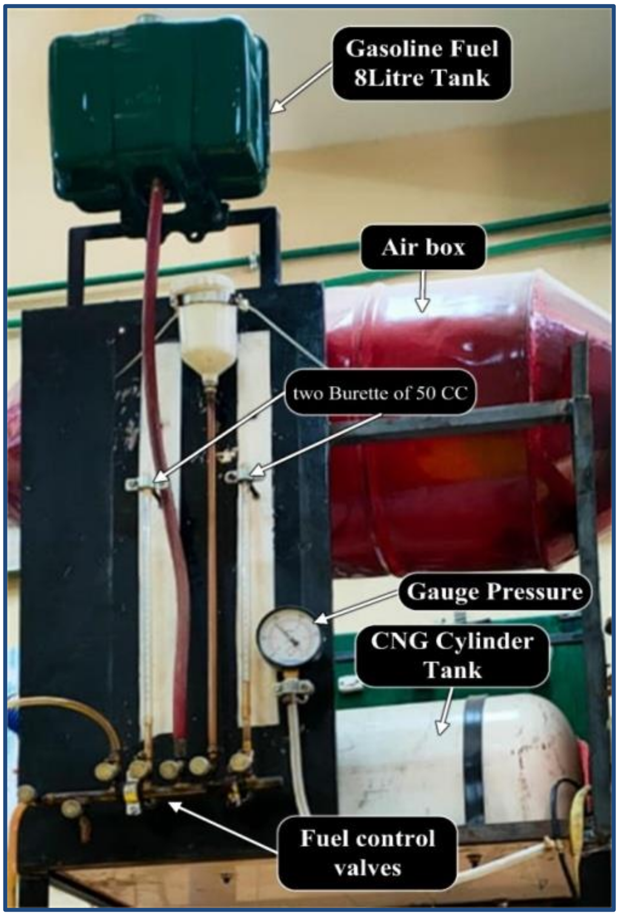

Fig. 4. Fuel measurement and control system

Table III. Physiochemical properties of gasoline vs CNG

Description	**Gasoline (H/C=1.87)**	**CNG (H/C=4)**
Molecular weight(g/moll)	~109	~17.3
Stoichiometric (A/F)s mass	14.7	17.2
Octane/Cetane number	~92	~125
Stoichiometric mixture density (kg/m3)	1.42	1.25
Lower heating value(MJ/kg) (assumes steam is produced)	43.5	47.5
L.H.V. of stoichiometric mixture (MJ/kg)	2.85	2.62
Flammability limit in air (vol% in air)	1.4-7.6	4.3-15.2
Flame propagation speed (m/s)	0.5	0.41
Adiabatic Flame Temp. (1C)	2150	1890
Combustion Energy (MJ/m3)	42.7	24.6
Auto-ignition Temp(1C)	258	540

In the experimental work, the load comes on and varies by an electrical loading board. The board consists of ten lamps of 0.5 KW and 8 KVA variac. The load is increased by 25% step to reach the full load (0, 25%, 50%, 75%, and 100%).

The experimental procedure is done as follows for each blend of the fuels:

- The engine starts for 15 minutes using pure gasoline only in the aim of preheating.
- The quantity of hydrogen and compressed natural gas (CNG) gas supplied to the engine is measured and controlled by flow meters.
- For each load (0, 25%, 50%, 75%, 100%) the engine was left to reach the steady operation state, approximately 10-15 mins for each case.
- The fuel consumption and exhaust gases are recorded for each load upon each blend.

This process is carried out five times for each combination. Five different CNG concentrations were investigated, ranging from 0.5 to 2.5 L/min with a 0.5 L/min step increase. At a rate of 8 L/min, the amount of hydrogen is constant throughout the experiment.

To talk about the properties of SI combustion using mixes of natural gas, hydrogen, and gasoline. The "HONDA" 4-stroke, single-cylinder, air-cooled SI engine that was modified to run on SI combustion mode was used for the experiments. Figs. 1, 2, and 3 depict the schematic diagram and the actual illustration of the SI engine's contents from two different perspectives, respectively. The engine was used in the experiments so that the engine load was the only variable. The temperature of the lubricating oil is almost constant at 90°C.

The purpose of the test rig was to examine the engine's emissions and performance. A SI engine, a natural gas cylindrical tank, an air box with an inclined tube manometer, a 5KW load board with a 10KVA variac to regulate the load, a measuring board for gasoline consumption, an emission gas analyzer, and sensors for temperature and load measurement make up the test rig. The unit that generates hydrogen is detached.

The experimental procedure for all mixes involved starting the engine, preheating it with pure gasoline for 15 minutes, and then adding the appropriate amount of CNG to the air stream at the mixing chamber together with hydrogen. The carburetor, which absorbs the appropriate amount of fuel for the load, is where the entire combination is going. To reach the full load, the load was increased by 25% at intervals of 0, 25%, 50%, 75%, and 100%. The engine was given ten to fifteen minutes to reach the steady functioning state for each load. Pure gasoline and a certain quantity of CNG were used to create the blend composition in each instance. A range of CNG concentrations were evaluated, with a 0.5 L/min step increase between 0.5 and 2.5 L/min. Eight L/min of hydrogen was the only quantity tested. The check valve is used to prevent backflow behind the CNG bottles. CNG is routed to the regulator via an ex-proof pipeline after passing past the check valve. When a mixing chamber is employed before the intake manifold, the constituents (CNG, HHO, and air) are combined very efficiently. As a result, pollutants are reduced, engine stability is improved, and fuel efficiency is raised. The amount of compressed natural gas (CNG) supplied to the engine is measured and controlled by the flow meters, as seen in Fig. 2. Intake-air, engine oil, and exhaust temperatures were monitored, along with the amount of gasoline fuel used and the emissions of exhaust gasses. The voltage and current of the variac's output were used to measure the load.

III. Results and Discussions

This section compares the performance of five gasoline, HHO, and CNG blends against that of pure gasoline. In addition to the proportion and temperature of exhaust gas emissions, the parametric indicators of engine performance include brake thermal efficiency and brake specific fuel consumption.

Engine performance is studied by the following statistics, which show the engine exhaust gas temperature, brake-specific fuel consumption, and engine thermal efficiency under different engine loads at a constant speed of 3000 rpm.

A. Brake thermal efficiency-BTE

Brake thermal efficiency, one of the most important engine parameters, is the quantity of chemical energy converted from fuel into useful work. The brake thermal efficiency is displayed in Fig. 5. At full load, the maximum efficiency of the CNG mixes 0.5, 1.0, 1.5, 2.0, and 2.5 is 25.1%, 24.3%, 23.1%, 23.0%, and 22.0%, respectively, compared to 21.1% for gasoline. Additionally, over the load power range of 0-5.3 KW, the average efficiency of the same blends are 21.60%, 20.88%, 19.84%, 19.76%, and 18.81% compared to 17.64% for gasoline.

In contrast, the inclusion of compressed natural gas often raises the octane number of fuel mixtures, and the presence of hydrogen enhances the combustion process, thus the efficiency of all blends is boosted. As shown in Fig. 5, gasoline with 0.5 L/min of CNG performs the best, differing from gasoline by 22.45%. The efficiency of a blend of 1.0 to 2.5 L/min is lower than that of a blend of 0.5 L/min because of the high concentration of CNG, which dominates the combustion process rather than gasoline. Furthermore, the CNG flame's combustion process burns slowly and tends to finish outside the exhaust manifold's combustion chamber. Additionally, the temperature of the exhaust gases yields high values as a result of that.

B. Brake specific fuel consumption (BSFC)

Brake specific fuel consumption, or BSFC, is the amount of gasoline required to generate one unit of brake power and is based on the calorific value of the fuel. The figure demonstrated that, due to enhanced energy controllability and better combustion quality, a higher load under all operating conditions results in a lower BSFC. Additionally, the chart indicates that the 0.5 L/min CNG blend was the optimal combination for BSFC.

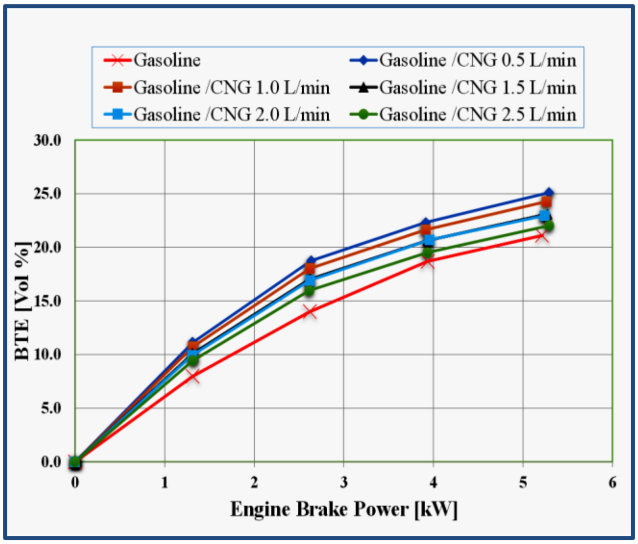

Fig. 5. The fluctuation of BTE under different load scenarios

C. Exhaust gas temperature-EGT

The temperature of exhaust gases is a crucial metric since it serves as a gauge for the engine's thermal stresses by indicating both the temperature of combustion and the amount of heat lost from the exhaust gases. Fig. 7 shows the change in engine exhaust gas temperature with engine load for various blend ratios of gasoline and CNG.

In the case of 0.5 L/m, this small amount of natural gas (CNG) likely led to an increase in the octane number of blend and improved brake thermal efficiency. However, the decrease in exhaust gas temperature with the increase in the rate of natural gas can be explained by several factors. One of the main reasons is that natural gas contains a higher percentage of hydrogen compared to gasoline. The combustion of hydrogen produces larger amounts of water (water vapor).

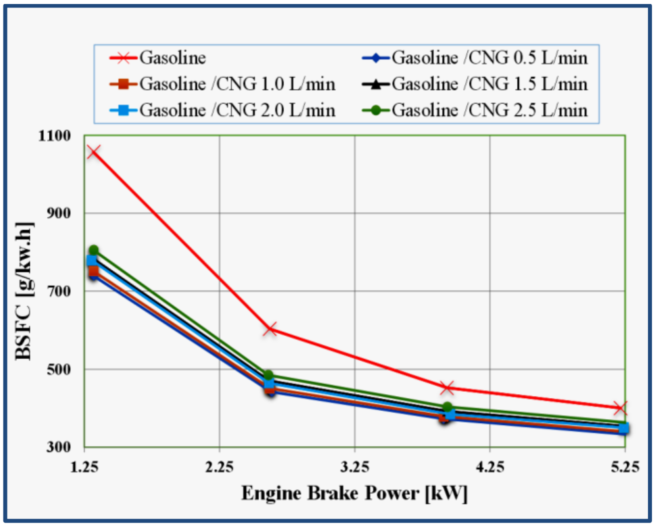

Fig. 6. The fluctuation of BSFC under different load scenarios

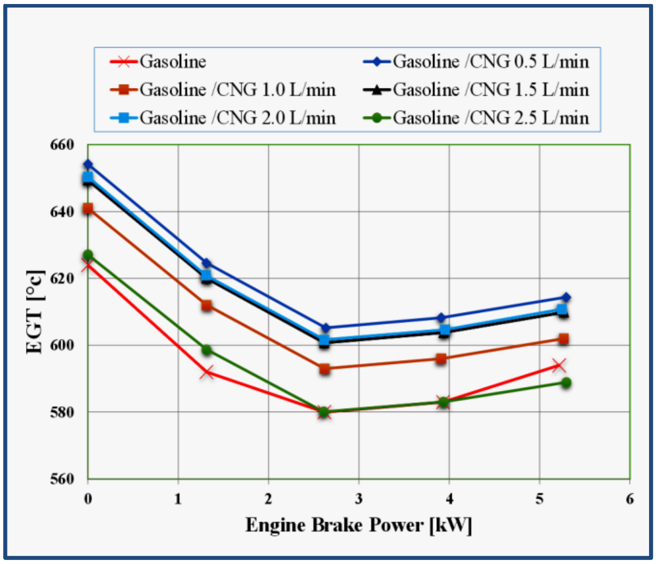

Fig. 7. The fluctuation of EGT under different load scenarios

The impact of feeding a gasoline engine with CNG and HHO on emissions of carbon monoxide (CO), carbon dioxide (CO2), nitrogen oxide (NOx), and unburned hydrocarbon (HC) is depicted in Figs. 8, 9, 10, and 11.

D. Carbon monoxide

Given that carbon monoxide is a toxic and combustible gas, it is a crucial characteristic. Because of the low combustion temperature and low oxygen level, incomplete combustion results in partial oxidation of carbon, which determines the CO concentration. As shown in fig. 8, the gasoline-to-CNG ratio of the blends has a considerable impact on CO. The figure demonstrated that CO emissions rise for all operational scenarios as load increases due to oxygen shortage compared to fuel. Natural gas burns more efficiently, reducing incomplete combustion that produces CO. Natural gas has higher hydrogen content, requiring less oxygen for complete combustion. This result in less CO produced so for all blends; CO concentration is reduced compared to gasoline. The least CO concentration is for 1.5 L/min CNG blend (0.73%).

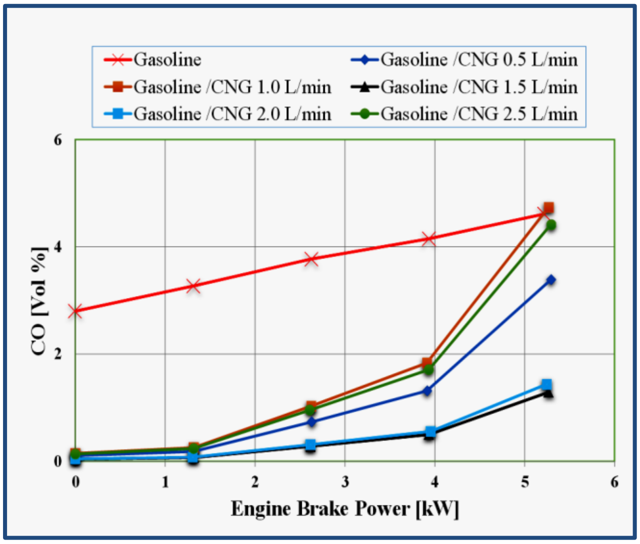

Fig. 8. The fluctuation of CO under different load scenarios

E. Carbon Dioxide

As shown in Fig. 9, the air-to-fuel ratio of the blends has a considerable impact on CO2; therefore, utilizing a blend of CNG gas lowers the amount of CO in the exhaust since it uses less gasoline. Also, the better the quality of the combustion process, the greater the efficiency, and the higher the concentration of CO2 in the exhaust. Therefore, we find that the highest concentration of CO2 is found in 0.5 L/min CNG blend.

F. Oxides of nitrogen

The NOx emission is greatly influenced by the temperature of the combustion chamber, the residence duration of the combustion, and the oxygen supply. The impact of brake power on NOx variation for gasoline and CNG combinations is shown in Fig. 10. The figure illustrates how an increase in engine load always results in a rise in NOx emissions from the exhaust because it raises the temperature of the combustion chamber. The combustion chamber's internal processes are neither consistent nor uniform throughout. Complete combustion and plenty of air produce nitrogen oxides and high temperatures in some places. In other places, the fuel to air ratio is higher, which produces carbon monoxide and other byproducts of incomplete combustion. Temperatures and gas ratios measured from the exhaust gases are only averages of the different things that happened inside the combustion chamber.

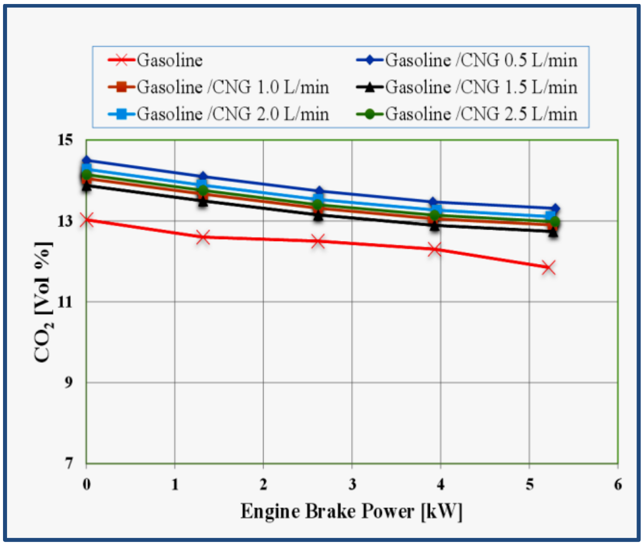

Fig. 9. The fluctuation of CO2 under different load scenarios

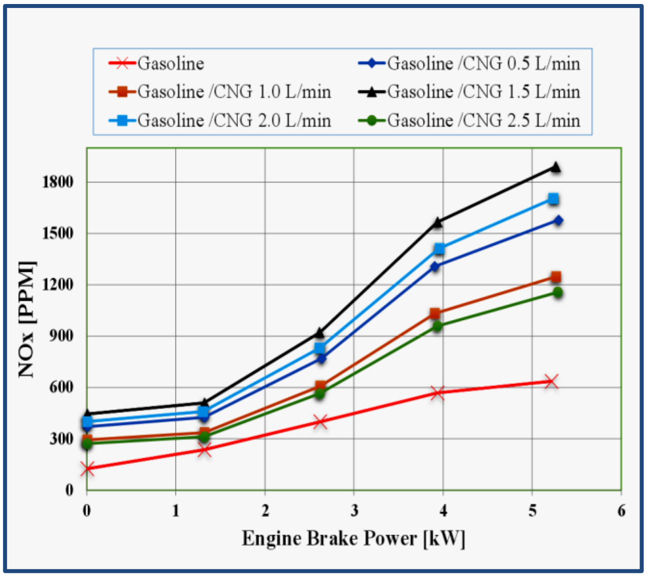

Fig. 10.The fluctuation of NOx under different load scenarios

G. Unburned hydrocarbons-UHC

Unburned hydrocarbons are the result of uncompleted combustion of the fuel stuck in the gap volumes, an excessively lean or rich mixture, and liquid wall wetting. The engine's variations in HC emissions when running on gasoline, HHO and CNG blends are shown in Fig.11. Because full combustion increases the temperature and effectiveness of the combustion process, an increase in HC emissions was seen in all operating scenarios as the load increased. As the graph illustrates, the HC ratio typically rises with load because of the relative lack of fuel against air as load increases.

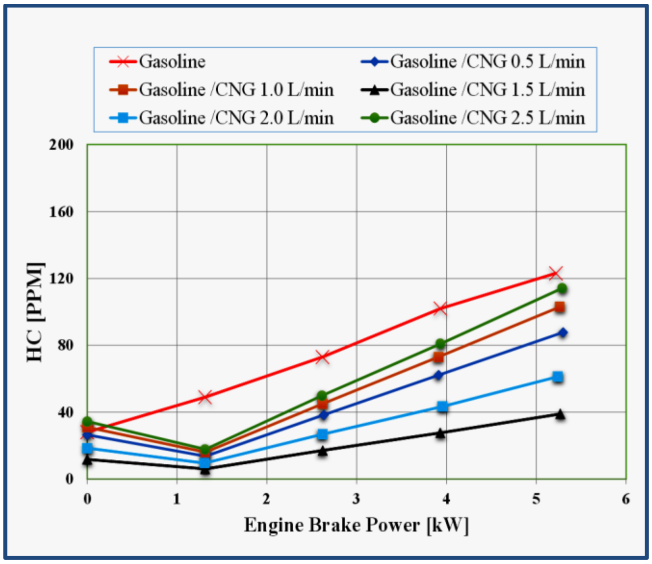

Fig. 11. The fluctuation of HC under different load scenarios

IV. Conclusion

In lab experiments, the performance and emissions of an experimental engine powered by an air-cooled, 4-stroke, and OHV single cylinder Honda commercial OHV engine have been analyzed. The intake manifold combines natural gas, hydroxyl gas and fresh air. The gas analyzer was used to sample and measure exhaust gas concentrations.

The experiments yielded the following conclusions:
The use of CNG-HHO blends with gasoline has generally led to an increase in thermal efficiency.

- The optimal blend ratio was 0.5 L/min, which resulted in a 22.45% gain in average thermal efficiency, raising it to 21.6% from 17.64% for gasoline.
- The average carbon monoxide ratio decreased in all blends compared to gasoline.
- • Compared to gasoline at 4.17%, the optimal blend ratio for generating the lowest carbon monoxide percentage was 1.5 L/min, yielding an average of 0.73%, an improvement of 82.5%.
- The average unburned hydrocarbons concentrations decreased in all blends compared to gasoline.
- • The optimal blend ratio for achieving the lowest quantities of unburned hydrocarbons was 1.5 L/min, yielding an average of 28 ppm, which was 71.72% better than gasoline's 99 ppm.
- The drawbacks of using CNG-HHO blends with gasoline are the increase in nitrogen oxides (NOx) concentrations in the exhaust gases. Since in all combinations, the concentration of NOX increased compared to gasoline.

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CONFLICTS OF INTEREST:

The authors do not have any conflict of interest.

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