Experimental based comparative exergy analysis of a spark-ignition Honda GX270 Genset engine fueled with LPG and syngas

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Abstract
The present study investigates three different fuels such as gasoline, liquefied petroleum gas (LPG), and syngas in spark-ignition Honda GX270 Genset engine under wide-open throttle position on its performance, combustion characteristic as well as availability analysis. The results showed that when the engine operated with gasoline fuel, the brake thermal efficiency was higher than that of LPG and syngas by 6.2% and 7.4%, respectively, throughout the engine load condition. Brake-specific fuel consumption of the engine with syngas (660 g/kW h) and LPG fuel (812 g/kW h) was higher than that of the gasoline fuel (510 g/kW h) at the 4.5 kW of engine load. The engine emission results showed syngas operation caused a significant reduction in NOx by 58.4%, CO by 16.5%, HC by 23.2% compared to gasoline fuel at peak load conditions. On the other hand, exergy analysis concludes the exergy efficiency for all the test fuels increases with an increase in engine load due to a high rise in shaft output. At a 4.5 kW power output, the exergy efficiency of the engine was improved to 46.45% from 45.62% and 29.73% with syngas, gasoline, and...
1 | INTRODUCTION

The use of alternative fuels in internal combustion (IC) engines have received much interest nowadays due to the dramatic increase in fuel costs and strict emission regulations. Various alternative fuels for IC engines have already existed, almost from the invention of automotive vehicles. In general, gaseous fuels are the most promising alternatives to gasoline engines due to their high heating values, high octane numbers, lesser harmful emissions, and reasonable costs. Gaseous fuels like liquefied petroleum gas (LPG) and compressed natural gas are commonly used in commercial vehicles over the last decade, showing promising outcomes in the case of fuel efficiency and exhaust emissions. Part from the commercial vehicle engines, these alternative fuels like LPG and hydrogen can also apply to stationary engines used for electrical power generation purposes. Besides, fuels like syngas produced from the gasification process with lower calorific value can be used as an alternative for stationary engines. Syngas is normally derived from a feedstock containing carbon such as biomass by the gasification process. It mainly consists of carbon monoxide (CO), natural gas, hydrogen, carbon dioxide (CO₂), and nitrogen. Syngas is a low-carbon, clean-burning fuel, and renewable in nature. Since the stationary engines will idle in position, the syngas production unit’s implementation in the nearby stationary engine space could be easy and inexpensive compared to automotive engines. Among the various gaseous alternative fuels, LPG, and syngas appear to be the most promising alternatives for stationary gasoline engines. This could be attributed to its powerful ignition characteristics combined with relatively lower emissions. Also, the syngas-powered engines pay better octane values, higher self-ignition temperatures, greater combustion efficiency, and faster flame propagation capabilities, making them valuable alternatives.

However, a detailed assessment of energy and exergy analysis on LPG/syngas-fueled spark ignition (SI) engines is limited in past literature studies. Most of the research in this area only focused on the LPG/syngas-fueled engines’ emissions and performance behavior. However, energy and exergy analyses are necessary to optimize the performance of LPG/syngas-fueled engines.

IC engines’ energy efficiency, also known as first law efficiency, cannot predict the best possible performance in it. However, the second law efficiency or exergy efficiency can provide energy efficiency deficiency as it considers both the system and its environment. Exergy or availability analysis is performed on the IC engines to determine the maximum possible work output from a given fuel energy input. In an availability analysis, sources of irreversibilities are identified and minimized to increase the IC engine efficiency.

Numerous studies were carried out on availability analysis in both SI and compression ignition (CI) engines. Using LPG in a SI engine, the authors have found through exergy analysis that destruction availability was minimum for a lower bore-to-stroke ratio operation. Dhyani and Subramanian reported that combustion irreversibilities were reduced in gasoline and hydrogen-fueled multicylinder SI engine. A similar kind of numerical work by Rakopoulos and Michos reported the reduction of irreversibilities due to the addition of hydrogen in a biogas-fueled single-cylinder SI engine. It has supported another work explaining the increase in the engine’s exergy efficiency. With the addition of hydrogen, there is an increase in the in-cylinder temperature and a decrease in entropy generation. A similar type of modeling work was reported by Ismail and Mehta. They have concluded that the availability destroyed during the chemical reaction was the major source of combustion irreversibility. Some researchers have carried out availability analysis by varying engine design and operating parameters with methane/hydrogen-fueled SI engines. Caton et al. found almost the same combustion irreversibility with varying load in a multicylinder SI engine in their works. However, the engine parameters like equivalence ratio, amount of oxygen during suction affected the combustion irreversibility. The authors found a similar observation type with equivalence ratio in hydrogen injected fueled single-cylinder SI engine. The researchers found a reduction in the pumping loss under part-load operations of the hydrogen–methane SI engine.

In another work in a turbocharged hydrogen SI engine, the researchers have observed that the exergy efficiency was increased with increasing speed and load conditions. At the stoichiometric condition, the
SI engine gave the best trends of the availability components. But, these trends have deteriorated with higher combustion duration. A similar type of trend was found in numerical analysis by the researchers in a single-cylinder direct-injection hydrogen-fueled SI engine. In a different type of exergy analysis, the authors have found the irreversibility associated with chemical reaction was reduced due to higher flame temperature and oxygen addition. Also, it was observed that combustion irreversibility was decreased by reducing the combustion temperature by fuel–air staging and air preheating methods.

It is clear from the above that hardly any literature is accessible on availability analysis with LPG-fueled SI engines. Although some literature discussed neat or blended hydrogen-fueled SI engines, no previous work analysis is available on using syngas in SI engines. Therefore, this study tried to fulfill the research gaps in which an availability analysis has been performed on an LPG- and syngas-fueled single-cylinder SI engine as a function of engine load. For the evaluation purpose, the availability analysis of LPG and syngas has been compared to the gasoline performance. The compared analysis will assist the engine designer to develop a better LPG or syngas run SI engine.

## 2 EXPERIMENTAL DETAILS

### 2.1 Test engine setup with the fuel supply system

The test engine used for the experimentation is a Honda (GX270 model), single-cylinder, four-stroke, air-cooled, stationary gasoline SI developing power of 4.6 kW at the rated speed of 3000 rpm. The fuel (gasoline and LPG) properties were shown in Table 1 and the syngas composition was displayed in Table 2. The test engine's technical specifications are provided in Table 3, and the schematic arrangement of the experimental setup is displayed in Figure 1. A high-pressure cylinder (150 bar) was used to supply hydrogen, which was then reduced to 1.5 bar using a pressure regulator. LPG fuel was supplied to a test engine through a high-pressure (130 bar) cylinder by reducing the pressure to 1.5 bar using a pressure regulator. LPG fuel was transmitted through a precise pressure relief valve to control the flow rate, followed by a gas flow meter that measured LPG flow in liters. Then LPG is supplied through a nonreturn valve, which prevents the backflow of hydrogen. To avoid explosions in the LPG supply line, fuel was passed through the flame arrestor to the engine. The LPG was then passed across a flame trap, which will be used to prevent flashbacks in the inlet manifold. As a safety precaution, the flame trap's exterior was equipped with a polythene diaphragm. This diaphragm will break in the case of any serious flashback by preventing any rise in pressure that would cause the cylinder to explode. Then LPG fuel was supplied to the engine through a gas carburetor mounted in the intake manifold from the flame trap. With the same arrangement, syngas was supplied to the engine separately. Syngas supply was made with five different cylinders that contain a different composition of gases. Five different cylinders containing CH₄, CO, H₂, N₂, and CO₂ were brought together to form a syngas mixture. The gas pressure regulator was connected to all the cylinders to control the pressure in the supply line. Polyurethane tube has been used to bring in gases from pressure regulators to rotameters at a line pressure of 1 bar. Rotameters are put in to adjust the flow rate and have a fine control needle valve that can cater to alterations in syngas composition. Output gases from the rotameter have been taken to the mixing volume chamber. With proper mixing of gases to achieve syngas composition, the gases can exit the mixing volume chamber and enter the buffer box. From the buffer box, the gas goes to the flow meter. From the flow meter, the

| Properties                  | Gasoline | LPG Propane | LPG Butane |
|-----------------------------|----------|-------------|------------|
| Density (kg/m³)             | 765      | 509         | 585        |
| Lower heating value (MJ/kg) | 44.04    | 46.34       | 45.56      |
| Auto-Ignition temperature (°C) | 257  | 510         | 490        |
| Flame temperature (°C)      | 1720     | 1980        | 1775       |
| Flame speed (m/s)           | 0.35     | 0.4         | 0.4        |
| Stoichiometric air/fuel ratio (kg/kg) | 14.7:1 | 15.8:1      | 15.6:1     |
| Octane number               | 95       | 111         | 103        |

Abbreviation: LPG, liquefied petroleum gas.
syngas mixture was supplied into the engine through the gas carburetor.

### 2.2 Instrumentation

Eddy current dynamometer with a rated power out of 15 kW was used to measure the test engine’s power output. The exhaust gas constituents, such as NOx, HC, CO, and CO₂ were measured by an AVL (Di-gas-555) make exhaust gas analyzer. The analyzer generally works on the principle of NDIR to measure CO and CO₂ gases, whereas the electrochemical principle was employed to measure NOx emission. A Kistler makes a pressure transducer, and the charge amplifier was used to measure the in-cylinder pressure. LPG and syngas mixtures’ flow rate was measured and controlled by a mass flow rate controller.

### 2.3 Methodology

The investigation was made to study the performance, combustion, and emission characteristics of the Honda (GX270 model) gen-set SI engine in three phases. Initially, in the first phase of work, the test engine operated with gasoline fuel under various load conditions. Throughout the engine testing, the throttle position is fixed to operate under a wide-open throttle position. Spark timing was optimized for the maximum brake torque and brake thermal efficiency (BTE) of an engine. The optimized BTE value was 27.0% for wide-open throttle conditions at peak load. Next, in the second phase, the engine intake manifold was modified by incorporating a specially designed gas carburetor to operate with an LPG fuel. For various load conditions, an experiment was carried out using LPG as fuel. The properties of gasoline, LPG, and syngas fuel are presented in Table 2. Five cylinders containing CO, H₂ (hydrogen), CO₂, CH₄ (methane), and N₂ (nitrogen) were brought together to form a syngas mixture. In the third phase of work, syngas (CH₄—5%, N₂—30%, CO—15%, H₂—40%, CO₂—10%) on a volume

| TABLE 3 Technical specification of the test engine |
|---------------------------------|-----------------------------|
| **Manufacturer**                | Honda                      |
| **Model**                       | (GX270) Genset engine      |
| **Engine type**                 | Single cylinder, gasoline-fueled, four-stroke, air-cooled |
| **Bore and stroke**             | 77 and 58 mm               |
| **Compression ratio**           | 8.5:1                      |
| **Spark timing**                | 27° before TDC @ MBT       |
| **Speed**                       | 3000 rpm                   |
| **Rated power**                 | 4.7 kW                     |
| **Engine capacity**             | 270 CC                     |
| **Loading device**              | Eddy current dynamometer   |

Abbreviation: MBT, maximum brake torque.
basis (Table 3) was supplied through the gas carburetor to the engine and investigated on the test engines emission and combustion behavior.

2.4 | Uncertainty analysis

Accurate calibration with ideal atmospheric conditions would be extremely vital when using precision measurement instruments for consistency. Uncertainty analysis provides an extensive view of experimental reproducibility by calculating appropriate errors during testing. The experimental uncertainty analysis evaluates performance and emission variable measurement errors due to the experiment technique, observation precision, calibration, and instrumentation used in given atmospheric conditions. Uncertainty research identifies two main elements: repetitive measurement random deviation and the other is precision bias. Estimation of the uncertainty percentages of different engine output parameters such as brake-specific fuel consumption (BSFC), speed, BTE, oxides nitrogen, hydrocarbon (HC), and CO was done and revealed in Table 4. The overall uncertainty is shown in Equation (1).

\[
\text{Overall uncertainty of the experiments} = \sqrt{(\text{BTE})^2 + (\text{BSFC})^2 + (\text{speed})^2 + (\text{CO})^2 + (\text{HC})^2 + (\text{NO})^2 + (\text{pressure transducer})^2} \\
= \sqrt{(0.5)^2 + (0.5)^2 + (0.2)^2 + (0.25)^2 + (0.5)^2} \\
= \pm1.70\%.
\]

The experimental uncertainty was determined to be ±1.70% after evaluating the uncertainty values of equipment used in the experimentation. The above value is clearly within the appropriate range of uncertainty, that is, less than ±5.0%.

3 | AVAILABILITY ANALYSIS

The availability (exergy) analysis refers to the capability of the useful work output or availability of a system. It can predict the maximum quantity of useful work accessible by a system in equilibrium with the environment. In an IC engine, chemical availability is the availability input \( (A_{\text{input}}) \) by the fuel.

Availability input of gasoline,

\[
A_{\text{input}} = \left[ 1.0338 \times \left( \frac{\dot{m}_{\text{gasoline}}}{3600} \right) \right] \times LHV_{\text{gasoline}}, \text{ kW}
\]  

where 1.0338 is a constant for liquid gasoline fuel.\(^3^4\)

Availability input of LPG\(^3^5\)

\[
A_{\text{input}} = \left[ 0.95 \times \left( \frac{\dot{m}_{\text{LPG}}}{3600} \right) \times HHV_{\text{LPG}} \right], \text{ kW}
\]  

Availability input of syngas,\(^3^6\)

\[
A_{\text{input}} = \left[ 0.985 \times \left( \frac{\dot{m}_{\text{syngas}}}{3600} \right) \times LHV_{\text{syngas}} \right], \text{ kW}
\]

\(A_{\text{input}}\) is transformed into various availability forms.

| Instruments | Range | Accuracy | Uncertainties (%) |
|-------------|-------|----------|-------------------|
| AVL −555 DI-Gas Exhaust gas analyzer | NO 0–5000 ppm | ±50 ppm | ±1.5 |
| | CO 0%–10% | ±0.03% | ±0.25 |
| | HC 0–10,000 ppm | ±20 ppm | ±0.50 |
| AVL GH14d/AH1 pressure transducer | 0–200 bar | ±0.1 bar | ±0.25 |
| Exhaust gas temperature sensor | 0–1000°C | ±1°C | ±0.30 |
| Speed sensor | 0–10,000 rpm | ±10 rpm | ±0.20 |
| Buret measurement | 0–100 cc | ±0.1 cc | ±1.5 |
| Digital watch | | ±0.5 s | ±0.25 |
| AVL 365C crank angle encoder | 0–720° | | ±0.20 |
| Calculated BTE | | | ±0.50 |
| Calculated BSEC | | | ±0.50 |
Shaft availability,

\[ A_{\text{shaft}} = \text{Brake power output, kW} \quad (5) \]

Availability lost to cooling water,

\[ A_{cw} = Q_{cw} - [(\dot{m}_w/3600) \times C_{pw} \times T_0 \times \ln(T_2/T_1)], \text{ kW} \quad (6) \]

In the present work, the IC engine was an air-cooled one. Hence, \( A_{cw} \) is not considered in the availability analysis.

Availability lost to exhaust gasses,

\[ A_{eg} = Q_{eg} + [(\dot{m}_{eg}/3600) \times T_0 \times (C_{peg} \ln[T_a/T_3] - R_{eg} \ln[P_a/P_{eg}])], \text{ kW} \quad (7) \]

where \( R_{eg} \) is the gas constant for exhaust gas, \( P_a \) is the atmospheric pressure, and \( P_{eg} \) is the exhaust gas pressure.

Destroyed availability,

\[ A_{\text{destroyed}} = [A_{in} - (A_{\text{shaft}} + A_{cw} + A_{eg})], \text{ kW} \quad (8) \]

Exergy efficiency (also known as second law efficiency) helps to distinguish between energy utilization and useful energy.

Exergy efficiency,

\[ \eta_H = \frac{\text{Availability covered}}{\text{Availability input}} = 1 - \frac{\text{Availability destroyed}}{\text{Availability input}} \]

\[ \text{that is, } \eta_H = 1 - \frac{A_{\text{destroyed}}}{A_{in}}. \quad (9) \]

4 | RESULTS AND DISCUSSION

In this section, performance and emissions parameters such as BTE, BSFC, CO, nitric oxide, unburned HCs, CO\textsubscript{2} are discussed for all the test fuels (gasoline, LPG, and syngas). Apart from these, combustion characteristics like in-cylinder pressure, heat release rate, and peak mean gas temperature were discussed. Next, a detailed study on availability analysis was discussed in this section to examine the heat balancing in an engine under three different fuels.

4.1 | Performance parameters

4.1.1 | Brake thermal efficiency

The deviation of BTE depending on different engine load conditions for gasoline, LPG, and syngas fuels under WOT conditions was shown in Figure 2. From viewing the figure, it is evidently stated that the maximum BTE was obtained as 27.0\% for gasoline at 4.5 kW engine load, whereas at the same engine load condition, the BTE of LPG and syngas fuels were get reduced, and it is noted to be 25.0\% and 22.8\%, respectively. This reduction in BTE with LPG and syngas fuels is due to the reduction of flame speed of gaseous fuels. Syngas gas mode achieved lower BTE due to further reduction in the combustion speed due to a mixture of several gases.\textsuperscript{37}

4.1.2 | Brake-specific fuel consumption

Under WOT position, the variation of BSFC according to different engine load conditions for gasoline, LPG, and syngas fuels was depicted in Figure 3. It was observed from the figure that the BSFC for LPG and syngas fuels were increased at all the engine loads compared to gasoline fuel. At the maximum engine load of 4.5 kW, the BSFC value for LPG and syngas fuel were noted to be 812 and 660 g/kWh, respectively, while it was 510 g/kWh for gasoline. From the property shown in Table 1, it was noted that the heating value of syngas and LPG fuel was lower than gasoline fuel. Hence the energy required for syngas and LPG for producing the same power output produced by the gasoline fuel is more.\textsuperscript{38}
This indicates more amount of syngas and LPG fuel must be utilized to attain the same power. The reduction in volumetric efficiency of an engine under syngas and LPG fuel operation leads to an increase in fuel consumption. At higher loads, the presence of 40% H₂ in syngas mode produced lower BSFC than the LPG mode due to better combustion.

4.2 | Emission parameters

4.2.1 | Oxides of nitrogen (NOx) emission

In general, the formation of NOx emission in the SI engine is primarily due to higher chamber temperature development. With the help of the temperature as mentioned above and oxidation of nitrogen molecules available in the inducted air mixture, it will result in NOx formation. Figure 4 demonstrates the change of NOx emission corresponding to the different engine loads for gasoline, LPG and syngas fuels under WOT position. As realized in the figure, higher NOx emissions were attained as the engine load increased for all the test fuels. At WOT condition, NOx emission was 1463 and 1090 ppm for gasoline and LPG fuel, respectively, at a 4.5 kW engine load. But, the value of NOx for syngas fuel operation at the maximum engine load condition was observed to be 124 ppm. The mass or amount of fuel mixture burned in the chamber enhanced the cylinder combustion temperature, primarily at higher load conditions. A huge reduction in NOx emission was achieved with syngas operation at all the engine loads, compared to gasoline and LPG fuel operation. This reduction in NOx emission with syngas operation is mainly due to the lower heating value of syngas fuel. The higher vaporization causes a significant reduction in cylinder peak temperature, and hence the NOx emission gets decreased.

4.2.2 | Hydrocarbon emission

Figure 5 exhibits HC emission variation depending on the different engine loads for gasoline, LPG, and syngas fuels under WOT position. The graph clearly shows that the HC level gradually decreases for gasoline and LPG fuel as the engine load increases, while it is maintained with similar values for syngas operation. Compared to gasoline fuel, LPG, and syngas usage shows an average decrease of 23.3% and 15.2% in HC level, respectively, at the maximum engine load of 4.5 kW. The decrease in HC level for syngas operation is due to the breakdown of HC bonds with increases in chamber temperature inside the cylinder. Another prominent reason for reducing HC emission levels for syngas and LPG operations is the formation of a homogeneous mixture in an intake system. Since the syngas and LPG fuels are in a gaseous state, the mixture preparation in a carburetor would result in a homogenous mixture compared to gasoline fuel. Similarly, increasing the engine load will increase the burning rate and turbulence intensity inside the cylinder, resulting in superior combustion and reduced HC emission formation.

4.2.3 | CO emission

Figure 6 reveals CO emissions variation corresponding to the different engine loads for gasoline, LPG, and syngas fuels under WOT position. For all the test fuels, CO emission shows a declining tendency with increasing the engine load condition. With the usage of syngas fuel, CO emissions significantly reduced by 93.3% and 96.6% at a maximum engine load of 4.5 kW compared to gasoline and LPG fuel, respectively. CO emission was observed at a 4.5 kW engine load as 1.95%, 0.92%,
and 0.06% for LPG, gasoline, and syngas fuel, respectively. Compared to LPG operation for syngas operation, it has been noticed that reducing the higher level of CO emissions at all the engine loads. This reduction was mainly due to the lower CO content in the syngas attributed to lower CO emissions. On the other hand, LPG operation shows a significant rise in CO emissions due to lower volumetric efficiency. Also, the burning of syngas air mixture improves combustion efficiency and increases cylinder temperature, attributed to lower CO emissions.

4.2.4 | CO$_2$ emission

In general, the emission of CO$_2$ will increase inside the engine cylinder due to the faster combustion reaction with enhancing combustion temperature inside the combustion chamber. Figure 7 displays the variation of CO$_2$ emission equivalent to the different engine loads for gasoline, LPG, and syngas fuels under WOT position. As perceived in the figure for all the test fuels, higher CO$_2$ emissions were achieved when the engine load increased. Under WOT conditions; syngas usage shows higher CO$_2$ emission compared to LPG fuel operation at all the engine load conditions. An average of 34.2% and 25.6% increase in CO$_2$ emission were noticed with syngas operation compared to LPG and gasoline fuel. At 4.5 kW engine load, CO$_2$ emission was observed to be 14.02%, 12.24%, and 11.06% for syngas, gasoline, and LPG fuel, respectively. The reduction in CO$_2$ emission with LPG fuel operation is mainly due to the lower carbon molecules present in the LPG fuel compared to gasoline. Syngas operation increases the combustion reaction rate, which increases the cylinder temperature that attributes to higher CO$_2$ emission. Also, syngas contains 10% CO$_2$ in the gas composition.

4.3 | Combustion parameters

4.3.1 | Cylinder pressure

The cylinder pressure curve shows the dissemination of engine loads due to the combustion reaction of the fuel mixture inside the cylinder with respect to crank angle. Figure 8 demonstrates the alteration of in-cylinder pressure with respect to crank angle for gasoline, LPG, and syngas at the maximum engine load of 4.5 kW. The in-cylinder pressure for gasoline operation shows a higher value of 34.2 bar, while the pressure was measured to be 28.2 and 30.4 bar for LPG and syngas fuel, respectively. Using syngas and LPG fuel, there has been a significant reduction of cylinder pressure, roughly around 17.5% and 11.2%, compared to gasoline fuel. The lower flame speed of syngas and LPG fuel–air mixture tends to achieve inferior combustion inside the cylinder, resulting in lower cylinder pressure than gasoline fuel.

Since the ignition temperature of LPG and syngas fuel was much higher than gasoline, those fuels ignition tended to late compared to gasoline mixture. For syngas and LPG fuels, the peak pressure was roughly 5° late compared to gasoline fuel.

4.3.2 | Heat release rate

Figure 9 demonstrates the change of heat release rate concerning crank angle for gasoline, LPG, and syngas at the maximum engine load of 4.5 kW. The heat release rate curve shows the energy released by the combustion of fuels inside the cylinder concerning the crank angle. The maximum heat release rate was found as 66.9 J/deg CA with gasoline operation, whereas the heat release rate was measured to be 60.2 and 57.3 J/deg CA for syngas and LPG fuel, respectively. Using LPG and syngas fuel, a
marginal decrease in heat release rate was found compared to gasoline fuel.

4.3.3 | Peak mean gas temperature

Figure 10 illustrates the difference under different engine loads of the overall mean in-cylinder gas temperature for gasoline and syngas petrol. As is visible in Figure 10, the maximum mean temperature of the in-cylinder gas for the syngas process is slightly lower than gasoline fuel operation. This is because the syngas fuel-air mixture induction reduces the cylinder’s temperature at the end of the compression stroke and cools down the in-cylinder atmosphere. The peak mean cylinder gas temperature of 764 and 1010°C for syngas and gasoline fuel was observed at 4.5 kW engine load, respectively. The increase in CO₂ molecules decreases the oxidizing potential of CO, resulting in a reduction in the cylinder gas's pressure and temperature. Reducing the peak temperature of the combustion gas allows the emission of NOx to decrease. The fuel burning rates are lower with syngas fuel operation due to the presence of more diluted gases such as CO, CO₂, and N₂ and outcomes that minimize the increase in-cylinder gas temperature. The combustion process occurs without much intensity for syngas operation due to its poor calorific value, lower flame propagation, and longer combustion time may be the explanations for the peak reduction mean gas temperature.

4.4 | Availability analysis

The experimental data are considered for the availability analysis and the available balance for the gasoline, LPG, and syngas fuels with varying engine loads are presented. The availability balance of each fuel mode is described in different terms: availability input \((A_{\text{in}})\), shaft availability \((A_{\text{shaft}})\), availability lost through exhaust gas \((A_{\text{exhaust}})\), and destroyed availability \((A_{\text{destruction}})\) because of air cooling and irreversibilities like friction, radiation, and so forth. To know the better accuracy of engine performance, the exergy efficiency of each fuel is presented. The result of availability in percentage (Figures 11–15) and availability in rate (Figures 16–20) is shown.

For all the tested fuels, the shaft availability started to increase when the load increases, as shown in Figures 11–20. This is due to higher shaft output produced for the supply of a greater amount of fuel energy at higher loads. The shaft availability of gasoline is significantly higher than that of LPG and syngas fuels. At no-load, the percentage shaft availability for gasoline was 5.75%. In contrast, it was 3.28% and 4.01% with LPG and syngas, respectively. At maximum load, it was 27.7%, 22.47%, and 21.87% with gasoline, LPG, and syngas, respectively. This indicates that gasoline has the best fuel conversion capability for the entire load conditions. At
100% load, LPG has better fuel to power conversion capability than the syngas.

Figures 16–20 present the availability input (kW) of the tested fuels at different engine loads. As the engine load increases, availability input increases due to higher shaft output requirements. Due to better fuel energy to shaft work conversion ability of syngas, the fuel availability was lowest at all loads compared to gasoline and LPG. This is due to better combustion of hydrogen composition in syngas. The poor combustion of LPG at low loads requires higher availability input (11.58 kW at no-load). However, after 50% load,
Similarly, it was recorded as 9.21 and 15.99 kW for gasoline at no-load and 100% load.

All the tested fuels showed increased availability loss through exhaust gas when the engine load increased. The variation of exhaust gas availability in percentage and rate form concerning load is shown in Figures 10–20, respectively. At higher loads, the usage of a greater quantity of fuel increased the combustion temperature. It causes higher exhaust gas temperature and exhaust gas availability. For the entire load operation, the syngas shows maximum exhaust gas availability, followed by gasoline and LPG. With hydrogen in syngas, the flame speed becomes higher and hence, the rate of combustion.54 This improves the in-cylinder temperature of syngas fuel. Thus, the increase in exhaust gas temperature and exhaust gas availability for syngas operations.57,58 At 100% load, the maximum exhaust gas availability was 24.51% with syngas and 17.95% and 7.26% with gasoline and LPG.

The destroyed availability is the sum of air cooling, friction, combustion, and other irreversibilities. At low loads, the work conversion capabilities of fuels are less due to the low combustion temperature. As the load increases, better combustion of fuels generates higher combustion temperature and pressure within the cylinder. This lowers the percentage of destroyed availability. The percentage of destroyed availability was least with gasoline, followed by syngas and LPG up to 50% load (Figures 11–15). However, after 50% load, due to better combustion and improved in-cylinder temperature, syngas produces a minimum percentage of destroyed availability as compared to gasoline and LPG. At 50% load, the percentage destroyed availability was 62.54% with gasoline followed by 65.05% and 80.57% with syngas and LPG, respectively. Whereas, at 100% load, it was 53.62% with syngas followed by 54.38% and 70.27% with gasoline and LPG, respectively. Similar types of observation were reported by various researchers in their study.22,23

The exergy efficiency (Figure 21) generally increases with an increase in engine load due to a high rise in shaft output. The engine’s exergy efficiency is found to be higher for gasoline operation up to 50% load. After this, due to reduced destroyed availability and enhanced combustion, the syngas engine mode produces higher exergy efficiency as compared to gasoline and LPG mode. At 50% load, gasoline mode produces 37.47% exergy efficiency, whereas 34.98% and 19.44% with syngas and LPG mode, respectively. At a maximum load of 100%, syngas exergy efficiency was improved to 46.45% from 45.62% and 29.73% with gasoline and LPG, respectively. This reveals that the syngas and LPG as alternative fuels in SI engines can only be ignored on their energy efficiency parameter.
5 | CONCLUSION

The experiments were conducted in a Honda (GX270) Genset SI engine using three different fuels such as gasoline, LPG, and syngas, and the results were compared systematically in an organized manner. The inlet manifold of the engine was added with a gas carburetor for syngas induction so as to carry out the experiment effortlessly. Furthermore, a detailed study on availability analysis was carried out to examine the heat energy distribution in an engine using different fuels. Although gasoline, LPG, and syngas characteristics are compared independently in this study, the summary of significant outcomes is given below.

- At a 4.5 kW engine load, the BTE of the LPG and syngas fuels were reduced by 7.4% and 15.5%, respectively, as compared to the gasoline case. The decrease in BTE can be improved for gaseous fuels by altering some engine parameters like ignition timing etc.
- A massive reduction in NOx emission was attained with syngas operation at all the engine loads, compared to gasoline and LPG fuel operation.
- Compared to gasoline fuel, LPG and syngas usage shows an average decrease of 43.3% and 55.2% in HC level, respectively, at the maximum engine load of 4.5 kW.
- Syngas mode produces the lowest CO emissions compared to other fuel modes. To produce lower CO emissions in LPG mode, the size of the inlet manifold is to be increased to maintain a stoichiometric A/F ratio.
- In-cylinder pressure for LPG and syngas at 4.5 kW load shows a significant reduction around 17.5% and 11.2%, compared to gasoline fuel. The lower flame speed of syngas and LPG fuel–air mixture tends to reduce in-cylinder pressure.
- The availability input is found highest at 100% load for the fuels individually. At this load, the maximum availability input was found to be 17.62 kW with LPG as fuel.
- A maximum of 27.7% of availability input has been converted into shaft availability by the gasoline fuel. Similarly, the gasoline fuel operation was able to produce 4.3 kW maximum shaft work at 100% load from a 4.5 kW SI engine. However, concerning exergy efficiency, syngas has been proved as the best fuel in the tested SI engine at 100% load. The maximum exergy efficiency has been observed as 46.45% with syngas compared to 45.62% and 29.72% with gasoline and LPG, respectively, at a 4.5 kW load.
- The increase in the exergy efficiency can be possible by utilizing the exhaust availability and destroyed availability. Maximum exhaust gas and destroyed availability of 24.51% and 53.52%, respectively, can be recovered from the syngas operation recovered at 4.5 kW load condition. Whereas the destroyed availability value for gasoline and LPG was calculated as 54.38% and 70.27% of availability input at the same load.

AUTHOR CONTRIBUTIONS

Ganesan Nataraj: Methodology; writing–original draft, review and editing; conceptualization; investigation; formal analysis. Bibhuti B. Sahoo: Writing–original draft, review and editing. Ekambaram Porpatham: Supervision; methodology; conceptualization and resources; formal analysis; project administration. P.V. Elumalai: Writing-review & editing. Olusegun D. Samuel: Writing-review & editing. Christopher C. Enweremadu: Writing-review & editing. Asif Afzal: Writing-review & editing. C. Ahamed Saleel: Writing-review & editing.

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