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Exploring the Effects of DEE Pilot Injection on a Biogas-Fueled HCCI Engine at Different Injection Locations

Nihal Mishra [1], Shubham Mitra [1], Abhishek Thapliyal [1], Aniket Mahajan [1], T. M. Yunus Khan [2,*], Sreekanth Manavalla [1,3], Rahmath Ulla Baig [4], Ayub Ahmed Janvekar [1] and Feroskhan M [1,*]

1 School of Mechanical Engineering (SMEC), VIT Chennai, Chennai 600127, India; nihalmish9@gmail.com (N.M.); shubham1riju@gmail.com (S.M.); abhishek.thapliyal2020@gmail.com (A.T.); aniketmahajan315@gmail.com (A.M.); manavalla.sreekanth@vit.ac.in (S.M.); ayubahmed.janvekar@vit.ac.in (A.A.J.)
2 Department of Mechanical Engineering, College of Engineering, King Khalid University, Abha 61421, Saudi Arabia
3 Electric Vehicles Incubation, Testing and Research Center, VIT Chennai, Chennai 600127, India
4 Department of Industrial Engineering, College of Engineering, King Khalid University, Abha 61421, Saudi Arabia; rbahmed@kku.edu.sa
* Correspondence: yunus.tatagar@gmail.com (T.M.Y.K.); feroskhan.m@vit.ac.in (F.M.); Tel.: +91-44-3993-2555 (F.M.)

Abstract: One of the popular ways to minimise the impact of emissions produced by engines is by enabling alternative fuels. Out of the many trending options for alternative fuels, biogas provides some unique advantages, such as being considered to be environmentally friendly, obeying the laws of renewable energy and generating the smallest carbon footprints. The two major drawbacks of traditional diesel engines are their high rate of NOx and significant amount of soot. The best candidates for overcoming these issues are HCCI engines; HCCI engines can provide better control over NOx generation and overall thermal efficiency can be improved to a greater level. These types of engines are compatible with both SI and CI. Now, to understand and analyse the behaviour of HCCI, the present work was focused on a modified single-cylinder CI engine. It was made to operate in HCCI mode by enabling the combination of biogas, along with diethyl ether (DEE), as a fuel mixture. To achieve better combustion, biogas was combined with air, while DEE acted as an ignition source, which can be introduced at three different locations. In total, the experiment was performed sixty times so as to achieve the best injection position. To obtain this information, other parameters, such as biogas flow rate, torque, methane fraction and DEE injection position, were also incorporated. The main results were consolidated by warping the output parameters such as brake thermal efficiency, equivalence ratio, air–fuel ratio, and brake-specific fuel consumption. Emission such as CO, HC, NOx, and smoke were taken into account. The results indicate that port injection provides higher thermal efficiency than manifold injections, while lower emissions were observed in manifold injections.

Keywords: biogas; DEE; manifold injection; port injection ultra-low NOx; HCCI

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1. Introduction

The usage of conventional fuels is increasing from day to day and leading to the rapid depletion of fuel reserves. Therefore, it is important to improve the existing technology in order to reduce their consumption and to substitute them with alternative fuels for future progress [1,2]. Several alternative fuels show promise as replacements for traditional fuels, including biodiesel, bio-alcohols (such as methanol, ethanol, and butanol), hydrogen, vegetable oils, propane, and biogas [3,4]. Biogas is composed of methane and carbon dioxide, with small amounts of NH3, hydrogen sulfide, and water vapor. It is a renewable and environmentally friendly energy source that helps to reduce the amount of waste that ends up in landfills. As we know, HCCI refers to Homogeneous Charge Compression

Ignition (HCCI), where, in engines, the introduction of a lean homogeneous mixture of air–fuel will be compressed and ignited [5]. Furthermore, it can be noted that the availability of CO_2 in biogas can have an adverse effect on the ignition quality [6].

Biogas is known for its high auto-ignition temperature, narrow flammability limits, and slow flame propagation [7]. With the higher octane number comes the advantage of utilisation in SI engines; on the other hand, there is a drastic reduction in both the thermal efficiency and HC emission [3]. The removal of CO_2 can improve its flammability limits and flame speed. Biogas can also be used in two modes in diesel engines—in dual fuel and HCCI modes. However, the dual fuel mode leads to high HC and CO emissions, particularly at low loads [8], and both biogas-fueled SI and dual fuel CI engines have low thermal efficiency [9]. The HCCI mode is an advanced technology that allows for high thermal efficiency and low NOx emissions [10]. In HCCI engines, air and fuel are thoroughly mixed and compressed to the point of auto-ignition [11]. Adding diethyl ether (DEE) can reduce ignition delay, which, in turn, lowers the in-cylinder temperature and enhances engine performance [12]. Unthrottled operation at light loads can provide a fuel economy comparable to that of a diesel engine, while homogenous charge at full load offers a power density similar to that of a gasoline engine [13]. HCCI engines are the best alternative available when the intention is to focus on low equivalence ratios without compromising on high energy output. With this approach, thermal efficiency can be boosted [14]. Thus, it can be noted that the pros of both SI and CI can be achieved with consideration of HCCI engines.

Among the list of the significant advantages of using HCCI, there are two key features that makes it first choice among the alternatives, i.e., firstly, its significantly low emissions and, secondly, its better utilisation of fuel. Biogas comes under the category of renewable energy, with the feature of being low carbon fuel. It is the optimum choice and top-rated candidate for HCCI, since it contains high hydrogen molecules and low carbon involvement. Since combustion is a complex phenomenon, getting HCCI emissions from engines with biogas integration has not been fully explored and information regarding its critical bifurcations is not available. The main reason for the trending or selecting of biogas, as a top shortlisted source for incorporating biogas into HCCI engines, is its low carbon generation capacity. This can be regarded as a unique feature; secondary advantages can be triggered, such as low rate of CO_2, with respect to fossil fuel. The main ingredient for the generation of biogas is an anaerobic phenomenon of various materials. Some of the materials included are domestic organic waste, small scale industrial waste, and outcomes from food processing industries and sewage treatment plants. The main constitutive part of biogas is CH4. Apart from CH4, it also has a limited quantity of CO_2 and dissolved/undissolved impurities. By considering methane composition and its application, it can be placed under the category of greenhouse gas. Furthermore, it has reached a global warming potential more than 25 times that of carbon dioxide over the last few decades [15]. However, when biogas is produced from waste materials, it is considered a low-carbon fuel because the carbon in the biogas is part of the carbon cycle and does not add to the atmospheric carbon.

When the combustion of biogas takes places, various emissions are generated from them, the most critical being NOx and CO, since they directly violate the environment and ecosystem. With the integration of HCCC engines, NOx can be reduced significantly in comparison to a conventional engine with a regular fuel input under the SI engine. NOx emissions are a major contributor to air pollution and are associated with respiratory problems, smog, and acid rain. The lower NOx emissions in HCCI engines can be attributed to the lean air–fuel mixture used in these engines, which reduces the combustion temperature and limits the formation of NOx. The major reason for the popularity of HCCI is due to its feature of obtaining low emissions without compromising on carbon footprint.

However, biogas combustion in HCCI engines also has some challenges that can affect its emission characteristics. One of the main challenges is the high variability of biogas composition, which can affect the engine performance and its emissions. Biogas produced from different feedstocks and production processes can have varying compositions of CH_4, CO_2, and impurities such as hydrogen sulfide (H2S) and siloxanes. These impurities can cause engine fouling, corrosion, and emission problems.

Another challenge is the auto-ignition of biogas, which can result in knocking and misfiring in HCCI engines. Biogas depends on organic waste and other sources, and it is able to achieve high octane numbers, leading to high resistance in terms of auto-ignition. However, the high variability of biogas composition can affect its octane number, and the use of biogas with low octane numbers can result in engine knocking and misfiring.

Several studies have been carried out focusing on interesting concepts and study outcomes aimed at achieving better emission control by integrating biogas as a key candidate under the hood of HCCI engines. Many researchers have focused on the boundary conditions and operating parameters in order to achieve higher thermal efficiency. For instance, Bari et al. [16] worked by taking gasoline as the prime source to carry out combustion, where its combustion characteristics were deeply focused. They conveyed that biogas in an HCCI engine can achieve lower combustion efficiency with much higher levels of CO_2 emissions. On the other hand, under the lean air–fuel mixture, it was reported that biogas had lower NOx emissions. Along similar lines, Kuti and Oyedun [17] took up challenge of evaluating various compositions of biogas with respect to the emission performance of a HCCI engine. The higher input of methane in biogas leads to low values of CO and HC data, while NOx showed an adverse effect. A much higher value of NOx was reported. Overall, HCCI engines presented many acceptable data in terms of efficiency and emissions. Finally, as an overview, it can be seen that biogas, which is mainly made from domestic organic waste, can be taken as a potential candidate for HCCI engines, since it focuses on low carbon content and high hydrogen content.

Khandal et al. [18] carried out performance studies on Hinge and cotton seed biodiesels in an HCCI engine at 40–80% load. They found higher HC emissions and similar CO emissions when compared to the CI engine mode. Also, a high amount of knocking was observed beyond an 80% load. Guo et al. [19] carried out an experimental comparative study on gasoline/ethanol blends in a TGDI engine under a couple of operating conditions. They found that NOx emissions fluctuated greatly under various conditions, the HC emissions were 10 times more during cold-start conditions compared to steady-state conditions, while CO emissions were high under high load and high speed conditions. Duan et al. [20] carried out a review study on strategies for controlling ignition timing and combustion in HCCI engines. Among other conclusions, they found that alternative fuels are more amenable for controlling the ignition timing and combustion phase of a HCCI engine compared to traditional fossil fuels. Harari et al. [21] experimentally studied the effect of injection parameters on an RCCI engine using compressed natural gas, compressed biogas, and diesel blends of Thevetia Peruviana methyl ester. They identified the fuel combinations which resulted in high break thermal efficiency and low emissions.

Teoh et al. [22] studied the effect of intake and premixed ratio on emissions in a partial HCCI-DI diesel engine. It was found that inlet air temperature had a strong influence on low temperature reaction and HCCI combustion timing, while a higher premixed ratio had more influence on reducing NOx emissions. Wu et al. [23] investigated the influence of palm oil diesel blends on Nox-smoke trade off characteristics in a CRDI diesel engine at different engine pressures and exhaust recirculation conditions. It was understood that, at high injection pressure, the smoke formation reduced but NOx emissions increased. The atomisation problem of palm oil appeared to be mitigated at high injection pressure. The CO_2 content of biogas directly affects its combustion properties, as CO_2 is an inert gas. A higher methane content typically results in improved combustion efficiency and power output. The calorific value of biogas, which depends on its composition and energy content, determines the energy released during combustion and, consequently, the engine's performance [24].

The major aspect upon which researchers spend time is in obtaining better control over the HCCI engine design, for which the ignition of the fuel–mixture plays vital role to ensure the complete burning of fuel takes place in the best possible way. The exact injection location is a prime factor parameter to ensure better combustion to takes place and unburned fuel can be reduced, since poor burning leads to high emission rate and overall efficiency can be affected. In this essay, we will discuss the importance of injection location in HCCI engines and its impact on engine performance.

The location of injection is a key parameter in ensuring that the fuel can be introduced into the combustion chamber in the best possible way.

In the case of HCCI, fuel mixing happens well before the mixture gets induced in the cylinder, while, in a conventional approach, fuel is directly introduced into the cylinder. The improper injection of fuel leads to many consequences, some of them including poor combustion and huge rate of emissions, hence maintaining the air–fuel mixture is a key parameter. The injection location is typically defined by the distance from the intake valve to the fuel injector, also known as the "injection timing".

The introduction of injection location into the chamber plays a vital role in combustion performance. Its location not only impacts the engine performance with power generation, but also imparts the ignition timing. A poor initiation of the combustion process leads to higher emission characteristics. In HCCI engines, the compression ratio is an important parameter which ensures that better combustion takes place; the optimum fuel–air mixture can ensure spontaneous ignitions take place. The timing of the ignition is critical to achieving optimal engine performance, as it affects the power output, fuel efficiency, and emissions. The injection location can affect the ignition timing by changing the residence time of the fuel, which can be varied to ensure better burning rates in the cylinder. Furthermore, the temperature of the air–fuel mixture, and the perfect blend of the mixture, can directly impact engine performance.

One of the main challenges of injection location in HCCI engines is achieving a proper fuel–air mixture that will ignite consistently across the entire engine cycle. To achieve this, the fuel must be introduced into the engine cylinder in a manner that allows for a consistent and homogeneous mixture of fuel and air. The injection location can affect this by changing the airflow patterns within the cylinder, which can impact the fuel–air mixing and ignition timing.

Several studies have focused on various conditions of combustion cylinders working in lean/rich modes by relocating the injection position in HCCI engine performance. For instance, Chen et al. [25] took DME as fuel in testing for various injection positions to ensure better thermal performance. They reported that the position depends on the ignition timing and total duration needed to perform the combustion. It was noted that the location varied with respect to the spark plug. When the location was near to the spark plug, it performed better. Later, Lee et al. [26] took up the challenge of working along similar lines, focusing on the location parameter with the help of an HCCI engine. The team reported that the optimal injection point is in the best position if placed near to the exhaust valve. With this, improved fuel-air mixing and ignition timing were reported and showcased.

Another important factor to consider when designing injection locations in HCCI engines is the fuel type. Different fuels have different ignition characteristics, and the optimal injection location may vary depending on the fuel type. For example, diesel fuel requires a higher compression ratio and a longer ignition delay compared to gasoline, which can affect the optimal injection location.

Now, with detailed work performed by various researchers, injection location can be regarded as a critical parameter with respect to the design of HCCI engines, since it does not affect the fuel–air mixing or ignition timing, but significantly affects the combustion characteristics of the engine. The optimal injection location depends on several factors, including the fuel type, engine geometry, and operating conditions. Future research in this area will be essential in optimising the injection location and achieving the full potential of HCCI engines.

2. Experimental Setup

The experimental arrangement used in the research is depicted in Figure 1. The setup involved modifying a single-cylinder, four-stroke CI engine into a water-cooled HCCI engine. For the study, Kirloskar 8 HP engine was utilised. Simulated biogas consisting of a mixture of CH4 and CO_2 was used, which was stored in separate cylinders. Flow control valves and calibrated thermal mass flow meters were present in the cylinders, enabling the researchers to regulate the biogas flow rate and the proportion of CH4 to CO_2. The gas mixture was mixed with incoming air, and DEE was used as the pilot fuel, which was delivered to the engine via injectors located in the inlet port and manifold. The setup also included an eddy current dynamometer, a digital weighing balance for measuring DEE consumption, a 5-gas emission analyser, a smoke analyser, and a timing control circuit for DEE injection.

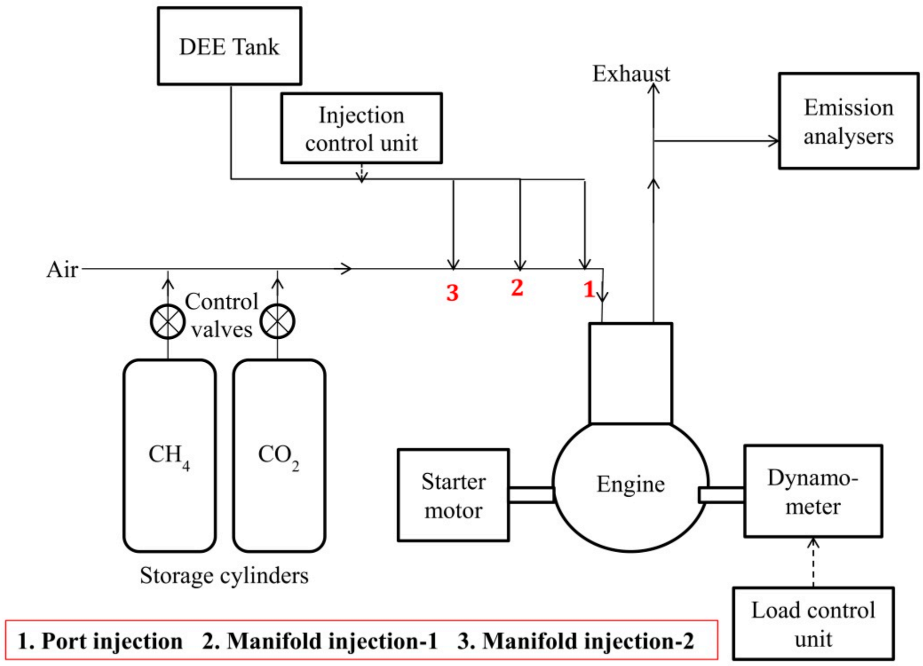


Figure 1. Experimental setup block diagram.

3. Methodology

In this study, air and biogas were introduced into the engine through the inlet manifold, and DEE was injected at one of the three locations illustrated in Figure 1, namely the port, manifold1, or manifold2 (10 cm upstream of manifold 1). The performance and emission characteristics of the engine were assessed for each of these positions, considering different biogas flow rates and methane fractions under various operating conditions, as listed in Table 1. The engine speed was kept constant at 1800 rpm, and the DEE flow rate was adjusted to maintain this speed. Details of the measuring instruments and uncertainty estimates of the output parameters are provided in Tables 2 and 3, respectively.

Table 1. Operating parameters.

Intake Condition	Level 1	Level 2	Level 3	Level 4
Injection position	Port	Manifold1	Manifold2	-
Biogas flow rate (lpm)	8	12	-	-
Methane fraction (%)	60	100	-	-
Torque (N.m)	5	10	15	20

Table 2. Details of the measuring instruments.

Quantity Measured	Measuring Device
Flow rate of CH_4	Thermal mass flow meter
Flow rate of CO_2	Thermal mass flow meter
Torque	Eddy current dynamometer
Flow rate of neat diesel	Burette
Air flow rate	Orifice meter
Smoke emissions	AVL 437C smoke meter
CO emission	AVL 444N gas analyser
HC emissions	
NO_x emissions	

Table 3. Uncertainty estimates of the output parameters.

Output Parameter	Uncertainty (±)
CO emission	3%
HC emissions	3%
Brake thermal efficiency	2.46%
Diesel consumption	1%
Smoke emissions	1%
NO_x emissions	1%

4. Results and Discussions

This section describes the trends observed in performance and emission charateristics during the parametric studies.

4.1. Brake Thermal Efficiency

Figure 2a illustrates the changes in brake thermal efficiency at different DEE injection positions for a biogas flow rate of 12 L per minute with 100% methane concentration (pure methane). The results show that port injection produces the highest brake thermal efficiency values. This may be due to the favorable mixture formation resulting from the injected DEE, which requires a lower injection quantity. An upstream injection in the manifold can lead to the over-mixing of DEE, which can adversely affect ignition. The lower DEE requirement for port injection is supported by the variations shown in Figure 3. A manifold injection can also cause greater air flow resistance, increasing the overall equivalence ratio (refer Figures 4 and 5) and decreasing thermal efficiency. Figure 2b reveals that changes in methane concentration do not significantly affect efficiency. Furthermore, Figure 2c shows that an increase in biogas flow rate results in a reduction in brake thermal efficiency. This is possibly because a large proportion of the inducted methane remains unutilised. This is confirmed in Figure 6, presented later. Additionally, a high biogas flow rate reduces the air intake and thus affects the mixture formation and combustion. When the biogas flow rate and methane fraction are low, the HCCI mode can only be used up to 2 kW due to the occurrence of knock. However, if the biogas flow rate and methane fraction are increased, the knock limit can be extended up to 3 kW. The speed of biogas combustion is linked with an increase in brake power, resulting in improved thermal efficiency [27].

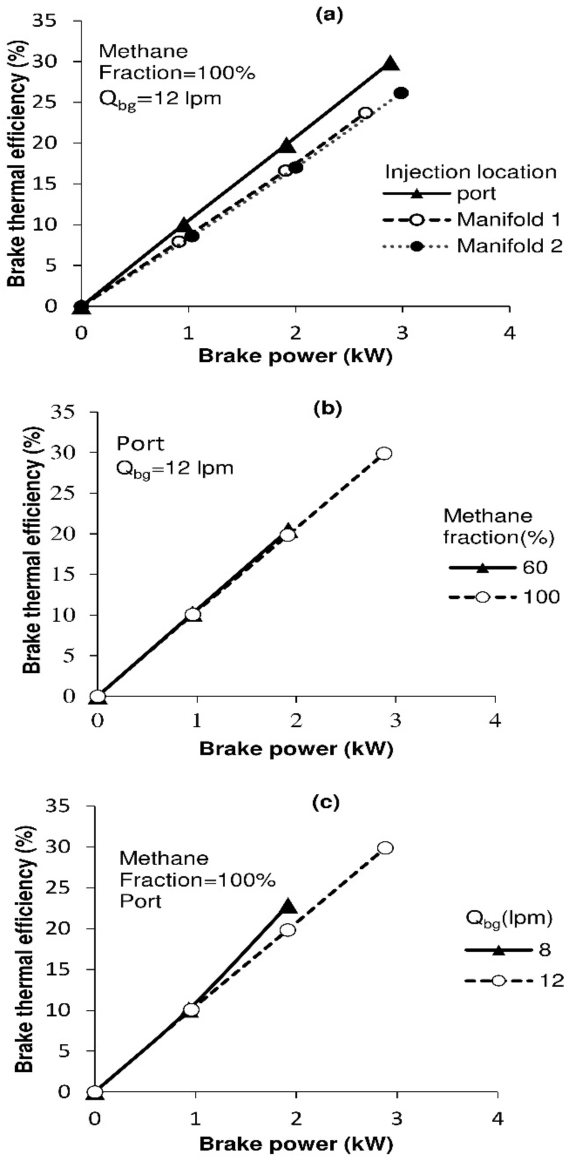


Figure 2. Effect of (**a**) injection location, (**b**) methane fraction and (**c**) biogas flowrate on brake thermal efficiency.

4.2. Brake Specific Fuel Consumption

Figure 3a demonstrates the changes in brake power and brake specific fuel consumption (BSFC) according to the location of DEE injection. As stated earlier in Section 4.1, the use of DEE injection in the port necessitates the smallest amount of DEE and, therefore, results in the lowest BSFC. Figure 3b shows that methane fraction does not significantly affect BSFC, while Figure 3c shows that, at higher brake power, BSFC is marginally more for high biogas flow rate because of the incomplete combustion of the excess biogas supplied and insufficient air. Port injection can provide lower BSFC than manifold injection in HCCI engines because it allows for better control of the combustion process. When fuel is injected directly into the combustion chamber, it can be more precisely metered and timed to match the engine's operating conditions. This can result in more complete combustion, which means more of the fuel's energy is converted into useful work and less is wasted as heat.

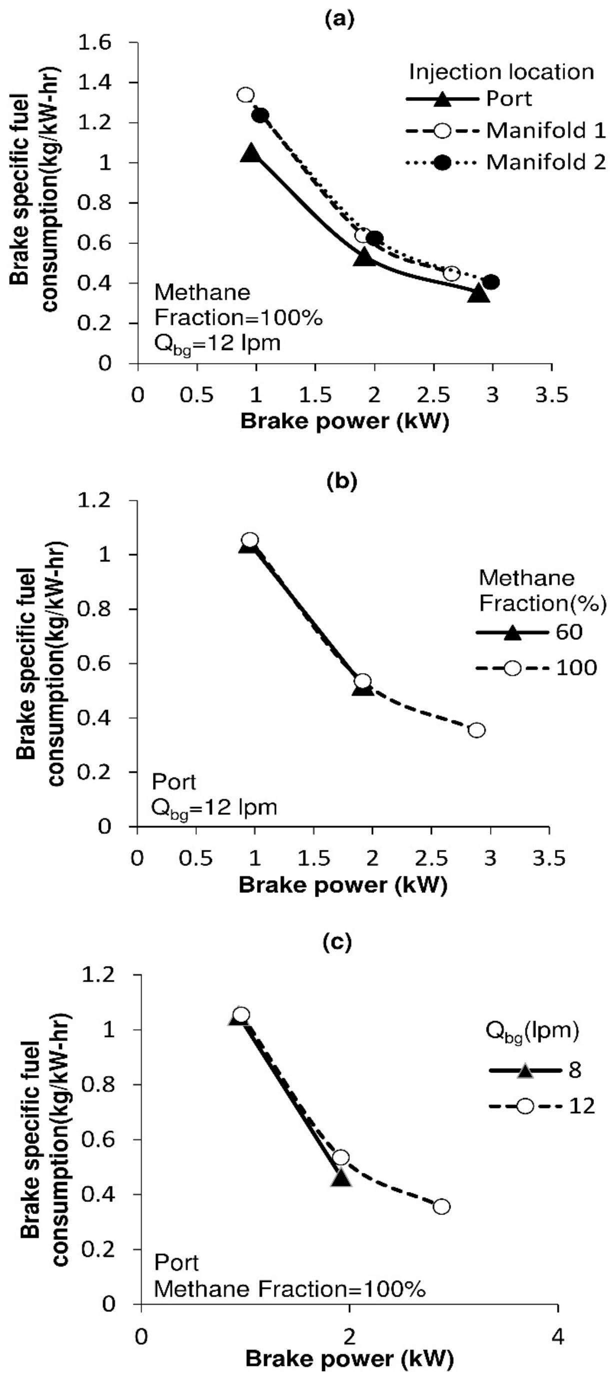


Figure 3. Effect of (**a**) injection location, (**b**) methane fraction and (**c**) biogas flowrate on brake specific fuel consumption.

In addition, port injection can also reduce the risk of pre-ignition and knock, which can occur when the fuel–air mixture ignites too early or too late. This is because the fuel is injected directly into the combustion chamber, where it can be more evenly distributed and mixed with the air, reducing the likelihood of hot spots that can cause premature ignition.

4.3. Air–Fuel Ratio

Figure 4a displays the changes in air–fuel ratio at different DEE injection positions. As explained in Section 4.1, manifold injection reduces the amount of air intake and increases DEE injection, leading to a decrease in air–fuel ratio. As anticipated, this effect is more evident for upstream injection (Manifold 2). The same effect is observed with an increase in biogas flow rate (as shown in Figure 4c). An increase in methane concentration results in a decrease in the mass of biogas, since CH4 is less dense than CO_2. Consequently, the air–fuel ratio increases, as illustrated in Figure 4b. Port injection can provide a higher air–fuel ratio than manifold injection in HCCI engines because the fuel is injected directly into the combustion chamber, allowing for better control of the fuel delivery. This means that the fuel can be injected in smaller, more precise amounts and timed more accurately, resulting in a leaner mixture with a higher AFR.

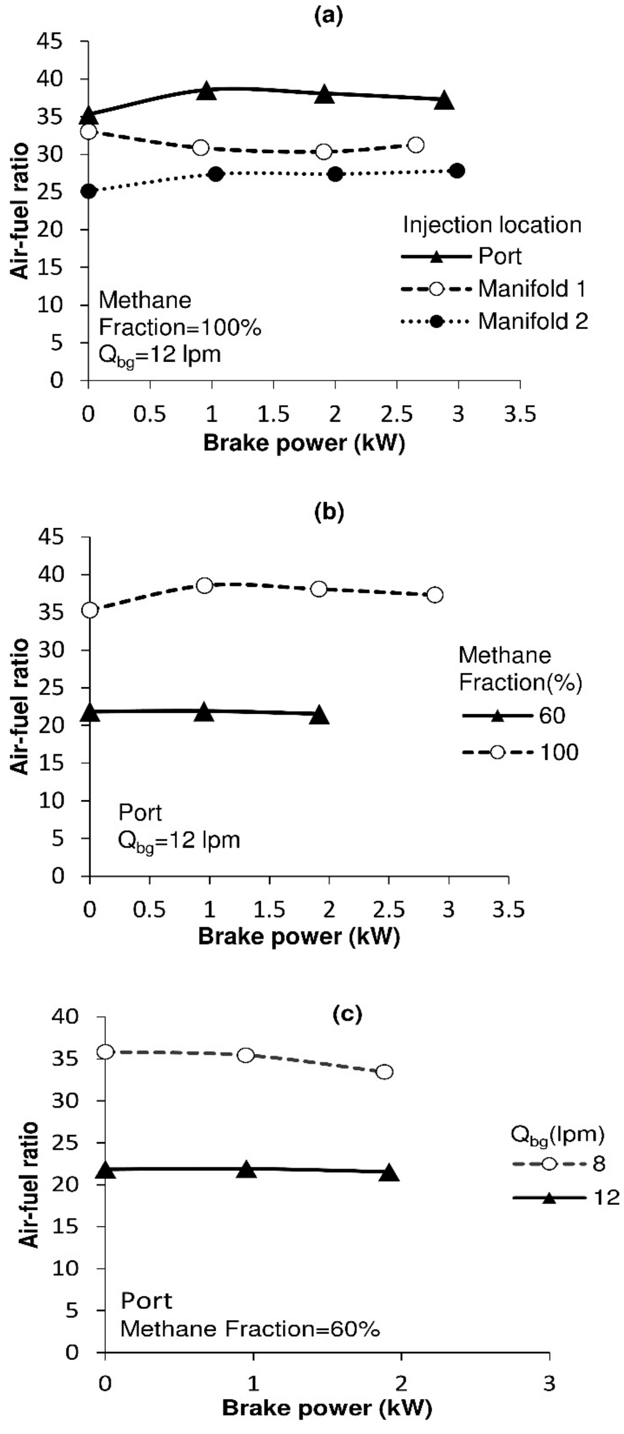


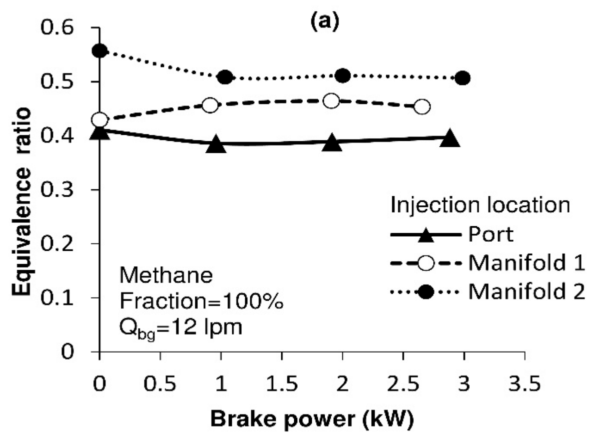
Figure 4. Effect of (**a**) injection location, (**b**) methane fraction and (**c**) biogas flowrate on air–fuel ratio.

In manifold injection, the fuel is injected into the intake manifold and then mixed with the air before entering the combustion chamber. This mixing process can result in a less precise control of the fuel delivery and can lead to a richer mixture with a lower AFR.

A leaner mixture with a higher AFR can improve the efficiency of the engine and reduce the emission of pollutants such as nitrogen oxides (NOx) and particulate matter (PM). However, it can also increase the risk of misfire and incomplete combustion, which can result in higher emissions of HC and CO.

4.4. Equivalence Ratio

The diagram in Figure 5a illustrates the influence of injection location on equivalence ratio. As discussed earlier, the use of manifold injection results in higher equivalence ratios compared to port injection, as a result of increased DEE injection and reduced air intake. Despite the fact that the air–fuel ratio increases with the increase in methane concentration (as seen in Figure 4b), the stoichiometric air–fuel ratio also increases due to the greater combustible fraction. As a result, the equivalence ratio increases, as shown in Figure 5b. Higher biogas flow rates lead to an increase in air displacement in the intake, which results in an overall higher equivalence ratio, as shown in Figure 5c.



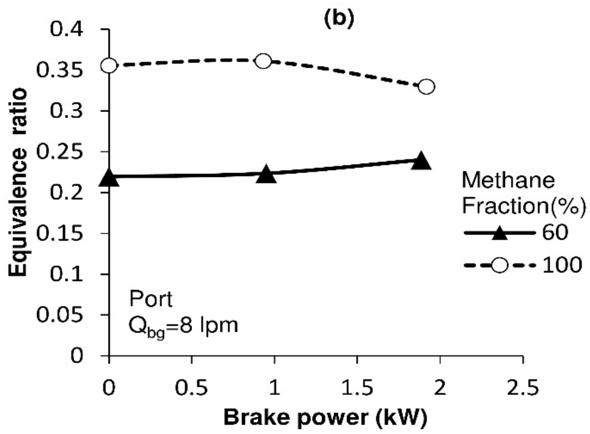


Figure 5. *Cont.*

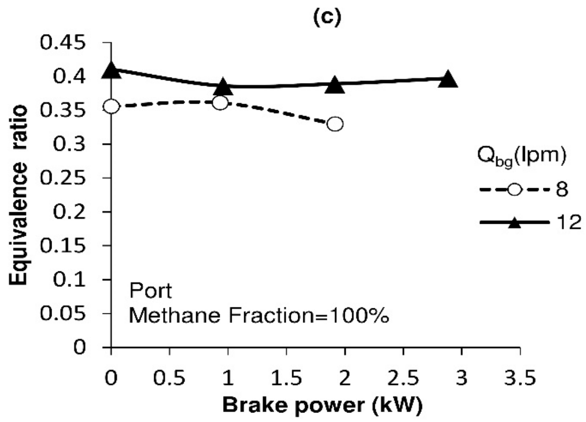


Figure 5. Effect of (**a**) injection location, (**b**) methane fraction and (**c**) biogas flowrate on equivalence ratio.

4.5. HC Emission

The effect of injection position on HC emissions is demonstrated in Figure 6a. Generally, higher HC emissions are observed in port injection. This may be due to the incomplete mixing of DEE with air, resulting in some areas being too rich. The close proximity of the injection to the cylinder may also lead to wall impingement of the DEE jet, which could contribute to this effect. This also explains the marginally higher emissions in Manifold 1 compared to Manifold 2 at low loads. The trend, however, reverses at higher loads, as Manifold 1 has an overall lean mixture compared to Manifold 2 (as seen in Figure 5a). Higher in-cylinder temperatures at higher loads enhance the combustion quality and reduce the HC emissions. An increase in methane concentration raises the overall equivalence ratio, resulting in higher HC emissions, as illustrated in Figure 6b. A similar effect is observed when increasing the biogas flow rate (as shown in Figure 6c). The HCCI engine generates higher hydrocarbon (HC) emissions compared to conventional CI engines due to its unique combustion process. HCCI combustion operates with a rich air–fuel mixture, leading to incomplete combustion and increased HC emissions. The lean mixture impedes the complete oxidation of hydrocarbon molecules, allowing some to escape combustion. Additionally, premature ignition and knock can occur, contributing to HC emissions. HCCI engines lack direct injection, which can cause fuel impingement on chamber walls, leading to deposits that vaporise and contribute to HC emissions. Managing HC emissions in HCCI engines requires the precise control of combustion parameters, optimising air–fuel mixture homogeneity, and improving fuel atomisation and vaporisation [11,19,24,28].

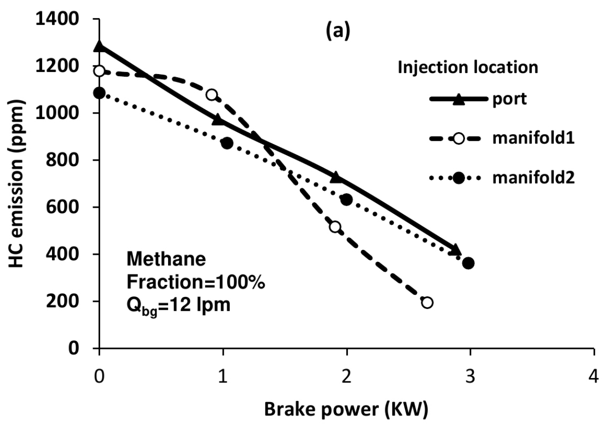
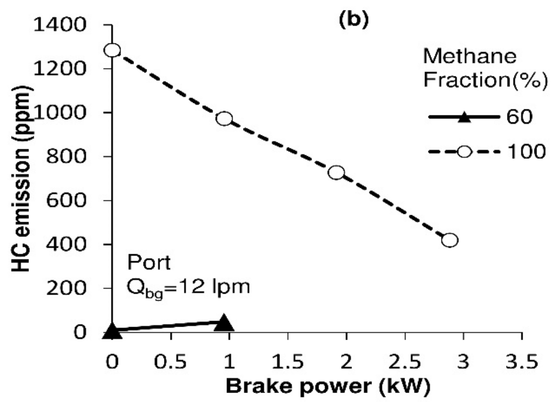


Figure 6. *Cont.*



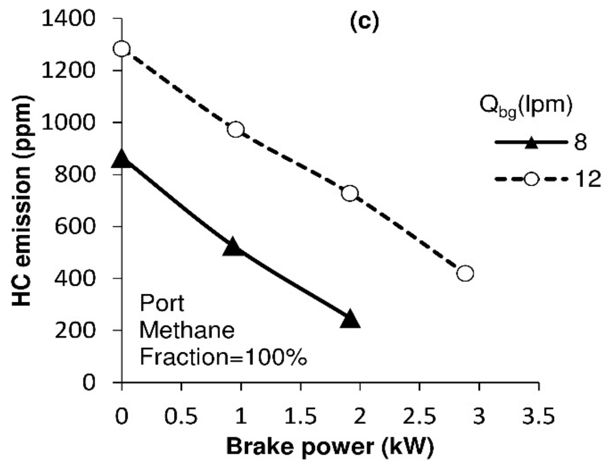


Figure 6. Effect of (**a**) injection location, (**b**) methane fraction and (**c**) biogas flowrate on HC emission.

4.6. CO Emission

CO emission is strongly dependent on the equivalence ratio. Hence, Manifold 1, which has the highest equivalence ratio, exhibits high CO emissions, as shown in Figure 7a. Port injection also causes significant CO emissions under some operating conditions, owing to the presence of locally rich pockets, as discussed in Section 4.2. An increase in CO emissions with methane enrichment and biogas flow rate (see Figures 7b and 7c, respectively) is also attributed to higher equivalence ratios. Port injection involves injecting fuel directly into the intake ports of the engine, upstream of the intake valves. This prevents the fuel from mixing more thoroughly with the incoming air, resulting in a less homogeneous mixture. However, since the fuel is injected upstream of the combustion chamber, it has less time to vaporise and mix with the air, which can result in higher levels of carbon monoxide (CO) emissions. On the other hand, manifold injection involves injecting fuel directly into the intake manifold, downstream of the intake valves. This results in a more homogeneous mixture and fuel has more time to vaporise and mix with the air before it reaches the combustion chamber. This can result in lower levels of CO emissions. The HCCI engine produces higher CO emissions compared to CI engines due to factors such as incomplete combustion and rich air–fuel mixtures. The rich mixture limits the availability of oxygen, hindering complete oxidation and resulting in increased CO emissions. Lower combustion temperatures in HCCI engines contribute to slower combustion rates and reduced time for complete carbon oxidation, further elevating CO emissions. Additionally, the possibility of premature ignition or knock can lead to incomplete combustion [11,19,24].

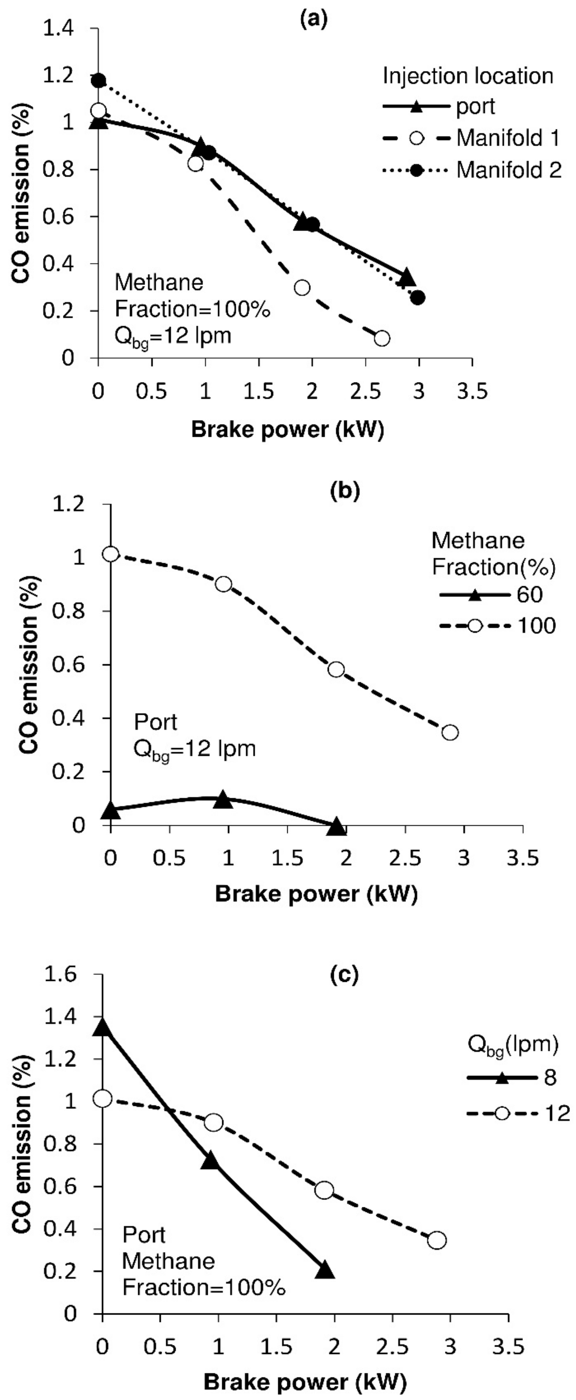


Figure 7. Effect of (**a**) injection location, (**b**) methane fraction and (**c**) biogas flowrate on CO emission.

4.7. Smoke Emission

Figure 8a illustrates how the position of DEE injection affects smoke emissions. As previously mentioned, locally rich areas are created during DEE port injection, resulting in higher smoke emissions. When brake power increases, there is more DEE consumption, leading to an increase in smoke emissions. In addition, insufficient air supply is responsible for increased smoke emissions with an increase in methane concentration and biogas flow rate, as depicted in Figures 8b and 8c, respectively. However, it should be noted that HCCI operation produces significantly lower smoke emissions than conventional diesel operation. Port injection directly injects fuel into the engine's intake port, which can lead to uneven fuel distribution among the cylinders. This can result in incomplete combustion and higher smoke emissions. In HCCI engines, fuel must vaporise quickly in order to mix with air in the combustion chamber and ignite correctly. With port injection, there is less time for fuel to vaporise before it reaches the combustion chamber, leading to incomplete combustion and higher smoke emissions. With manifold injection, fuel is injected directly into the combustion chamber at the appropriate time during the combustion cycle. In contrast, port injection makes it more challenging to control the timing of fuel injection, which can also lead to incomplete combustion and higher smoke emissions.

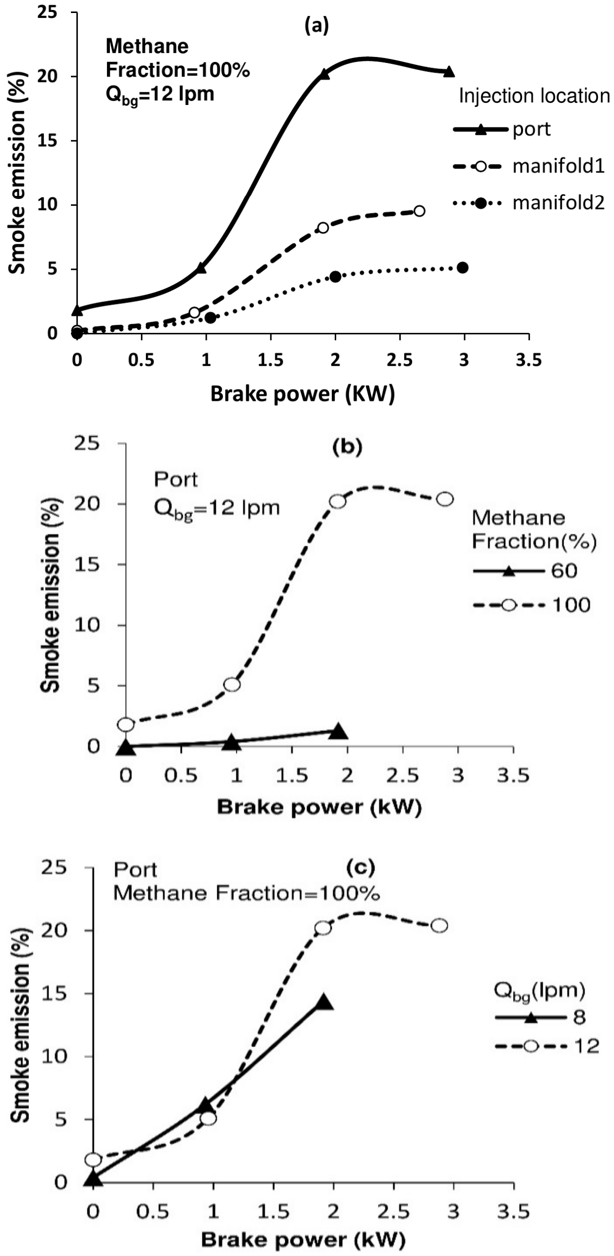


Figure 8. Effect of (**a**) injection location, (**b**) methane fraction and (**c**) biogas flowrate on smoke emission.

4.8. NOx Emission

Firstly, NOx emissions in a CI engine can be influenced by biogas flow rate. When more biogas is introduced into the engine, the combustion temperature rises, resulting in increased NOx emissions. This is due to the fact that higher combustion temperatures promote the formation of NOx. Secondly, NOx emissions can also be affected by the methane fraction in biogas. While methane burns more cleanly than other hydrocarbons and produces lower CO_2 emissions, it can produce higher NOx emissions due to its high combustion temperature. Thus, an increase in the methane fraction can result in higher NOx emissions. Lastly, the injection location in an HCCI engine can also impact NOx emissions. The location of fuel injection refers to where the liquid fuel is injected into the engine. Injection near the cylinder walls can lead to higher NOx emissions due to increased combustion temperature, while injection near the center of the cylinder can lead to lower nOx emissions due to better mixing and lower combustion temperatures [29]. However, HCCI operation is characterised by low-temperature combustion due to multipoint ignition and, as a result, NOx emissions were close to zero in most cases and are therefore not displayed in the plot. A comparison of emissions for various modes is shown in Table 4.

Table 4. Comparison of HC, CO, NOx, and smoke emissions for diesel, dual fuel, and HCCI modes [29].

Engine Mode	HC Emission (ppm)	CO Emission (%)	NOx Emission (ppm)	Smoke Emission (%)
Diesel-only	50–100	0.08–0.16	36–929	32–60
Dual fuel (8 lpm of biogas with 100% methane)	235–449	0.14–0.22	42–760	22–40
***HCCI* (8 lpm of biogas with 100% methane)**	200–850	0.2–1.4	0–5	0–22

5. Conclusions

The conclusions of the study are summarised as follows:

- The selection of intake parameters and injection location in the DEE were crucial in achieving the desired outcomes.
- The efficient management of methane quantity and biogas flow rate was successfully achieved.
- The performance evaluation across critical levels focused on the emission characteristics of the HCCI engine.
- At 1800 rpm, port injection demonstrated superior thermal efficiency compared to manifold injections.
- Manifold injections resulted in lower emissions, including reduced smoke and NOx, compared to conventional methods.
- Increasing the biogas flow rate had the potential to enhance the maximum operating load limit by reducing knock, albeit with a slight decrease in thermal efficiency.

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