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Review

Syngas application in various engines

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Abstract: Current engines are not designed to use syngas as fuel, which presents challenges such as differences in air-to-fuel ratio and fuel properties compared to traditional fuels like gasoline and diesel. This research recommends applying dual combustion, regulating pressure rate, using catalysts and employing EGR (exhaust gas recirculation), in order to improve engine efficiencies while reducing emissions. This study concludes that syngas is more effectively utilized in diesel and HCCI engines (homogeneous charge compression ignition) than in gasoline engines due to the cycle variations impacting efficiency. With technological advancements, syngas and other alternative fuels can be developed to reduce emissions and production cost, justifying their implementation.

***Keywords*:** Syngas; engine; HCCI; emission; compression ratio

1. Introduction

More attention has been paid to solar and wind energy as renewable sources, while biomass, particularly biogas (obtained from a biochemical process), is often overlooked. Another alternative, syngas (obtained from a thermochemical process), has not received the same level of attention despite its potential. This study aims to highlight the benefits and applications of syngas as a valuable renewable energy source. Biofuels are considered a future alternative for internal combustion engines, offering potential for reduced emissions, such as NOx, and aiding in knocking tendency reduction [1]. The primary technical challenge for gas fuels in internal combustion engines is the presence of tar in the combustion chamber. Despite internal combustion engines being more tolerant to contaminants compared to gas turbines, high tar concentration could lead to frequent breakdowns if not properly cleaned or reduced. This challenge may be exacerbated in direct injection engines due to the small injector nozzle diameter, potentially causing nozzle blockage [2]. Unfortunately, research on the use of syngas/producer gas in internal combustion engines has been hindered by gas variation [3]. According to Maniatis et al [4], the use of producer gas in internal combustion engines shows high market potential and technological feasibility, but tar removal is a prerequisite before usage. The aim of this study is to evaluate gaseous fuel produced through thermochemical processes such as syngas and producer gas, as an energy alternative for use in Otto, Diesel and HCCI engines. The main contributions of this study include analyzing the critical performance parameters of engines running on these gaseous fuels, particularly syngas and producer gas. Furthermore, this study poses strategies to enhance engine efficiency with these alternative fuels and explores various options to mitigate or reduce emissions.

2. Syngas Applied in Internal Combustion Engines

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Gaseous fuels, in general, are considered suitable for internal combustion engines due to their ease of forming a mixture with air [5]. According to Myounghoo et al [6], when an engine operates at a low load, it is difficult to achieve the stoichiometric air-fuel ratio due to poor feed, which is a common issue with engines running on alternative gases. Improving the design of engines intended for gas producer operation requires considerations such as injectors, compression ratio, ignition advance, and combustion chamber design (Figure 1) to achieve better dual-fuel engine performance [7]. The main requirement of any gaseous fuel for dual combustion engines is ensuring that the air-fuel mixture is adequate. This can prevent issues such as early ignition, high pressure increase rate, high peak pressure, and overheating of the cylinder walls [8]. The use of catalysts has proven to be an effective way of obtaining quality gas mixtures, improving performance and reducing emissions [9]. Additionally, the maintenance cost for engines using gaseous fuels are lower than for gasoline or diesel engines because gaseous fuels reduce carbon deposits and do not mix with lubricants, maintaining viscosity [10].

According to Colorado et al [11], they analyzed a trigeneration system (producing electricity, cold water, hot water) using an internal combustion engine powered by biomass gas. They concluded that adapting a fixed bed gasifier to a compact cogeneration system is a viable energy alternative to meet the energy and thermal demands of rural areas.

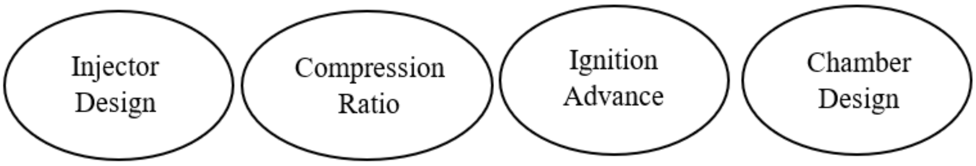

Figure 1. Engine Parameters Influencing Gaseous Fuel Performance

Ignition delay is a critical parameter that affects any gaseous fuel due to longer delay periods, which are unacceptable as increased thermal pressure can lead to knocking issues [12]. Therefore, syngas faces a greater challenge as it must adapt to specific engine characteristics, requiring modifications to the combustion system and engine control [13].

2.1 *Syngas Applied in Gasoline Engines (SI)*

The slower combustion of the gasifier and low heating speed result in tar formation [14]. This tar causes corrosion in SI engine components and equipment, leading to a mixture of soot and ashes with traces of tar and steam, causing wear on engine components [15]. This leads to high HC and CO emissions, as well as a 20-30% reduction in power when using producer gas [14], therefore, it is necessary to minimize the amount of tar produced. According to Hasler et al [16], a 90% reduction in tar in the cleaning system is necessary for satisfactory internal combustion engine operation. The use of syngas in SI engines has been limited to carbureted and port-injected engines [17]. However, these engine types are not suitable for gaseous fuels due to their lower volumetric efficiency, resulting in power loss. New research suggests that syngas should be fed into a direct injection (DI) SI engine to achieve improvements in HC and CO reductions, obtaining combustion and performance characteristics comparable to engines fueled with compressed natural gas (CNG) [18]. Nevertheless, higher Brake Specific Fuel Consumption (BSFC) and a limitation on injection duration with late injection times can be observed with syngas. These restrictions lead to a limitation in the air-fuel stoichiometric ratio, limiting maximum brake power, all attributed to the low calorific value of syngas [18]. The combination of synthetic gases with traditional fuels can result in stable combustion, even when 80% of the traditional fuel is replaced by gaseous fuels [19].

2.1.1 *Efficiency of Syngas in SI Engines*

The challenge of using a lower calorific value gas like syngas leads to a lower heat release rate and, consequently, unstable combustion, resulting in lower engine efficiency and larger cycle variations. These cyclic variations in the combustion process are significant, causing power losses and limiting engine operation. Additionally, faster-burning cycles are more prone to knocking, potentially limiting the compression ratio [20]. SI engines fueled with pure methane instead of gasoline experience a reduction in maximum power of around 10-20%. This power loss can be compensated by increasing the engine compression ratio [21]. However, if the compression ratio is too high, engine power can lead to detonation. To ensure normal engine ignition, the compression ratio, for example, in the case of coke oven gas, should not exceed 12 [22]. According to Muñoz et al [23], tests on SI engines with producer gas resulted in a 50% reduction in power compared to using gasoline.

Similar work by Dasappa et al [24], experimented with a 100 kW SI engine with producer gas for over 1000 continuous hours with a compression ratio of 8.5, resulting in a 45% reduction in overall maximum efficiency of 18%. In the study presented by Brusca et al [25], a mixture of acetylene and alcohol in a single-cylinder, 4-stroke SI engine with 2 injectors showed a 25% decrease in engine performance compared to gasoline. They asserted that CO, HC, and NOx emissions decreased when using acetylene and alcohol compared to gasoline. Applying SI engines with gaseous biofuels may have deficiencies in both performance and emissions generation. Strategies proposed by Sridhar et al [26], such as modifying a diesel engine into an SI engine, successfully tested gaseous fuel operation by increasing the compression ratio to 17:1 without causing detonation. This compression ratio criterion may vary according to each author's judgment, as shown in Table 1, demonstrating that the compression ratio criterion can vary, possibly due to the variability of the fuel gas compression, which is not constant by nature [27]. Sridhar et al [26] noted that power loss is similar to dual-fuel engines but with lower CO emissions. However, they found that higher compression ratios also lead to increased NOx emissions, which could be moderated by modifying the spark timing. Table 2 presents strategies to improve gaseous fuel in SI engines.

Table 1. Highest Compression Ratio Without Detonation Using Gaseous Fuels

Suggested Compression Ratio	Reference
Up to 17:1	[26]
Should not increase beyond 13:1	[28]
Should not exceed 12:1	[27]

Table 2. Methods to mitigate the deficiency of CO_2 presence of syngas in SI engine

Strategy	Lean Conditions	Reference
Small amounts of biogas	Yes	[29]
Blend of synthesis gas with gasoline	Yes	[30]
CO_2 reduction	Yes	[31]
Utilization of lean combustion while maintaining a stoichiometric air-fuel ratio	No	[32]
Higher compression ratio for increased efficiency	No	[28]
Spark timing modification	No	[26]
Use of a gas carburetor with appropriate design	No	[33]

2.1.2 *Emission Generation in SI Engine*

To reduce NOx emissions when using gaseous biofuels, specific strategies are required for their reduction, such as delaying the spark ignition timing in the SI engine. However, this may be accompanied by a reduction in the thermal efficiency of the engine and, at the same time, an increase in HC emissions [28]. Establishing a standard for NOx reduction strategies for lean fuels is challenging [34]. Table 3 shows the relationship between the type of fuel and the generated emissions. Syngas has two main forms of emission generation due to its low calorific value (lean gas). Unburned syngas can generate CO, and incomplete combustion of syngas hydrocarbons can also lead to HC emissions [35].

Table 3. Type of Gas and Emission Generation

Gas type	Generated	Reduces emission	Increases emission	Reference
Synthesis Gas	Gasification	CO	-	[36]
Biogas	Fermentation	NOx	HC	[34]
Producer Gas	Agricultural and municipal waste	-	HC and CO	[37]
Biogas	Natural Gas with added CO_2 (simulated biogas)	NOx	CO	[32]

The high costs associated with exhaust gas treatment, such as Selective Catalytic Reduction (SCR) and oxidation catalysts, pose challenges for their development. However, SI engines allow the use of three-way catalysts, which can be effective in reducing NOx, HC, and CO with affordable costs [38].

2.1.3 *Application of Gaseous Fuels in Dual-Fuel SI Engine*

A Flexible Fuel Vehicle FFV) or a dual-fuel combustion vehicle, such as an alternative fuel car or light-duty truck, is equipped with a multi-fuel engine capable of using more than one fuel, typically blended in the same tank. The mixture is burned in the combustion chamber, and these vehicles are known as flex-fuel vehicles. FFVs differ from biofuel vehicles in that the latter store fuels in separate tanks [39]. Biofuel vehicles come equipped with two fuels, meter, and a switch to transition from fuel gas to gasoline as desired by the driver. This type of engine development is based on conventional gasoline engines where the fuel system has been modified to operate as either gasoline or gas. Most of these kits are unable to fully utilize the potential of gaseous fuel for spark ignition, resulting in a performance of 14–18%, which is less compared to gasoline with an efficiency of 20% [10].

In the work of Lemke et al [40], they adapted a 2009 Chevrolet gasoline truck to use biomethane and gasoline in biofuel mode. Regarding emissions, they observed an increase in HC levels but a reduction in CO_2, NOx, and CO. They also noted a slight reduction in fuel savings and a decrease in performance, although not significant. In the study by Vural et al [41], they used acetylene gas in an SI engine with gasoline. The experiments were conducted between 1600 and 3200 rpm, increasing in 400 rpm increments. They observed a decrease in CO, CO_2, HC, and NOx emissions in dual-fuel mode. Figure 2 illustrates the operation of acetylene as fuel in an engine.

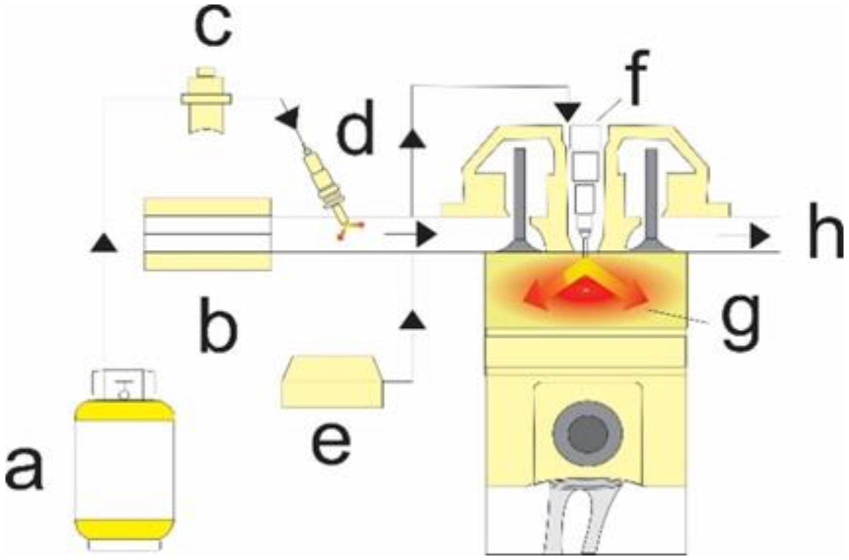

Figure 2. Acetylene Engine Operation; a) Acetylene gas, b) Air filter, c) Pressure regulator, d) Acetylene gas injector, e) Combustion analysis, f) Diesel injector, g) Combustion, h) Exhaust outlet

2.2 *Syngas Applied in Diesel Engines (CI)*

Diesel engines offer better durability and, in some cases, require less maintenance than spark ignition engines. This is due to the high compression ratio and low speeds; the reduction in diesel engines running on producer gas ranges between 15-30%, which is significantly higher compared to SI engines, even when SI engines are used in dual-fuel mode. The efficiency remains lower [42].

2.2.1 *Operating CI engine conditions in Dual-Fuel*

A simple diesel engine can be transformed into a dual-fuel diesel engine by connecting it to a gas mixer with an intake manifold. It is also necessary to install a fuel control mechanism to limit the supply of liquid fuel. The engine's output power is typically controlled by varying the flow of the gaseous fuel, allowing for a substitution of diesel fuel of up to 85%. The use of gaseous fuel as the primary fuel in the engine is shown in Table 4, indicating the percentage of gaseous fuel based on its type. The most notable feature of dual-fuel combustion is the ability to switch from dual-fuel mode to diesel mode almost simultaneously in case of a shortage of the primary fuel [43]. According to Kapadia [44], who analyzed two different fuel supply methods, with a premixed gas supply to the engine's manifold, the results showed high overall efficiency at power levels up to 1.4 kW using a gas injection manifold [45]. The use of gaseous fuel along with injected fuel in a dual-fuel combustion engine leads to more complex combustion due to the involvement of two fuels with different properties burning simultaneously within the engine cylinder [46].

Dual-fuel engines are known for their fuel savings and reduced smoke and NOx emissions. However, some researchers have reported lower performance and increased HC and CO emissions when using producer gas [7,47].

The benefits of dual-fuel operation include combustion stability and, consequently, engine performance, regardless of fluctuations in gas composition [48]. Additionally, the power reduction caused by the low heating value is less compared to using syngas as the sole fuel [36]. The performance of dual-fuel diesel engines has been found to be nearly equal to that of using only diesel fuel, as long as the calorific value of the gaseous fuel is not too low [49]. It is known that at lower loads, dual-fuel operation tends to exhibit poor thermal efficiency, lower fuel utilization, a prolonged ignition delay, and higher emissions attributed to the low ignition capacity of gaseous fuels [50]. Low-speed engines are recommended for dual-fuel operation due to their slow combustion characteristics and lower combustion speed of the producer gas [7]. The performance of dual-fuel engines under light load conditions shows less fuel utilization, low thermal efficiency, higher pollutant emissions, and a long ignition delay [51]. Dual-fuel operation with producer gas is simple, and power reduction is limited to 20-30%. Dual-fuel operation is an effective alternative for the application of renewable fuels, with reported diesel savings of up to 70-90% [19, 52]. According to Banapurmath et al [53], a power reduction of 20-30% was reported in dual-fuel mode with producer gas. The main disadvantages of dual combustion are the negative impact on engine efficiency and CO emissions compared to normal diesel operation [54]. Spaeth [55] compared the performance of a CI engine in dual-fuel mode fueled with synthesis gas and methane, concluding that the engine's performance with methane was better than with synthesis gas in dual-fuel mode. In another study presented by Rinaldini et al [56], they analyzed the potential of a turbocharged diesel engine with diesel and synthesis gas, finding that the use of synthesis gas not only reduces diesel consumption but also improves combustion quality. Finally, in Das et al [57] study, they investigated a slight drop in the average thermal efficiency from 32-35% to 28.7% in dual-fuel mode with biomass, concluding that dual-fuel mode with wood chips and corn cobs is comparable to diesel.

Table 4. Percentage of gaseous biofuel used in a dual-fuel diesel engine

Type of Biofuel	Percentage	Reference
Biogas	85%	[58]
Produce Gas	70-90%	[19, 52]
Producer Gas	50%	[59]
Producer Gas	85%	[26, 60]
Biogas	90%	[61]
Biogas	60%	[62]
Producer Gas	31%	[63]

2.2.2 *Pilot Fuel Characteristics in Dual-Fuel CI Engine*

In a dual-fuel combustion engine, the charge consists of gaseous fuel (primary fuel) and air. However, due to the poor ignition quality of the gaseous fuel, a compressed mixture of air and gaseous fuel does not ignite automatically [64]. To address this issue, a small quantity of diesel, known as pilot fuel, is injected. This injected pilot fuel auto-ignites and becomes the ignition source for the induced gaseous fuel. One of the significant advantages of dual-fuel engines is their ability to use a wide variety of gaseous fuels without modifying the engine [65]. However, challenges may arise in terms of high emissions of HC, CO, and NOx [66]. Liquid fuel can be injected by conventional diesel injection equipment, contributing a small fraction to the engine's output power [67]. Nonetheless, pilot fuel has a substantial influence on dual-fuel combustion as it initiates the combustion process [43]. The required quantity of pilot diesel fuel for ignition ranges between 10% and 20%, and the formation of NOx increases relative to the pilot fuel quantity [68]. According to Boloy et al [69], the combustion of diesel/biodiesel B_{20} in internal combustion engines increases CO_2 and particle emissions compared to the combustion of synthesis gas in the engine. Therefore, synthesis gas exhibits better environmental sustainability in fuel combustion. In the analysis by Choudhary and Nayyar [70], the optimization of acetylene gas flow rate in a diesel engine was studied, and their research concluded that combustion, performance, and emission parameters are optimized with an induction flow rate of 7 L per hour. In Sharma et al [71] study, experiments were conducted on a diesel engine using acetylene and ethanol. The study aimed to reduce the temperature within the combustion chamber, and it was expressed that acetylene is a good alternative fuel for internal combustion engines.

2.2.3 *Speed and Load Characteristics in CI Engine*

Research studies [53, 72] have reported that, under dual-fuel operation, poor utilization of gaseous fuel occurs at low loads, resulting in lower engine performance and higher CO emissions compared to normal diesel operation [53]. However, under high load conditions, thermal energy is mainly released from gaseous combustion, allowing for efficient energy utilization [8]. Therefore, dual-fuel engines are technically suitable for operating under high loads, providing high thermal efficiency and low emissions [67]. The use of synthesis gas in dual-fuel mode in CI engines shows positive impacts on reducing emissions such as CO and NOx but negative impacts in terms of lower brake power and increased emissions like HC compared to the behavior of normal diesel [12]. Lean stratified charge combustion is an effective way to enhance syngas for engine technology, but care must be taken regarding power limitation due to its limited injection duration [18]. According to Ramadhas et al [52] and Ramadhas et al [60], the use of diesel-syngas in dual-fuel mode reduces emissions of NOx, HC, and smoke, although CO emissions increase, with a considerable decrease in efficiency detected at partial loads.

2.2.4 *The conditions of the intake manifold, injection, and compression ratio in a CI engine*

Converting an engine to operate in dual-fuel mode generally has the potential to reduce its power output. To minimize this power loss, the heating value of the air and gas mixture can be increased by increasing the compression ratio, advancing the injection synchronization, or both, all of which help minimize power loss [2]. HC and CO emissions are also higher in dual-fuel operation, which can be addressed by advancing the synchronization of the pilot fuel injection and increasing the compression ratio, reducing HC and CO in dual-fuel combustion [73]. Gaseous fuel is mixed with intake air during the suction stroke of the dual-fuel CI engine, either by multiple injection or direct injection into the cylinder [74]. However, better thermal efficiency has been reported with advanced injection timing and increased injection pressure [47]. The stoichiometric mass ratio in the air/fuel mixture is between 1.0 and 1.2 compared to methane's 17, requiring appropriate mixing devices and dispenser (meters) for the engine to operate at high performance. Conventional carburetors are suitable for high-calorific gases, forming a mixture with a high stoichiometric ratio. However, modified carburetors are required for low-calorific gases [75]. The increase in emissions in the engine is a problem in both gas and air supply, depending on the vacuum created by the engine. If the air intake is reduced, it will have a negative impact on the combustion process as oxygen availability decreases. Another way to solve the emission increase problem is to reduce the nitrogen content in the producer gas [76]. To improve the combustion efficiency using synthesis gas, Roy et al [77] recommend that the influence of intake pressure (101–200 kPa) can enhance combustion in a dual-fuel gas pyrolysis engine with micro-pilot ignition. Research indicates that higher indicated mean effective pressure (IMEP) with an intake pressure of 200 kPa improves thermal efficiency.

2.3 *Gaseous Biofuel in HCCI Engine*

A promising alternative combustion process is the Homogeneous Charge Compression Ignition (HCCI) engine, which achieves auto-ignition with a very lean and homogeneous air-fuel mixture. Auto-ignition occurs in various regions of the combustion chamber, resulting in the absence of a flame [78]. The lean and homogeneous charge leads to low emissions of NOx and smoke, allowing for high combustion efficiency due to simultaneous combustion in different regions of the chamber. As a result, HCCI engines can achieve high thermal efficiencies [79].

2.3.1 *The HCCI engine and its flexibility in using alternative fuels*

The adaptability of the HCCI engine to a wide variety of fuels enables it to operate with any fuel, as long as the fuel can evaporate and mix with air before ignition [80]. This flexibility makes HCCI engines highly promising. HCCI combustion occurs at high compression ratios but requires measures for controlled auto-ignition in fuel/air loads to prevent excessive pressure rise leading to engine knock. Strategies that can be applied include preheating the intake charge [81], variable compression ratio [82], external and internal Exhaust Gas Recirculation (EGR) [82, 83], external and internal fuel reforming [83] and variable valve timing (VVT) [81].

2.3.2 *Challenges in the HCCI Engine*

Fuel feed engines HCCI with producer gas is an attractive proposition due to the low calorific value of alternative gas. However, the presence of undesirable particles such as tars, nitrogen compounds, and alkalis poses a problem in all producer gas applications. The concentration of tars, in particular, can lead to deposits on engine components (intake manifold, valves, piston crowns, and cylinder walls), reducing engine capacity and performance [84]. One major challenge in HCCI engine application is that combustion can become excessively rapid, causing knock [85]. High combustion rates have been observed at high loads, limiting the operational range of HCCI engines [86]. Combustion cannot be achieved at low loads due to the use of lean mixtures and the low temperatures prevailing in the combustion chamber. Therefore, the range of loads where HCCI combustion can occur is limited [5]. The disadvantage of the HCCI engine is that it may result in increased CO and HC emissions. It also faces difficulty in controlling auto-ignition and combustion duration at various speeds and engine loads, leading to a decrease in power output [87]. While the HCCI engine has high potential for application in gaseous fuels, practical use requires ignition timing control and operational control to ensure durability, aspects that are yet to be thoroughly investigated [88].

2.3.3 *Efficiency and Emissions in HCCI Engine*

The HCCI engine is an evolving technology that reduces NOx emissions and operates with efficiencies close to diesel engines. HCCI homogeneously mixes air and fuel, which ignites through compression, resulting in low combustion temperatures [87]. Low-temperature combustion leads to low NOx levels and minimal soot formation. Additionally, higher thermal efficiencies are expected due to the high compression ratios it operates with. Another benefit of the HCCI engine is its ability to burn a large quantity of low calorific value fuels [89]. According to Haggith et al [90], applying producer gas (wood gas) in an HCCI engine results in stable combustion, achieving a wide range of loads. They concluded that with this fuel and engine combination, it could be an acceptable alternative.

3. Conclusions

It has been documented that technological development significantly influences the application of synthetic gas and syngas. For example, the advantages of using direct injection over port injection, where the limitations of syngas low calorific value can be solved with a combination of other fuels, whether traditional or alternative. This study highlights the importance of developing strategies that reduce emissions and improve engine efficiency with alternative gaseous fuels. As well as ensuring optimal engine behavior, including normal ignition, compression ratio and emission reduction, is crucial. For future research, it is recommended to perform a cost-benefit analysis, where the cost represents the expense of producing higher quality of syngas and the benefits represents the reduction of CO and HC emissions. Another topic of great relevance is the design of the engine based on dual combustion. Future research should consider the design of the combustion chamber and injectors. Additionally, a study on solutions for minimizing heat losses in thermal engines, which can lead to energy and power loss and increased gaseous fuel consumption, would be valuable.

Conflict of interest

There is no conflict of interest for this study.

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