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Strategies to achieve controlled auto-ignition (CAI) combustion: A review

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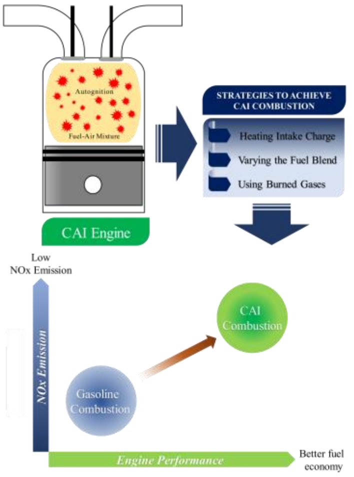

Highlights:

- A comprehensive review of controlled auto-ignition (CAI) was discussed.
- The comparison of CAI and homogeneous charge compression ignition (HCCI) and its differences were reviewed.
- The several strategies to achieve CAI combustion were highlighted to meet the emissions target while maintaining engine performance.

Abstract

Conventional gasoline engines suffer from low performance and NOx emissions. Controlled auto-ignition (CAI), sometimes referred to as homogeneous charge compression ignition (HCCI), is a promising concept to solve such problems. CAI has the potential to improve spark ignition (SI) engine fuel economy while at the same time solving the trade-off of NOx-soot emissions found in compression ignition (CI) engines. The CAI engine can reach a fuel economy comparable to that of a conventional diesel engine with ultra-low NOx and negligible soot emissions. However, controlling auto-ignition remains the biggest difficulty that hinders the implementation of CAI as a commercial engine. Research towards a cleaner and more efficient engine is driven by the progressively stringent emission regulation imposed worldwide. Therefore, the CAI was developed to meet the emissions target while maintaining engine performance. CAI works on the principle of lean mixture and auto-ignition. To obtain CAI combustion, the temperatures in the cylinder must be sufficient to initiate auto-ignition. Without the use of a spark plug or injector, the CAI suffers from a direct control mechanism to start the combustion. The most practical approach to controlling the initiation of auto-ignition in CAI is diluting the intake charge by either trapping the residual gas or recirculating the exhaust gas. Both approaches enable the engine to achieve CAI combustion without requiring significant modifications to control the onset of CAI combustion phase.

Keywords: CAI; HCCI; Engine; Performance; Combustion; Emission

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Nomenclature

AFR	Air-fuel ratio	IVC	Intake Valve Closed
ATAC	Active-Thermo-Atmosphere Combustion	LTC	Low Temperature Combustion
bhp	brake horsepower	NO	Nitrogen Monoxide
CA	Crank Angle	NOx	Nitrogen Oxide
CAI	Controlled auto-ignition	NVO	Negative Valve Overlap
CI	Compression ignition	PAW	Progress Aero Works
CO	Carbon Monoxide	PFI	Port Fuel Injected
CVVT	Continuously Variable Valve Timing	PM	Particulate matter
DI	Direct Injection	PPCI	Partially Premixed Compression Ignition
DME	Dimethyl Ether	PVO	Positive Valve Overlap
EGR	Exhaust Gas Recirculation	RCCI	Reaction Controlled Compression Ignition
EMS	Engine Management System	rpm	rotation per minute
HC	Hydrocarbon	SACI	Spark-Assisted Compression Ignition
HCCI	Homogeneous charge compression ignition	SI	Spark ignition
ICE	Internal combustion Engine	TDC	Top Dead Center
IMEP	Indicated Mean Effective Pressure	VCR	Variable Compression Ratio

1. Introduction

Fuel cell, electric and hybrid vehicles have emerged as promising technologies that can achieve that ultimate goal [1], [2]. The technological features that must be enhanced to fully enable the markets include performance, environmental issues and price. The issue has addressed the status of clean energy technologies, with a focus on the obstacles that still need to be overcome [3]. However, in the short and medium term, such technologies are highly unlikely to meet the aforementioned goal [4], [5].

The ICE is more likely to meet the emission target [6]. In a diesel or CI engine, in addition to NOx, the typical high PM emissions need to be reduced by several techniques, such as changing injection pressure [7], using alternative fuels [8] and adding nanoparticle additives [9]. To comply with the emissions regulation, using PM filters is sometimes necessary [10], [11]. The filtration system and catalysis grow in demand and represent research opportunities. Despite the fact that the current filtration system has a high-efficiency percentage, the remain of emissions are not being treated, and there is still area for development [12]. The investigation of emissions is still the main problem in advancing technology [13]. It was shown that only an efficient approach to overcome emissions with advanced technologies would retain their importance and enable truly cleaner ICE, which will satisfy the emission standards [14].

To reduce both NOx and PM emissions, the NOx after treatment and the PM filter can be used, but it comes with a penalty for fuel consumption [15]. Developing novel combustion technologies for ICEs is the most effective solution to meet recent emission limits and environmental concerns. Also, both the thermal efficiency and fuel economy of engines have seen significant improvements as a result of recent technological advancements, such as CAI and HCCI.

Although its a relatively new combustion concept, CAI and HCCI have been investigated since the 1960s [16], [17]. Stringent emissions levied in the mid-1990s have triggered renewed interest in CAI and HCCI combustion. **Figure 1** compares CAI with conventional gasoline or SI and CI engines. In diesel engines, some early 2-stroke and 4-stroke engines operate on the concept of premixed mixtures using early injection into the preheated chamber [18]. In the 1940s, Progress Aero Works (PAW) developed a small 2-stroke diesel model aeroplane fuelled with kerosene, oil, and ether blends [19]. The fuel blends flow into the intake through a carburettor, forming a mixture of air and fuel. To start the engine, the compression screw was used to set the engine to a higher compression ratio. Once the engine started, compression was unscrewed to obtain maximum power. The engine could produce 0.06 to 1.2 bhp at speeds from 10,000 rpm to more than 20,000 rpm using the concept of HCCI combustion.

In gasoline engines, although numerous studies mentioned that the first CAI engines were first systematically conducted by Onishi and Noguchi in the late 1970s [20], [21]. It was Nikolai Semenov, the Russian scientist, and his teams who initiated the theoretical and practical of CAI combustion in gasoline engines 40 years before Onishi [22]. They established the theory of ignition to control the combustion process of ICE. This is done to understand the ignition of SI and CI engines. In the 1970s, Semenov and Gussak et al. achieved controlled combustion using the LAG (avalanche-activated combustion) [23]. To control the heat release rate, a lean intake charge was used. It was supplied by a partially burned mixture at high-temperature discharge from a separate prechamber.

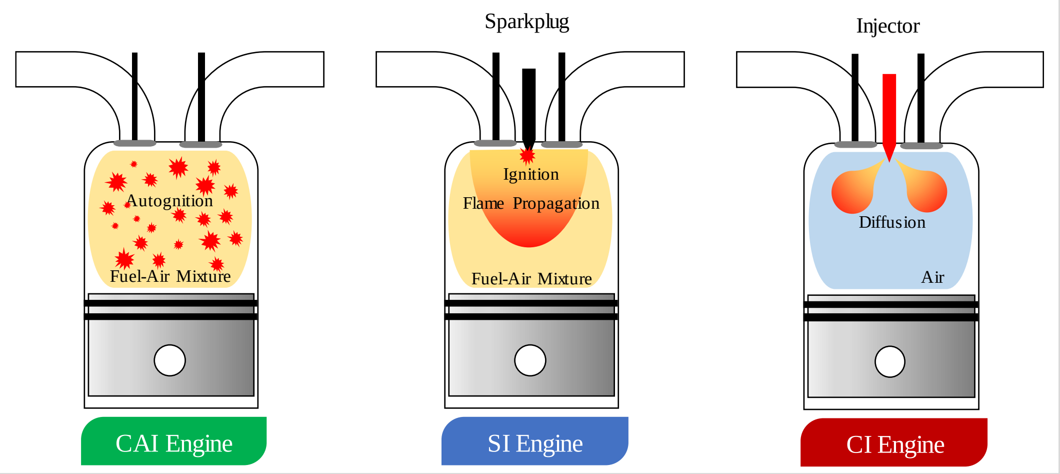

Figure 1. Comparison CAI, SI and CI engines

In other studies, Honda achieved the first automotive production of the CAI engine using the 2-stroke engine [24]. Honda successfully decreases fuel consumption and HC by almost a third and a half, respectively. This was done using residual gases whose thermal energy helps to ensure the CAI combustion. The success of the HCCI engine in 2-stroke gasoline engines triggered the research and development of its concept in 4-stroke engines. Najt and Foster initiated the CAI combustion in gasoline engines and Thring further explored the use of external EGR and the effect of AFR on performance [25]. Thring proposed the name HCCI, which would later be adopted by numerous researchers around the world [26].

As mentioned in the previous paragraph, the term HCCI was initially introduced by Thring, which is applied to both diesel and gasoline engines. Though, it is important to consider that in some literatures; the CAI is frequently used for gasoline engines exclusively. The term of CAI is more suitable for gasoline engines because their auto-ignition is not triggered by CI like diesel engines. Instead, auto-ignition is triggered by heating from the hot burned gases. Moreover, in reality, the term of homogeneous charge is an idealistic terminology; charge stratification is often observed, especially between the trapped burned gases and the air/fuel mixture. In reality, charge stratification is occasionally used to change auto-ignition and control the heat release rate in CAI engines [3]. The compression is not the only means to achieve the auto-ignition and to obtain the premixed air/fuel mixture, other factors also play a significant role, such as external or internally heating. Therefore, the CAI is often preferred for gasoline engines, whereas the term HCCI is used for diesel engines. For consistency's sake, this paper uses the term CAI instead of HCCI or HCCI-gasoline throughout this article to represent the use of auto-ignition combustion in gasoline engines. Several research groups have introduced numerous names for CAI or HCCI, such as PPCI, RCCI, and LTC [2]. In spite of its variety, the terminologies imply two basic philosophies: the auto-ignition of its combustion and the premixed of the air/fuel mixture.

CAI combustion is a promising concept to improve engine fuel economy while at the same time significantly reducing NOx emissions. Some studies have shown that CAI combustion has been successfully applied [21], [25]. The experimental and the simulation have been conducted by Wiemann et al. [27] with good agreement results without any frequent misfires. Cinar et al. [28] also investigated extending the operating range using low lift cams on knocking and misfiring operating zone at leaner AFR as inlet air temperature increased. Unlike previous studies, Calam [29] observed the effects of the new fusel oil blend usage with the successful result of increasing thermal efficiency, reducing NOx and extending operating range through the knocking limit. Hunich et al. [30], [31] focused on investigating the NVO approach and its effect on engine performance. However, some challenges of CAI have been faced and continuously investigated.

CAI combustion is triggered by auto-ignition rather than spark ignition and subsequent flame front propagation [32]. It attracted some attention in the field of research. One major difficulty in implementing CAI is the control of its auto-ignition. The idea of CAI was initiated over 30 years ago. However, some issues have not yet been solved. Considering the above discussion, the technologies now depend on previous findings and lead to future technologies. In spite of plentiful review papers have been published, strategies to achieve CAI combustion in gasoline engines were infrequently discussed comprehensively. Therefore, this paper aims to provide a brief CAI combustion so that the role of each strategy found in the literatures could be specifically understood. This paper employs the strategies to achieve CAI combustion by reviewing numerous recent studies of a gasoline engine. The review discusses a breakthrough in the development of

CAI engines, such as pioneering research in HCCI gasoline engines and the approach to achieve CAI combustion; several strategies to achieve CAI combustion. Each of the strategies is discussed in detail in different sub-sections. Moreover, different strategies and their effects are summarized.

Following the above discussion, this paper firstly sets breakthroughs in developing CAI engines, such as pioneering research in HCCI gasoline engines and the approach to achieve CAI combustion, in Section 2. Then, Section 3 elaborates on several strategies to achieve CAI combustion, such as heating the intake charge, varying the fuel blend and using burned gases. Lastly, Section 4 completes the paper with some conclusions and future research directions.

The literature reviewed in this study was selected by selecting relevant literature and extracting findings information. Databases such as Google Scholar, Web of Science, Science Direct, and Nature were searched using the following keywords: controlled auto-ignition, CAI and HCCI in a gasoline engine. The filter for document type was set to “Article” and “Review”. Furthermore, reference lists were examined for specific selection, and the research considered old and recent relevant literature. Then, by listing a set of ideas, we extracted findings from the selected literature, such as the difference between CAI and HCCI, the pioneering research on CAI/HCCI engine, the development, strategies to get CAI combustion and further research. Considering that the literature we reviewed is mainly based on CAI/HCCI combustion, we also provide a brief overview of the development history.

2. Breakthrough in The Development of CAI Engine

The first successful CAI experiment in a four-cylinder engine was conducted by Stockinger et al. [33]. They used a higher compression ratio and intake air preheating to ensure auto-ignition. It was found that the HCCI combustion could be achieved, but only at a very limited speed and load. In the late 1990s, Olsson et al. [33] successfully performed HCCI combustion in a 12-litre 6-cylinder engine. This was the largest gasoline engine with HCCI combustion, but the engine was based on a diesel engine. They used a number of combined approaches, i.e. using isooctane and heptane via a closed-loop control, turbo-charging, high compression ratio, and intake air heating. Auto-ignition was found to be effectively achieved for a wide range of speed and load.

Although previous studies found that CAI was successfully implemented in 4-stroke engines, it is not considered practical, as it requires external charge heating and a high compression ratio or fuel blends. In the 2000s, Lotus and Volvo found that HCCI combustion of 4-stroke gasoline engines could be achieved by closing the exhaust valve early using fully flexible variable valve actuation systems [25]. This approach is known as the NVO. Another approach proposed by IFP and Brunel University that successfully achieved CAI combustion in a 4-cylinder engine for a decent range of speed and load is by modifying the camshafts [34]. The most popular approach to CAI combustion in gasoline engines may be residual gas trapping and exhaust gas recirculation. Both are used to start and control the combustion phasing with no major modifications needed.

2.1. Pioneering Research in HCCI Gasoline Engines

Research in HCCI was started in the late 1960s. Initially, it was developed to solve several problems in the load conditions of the parts of a two-stroke engine. These problems include unstable, irregular, and incomplete combustion that results in a large amount of unburned hydrocarbon. The irregularities of combustion and auto-ignition were considered to be the limitation of a two-stroke engine. The research was carried out on lean two-stroke combustion with part load by Souk Hong Jo and Nippon Clean Engine (NiCE) [35]. They found that both irregularities in combustion and auto-ignition could be successfully controlled.

Later in the late 1970s, Onishi and Souk Hong Jo achieved stable combustion under part load conditions for lean mixtures without using a spark plug [36]. They found improved fuel efficiency, exhaust emissions, noise, and vibration. Since the spark plug was not required, the flame front did not exist. This new combustion process was named ATAC. In the same year, Noguchi published a paper with the same concept of two-stroke auto-ignition. He and his teams named it the TS (Toyota-Soken) combustion process [37]. Significant improvements in efficiency and emissions were achieved without the flame front. Interestingly, they are the first research group to propose using residual gases to control the auto-ignition process.

In the 1990s, Ishibashi experimented with two-stroke motorcycle engines to study the combustion process of auto-ignition [38]. He found that auto-ignition can be controlled by adjusting the amount of active residual gases both in the cylinder and in the cylinder pressure before compression. This was achieved using an appropriate charge control exhaust valve, which combined variable exhaust port timing with exhaust throttling. Ishibashi named this AR (Activated Radicals) combustion.

In gasoline engines, although numerous studies mentioned that the first HCCI gasoline engines were first systematically conducted by Onishi and Noguchi in 1979. Nikolai Semenov, the Russian scientist, and his teams initiated theoretical and practical combustion of HCCI in gasoline engines 40 years before Onishi [39]. They established the theory of ignition to control the combustion process of internal combustion engines. This is because the physical combustion process has some limitations to fully understanding the ignition of SI and CI engines. In the 1970s, Semenov and Gussak et al. were able to achieve controlled combustion using the LAG (Lavinia Aktivatisia Gorenia) or in English known as Avalanche Activated Combustion [40], [41]. To control the heat release rate, a lean intake charge was used. It was supplied by a partially burned mixture at high-temperature discharge from a separate prechamber.

Honda achieved the first commercial automobile production of HCCI in gasoline engines using the 2-stroke engine [38]. Honda successfully decreased fuel consumption and HC by almost a third and a half, respectively. This was done using residual gases whose thermal energy helps to ensure the combustion of HCCI. The success of the HCCI engine in 2-stroke gasoline engines triggered the research and development of its concept in 4-stroke engines. Najt and Foster initiated the combustion of HCCI in gasoline engines [42] and Thring further explored the use of external EGR and the effect of AFR on performance [43]. In this study, Thring proposed the name HCCI which will later be adopted by numerous researchers throughout the world.

In the 2000s, Lotus and Volvo found that HCCI combustion of 4-stroke gasoline engines could be achieved by closing the exhaust valve early using fully flexible variable valve actuation systems. This approach is known as negative valve overlap [26]. Another approach was proposed by IFP and Brunel University that successfully achieved HCCI combustion in a 4-cylinder engine for a decent range of speed and load by modifying the camshafts [26].

2.2. Approach to Achieving CAI Combustion in Gasoline Engines

The biggest advantages of utilizing the concept of HCCI combustion in a gasoline engine are improved fuel economy and ultralow NOx emissions. However, it suffers from a narrow operating range. To adopt the HCCI combustion entirely, its operating range must be significantly extended. Note that control of the closed loop in real time and switching between conventional SI combustion and HCCI combustion are also critical. The most popular approaches to HCCI combustion in gasoline engines found in the literature are residual gas trapping and exhaust gas recirculation. Both are used to start and control the combustion phasing, with no major modification needed.

Residual gas trapping works by closing the exhaust valve relatively early to trap residual gas. Then large amounts of burned gases were trapped inside the cylinder during exhaust stroke. To prevent such gases from circulating into the intake manifold, the intake valve should be opened after the TDC. Therefore, this approach is also known as NVO. Since the charge temperature of the trapped gas is relatively high, the NVO approach could be used to extend the HCCI combustion for a low-load operating range. However, high loads can result in well-advanced ignition, where the pressure rise rate is very fast. Thus, the use of EGR is preferable in high-load conditions. Khameneian et al. [44], [45] proposed a dynamic model to examine the in-cylinder mixture temperature at different conditions such as IVC, as well as mass of trapped air and residual gas. The application of wet ethanol has introduced by Lanzanova et al. [46] to investigate the effects of residual gas trapping, which was equipped with a fully variable electro-hydraulic valve train. Other influenced parameters, such as pressure, performance and emission, were estimated by Khoa et al. [47] to investigate the internal exhaust residual gases recirculation. Maldonado and Kaul [48] evaluated the effectiveness of capturing the impact of misfires and partial burns on the residual gas estimate for high-EGR operation.

Another well-established approach to achieving HCCI combustion in gasoline engines is the use of EGR. Numerous investigations have discussed the use of EGR for HCCI combustion in gasoline engines. Parthasarathy et al. [49] analyzed the performance of engine powered by tamanu methyl ester with various inlet air temperature and exhaust gas recirculation ratios. Beside experimental investigation, numerical analysis has been analyzed. Ali et al. [50] studied a numerical analysis to control the combustion performance of a syngas-fueled HCCI engine using different piston bowl geometry and EGR. In addition, Rather and Wani [51], [52] also studied a numerical analysis on EGR temperature's effects on combustion and emissions performance. By the application of wet ethanol, Herzer et al. [53] observed the chemical kinetic mechanisms for combustion with EGR.

This method works by recirculating the exhaust gases back to the cylinder. There are two strategies in EGR, the first is the internal EGR and the second is rebreathing. The internal EGR method through PVO is used to recirculate the exhaust gases. However, to ensure the combustion of HCCI, the use of air heating or a high compression ratio is required as the PVO cannot obtain enough hot residual gas. A more practical approach to achieving HCCI combustion is by using the rebreathing approach. This approach works by recirculating the exhaust gas back into the cylinder. This is achieved either by reopening the exhaust valve during the intake stroke or extending the exhaust valve into the intake stroke. Unlike NVO, the rebreathing approach can extend the operating range of the HCCI engine up to a higher load due to lower charge temperature. This is because of the heat loss phenomenon during the exhaust gas exchange process. In NVO, the heat loss phenomena are not observed because the hot burned gas is trapped and used directly. Therefore, the NVO is more appropriate in low load conditions. However, it is more suitable to use the rebreathing approach at a high load. The adoption of rebreathing and trapping exhaust gases has been used extensively to achieve HCCI combustion. They are practical, affordable, and easy to implement without major modification.

The mixture temperature plays an important role in CAI combustion. This is because its combustion occurs only after the homogeneous mixture reaches its auto-ignition temperature. The thermal level of a 2-stroke CAI engine is generally higher than that of a 4-stroke engine. The firing rate of a 2-stroke engine is twice that of a 4-stroke engine, thus generating more combustion heat. Furthermore, since its gas exchange process is less efficient, the residual gas fraction of a 2-stroke engine is also larger. As a consequence, its burned gases mix relatively faster with fresh charge before the mixture is compressed instantaneously.

In comparison, the active radicals of burned gas in a 4-stroke engine may stop due to its long period of expansion, exhaust, intake, and early compression strokes. As a result, it is relatively more difficult to raise the mixture temperature of a 4-stroke engine. The thermal energy should be sufficient to reach the auto-ignition temperature required for combustion.

Research in a 2-stroke CAI engine was initiated just before the 1970s. It was originally established to resolve a number of part-load problems. As discussed in the introduction of this section, it is relatively easier to raise the mixture temperature of a 2-stroke engine compared to a 4-stroke engine. The achievement of CAI in a 2-stroke engine in which significantly low NOx emissions were achieved without the need for after-treatment systems has motivated researchers to transfer its success to a 4-stroke engine.

3. Strategies to Achieve CAI Combustion

The idea of CAI combustion was started more than 40 years ago. However, some issues have not yet been solved, which hinders it as a mass-produced automotive engine. The most straightforward method to achieve CAI combustion in a gasoline engine is heating the intake mixture. Another approach to achieve CAI combustion is to increase the compression ratio to the temperature and pressure of auto-ignition using the VCR mechanism. Besides heating the intake mixture and using VCR, biofuels can also achieve CAI combustion. Lastly, the most favourable and practical approach is probably to use burned gases inside the cylinder, either by trapping them or by using internal recirculation.

3.1. Heating the Intake Charge

Najt and Foster [42] successfully achieved CAI combustion in gasoline engines using intake charge heating. The intake air temperature was heated to start CAI combustion, while a highly diluted mixture was used to govern heat release. To increase the temperature of the intake mixture, a heat exchanger can be used to use the waste heat from either the exhaust or the engine coolant. The charge temperature can also be increased by early combustion using pilot fuel that is burned before compression stroke. However, this approach reduces thermal efficiency as the pilot fuel is injected at relatively low cylinder pressure, thus preventing the transfer of chemical energy of the fuel to mechanical energy.

Cinar et al. [54] investigated the intake air temperature in the CAI engine with the blends of 20% n-heptane and 80% isooctane fuels. Intake air was varied from 40 to 120 ° C. It was found that with an increase in the intake air temperature, the pressure in the cylinder and the rate of heat release increased. The higher intake temperature also advanced combustion and shortened the combustion duration. At a high intake temperature of 100 to 120 °C, the specific fuel consumption and NO emissions increased. CO and HC emissions initially increased but decreased subsequently after the intake temperature of 90 °C,

In addition to heating the intake mixture, another approach to achieve CAI combustion is by increasing the compression ratio up to the temperature and pressure of auto-ignition. However, this method is quite challenging, as a VCR engine should be used for both SI and CAI combustion. **Figure 2** and **Figure 3** show the experimental setup and the pressure and heat release rate at various intake air temperatures, respectively.

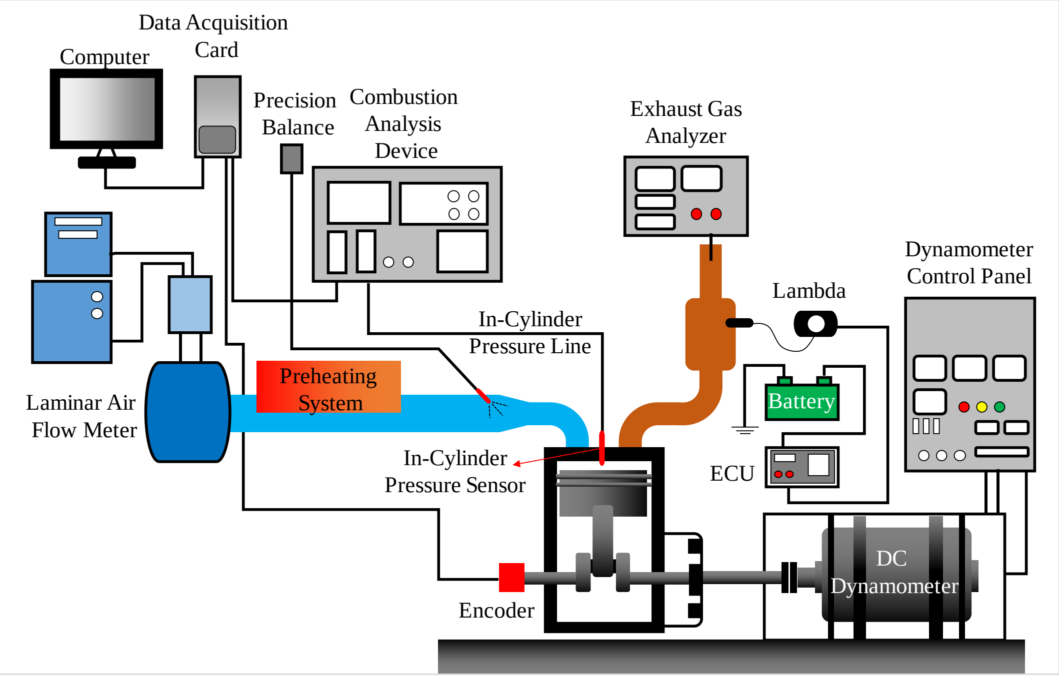

Figure 2. The experimental setup [54]

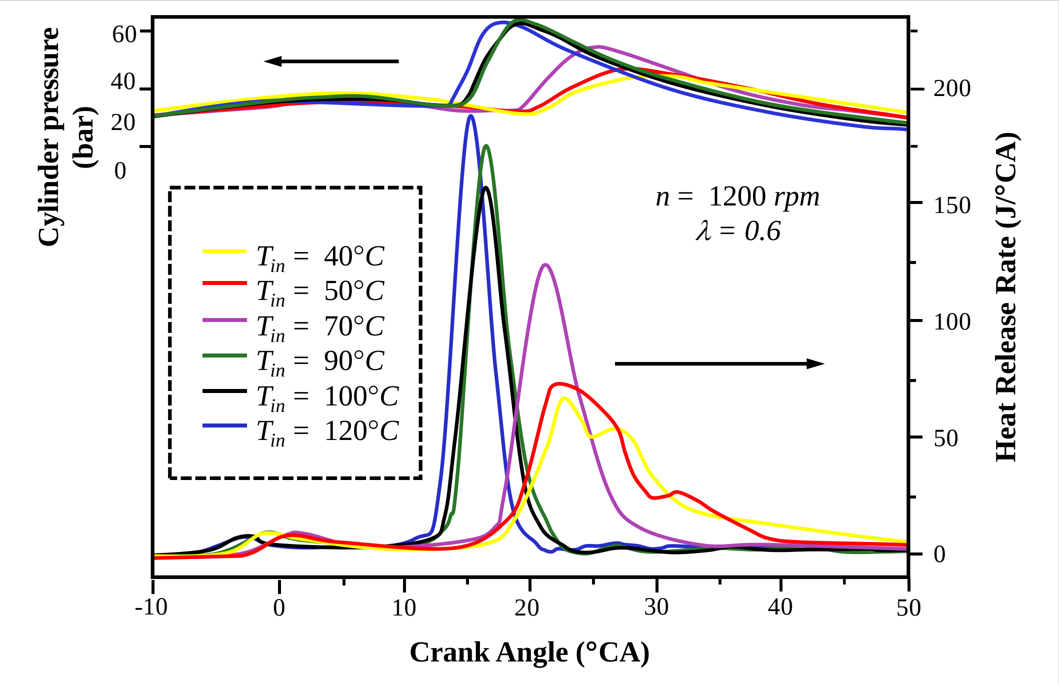

Figure 3. The pressure and heat release rate at various intake air temperatures [54]

3.2. Varying the Fuel Blend

When considering its auto-ignition process, fuel characteristics are critical in HCCI combustion. The evaporation properties are responsible for the homogenization process, while the auto-ignition quality of the fuel plays an indispensable role in the start of combustion. The auto-ignition is also influenced by the pressure and temperature history of the unburned fuel/air mixture, with different fuels having different properties. While fuels in SI engines have a low tendency to auto-ignition, fuels in CI engines have a high tendency to auto-ignition. In CAI engines, the auto-ignition of the fuel varies depending on the engine design and operating conditions.

Another approach is to vary the fuel mixture. Variation in fuel mix can be achieved using a combination of supercharging and intake air heating. Isooctane and heptane, for example, can be used to achieve CAI combustion over a large speed and load range. The same approach can be carried out using blends of DME and methane. However, a challenge with variation in fuel blends is the need for additional equipment to accommodate the use of a dual-fuel system. In addition, fuel injection timing and split injections can be used to achieve and control CAI combustion. In fact, it enables smooth switching between SI and CAI combustion.

3.3. Using Burned Gases

The most favourable and practical approach to achieve CAI combustion is by using burned gases inside the cylinder, either by trapping them or by using internal recirculation. These two approaches are also known as internal EGR. The application of internal EGR depends on the valve timing strategies to recirculate the exhaust gases back into the cylinder. On the other hand, the external EGR works using a recirculation pipe to send some exhaust gases back into the intake port before entering the cylinder. As for the internal EGR, the thermal energy of large amounts of burned gases will increase the temperature of the mixture to the point of auto-ignition. In addition to achieving auto-ignition temperature, the hot burned gases will also control the heat release rate of the combustion. Therefore, CAI combustion can be achieved using the hot burned gas in a normal compression ratio without the use of preheating equipment.

The burnt gas could be realized using residual gas trapping. The inlet valve is opened late so that a fresh mixture of fuel + air (PFI) or air (DI) enters the cylinder filled with trapped burned gases. Therefore, this approach is also known as NVO due to its early closing of the exhaust valve and late opening of the intake valve. The cold fresh mixture obtains the thermal energy from the residual gases, and after the intake valve is closed, the in-cylinder charge is then compressed by the piston moving towards TDC. This is where the auto-ignition occurs in the CAI engine.

Cinar et al. [28] investigated the effect of the valve lift on the combustion and emissions of a CAI engine. The operating range was successfully extended using low lift cams in knocking and misfiring operating zones. Four pairs of cams with low lifts were investigated. He et al. [7] investigated the combustion and emission characteristics of a CAI engine fuelled with butanol-gasoline mixtures. CAI combustion was obtained by negative valve overlap using VVT and VVL devices on both the intake and exhaust valves. The maximum intake valve lift was 2 mm with a duration of 170 °CA, while the maximum exhaust valve lift was 1 mm with a duration of 127 °CA. It was found that advanced auto-ignition and shorter combustion duration were reported with the increasing amount of butanol. However, the IMEP decreases with increasing butanol content and engine speeds. This is due to the lower calorific value of butanol compared to gasoline. Moreover, the negative work caused by the earlier and faster auto-ignition of butanol also contributed to the lower IMEP of butanol blends. An interesting finding from this study was that the octane number cannot be used to determine the auto-ignition of a highly diluted charge of a CAI engine. This can be seen in the auto-ignition that occurs earlier with an increase in the butanol content, despite the high octane number of butanol being higher than that of gasoline.

Lee et al. [55] improved the low load limit of a CAI engine using direct injection during negative valve overlap. They used a CVVT system operated by hydraulic pressure from the engine oil pump at both the intake and exhaust cams. The normal camshaft lift of 6 mm was replaced by a low lift of 2 mm to achieve CAI combustion. For both the intake and exhaust valves, the valve timing was 40^{o} CA. Due to the use of NVO with early closing of the exhaust valve, two pressure peaks were observed in the cylinder due to the second compression during the exhaust process. In addition to using the NVO approach, this study employed a combination of some other strategies to extend the operating range of the CAI engine. This includes EGR stratification, asymmetric injection, and open valve injection.

Valero-Marco [21] used modified valve trains to keep residual hot gases inside the cylinder to achieve CAI combustion. A direct injection water system was also used to extend the operating range towards higher loads. It was found that the mixture reactivity can be controlled by injection of water, so that high-pressure rise rates and the knocking tendency can be reduced. As a result, combustion stability was achieved and the maximum load of CAI combustion was increased to 10 bar IMEP compared to just 3.5 bar IMEP without water injection. Although the NVO was able to ensure the auto-ignition process, knocking and excessive pressure rise rates would occur when the load was increased. Therefore, water injection was required to maintain combustion. This study indicates that direct injection of water has the potential to expand the maximum load of the CAI engine when combined with the NVO strategy. **Figure 4** shows the in-cylinder pressure in SI vs CAI mode.

Another approach to hot-burned gas is called rebreathing. In general, internal recirculation of burned gases works by recirculating the exhaust gases back into the cylinder. This can be achieved through PVO to recirculate the exhaust gases. However, to ensure the CAI combustion, the use of air heating or a high compression ratio is required, as PVO cannot obtain enough hot residual gas. A more practical approach to achieving CAI combustion is to use the rebreathing approach. This approach works by reopening the exhaust valve during the intake stroke or extending the exhaust valve into the intake stroke.

The rebreathing method, as its name suggests, tries to reduce pumping losses by sucking back the exhaust gas within the intake stroke using a normal exhaust stroke, while the residual trapping method works by maintaining the residual gas inside the cylinder. Unlike the residual gas trapping, the rebreathing approach can extend the operating range of the CAI engine up to a higher load due to lower charge temperature. This is because of the heat loss phenomena during the exhaust gas exchange process of the rebreathing method. In the residual trapping method, the heat loss phenomena are not observed as the hot burned gas is trapped and used directly. At a high load, using the residual gas trapping method can result in too early auto-ignition, where the pressure rise rate is very fast. Therefore, residual trapping is more appropriate under low-load conditions. For high-load conditions, it is more suitable to use the rebreathing approach. In the meantime, the use of spark discharge can help CAI combustion for better performance and fuel economy. SACI combustion was investigated.

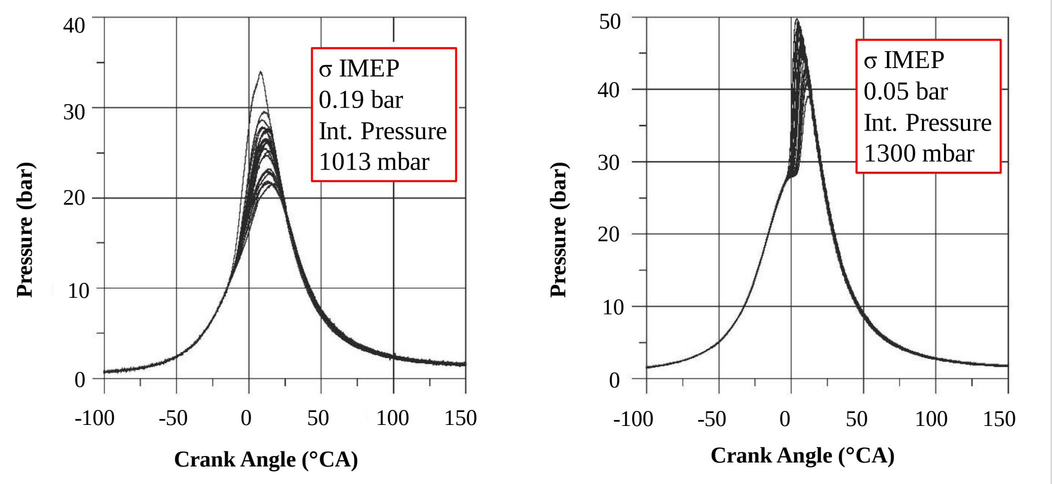

Figure 4. In-cylinder pressure in SI (left) and CAI (right) [21]

4. Conclusion and Future Research Directions

CAI combustion technologies were not novel technology. However, it has been developed over the three decades by focusing on efficiency and environmental issues. Auto-ignition was considered the main obstacle to overcome to realize the potential advantages of CAI combustion. Numerous studies have successfully performed the different strategies to achieve controlled auto-ignition. The most significant advantages of using the concept of CAI combustion is improved fuel economy and ultralow NOx emissions. Several strategies to achieve CAI combustion have been discussed comprehensively, such as by heating the intake charge, varying the fuel blend and using burned gases.

To fully adopt CAI combustion, its operating range must be significantly extended. It is also important to control the real-time closed-loop and the switching between conventional SI and HCCI combustion. Note that the CAI engine suffers from a cold start and a narrow operating range where it can only be run under part-load conditions. Moreover, controlling its combustion phasing in a wide range of speeds and load is also a challenging task. To solve all these problems, the engine may be operated in a mixed mode. At low and medium loads, the engine is operated using the CAI mode, while the conventional SI mode is used for cold start, idle, and high loads. The transition between these two modes can be achieved using the valve train and the EMS.

The most favourable and practical approach to achieve CAI combustion is by using burned gases inside the cylinder, either by trapping them or by using internal recirculation. The early closing of the exhaust valve traps the burned gases. Subsequently, the gases are compressed during the exhaust stroke. In the next cycle, the intake valve opens late, and fresh mixture (PFI) or fresh air (DI) enters the cylinder and mixes with trapped burned gases. As a result, the fresh mixture is able to obtain thermal energy from the burned gases. Once the intake valve is closed and the mixture is compressed by the piston moving to the TDC, the auto-ignition of the mixture occurs before combustion eventually takes place near the TDC. The pressure peak is observed around the TDC, but another pressure peak is also found because the trapped gases are compressed and expand. To avoid trapped gas flow to the intake port, the intake valve should be opened late.

Compared to other strategies, the adoption of rebreathing and trapping exhaust gases has been used extensively to achieve CAI combustion. They are practical, affordable, and straightforward to implement without major modifications apart from a new valve train and control system. The only modification is the camshafts. The use of burned gas or internal EGR in the CAI engine requires flexibility of the valve train system. Both gas trapping and rebreathing need fully variable mechanical valve train systems and fully flexible electro-hydraulic or electromagnetic valve train systems. However, such systems are complex and expensive. Therefore, the mechanical camshaft remains to be used due to its superior reliability and durability.

Authors’ Declaration

Authors’ contributions and responsibilities - The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation, and discussion of results. The authors read and approved the final manuscript.

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References

[1] I. Veza, M. F. Roslan, M. F. M. Said, and Z. A. Latiff, “Potential of range extender electric vehicles (REEVS),” in *IOP Conference Series: Materials Science and Engineering*, 2020, vol. 884, no. 1, p. 12093, doi: 10.1088/1757-899X/884/1/012093.

[2] I. Veza *et al.*, “Electric Vehicles in Malaysia and Indonesia: Opportunities and Challenges,” *Energies*, vol. 15, no. 7, p. 2564, 2022, doi: 10.3390/en15072564.

[3] Z. P. Cano *et al.*, “Batteries and fuel cells for emerging electric vehicle markets,” *Nature Energy*, vol. 3, no. 4, pp. 279–289, 2018.

[4] S. M. N. Rahaju *et al.*, “Acetone-Butanol-Ethanol as the Next Green Biofuel-A Review,” *Automotive Experiences*, vol. 5, no. 3, pp. 251–260, 2022.

[5] I. Veza *et al.*, “Lessons from Brazil: Opportunities of Bioethanol Biofuel in Indonesia,” *Indonesian Journal of Computing, Engineering and Design (IJoCED)*, vol. 4, no. 1, pp. 8–16, 2022.

[6] M. Q. Rusli *et al.*, “Performance and emission measurement of a single cylinder diesel engine fueled with palm oil biodiesel fuel blends,” in *IOP Conference Series: Materials Science and Engineering*, 2021, vol. 1068, no. 1, p. 12020, doi: 10.1088/1757-899X/1068/1/012020.

[7] D. N. Cao, A. T. Hoang, H. Q. Luu, V. G. Bui, and T. T. H. Tran, “Effects of injection pressure on the NOx and PM emission control of diesel engine: A review under the aspect of PCCI combustion condition,” *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, pp. 1–18, 2020.

[8] A. Dimitriadis *et al.*, “Improving PM-NOx trade-off with paraffinic fuels: A study towards diesel engine optimization with HVO,” *Fuel*, vol. 265, p. 116921, 2020.

[9] M. A. Fayad, B. R. AL-Ogaidi, M. K. Abood, and H. A. AL-Salihi, “Influence of post-injection strategies and CeO2 nanoparticles additives in the C30D blends and diesel on engine performance, NOX emissions, and PM characteristics in diesel engine,” *Particulate Science and Technology*, vol. 40, no. 7, pp. 824–837, 2022.

[10] R. Suarez-Bertoa *et al.*, “On-road emissions of passenger cars beyond the boundary conditions of the real-driving emissions test,” *Environmental research*, vol. 176, p. 108572, 2019.

[11] F. Leach *et al.*, “A Review and Perspective on Particulate Matter Indices Linking Fuel Composition to Particulate Emissions from Gasoline Engines,”,” *SAE Int. J. Fuels Lubr.*, vol. 15, no. 1, 2022.

[12] C. K. Lambert, “Current state of the art and future needs for automotive exhaust catalysis,” *Nature Catalysis*, vol. 2, no. 7, pp. 554–557, 2019.

[13] J. D. Smith *et al.*, “Real-time particulate emissions rates from active and passive heavy-duty diesel particulate filter regeneration,” *Science of The Total Environment*, vol. 680, pp. 132–139, 2019.

[14] A. Kozina, G. Radica, and S. Nižetić, “Analysis of methods towards reduction of harmful pollutants from diesel engines,” *Journal of Cleaner Production*, vol. 262, p. 121105, 2020.

[15] T. Selleri, A. D. Melas, A. Joshi, D. Manara, A. Perujo, and R. Suarez-Bertoa, “An overview of lean exhaust denox aftertreatment technologies and nox emission regulations in the european union,” *Catalysts*, vol. 11, no. 3, p. 404, 2021.

[16] M. F. Roslan, I. Veza, and M. F. M. Said, “Predictive simulation of single cylinder n-butanol HCCI engine,” in *IOP conference series: Materials science and engineering*, 2020, vol. 884, no. 1, p. 12099, doi: 10.31224/osf.io/y53bn.

[17] I. Veza *et al.*, “Strategies to Form Homogeneous Mixture and Methods to Control Auto-Ignition of HCCI Engine,” *International Journal of Automotive and Mechanical Engineering*, vol. 18, no. 4, pp. 9253–9270, 2021, doi: 10.15282/ijame.18.4.2021.09.0712.

[18] U. Azimov, E. Tomita, N. Kawahara, and Y. Harada, “Premixed mixture ignition in the end-gas region (PREMIER) combustion in a natural gas dual-fuel engine: operating range and exhaust emissions,” *International Journal of Engine Research*, vol. 12, no. 5, pp. 484–497, 2011.

[19] H. R. Chauhan, K. Preksha, S. K. Dabhi, and V. G. Trivedi, “A Technical Review HCCI Combustion in Diesel Engine,” *International Journal for Innovative Research in Science & Technology*, vol. 1, no. 10, 2015.

[20] A. K. Agarwal, A. P. Singh, and R. K. Maurya, “Evolution, challenges and path forward for low temperature combustion engines,” *Progress in energy and combustion science*, vol. 61, pp. 1–56, 2017.

[21] J. Valero-Marco, B. Lehrheuer, J. J. López, and S. Pischinger, “Potential of water direct injection in a CAI/HCCI gasoline engine to extend the operating range towards higher loads,” *Fuel*, vol. 231, pp. 317–327, 2018.

[22] A. K. Oppenheim, *Combustion in piston engines: technology, evolution, diagnosis and control*. Springer, 2004.

[23] N. Gombosuren, “Ultra-Lean Combustion of SI Engine Using Alternative Stratification Principles,” 2020.

[24] H. Zhao, *HCCI and CAI engines for the automotive industry*. Elsevier, 2007.

[25] M. Izadi Najafabadi and N. Abdul Aziz, “Homogeneous charge compression ignition combustion: challenges and proposed solutions,” *Journal of combustion*, vol. 2013, 2013.

[26] H. Zhao, “Overview of CAI/HCCI gasoline engines,” in *HCCI and CAI engines for the automotive industry*, Elsevier, 2007.

[27] S. Wiemann, R. Hegner, B. Atakan, C. Schulz, and S. A. Kaiser, “Combined production of power and syngas in an internal combustion engine–Experiments and simulations in SI and HCCI mode,” *Fuel*, vol. 215, pp. 40–45, 2018.

[28] C. Cinar, A. Uyumaz, H. Solmaz, and T. Topgul, “Effects of valve lift on the combustion and emissions of a HCCI gasoline engine,” *Energy Conversion and Management*, vol. 94, pp. 159–168, 2015.

[29] A. Calam, “Effects of the fusel oil usage in HCCI engine on combustion, performance and emission,” *Fuel*, vol. 262, p. 116503, 2020.

[30] J. Hunicz, M. Mikulski, M. S. Geca, and A. Rybak, “An applicable approach to mitigate pressure rise rate in an HCCI engine with negative valve overlap,” *Applied Energy*, vol. 257, p. 114018, 2020.

[31] J. Hunicz, “An experimental study of negative valve overlap injection effects and their impact on combustion in a gasoline HCCI engine,” *Fuel*, vol. 117, pp. 236–250, 2014.

[32] Y. Zhang and H. Zhao, “Investigation of combustion, performance and emission characteristics of 2-stroke and 4-stroke spark ignition and CAI/HCCI operations in a DI gasoline,” *Applied energy*, vol. 130, pp. 244–255, 2014.

[33] J.-O. Olsson, P. Tunestål, G. Haraldsson, and B. Johansson, “A turbo charged dual fuel HCCI engine,” *SAE Special Publications (Vol. 2001)*, vol. 1, no. 1896, p. 1896, 2001.

[34] H. Zhao, J. Li, T. Ma, and N. Ladommatos, “Performance and analysis of a 4-stroke multi-

cylinder gasoline engine with CAI combustion," 2002.

[35] S. H. Jo, P. Do Jo, T. Gomi, and S. Ohnishi, "Development of a low-emission and high-performance 2-stroke gasoline engine (NiCE)," *SAE Transactions*, pp. 1425–1433, 1973.

[36] S. Onishi, S. H. Jo, K. Shoda, P. Do Jo, and S. Kato, "Active thermo-atmosphere combustion (ATAC)—a new combustion process for internal combustion engines," *SAE Transactions*, pp. 1851–1860, 1979.

[37] M. Noguchi, Y. Tanaka, T. Tanaka, and Y. Takeuchi, "A study on gasoline engine combustion by observation of intermediate reactive products during combustion," *SAE Transactions*, pp. 2816–2828, 1979.

[38] Y. Ishibashi and M. Asai, "Improving the exhaust emissions of two-stroke engines by applying the activated radical combustion," *SAE transactions*, pp. 982–992, 1996.

[39] N. N. Semenov, "Chemical kinetics and chain reactions," 1935.

[40] L. A. Gussak, V. P. Karpov, and Y. V Tikhonov, "The application of lag-process in prechamber engines," *SAE Transactions*, pp. 2355–2380, 1979.

[41] L. A. Gussak, "High chemical activity of incomplete combustion products and a method of prechamber torch ignition for avalanche activation of combustion in internal combustion engines," *SAE transactions*, pp. 2421–2445, 1975.

[42] P. M. Najt and D. E. Foster, "Compression-ignited homogeneous charge combustion," *SAE Transactions*, pp. 964–979, 1983.

[43] R. H. Thring, "Homogeneous-charge compression-ignition (HCCI) engines," SAE Technical paper, 1989.

[44] A. Khameneian *et al.*, "Model-based dynamic in-cylinder air charge, residual gas and temperature estimation for a gdi spark ignition engine using cylinder, intake and exhaust pressures," *ASME 2020 Dynamic Systems and Control Conference, DSCC 2020*, vol. 2, no. January, 2020, doi: 10.1115/DSCC2020-3280.

[45] A. Khameneian *et al.*, "A real-time control-oriented discrete nonlinear model development for in-cylinder air charge, residual gas and temperature prediction of a Gasoline Direct Injection engine using cylinder, intake and exhaust pressures," *Control Engineering Practice*, vol. 119, p. 104978, 2022.

[46] T. D. M. Lanzanova, M. Dalla Nora, M. E. S. Martins, P. R. M. Machado, V. B. Pedrozo, and H. Zhao, "The effects of residual gas trapping on part load performance and emissions of a spark ignition direct injection engine fuelled with wet ethanol," *Applied Energy*, vol. 253, p. 113508, 2019.

[47] N. X. Khoa, Y. Q. Nhu, and O. Lim, "Estimation of parameters affected in internal exhaust residual gases recirculation and the influence of exhaust residual gas on performance and emission of a spark ignition engine," *Applied Energy*, vol. 278, p. 115699, 2020.

[48] B. P. Maldonado and B. C. Kaul, "Evaluation of residual gas fraction estimation methods for cycle-to-cycle combustion variability analysis and modeling," *International Journal of Engine Research*, vol. 23, no. 2, pp. 198–213, 2022.

[49] M. Parthasarathy *et al.*, "Performance analysis of HCCI engine powered by tamanu methyl ester with various inlet air temperature and exhaust gas recirculation ratios," *Fuel*, vol. 282, p. 118833, 2020.

[50] K. Ali, C. Kim, Y. Lee, S. Oh, and K. Kim, "A numerical study to control the combustion performance of a syngas-fueled HCCI engine at medium and high loads using different piston bowl geometry and exhaust gas recirculation," *Journal of Energy Resources Technology*, vol. 143, no. 8, 2021.

[51] M. A. Rather and M. M. Wani, "A numerical study on the effects of exhaust gas recirculation temperature on controlling combustion and emissions of a diesel engine running on HCCI combustion mode," *International Journal of Automotive Science and Technology*, vol. 2, no. 3, pp. 17–27, 2018.

[52] M. A. Rather and M. M. Wani, "Computational study on the effects of exhaust gas recirculation on thermal and emission characteristics of HCCI diesel engine," *Automotive Science and Engineering*, vol. 8, no. 4, pp. 2833–2839, 2018.

[53] F. A. Herzer, J. L. S. Fagundez, M. E. S. Martins, and N. P. G. Salau, "Chemical kinetic mechanisms for HCCI combustion of wet ethanol with exhaust gas recirculation," SAE Technical Paper, 2020.

[54] C. Cinar, A. Uyumaz, H. Solmaz, F. Sahin, S. Polat, and E. Yilmaz, "Effects of intake air temperature on combustion, performance and emission characteristics of a HCCI engine fueled with the blends of 20% n-heptane and 80% isooctane fuels," *Fuel Processing*

Technology, vol. 130, pp. 275–281, 2015.

[55] C. H. Lee and K. H. Lee, “An experimental study of the combustion characteristics in SCCI and CAI based on direct-injection gasoline engine,” *Experimental Thermal and Fluid Science*, vol. 31, no. 8, pp. 1121–1132, 2007.