Advanced Combustion for Improving Thermal Efficiency

Subjects: Transportation

Contributor: Rami Y. Dahham, Haiqiao Wei, Jiaying Pan

Improving thermal efficiency and reducing carbon emissions are the permanent themes for internal combustion (IC) engines. Improving thermal efficiency and reducing fuel consumption and greenhouse gas (GHG) emissions motivate the technological progress of the automobile and engine industry.

Keywords: thermal efficiency ; thermodynamic cycle ; gas exchange ; combustion technologies

1. Low-Temperature Combustion

The LTC is one of the promising advanced techniques for in-cylinder combustion to minimize emissions with a beneficial impact on high efficiency and specific fuel consumption. It features improved mixture preparation, fuel atomization, reduced combustion temperature, and lower local equivalence ratios, which simultaneously increase the chances of reducing emissions while retaining higher thermal efficiency. The LTC is mostly accomplished through several approaches, namely the HCCI, RCCI, PPC, SACI, etc. [1].

1.1. Homogeneous Charge Compression Ignition

For the HCCI mode, a mixture of air and fuel homogeneous or well-mixed ignite without a spark at the end of the compression stroke. Combustion occurs in many locations in HCCI engines due to the self-ignition of the mixture that reaches its chemical activation energy, and automatic combustion occurs without any apparent propagation of flame front or diffusion flame. Furthermore, one-third to one-half of the operating load can be used for SI and CI modes, and the remaining load for HCCI mode.

Polat et al. [2] examine the effects of boost pressure on combustion and output at a low CR of an early direct-injection HCCI engine. The experiments were conducted using n-heptane fuel at various intake manifold absolute pressures from 1.0 to 1.6 bar at different engine loads. As a result, the operating range can be expanded, and the HCCI combustion process can be operated at a low CR of 9.2 by supercharging application. As the boost pressure rose, an improvement in thermal efficiency was seen. The volumetric efficiency, in-cylinder gas temperature, and in-cylinder pressure were increased with increased intake manifold pressure, and the combustion phase was advanced. Therefore, combustion events with CA50 2–3° CA aTDC demonstrate the highest thermal performance, especially under low boost pressures. The test results have shown that the HCCI operating range can be prolonged, particularly at high load limits, by increasing the intake manifold pressure.

Maurya et al. [3] investigated combustion characteristics and emissions of HCCI engines fueled by ethanol under various inlet temperatures of 120–150 °C. The results showed an increase in combustion efficiency, indicated thermal efficiency, and gas exchange efficiency of 97.45%, 44.78%, and 97.47%, respectively, particularly at 393 K of air temperature and lambda 2.5. The low reactivity of n-butanol aids in obtaining optimal thermal efficiencies comparable to conventional diesel combustion (43–46%) is consistently accomplished [4]. Ganesh et al. [5] observed there was a reduction in the BTE when a mixture of vaporized jatropha methyl ester and the air is inserted into the cylinder through the intake stroke. The indicated thermal efficiency of ethanol/n-heptane blend fuels HCCI combustion can be increased up to 50% at high load due to the delay of the ignition timing by the ethanol addition [6][7]. Nagarajan et al. [8] experimentally investigated HCCI with 100% gaseous fuel LPG. They reported that the BTE increased at part loads for all EGR rates, but higher flow rates of EGR negatively affected the BTE at full load.

Because HCCI combustion uses heavily diluted charges with either a high degree of EGR or lean mixtures, the in-cylinder temperature will remain low, comparable to conventional diesel combustion. The principal shortcomings of this combustion mode have been summarized as follows [9]: (i) low power density, (ii) high combustion noise, (iii) limited operating load, (iv) low combustion efficiency, and (v) poor combustion phasing control. In terms of engine efficiency, 15% of thermal efficiency was observed for multiple injections [10]. In Refs. [3][11], 29–37% and 44.78% indicated thermal efficiency was obtained when lambda equals 2.0 and 2.5 respectively. In contrast, the BTE was decreased with vaporizer, and high EGR rate [12], and advanced injection timing [13] and it increased with injection timing [14].

Duan et al. [15] comprehensively reviewed various effective techniques such as fuel reactivity, fuel additives, alternative fuels, reactive species, reforming, and modification, which were used in HCCI engines to control combustion phasing and ignition timing (**Figure 1**). Main conclusions were found of these strategies applied in HCCI engines summarized as follows:

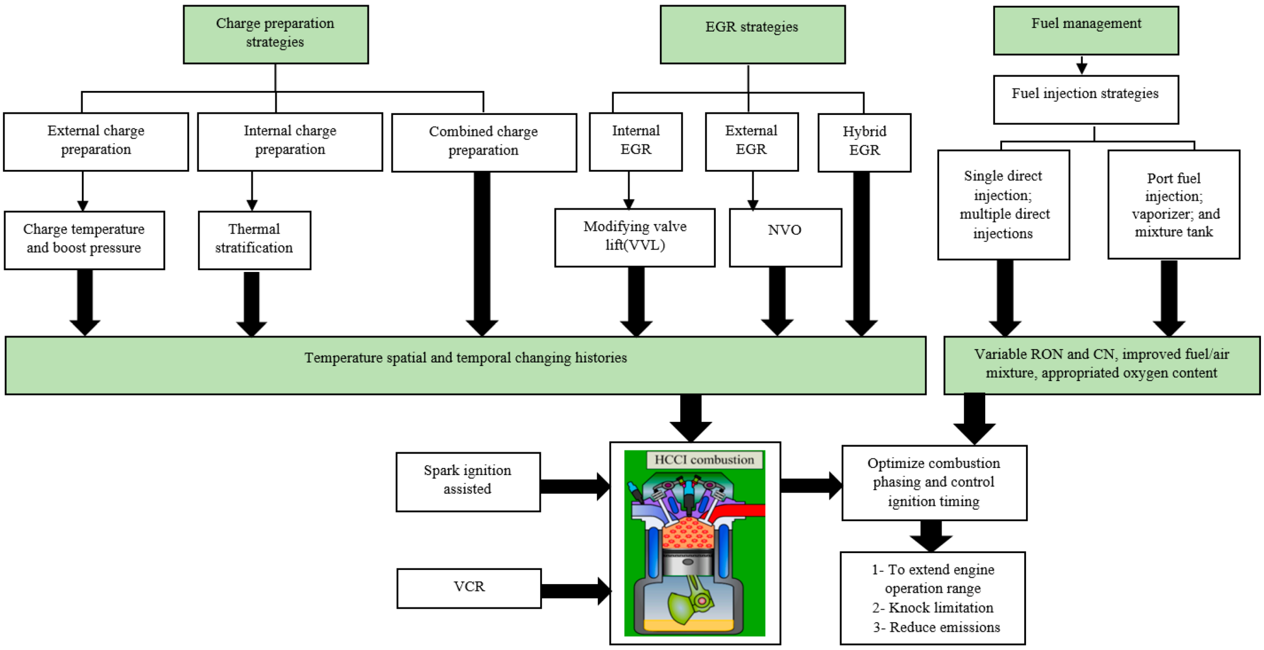

Figure 1. Schematic diagram of effective techniques used to control combustion phasing and ignition timing of HCCI engines [15][16].

- Designing, modifying, and controlling fuel compositions, and employing fuel physical-chemical properties in HCCI engines to improve the combustion phasing and ignition timing and expand operating loads.
- Fuel reactivity stratification may be an attractive method of controlling ignition timing and reducing the excessive PRR.
- Fuel reforming and modification were common techniques for adjusting the chemical components to control combustion phasing and ignition timing.
- As compared to preheated intake temperature, reactive species, and fuel additives have potential advantages in HCCI engines by lowering the intake temperature and making it easier to control the combustion timing.
- In contrast to conventional gasoline and diesel fuels, alternative fuels have remarkable superior advantages in regulating combustion phasing and ignition timing.
- Negative valve overlap is an efficient way of increasing in internal EGR of the HCCI engine, which leads to delay in the auto-ignition for high load, hence retard the combustion phasing.
- Combining external and internal mixture preparation can be considered effective method for controlling ignition timing and combustion phasing.
- The preheating of intake air and boosting the air pressure can shorten ignition timing and extend the load engine to high. Therefore, the combination of the two ways is commonly used in the HCCI engine.
- To stratify the temperature distribution in the cylinder of the unburned mixture before auto-ignition, thermal stratification can be used. It is an efficient technique for governing the HRR and controlling the auto-ignition.
- The combustion phasing and auto-ignition can be controlled using a variable compression ratio instead of preheating the air intake.

- Applying the SACI mode in the HCCI engine can give an effective approach that operates with lean mixture, controlling combustion phasing, expanding the engine's load range, and sustaining high thermal efficiency.

Pressure rise rate (PRR) increases as a premixed ratio increases while decreases with vaporizers, high EGR rate, and lean mixtures. Additionally, the maximum PRR was higher without EGR than that with EGR in all pilot quantities as well as it was very high for a rich mixture. This issue can be settled by delayed the combustion phasing to reduce the PRR. Delayed combustion phasing can, however, result in a sacrifice in efficiency. Though HCCI has a limited range of load operations and very rapid PRR due to the auto-ignitions characteristics, a load of up to 2 MPa of IMEP for naturally aspirated can be realized under steady-state conditions, but transient operation conditions remain a challenge. Furthermore, the very rapid pressure rise rate, other parameters can limit the HCCI's operating range, such as misfiring at low loads and engine knock at high loads. Therefore, numerous strategies are suggested to extend the high load operating limits through turbocharging or supercharging, VCR, SACI, and PPC operation, charge stratification, changing the coolant temperature, variable intake air temperature, VVT, EGR, injection timing, and utilizing alternative fuel with high octane number to avoid engine knock and misfiring [12][17][18][19][20][21].

1.2. Reactivity-Controlled Compression Ignition

RCCI is a dual-fuel combustion technique that uses an in-cylinder blend of at least two fuels with various auto-ignition characteristics to control the heat release rate (HRR) and combustion phase [22][23]. The major part of the total injected fuel should be low reactivity fuel (LRF), while the high reactivity fuel (HRF) is utilized to trigger the combustion process [24]. Unlike all other LTC modes, RCCI combustion can achieve significantly higher BTE, with comparatively lower PM and NO_x emissions [25][26]. In addition, it facilitates a smoother combustion process by diminishing engine knock [27], which offers good ringing intensity and is better than HCCI engines [28]. The other advantage of RCCI mode combustion is the ability to operate under a wide range of engine loads with acceptable pressure rise, and low ringing intensity, and can produce higher thermal efficiency ~56% [29][30]. Another merit of RCCI combustion is regarded as one of the best promising modes of LTC compared to the other methods and promising technology to improve thermal efficiency under highway navigating conditions. It can also be observed from this strategy for all tested fuels that the heat release rate was higher than conventional diesel combustion [1]. The key benefit of a dual-fuel system is dominating the combustion process by enhancing the blended fuel reaction. To distinguish the combustion process from HCCI or PCCI, led to the term RCCI. The foremost benefits of this strategy include [29]:

- Low emissions such as NOx and soot.
- The losses in heat transfer are lessened.
- Thermodynamic efficiency and fuel efficiency increased.

Although RCCI offers low emissions and high efficiency, it still has numerous challenges, such as excessively high MPRR at high loads and excessive UHC and CO emissions at low loads. These two restrictions limit the RCCI's working range to moderate loads, making it unsuitable for use in real-world applications [24]. Han et al. [31] showed that PCCI and HCCI combustion modes produced significantly lower soot and NO_x emissions, but RCCI mode combustion showed comparatively higher efficiency with superior combustion control compared to other LTC techniques also can have a lower peak pressure rise rate (PPRR) and a longer combustion duration. Notwithstanding the low combustion efficiency, the gross thermal efficiency of RCCI was somewhat higher due to reducing the losses of heat transfer arising from the decline of peak pressure rise rate. The outcomes of pump fuel revealed that it was seen the reactivity of the premixed fuel had increased, and the combustion efficiency was increased to a comparable value to that of the PPC (see **Table 1**) [32].

Table 1. Review and comparison between three different advanced combustion technologies [32].

Primary Reference Fuel				Pump Fuels		
Fixed Condition	**HCCI**	**PPC**	**RCCI**	**Fixed Conditions**	**PPC**	**RCCI**
GIE (%)	**47.1**	**45.6**	**47.5**	**GIE (%)**	**46.9**	**46.1**
NOx (g/kg-fuel)	**0.05**	**0.01**	**0.04**	**NOx (g/kg-fuel)**	**0.15**	**0.05**
COV of IMEP (%)	**2.6**	**2.5**	**2.6**	**COV of IMEP (%)**	**2.5**	**2.1**
Comb. Efficiency (%)	**92.8**	**93.1**	**91.5**	**Comb. Efficiency (%)**	**93.7**	**93.2**
PPRR (bar/deg)	**14**	**16**	**5.8**	**PPRR (bar/deg)**	**16.4**	**11.7**

Primary Reference Fuel				Pump Fuels		
Fixed Condition	**HCCI**	**PPC**	**RCCI**	**Fixed Conditions**	**PPC**	**RCCI**
CA50 ±σ50 [aTDC]	**3.5 ± 0.5**	**2.5 ± 0.3**	**2.2 ± 0.5**	CA50 ±σ50 [aTDC]	**3.2 ± 0.4**	**2.7 ± 0.9**

Several further studies confirmed that gasoline-diesel RCCI can minimize NO_x and soot emissions [33][34][35][36], but the gross indicated thermal efficiency greater than 55% is not replicated. On the other hand, some researchers have reported a remarkably high peak value of 56% at medium loads [29]. Splitter et al. [37] proposed that the gross indicated thermal efficiency of up to 60% was needed with reduced frictional and pumping losses. The findings demonstrate that, with optimization thermodynamic conditions, combustion management, disabling piston cooling, and increasing the compression ratio to 18.7, 60% gross indicated thermal efficiency have been achievable, offering a route to having reached 55% BTE. The BTE is directly proportional to the gross indicated thermal efficiency, where some restrictions can be observed that would reduce the thermal efficiency represented by PMEP and FMEP. Therefore, a maximum BTE can obtain if these losses decreased as much as possible with the possibility of increasing the gross indicated mean effective pressure ($IMEP_g$), as shown in **Figure 2**. The same authors [38] recorded a maximum GIE of 59% when using PFI of E85 and DI of diesel, with the possibility to extend the load easily compared to their previous work [37]. Additionally, at all tested load points up to 16.5 bar IMEPg, lower EGR rates were needed.

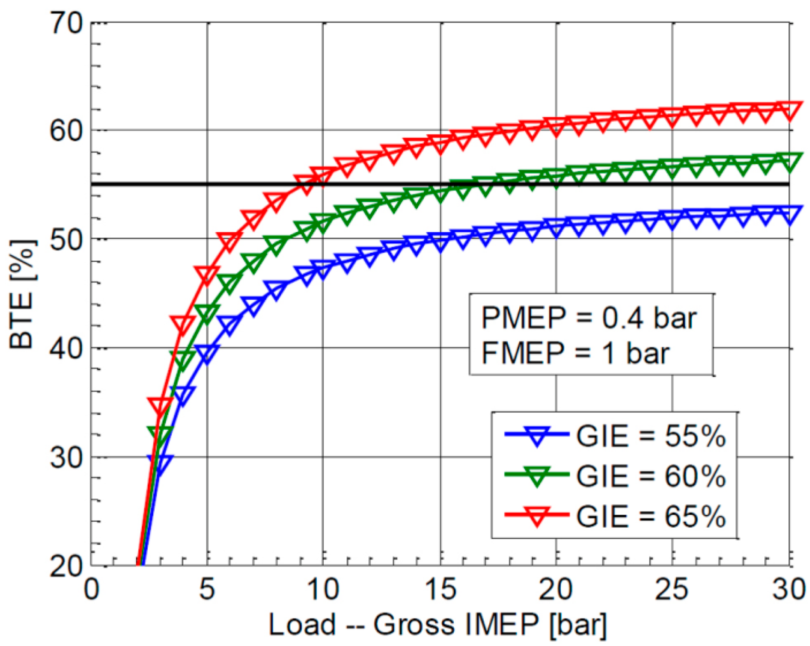

Figure 2. BTE as a function of IMEPg and gross thermal efficiency(GTE) (GIE: gross indicated efficiency synonymous to GTE) [37].

The most important results obtained from the review made by Reitz and Duraisamy [39] were: (i) gasoline/diesel offered high thermal performance over a broad range of load engines, with a maximum GIE of 56% under 0.93 MPa IMEP operating conditions on heavy-duty (HD) engines, (ii) the utilize of E85 and B20 permitted the maximum BTE of RCCI to increase from 40% with the gasoline-diesel operation condition to 43 %. Soloiu et al. [40] observed that RCCI leads to delayed ignition by 7 CAD compared to conventional diesel engines, resulting in a sharper rise in pressure. This strategy increased peak heat release rate (PHRR) and delayed ignition due to reactivity stratification and prolonged mixing time, causing faster flame speeds, as well as an increase in ITE reaching 58% at 4 bar IMEP. Another study conducted by Benajes et al. [41] showed that the thermal efficiency of RCCI operating with E85 was higher than with gasoline. In addition, a higher value of BSFC with E85 than with gasoline. Pan et al. [42] reported that the BTE increased up to 7.08% with 18.5 CR and under high loads due to a decrease in heat loss, resulting from the lower combustion temperature. Similarly, Gross and Reitz [43] reported increased BTE levels of 32.34% at 2300 rpm and 4.2 bar BMEP due to lower combustion losses. Biodiesel/diesel RCCI combustion leads to an increase of BTE by about 31% and reduces cylinder gas temperature due to the better-premixed combustion [44]. Mujtaba et al. [45] numerically investigated RCCI combustion fueled by NG/Diesel to optimize the engine efficiency using AVL-file software. The simulation results observed that 55.05% of GIE was obtained at 13.5 bar $IMEP_g$.

Other significant efforts have been made by Jing et al. [28] to review and summarized the effect of the LRF ratio on the engine performance of RCCI combustion. They found that as the low reactivity fuel (LRF) ratio increased, the engine performance improved. Recently, Butanol Isomers (n-butanol, iso-butanol, and tert-butanol) as an LRF besides n-heptane as HRF, injected directly into the cylinder, have been studied by Han and Somers. Their study was conducted from low to medium-high loads, and the results showed that the highest GIE could be obtained (>52%) with tert-butanol/n-heptane in most operating loads [46]. Pan et al. [47] found that iso-butanol/diesel RCCI has a longer ignition delay (ID), CA50-CA10 and combustion duration (CD), later combustion phasing, lower maximum PRR, and higher ITE, compared with the gasoline/diesel RCCI mode.

Recently, Eyal et al. [48] explored an innovative concept integrating the advantages of High-Pressure Thermochemical Recuperation and the LTC mode. This combination facilitates mitigating pollutant emissions and achieving high thermal efficiency in a wide range. The findings demonstrate a 4- to 9% improvement in thermal efficiency compared to conventional diesel combustion (CDC) with the same engine operating.

In summary, it was observed that LRF such as natural gas is permitted to extend load limits and combustion processes [39]. Moreover, this concept (RCCI) is presented to control better combustion and improve thermal efficiencies than other approaches, such as HCCI, PCCI, single-fuel PPC, dual-fuel HCCI, and PCCI [37]. RCCI combustion also has limitations, such as lessening combustion efficiency at low loads and restricting high load expansion due to excessive PRR [49][50], distributing LRF through port fuel injection (PFI), controlling cycle-to-cycle variation through the transient conditions, modification of fuel injection strategy, and lower exhaust temperatures also pose significant challenges for after-treatment systems. These can be alleviated by improving various control parameters [51] involving VVT, intake air temperature, injection strategy, EGR rate, boost pressure, etc.) [9].

1.3. Partial Premixed Combustion

The PPC concept originated from the PCCI engine but is more similar to modern diesel engines [52]. PCCI or PPCI are other acronyms for a PPC. PPC is an LTC concept with its combustion regime sandwiched between HCCI and diffusion combustion [53]. Along with some of the control authority of diffusion combustion, this approach affords low heat loss and pollutant emission. The use of PPC exhibits a significant reduction in heat transfer losses, resulting in an improved engine efficiency [54][55], and its benefits are similar to RCCI [9]. To achieve the PPC, the extension of ignition delay is an essential issue for that purpose, and it can be accomplished by excessive EGR rate, reduced CR, and fuel reactivity [14][56][57][58][59].

Moreover, PPC is a concept that involves fuel stratification to accomplish the desired combustion phasing and ignition timing. Multiple injections and advanced injection strategies are used with this concept to determine the stratification level. Additionally, it endeavors to utilize clean combustion and improved blending of fuels [54]. PPC is an intermediary combustion technique between HCCI and CCM, providing a sufficient ignition delay, hence improving the air-fuel mixture [60]. Combustion has been stratified through PPC, and the fuel-lean, besides fuel-rich regions, decreases NO_x and PM emissions without affecting efficiency. Furthermore, fuel injection timing and inlet air temperature were controlled during the combustion stages, although chemical kinetics continues to play a significant role. As a result, more attention has been devoted to the PPC inquiry in recent years [61][62][63].

Manente et al. [64] found that with the use of high-octane fuel in PPC, under high loads of more than 7 bar of IMEP, and 50% EGR, the combustion efficiency was more than 98%. In addition, the values of BTE can reach higher than 48%. Han et al. [65] evaluate the feasibility of employing n-butanol for two types of combustion modes, PPC and HCCI. The results show that both PPC and HCCI of n-butanol can produce low NO_x and close to zero smoke emissions while attaining diesel-similar engine efficiency. Zincir et al. [66] investigated the impact of intake temperature on the limitation of PPC at a low load fueled by methanol. The results revealed that with higher intake temperatures, the GIE began to increase (41–42%) because of an increase in combustion efficiency (96–99%) affected by intake temperature. This is attributed because higher intake temperatures under low loads can obtain more complete combustion. Another study conducted by Yin et al. [67] observed that the maximum GIE of 51.5%. When the refinery fuel was used; the GIE was increased up to 50% under high loads and about 45% for the other points. Furthermore, some differences can be observed in increasing and decreasing GIE, especially at the 16–20 bar of $IMEP_g$. This is due to several important reasons [68]:

- Increase thermal exhaust losses with other residual losses.
- Combustion was delayed for 20 bar $IMEP_g$ due to hardware limitations.
- Low fuel pressure, extended injection period, and long combustion duration.

Numerous studies reveal that the advanced SOI leads to decreased cylinder pressure and HRR [13][69], and the others show an increasing cylinder pressure and HRR [70][71]. It is observed sometimes increasing and sometimes decreasing, and this also includes BTE and BSFC. The reason is that each study has its operating conditions, such as engine type, injection pressure, injection type, fuel type with its blend, EGR rate, etc. In summary, the BSFC was increased in most studies because they depend on several parameters. On the other hand, an increase in BTE and combustion efficiency can be demonstrated because the combustion process of the PPC is very sensitive to boundary conditions.

The optimization of charge stratification is considered one of the essential factors to improve combustion performance, and it can be achieved by employing multiple injection strategies. Zhang et al. [72] analyzed the multiple injection strategies utilizing thermodynamic approaches to study how the combustion phasing, the heat release energy, and the heat transfer loss affect the GIE of PPC combustion in heavy-duty optical engines. The results showed that a higher GIE could be obtained in the late double injection with a later combustion phasing compared to the early double injection cases and 47.9% of GIE for the triple injection case. In addition, the interaction between the post-injection and main combustion was a critical point for combustion efficiency, although less influence on the combustion phasing. Additionally, Mao et al. [73] explored a multiple-injection strategy to achieve the highest BTE of 44% in a multiple-cylinder heavy-duty diesel engine [73]. Recently, Aziz et al. [74] investigated a multiple injection (double and triple) strategy on the performance of PPC at low load fueled by Methanol in a single-cylinder heavy-duty engine. They found that the GIE was improved using multiple injection strategies compared to a single injection. Another recent study was conducted by Dimitrakopoulos and Tuner [75] to reduce the high combustion instability (COV) at a low load of Gasoline PPC using glow plugs. The results showed that inlet air temperature was reduced by glow plugs, hence keeping the combustion stable and having an insignificant effect on efficiency.

In summary, the PPC can provide better mixing before the combustion since it is based on the prolonged ignition delay. Although PPC has many merits over HCCI, it presents some critical challenges related to combustion stability and controllability, high HRR, high PRR at low and medium loads, as well as poor combustion efficiency at low loads. Using multiple injections and throttling the engine and running at a lower lambda, RCCI and SACI are likewise methods to resolve the poor combustion efficiency at low loads. For high loads, further investigations are required to use oxygenated fuel with a high CN, glow plugs, high boost pressures, high EGR ratios around 50%, advanced injection strategies, and placed the main injection nearby TDC.

1.4. Spark-Assisted Compression Ignition

The SACI is an efficient strategy proposed to optimize the robustness of ignition control, achieve stable phase control, and extend the HCCI load range [76][77]. SACI strategy is based on a lean mixture via injecting fuel within the combustion chamber through the early intake stroke. An external ignition source was utilized to initiate a flame front propagation, and compression ignition is initiated by exceeding the auto-ignition threshold. The auto-alignment threshold relies on the air-fuel mix, fuel type, and residual gas amount [78]. The purpose of SACI is to achieve supplementary HCCI combustion control. SACI is an intermediary concept involving flame improvement initiated via spark discharge, accompanied by HCCI kinetic combustion. A spark discharge has been added to improve combustion stability in terms of the IMEP [79]. The combustion properties of HCCI, SACI, and SI mode were contrasted by Wang et al. [80]. They have found that SACI can attain higher thermal efficiency than spark ignition combustion, particularly at 8.2 bar of IMEP.

Many researchers have expanded the engine loads into the SACI system by modulating some variables [77], such as spark timing [76], internal and external EGR rates [81], intake temperature [82], and effective compression ratio with LIVC [83]. Chiodi et al. [84] have shown that ~44% indicated thermal efficiency is considerably higher than that of flame propagation combustion and reduces specific fuel consumption to a minimum. This rapid energy release results in the highest peak pressure, even higher than the limited flame combustion without knocking. This is noteworthy because the total energy released is substantially higher due to the lambda value being richer. Ortiz et al. [85] noted that the combustion strategies for HCCI and SACI showed potential increases in the ITE_{net} of up to 30%, with an additional 12.5% with the potential to incorporate less detrimental control strategies, as shown in **Figure 3**. Yun et al. [86] showed that the ignition delay became shorter due to the delay in spark timing, meaning that the beginning of the combustion would be rapid. Finally, using the spark assisted HCCI combustion, the operating range was extended. Furthermore, under higher load in SAPCCI mode, the BTE of low-octane fuel is better than the baseline G100 (~43%) [87].

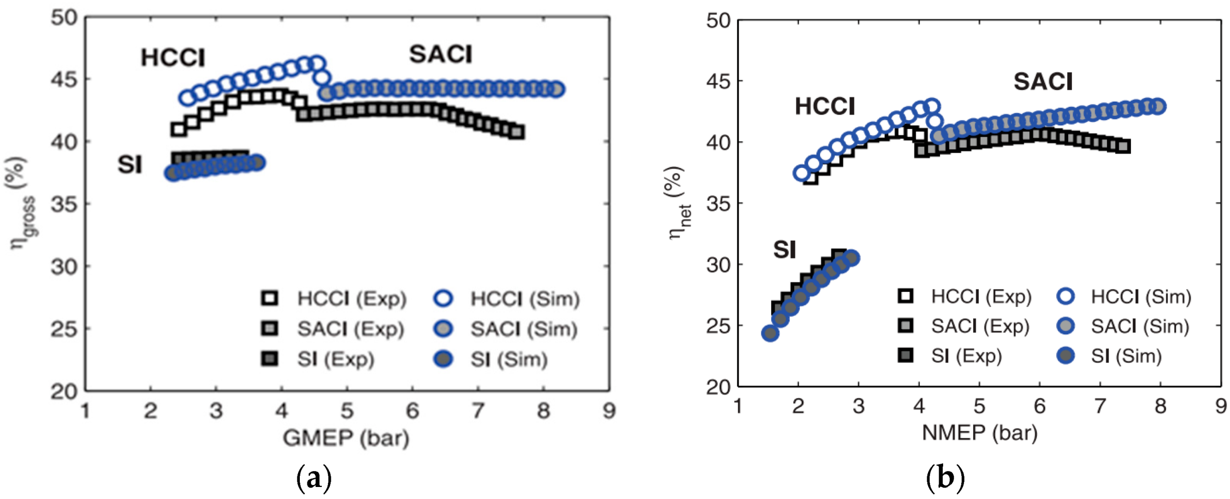

Figure 3. Comparison of simulation and experimental gross and net thermal efficiency vs. load (**a**) Gross indicated thermal efficiency (GIE) (**b**) Net indicated thermal efficiency (ITE_{net}) [85].

Zhou et al. [88] showed that the iEGR ratio and ignition timing were essential factors for controlling the SACI combustion process. As a result, iEGR principally controls the combustion phase by varying intake air mass flow and the initial in-cylinder temperature. To accomplish stable SACI combustion and overcome ringing, Chen et al. [89] employed late side injection to adjust fuel distribution. They found that controlling the peak HRR value between 81.72 J/CAD to 148.92 J/CAD can result in stable SACI without ringing. In addition, the late side injection strategy decreases auto-ignition flame speed, suppresses engine knock, and improves thermal efficiency, thereby realizing SACI combustion. Jacek et al. [90] explained how the SACI achieves appropriate PRR and combustion stability under high load boundary conditions, which was beneficial to the HCCI/SACI transition. The results showed the ability to operate SACI at IMEP of 5 bar with an SFC of 207 g/kWh for heavy-duty engines. It is essential that the PRR and variation of IMEP do not exceed 2.5 bar/CAD and 3%, respectively, thus affording the considerable potential of load extension. Biswas and Ekoto [91] concluded that the impact of ozone addition was more significant for the low loads. Moreover, ozone addition decreases specific fuel consumption by up to 9%, with enhanced combustion stability comparable to similar conditions without ozone.

Recently, a comprehensive review has been conducted by Robertson and Prucka [92] to determine the key factors required to realize a feasible production-workable control strategy for SACI engines. The literature demonstrated that brake thermal efficiency of up to 44% was achievable in the product. The efficiency advantages are determined by the increased compression ratio, higher specific heat ratio, reduced pumping work, lower heat transfer, and shortened burning period. They found that charge stratification can achieve flame propagation and reduce the auto-ignition of the reaction rates.

1.5. Summary of the LTC Modes

As addressed in the above studies, the LTC mode has faced several challenges such as load extension and control of the knocking at high load [1]. First, combustion control and ignition timing. Because this combustion mode is ruled by chemical kinetics, it is extremely complicated to control these parameters. However, combustion can be governed by the temperature-time history of the fuel-air mixture and the fuel's properties. Temperature-time history can be altered by adjusting the intake air temperature, VCR, EGR, etc. The second is combustion stability and its noise (misfiring and torque oscillation). The use of closed-loop combustion control can mitigate this issue by regulating combustion timing, such as ignition delay and peak PRR. The third is combustion phasing, which is based on the signal of in-cylinder pressure. Fourth, cold start. Three methods can resolve this issue, such as providing glow plugs, utilizing some fuel additives, and adding vaporizer to biodiesel fuels. Finally, an extension of the highest possible load limits. To overcome this issue, two ways can be adopted, e.g., adaptation booster and compound injection strategy and using diesel blended renewable fuel such as ethanol and biodiesel.

Among the different LTC technologies, it was observed that intelligent charge compression ignition (ICCI), which is not covered in this article, has unique merits and potential in high efficiency (up to 50% of ITE at medium loads), combustion efficiency is significantly higher at low loads, and low emissions under wide load range over other LTC modes, so it is a suitable combustion mode to overcome high MPRR at high loads and low efficiency at low loads. ICCI can be enhanced in-cylinder reactivity, reformulating the cylinder's concentration stratification and composition at low loads [93]. Thus, that is why this concept can produce higher thermal efficiency. Maybe soon the ICC mode will be attractive in commercial applications.

2. Highly Dilution Combustion

Highly dilution combustion has been known to afford advantages for higher thermal efficiencies and lower emissions [94]. High dilution is one type of LTC strategies improve efficiency by reducing pumping work and heat transfer, as well as increasing the ratio of the specific heat. However, the high dilution harms deflagration flame propagation, raises the ignition energy required for auto-ignition, and limits peak engine load [92]. Some innovative strategies have been proposed to overcome these drawbacks, including an advanced ignition system, hydrogen-enriched combustion, and thermochemical recuperation.

2.1. Advanced Ignition System

Advanced ignition systems have been studied as a technology for downsizing boosted engines with dilution combustion. These technologies comprise [95]:

- Laser ignition.
- Microwave high-frequency ignition.
- Dual-coil offset/ignition.
- Active and passive jet ignition.
- Multi-charge ignition.

Advanced igniting systems for gasoline engines are necessary to improve engine thermal efficiency under dilution combustion conditions [96]. In addition, many of these systems improve the combustible mixture's ignition energy or dispersed the ignition energy into the entire combustible charge [97]. Due to the plenty and complexity of ignition technologies, only three types will be discussed and briefly summarized here, and the scope of their impact on thermal efficiency is as follows:

- Laser ignition system (LIS).
- Low-temperature plasma (Corona ignition system (CIS).
- Turbulent jet igniters (TJI).

2.2. Laser Ignition System (LIS)

It has been pointed out that the LIS can raise the peak cylinder pressure by 5% and 15% on average, respectively [98]. The laser source that is used to initiate combustion has several potential advantages. Although there are still some limitations, they have come to be an attractive research field to substitute conventional electrical discharge systems [97][98][99][100]. The main advantages of the laser ignition system are:

- It is an electrode-less ignition system.
- No electrodes were eroded or quenched effects.
- A laser ignition system's lifetime will far surpass the spark plug's lifespan.
- Random position of ignition plasma, capability for the leanest mixture, and precision ignition timing.

Laser ignition can precisely control the ignition energy deposited in the ignition plasma and feasibility multi-point ignition easily. These advantages of laser ignition have great potential in practical applications and could be used dramatically to improve the combustion process, which has increased research about laser ignition in the past few years [101]. One of the significant advantages of LIS is that it is easy to perform multi-point ignition, which is essential to burn lean mixtures, overcome the loss of flame speed, and reduced combustion duration [102][103][104][105]. The various strategies to implement multi-point laser ignition in a constant volume chamber of an engine have been studied [101][106][107]. The possibility of multi-point laser-induced ignition has been proved for the combustible mixture for either constant volume [104][105][107][108] or IC engines [109][110][111]. A significant improvement in the combustion of a lean mixture has been obtained by igniting the mixtures at multiple positions. An increment in peak pressure and PRR was seen for multi-point laser ignition compared to the single-point ignition.

Bihari et al. [112] observed that laser ignition improved combustion stability under all operating conditions; furthermore, they noted that the lean ignition limit could be significantly extended. The study also found that the BTE obtained was 32% when the laser ignition system is applied. Pal and Agarwal [113] observed that the BTE improves for both LIS and SI with BMEP rise. Additionally, the superior combustion of the hydrogen-air mixture within the combustion chamber is associated with higher BTE. Furthermore, this results in higher combustion efficiency inside the combustion chamber and a higher BTE for laser ignition (LI) than SI. Patane and Nandgaonkar [101] have reviewed several technologies utilized for multi-point laser ignition. They found that the increase in laser energy indicates improved combustion characteristics.

Recently, Prasad et al. [114] found that a maximum BTE is obtained for 31° CA bTDC ST (spark timing) for all hydrogen-compressed natural gas (HCNG) mixtures, and it was reduced for both advanced and retarded sparking timings. This experimental study also shows that laser ignition is proper for HCNG engine deployments.

2.3. Corona Ignition System (CIS)

In the past few years, radio frequency (RF) corona ignition technology has attracted much attention. The benefits of the corona ignition system (CIS) comprise continuous energy delivery, large ignition volume, and the feasibility of combustion diagnosis. In addition, the CIS can promote near-simultaneous and near-located multiple ignition points, thereby reducing the (0–10) burning duration [115]. A high-frequency power supply, a resonant igniter, and corresponding network circuits are the key elements. Therefore, the CIS can make combustion stable and extend engine operating range and lean stability limits compared to other ignition systems [116][117][118][119]. In comparison to the conventional spark ignition systems, the CIS can create a significantly larger high-intensity plasma ignition source, as shown in **Figure 4**.

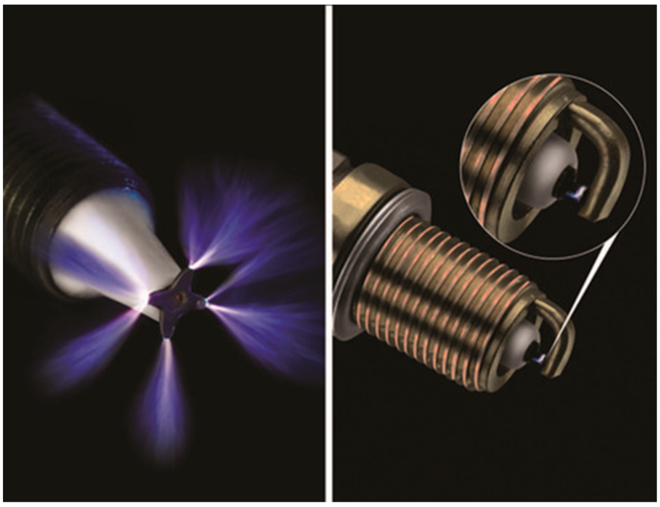

Figure 4. Difference between ACIS (**left**) and conventional spark plug (**right**) [120].

Several studies demonstrated that the early flame propagation had been accelerated, and the dilution limitation was extended, resulting in more stable operation, improved fuel economy, and provides further efficiency benefits [95][121][122][123]. A less than 3% of the “coefficient of variation. (COV) of IMEP (COV_{IMEP})” and shorter ignition delay can be obtained using an advanced corona ignition system (ACIS) [95]. In addition, it was noted that the flame propagation, ignition, and flame kernel generation were more robust [115]. Moreover, the ACIS enables advanced combustion strategies like highly diluted mixtures, very high EGR, and lean-burn, further increasing fuel efficiency [120].

Recently, experiments had been conducted in a single-cylinder optical research engine through Biswas et al. [124] to investigate the effect of three types of ignition systems on the performance and emissions, including ACIS, barrier Discharge Igniter, and Nanosecond Repetitive Pulse Discharge (NRPD). The experimental outcomes revealed that the lean limit was extended in both ignition systems (ACIS and NRPD), where the COV_{IMEP} is less than 3% [124]. Another study conducted by Ricci et al. [125] showed that corona igniters can extend. the lean. stable limit by increasing the early flame growth speed.

In summary, among the non-thermal plasma ignition techniques, the CIS shows the most possibility for adapting to changing in-cylinder thermodynamic conditions. In contrast, one of the CIS challenges ensures corona discharge’s inception while avoiding arc touchdown, particularly in high-density conditions if a higher voltage is necessitated [96].

2.4. Turbulent Jet Igniters (TJI)

Another promising approach for improving dilution combustion is the pre-chamber technique with an auxiliary fuel supply system, usually called turbulent jet ignition (TJI) [126]. The TJI systems can be categorized into passive pre-chamber systems, in which the fuel is supplied externally into the pre-chamber, and active pre-chamber systems, in which fuel is injected inside the pre-chamber. A passive pre-chamber consisting of a cover with holes encapsulated a smaller volume of fluid. As shown in **Figure 5**, the pre-chamber is linked to the main chamber through one or more tiny orifices (~1.25 mm diameter) [127]. This leads to promoting the quenching of flame and penetration into the main chamber. The main chamber combustion is initiated by the reacting mixture of pre-chamber in multiple locations throughout thermal, chemical, and turbulent influences [127][128][129].

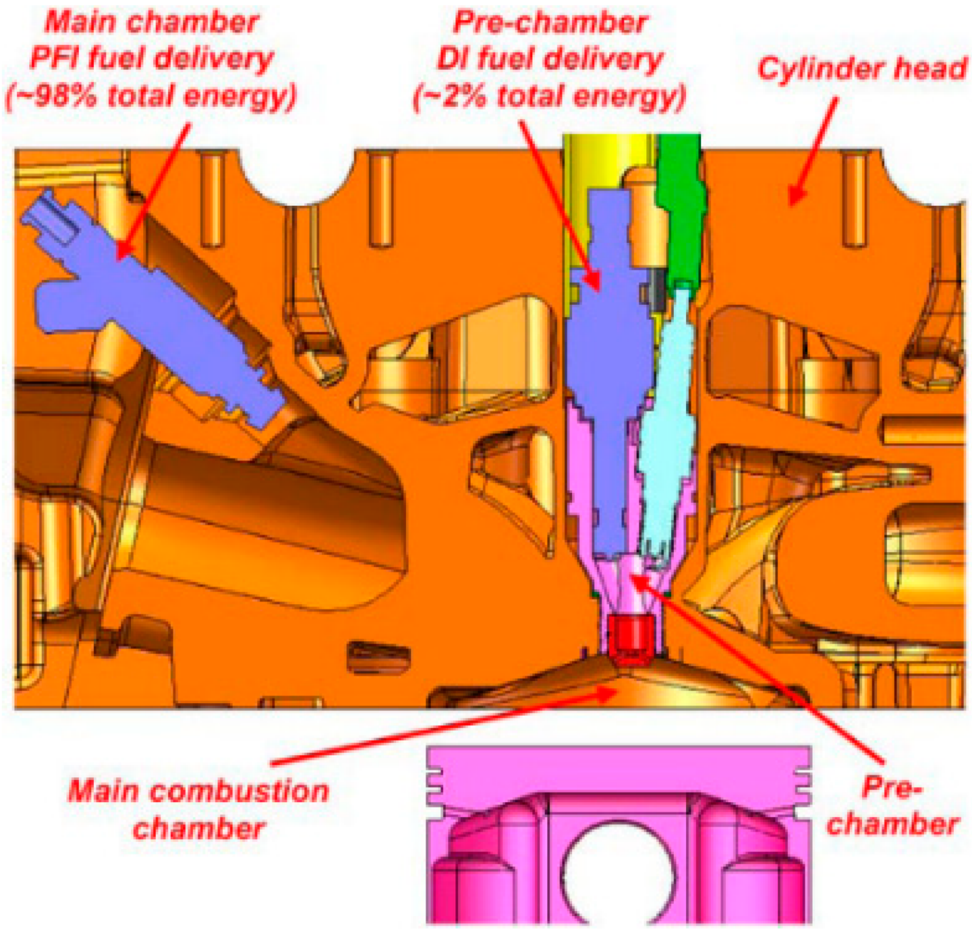

Figure 5. Schematic representation of pre-chamber [129].

The spark plug electrodes are utilized as an improver of ignition energy for the main combustion chamber [130][131]. The mechanisms behind the TJI combustion include the intricate coupling of factors [132][133], such as turbulent mixing, chemical reaction, flame quenching, and flame-piston impingement [134]. The TJI has the merits of enhancing burning rates and extending gasoline engine lean-burn limits. Some experimental studies by Refs. [129][135] reported an ITE_{net} of 42% using the TJI system, and it is an efficient way to extend the knock limit. Another work made by Bueschke et al. [136] proved that using the TJI leads to developing flame front, and a short combustion duration has been obtained. Furthermore, ultra-lean combustion and best fuel consumption can be achieved as well as improved engine performance by utilizing a fueled pre-chamber, which indicates that the TJI is more feasible for engine combustion under partial load conditions [126].

The TJI could be considered one of the solutions for increasing the flame speed and stabilizing the combustion process. Hua et al. [137] conducted experiments in a single-cylinder gasoline engine with different ignition systems, involving one-hole TJI, twin spark ignition, single spark ignition, and seven-hole TJI under various air/fuel equivalence ratios and various engine loads. The results showed that the cycle-to-cycle variants of the TJI combustion assessed by the COV_{IMEP} and coefficient of variation (COV) of peak pressure are significantly reduced due to the rapid combustion rate caused by the jet flame. Additionally, the single-hole TJI combustion seems to have the best combustion stability, particularly lowering COV of peak pressure.

Recently, Distaso et al. [138] analyzed the combustion by implementing the numerical simulation for the active pre-chamber technique of a lean operation engine. The analysis indicated that the overall operation of the TJI with an active pre-chamber could be subdivided into six principal phases, described as mixing, flame propagation, filling and scavenging, ejection, re-burning, and extraction and expulsion. At the TDC, approximately 40% of the cylinder volume has been occupied by flames, while traditional spark plugs only reported 18%. The results revealed an improvement in the engine performance compared to conventional spark plug when using a TJI system in terms of efficiency.

2.5. Hydrogen-Enriched Combustion

Hydrogen enrichment can significantly increase efficiency while reducing emissions without extensive engine modifications. One option for enriching the hydrogen source is to produce hydrogen on the vehicle through steam reforming methane actively [139]. The speed of the hydrogen flame is nine times greater than that of the diesel flame. Therefore, diesel combustion in the presence of hydrogen would achieve more fast and more complete combustion [140]. In addition, hydrogen is considered a high energy source because of the higher heating value, higher flame speed, low ignition energy, and the fact it does not have carbon atoms. These characteristics make it an essential source for emission control and the CI engine's performance improvement [141]. A mixture of hydrogen and methane showed that CO, CO_2, and HC decreased with the increase of hydrogen percentage while NO_x increment [142]. Excessive air ratio fueled with methane and hydrogen showed that the maximum PCP decreased with an increased excessive air ratio [143]. On the other hand, under injection timing of 5° ATDC with an injection duration of 90°, the BTE increased from 23.6% to 29.4% compared to diesel due to better mixing of hydrogen with air, resulting in enhanced combustion. Although 31.67% of the BTE can be achieved at 15° ATDC with 60° CA, an engine knock issue has been observed at this condition [144].

Karim et al. [145] reported that with increasing hydrogen content share, BTE had increased. Another study was conducted by Akansu et al. [144], and their conclusions were similar. Bari and Mohammad Esmaeil [140] observed that the BTE improved from 32% to 34.6%, 32.9–35.8%, and 34.7–36.3% at 19, 22, and 28 kW, respectively, by increasing the percent induction of H_2/O_2 mixture enrichment. This will lead to higher peak pressure near the TDC and generate a higher effective pressure for the work to be done, thereby contributing to efficiency improvements. Deheri et al. [141] revealed that the use of biogas in diesel engines decreases the BTE by up to 13% while increasing fuel consumption by up to 36%, which can be enhanced by using such techniques as advanced injection timing or higher compression ratios up to 10 to 12 %. In contrast, the combustion duration and ignition delay can be reduced by simultaneously providing biogas and hydrogen to the cylinder with advanced injection timing and higher CR. It appears that owing to the large flammability and high hydrogen flame speed, after hydrogen enrichment, the BTE at a lean-burn limit has been increased and reaches its maximum value of 18.99% when the fraction of hydrogen volume is one percent [146].

Zareei et al. [147] conducted a simulation study of a diesel engine fueled with hydrogen-compressed natural gas (HCNG) (the hydrogen amounts used in HCNG are 10, 20, 30, and 40%) using AVL Fire software based on the method of finite volume. The results reveal that the BTE has been improved when the concentration of hydrogen in the HCNG blend increased compared to CNG and pure diesel. This is because of the higher diffusivity of hydrogen (a homogenous mixture between hydrogen and air would be better). The BTE has increased up to 8.44% and 14.85% at 2400 and 1200 rpm, respectively, by utilizing 40% hydrogen in the HCNG blend compared to pure diesel, as shown in **Figure 6**. Alrazen et al. [148] analyzed the effect of the hydrogen addition to diesel engines on the performance and emissions. Therefore, an increase in BTE was observed due to short combustion duration, increased heat release, and cylinder pressure caused by hydrogen addition. In brief, hydrogen addition can help to enhance the poor combustion process of natural gas, which reduces the ignition delay, and improves the flame propagation speed, peak HRR, and peak cylinder pressure. Nevertheless, it also leads to a pinging sound and engine knock [149][150].

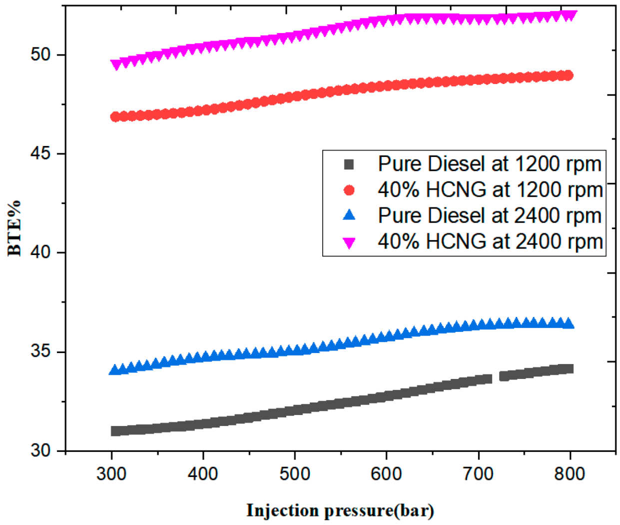

Figure 6. Illustrates the BTE under various injection pressures [147].

2.6. Thermochemical Recuperation

One viable method of waste heat recovery (WHR) to utilize the energy of the hot exhaust gas to maintain the endothermic fuel reforming reaction is defined as thermochemical recuperation (TCR) [151]. The TCR has two main advantages. First, through the endothermic fuel reforming reaction, the LHV of the fuel is increased due to the WHR process. Second, the mixture of gaseous reformed products usually has a higher hydrogen content, which increases burning velocity, a higher octane number, higher resistance to engine knock, and a more comprehensive range of flammability limits [152][153]. Therefore, the TCR can improve the efficiency due to the WHR process and lean burn operating feasibilities, thereby improving the ICE efficiency, approaching the theoretical Otto cycle, and the potential for increasing its compression ratio.

Popov et al. [154] have concluded that the TCR would improve energy efficiency by up to 10–25% compared to the traditional recuperation systems. Pashchenko et al. [155] analyzed the first law energy analysis of TCR by steam reforming several liquid biofuels, especially methanol, ethanol, glycerol, and n-butanol. The maximum efficiency of TCR use is at 600, 700, 850, and 900 K for methanol ethanol butanol, and glycerol, respectively. The results revealed that it was possible to choose the type of fuel owing to steam reforming, and it could be used for the first law energy analysis of the TCR system by steam reforming of liquid biofuels. However, Chakravarthy et al. [151] demonstrated that for a stoichiometric mixture of methanol and air, TCR could improve the ideal engine's second law efficiency by over 5% and about 3% for volume reforming and constant pressure, respectively. Furthermore, for ethanol and isooctane, the estimated second law efficiency increased by 9% and 11% for constant volume reforming, respectively. Brinkman and Stebar [156] indicated that the improved thermal efficiency resulted from the advantageous characteristics of H_2-rich methanol-reforming products, such as broader flammability limits and higher burning velocity, compared to gasoline.

As can be seen in **Figure 7**, employing the high-pressure methanol steam reforming (MSR) of 26 bar or higher and DI injector reference flow diameter (IRFD = 3.84 mm) affords engine efficiency enhancement of 12% to14% in comparison with the gasoline-fed counterpart. Additionally, the predicted improvement in the engine thermal efficiency will be much higher under partial loads. This is due to the lean-operating feasibilities permitted via the high hydrogen content in the reforming products [157]. Previous simulations have also shown that engine fueling with ethanol decomposition and methanol steam reforming (MSR) products reduces pollutant emissions more than gasoline [158].

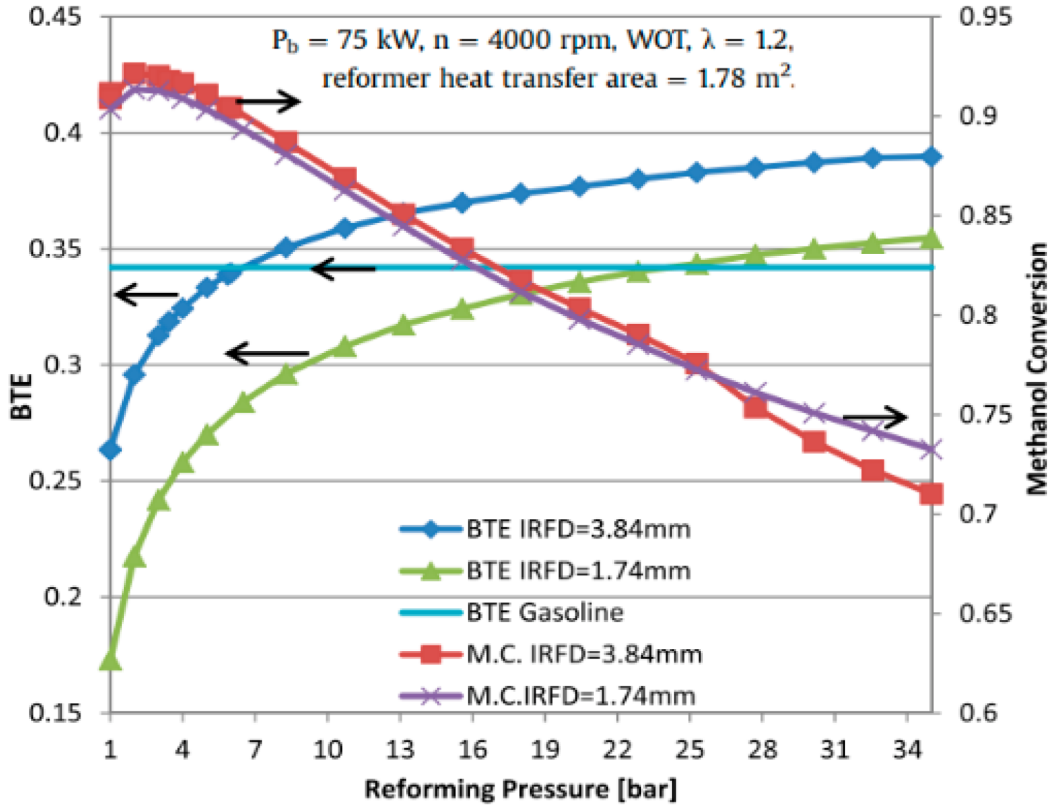

Figure 7. Relationship of methanol conversion and BTE on reforming pressure [157].

Another study by Poran and Tartakovsky [159] revealed that the engine feed with high-pressure methanol steam reforming leads to an improvement in an ITE of 18–39% (as shown in **Figure 8**), compared with gasoline feeding. Generally, the reformatted fuels have revealed a significant enhancement over gasoline in combustion performance, such as reducing COV for quicker HRR and a wide range of EAR. Tartakovsky and Sheintuch [160] provided an inclusive review of research on fuel reforming for IC engines. It involves a discussion of factors to consider before choosing the primary fuel. Steam reforming provides moderate thermochemical recovery and is suitable for methanol and ethanol feeds. Air reforming reduces the degree of recuperation but opens up opportunities for utilizing heavier fuels (like diesel and gasoline). Dry reforming (with carbon dioxide) can provide the best recuperation, but it is vulnerable to rapid coking.

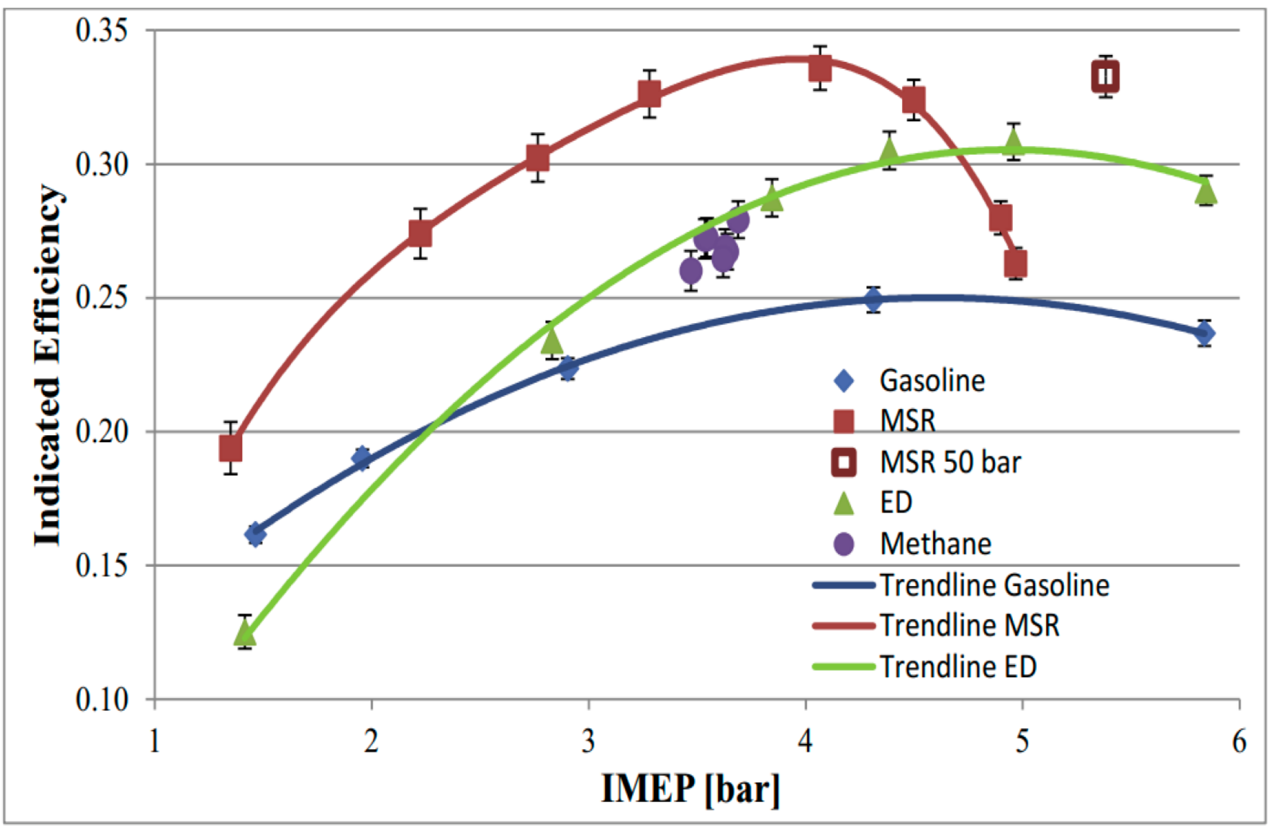

Figure 8. ITE at various load engines at 2800 rpm [159].

Recently, Hwang et al. [161] experimentally studied a "novel thermally incorporated steam reforming TCR reactor, which utilizes sensible and chemical energy in the exhaust to afford the required heat for hydrous ethanol steam reforming. Off-highway diesel engines were run at three different speeds and loads with diverging hydrous ethanol flow rates arriving fumigated energy fractions of up to 70%". The results show that the engine combustion and thermal efficiencies have suffered under low load conditions but exceeded conventional diesel combustion (CDC) values during high loads. The increase in operating temperatures permits CDC, such combustion efficiencies, while providing sufficient heat to generate a more significant energy content stream. In summary, TCR has significant benefits for improving IMEP and engine efficiency. Still, further research endeavored to improve IC engines' startup, and transient behavior with the TCR is needed to extend the range of feasible applications.

3. Other Advanced Technologies and Strategies

3.1. Ultra-High-Pressure Injection

Higher pressure injection has become a practical solution as implementing electronic fuel injection apparatus promotes engine performance and reduces emissions. In the past few years, 100 MPa injection pressure with an inline or a rotary pump system has been considered high pressure. However, in recent years, the pressure has risen to 160~180 MPa and even beyond 200 MPa. Likewise, engine power output was increased due to lower ignition delay duration at high injection pressure, leading to better BSFC [162]. On the one hand, raising the injection pressure enables increasing engine efficiency and decreases fuel consumption [163].

Researchers in diesel engine manufacturing start to talk about "30–300–3000" technologies as prospect trends, i.e., "30" represents high power density (30 bars of BMEP), "300" means 300 bars of peak cylinder pressure (PCP) to promote high thermal efficiency; and "3000" represents maximum fuel injection pressure in bar for governing NO_x, soot, and enhanced combustion efficiency [164]. Nowadays, the injection pressure has attained 2500–2700 bar [165], and a few studies have attempted to create fuel systems with 3000 bar injection pressure (Delphi, Denso). Gumus et al. [166] show that the increased injection pressure provided better outcomes for BTE and BSFC. Additionally, 41.31% of BTE was obtained with the B100 for 240 bar injection pressure. To obtain better diesel performance, some authors even put forward average suggestions on how to change the injection pressure [163]. High pressure directly decreases the diameter of droplets. This helps shorten the most prolonged combustion phase. Lee and Park [167] investigated atomization processes, spray break-up, droplet diameter, and velocity from a gasoline direct injector fueled with n-heptane under high injection pressure up to 300 bar. They affirmed that the injection pressure plays a crucial role in droplet breakup, but there is a limitation in injection pressure to improve droplet breakup.

Several studies have been conducted using an "ultra-high injection pressure" or "micro-hole nozzle" with its effect on the engine performance and emissions characteristics [168][169][170]. However, fuel injection equipment with "ultra-high-pressure injection" is still being created [171][172]. Li et al. [173] concluded that, for GDI injectors that use ethanol fuel, the "ultra-high injection pressure" up to 300 bar is a potential method to improve the homogeneity of the air/fuel mixture. The specific power must be increased concurrently with an increment in the injection pressure [174]. Mohan et al. [162] studied the effect of fuel injection strategies on improving engine performance and emissions control. They noted that increasing fuel injection pressure could improve fuel atomization and enhance the combustion process and thus increasing BTE. Aoyagi et al. [175] found that the merge of high EGR rate and high boost pressure as well as the high injection pressure up to 200 MPa is a practical and effective strategy that can simultaneously reduce the exhaust emissions and fuel consumption of diesel engines. They also observed that the BTE can be obtained at 46.3% and 49.7% under the PCP of 28 MPa and advanced the start of combustion (SOC) to −6° ATDC for single and six-cylinder, respectively.

The influence of "ultra-high injection pressure" on diesel ignition and flame characteristics was numerically studied using the KIVA-3V code with the KH/RT spray breakup model [176]. Due to the in-cylinder pressure build-up effect, the "ultra-high injection pressure" will not cause an increase in the length of the flame lift-off. Therefore, the flame lift-off lengths are approximately the same when the injection pressure is 180 MPa and 500 MPa. They reported that increasing the injection pressure means shorter injection duration, more rapid heat release, a shorter burn duration, faster flame penetration, and higher in-cylinder pressure rise when the amount of fuel injected is the same. In an investigation into the influence of "injection pressure of a diesel engine", Kim et al. [177] exhibited that the combustion pressure and HRR became high with increasing fuel injection pressure. As a result, the ignition delay period was lessened when injection pressure increased, but combustion duration was extended. In addition, the increase in injection pressure leads to improved fuel atomization, which improves the BSFC and BTE. In a study that set out to explore the impact of fuel injection pressure on diesel engines, Şen [178] observed that changing the fuel injection pressure looks to be a promising technique for improving combustion characteristics. It is the primary determinant of fuel stratification within the chamber and has a considerable impact on the combustion process. Moreover, high injection pressure releases fuel as smaller droplets, resulting in (i) a higher surface area to volume ratio, (ii) improves the vaporability of the fuel and forming complete combustion, (iii) shortening the combustion duration, (iv) decreases BSFC, and (v) improves the BTE at low speeds.

There are few fundamental studies currently investigating the combined impact of "ultra-high injection pressure" usage and "micro-hole nozzle" on the combustion processes and mixtures formation. Consequently, the use of an "ultra-high injection pressure" and "micro-hole nozzle" (d less than 0.10 mm) can provide significant improvements in diesel engine performance [179]. The combination of "ultra-high injection pressure" and "micro-hole diameter" helps avoid the interference of lift-off length and liquid length, reducing the formation of soot. Another study conducted by Zhai et al. [180] revealed that the injector with the "micro-hole diameter" and under "ultra-high injection pressure has a lower average spray equivalence ratio, better M ˙ A/M ˙ F ratio, and larger spray area and spray angle. Recently, Zhao et al. [165] experimentally found the cessation of an increment of fuel consumption under the injection pressure above 3500 bar. The fuel state change results in a decrease in the sound local velocity due to an increase in fuel temperature resulting from the increase in injection pressure. As the injection pressure increases, the fuel velocity from the nozzle holes and fuel consumption stop increasing.

Furthermore, the design of the nozzle orifice's influence on the combustion characteristics was investigated by Ewphun et al. [181] under PCCI mode conditions and multi-pulse "ultra-high-pressure injection". The experiments were performed on a "single-cylinder" engine at 0.55 MPa IMEPg at 1750 rpm, where the injection pulses were three pulses equally mass for the main injection at injection pressures of 1500, 2000, 2500, 3000, and 3500 bar. The results show an increase in thermal efficiency, NO_x, and smoke.

In summary, higher injection pressure results in higher thermal efficiency, and fuel consumption would be better. On the other hand, ultra-high injection pressures reduce soot emissions, essentially attributed to better air entrainment and spray atomization, leading to increased BSFC and NO_x. Therefore, fuel injection strategy modifications are required up to 300 MPa to attain higher thermal efficiency.

3.2. Variable Compression Ratio

The variable compression ratio (VCR) concept is a promising approach to improving engine performance, thermal efficiency, and decreased emissions. The higher compression ratio achieves faster laminar flame speed; hence, the ignition delay period will be shorter. High CR significantly improves the expansion efficiency and BTE. The VCR technology is characterized by higher power output under high load operating conditions and higher efficiency under lower load. This leads to a lessening in fuel consumption and CO_2 emissions [182]. Moreover, combining the advanced technology in combustion processes, internal aerodynamics, and emissions formation to VCR engines will assist high design power and torque engines as well as satisfy the compression ratio required [183][184][185].

Several authors reviewed the geometric methods and solutions used to implement VCR and predicted what benefits VCR would bring to current engine designs [186]. Based on the effort performed by Hariram and Vagesh [187], a decline in BSFC was observed by about 30% when CR raised from 16 to 18, and BTE increased by 13% at a full load of the VCR CI engine. Asthana et al. [182] exhibited that the change in the CR from 9 to 11 improved the BMEP by a moderate amount. Aoyagi et al. [175] performed experiments on a single-cylinder diesel engine to study the influence of the VCR on fuel consumption and pollutants under high EGR rate and high boosted pressure conditions. They observed 46.3% of BTE achieved when the ECR is reduced by employing a VVT system while retaining the PCP at 280 bar. Muralidharan et al. [188] conducted experimental research on biodiesel and its blend at a set compression ratio of CR = 21. The BTE is directly proportional to the applied load and increased, while SFC was inversely proportional to the applied load. Therefore, compared with diesel, the maximum BTE at full load is increased by 4.1%. Mohanraj and Kumar [189] noted that the BTEs of the biodiesel has been increased for all compression ratios (CR = 14~18), and the highest value was 30.57% for compression ratio 18. Bora et al. [190] found that the best BTE obtained at full load was 20.04% at a CR of 18 with a rice bran biodiesel-biogas dual fuel.

Pan et al. [191] observed that cycle to cycle variations could be significantly reduced by increasing CR at a given EGR ratio. This is mainly because of the influence of laminar flame speed and turbulence intensity, which increases with the increase of CR. Sharma and Murugan [192] have conducted experimental investigations under various compression ratios of 16.5, 17.5, and 18.5 with the oil gained from the pyrolysis of waste tires blended with diesel for about 80% and 20%. It showed a clear outcome that the BSEC would be diminished for the blend while the engine's compression ratio increased. In addition, the BTE increased by 8% (at full load) when the compression ratio rose from 17.5 to 18.5. In another study, the performance of dual-fuel diesel engines was evaluated by Bora and Saha [193] using rice bran biodiesel, and experiments were carried out under different loads and various compression ratios of 18, 17.5, and 17 with fixed injection timing of 23° BTDC. It was remarked that the BTEs at full load were 20.27%, 19.97%, and 18.39% at CRs of 18, 17.5, and 17, respectively.

Babu et al. [194] studied the impacts of fuel injection pressure and VCR experimentally for a single-cylinder compression ignition direct injection (CIDI) engine, which runs with a 40% Palm Stearin methyl ester blend. The results showed that the BTE was higher at an injection pressure of 21 MPa, and CR of 16.5, while the BTE had been higher for CR of 19 under the rated injection pressure of 19 MPa. Diesel with two biodiesel fuels (Simarouba and Jatropha) were blended to investigate the VCR effect on the combustion characteristics and emissions [195]. The main conclusion revealed that the increase in CR increased the PCP, HRR, and PRR; meanwhile, the combustion characteristics had been improved for all tested fuels. Kalbfleisch and Darbani [196] reviewed the effects of VCR on the BMEP, BSFC, and emissions. The increase in CR results in a higher mean BMEP, lower BSFC, and a higher HRR. Turning to a VCR engine can provide good performance under all loads and give a higher combustion rate. Additionally, it clearly shows that the VCR engine can improve combustion efficiency, reduce ignition delay (ID) under variable loads, and afford a higher compression ratio. In addition, VCR engines have better control capabilities at peak cylinder pressures (PCPs), thereby reducing fuel consumption [197]. Zhang et al. [198] observed that the changing CR from 15.7 to 18.9 leads to an increase ITE_g due to increasing the CR.

Recently, engine combustion and emission performance of single-cylinder diesel engines have been studied by Rosha et al. [199]. This study is fueled by 20% palm biodiesel and blended with diesel fuel under various compression ratios (16, 17, and 18). For palm biodiesel, peak cylinder pressure (PCP) was observed to be higher than neat diesel operation at CR of 17 then increased further with increasing CR from 16 to 18 owing to the improved BTE (14.9%) at higher compression ratios (CRs). The results show that the rise in compression ratio increases the BTE [199].

In summary, the VCR aims to decrease fuel consumption under low loads. It intends to minimize environmental damage by lessening the CO_2 emissions while affording improved power and torque under high loads. Finally, it shows that the biodiesel-diesel blend ratio and engine CR play a predominant role in enhancing engine performance and emissions. Although inclusive studies have been conducted on the performance of biodiesel blends in CI engines under fixed CR, there have been few dispersed studies on variable compression ratio (VCR) engines using biodiesel as the blended fuel.

3.3. Double Compression Expansion Engine

Though much technological enhancement has been made in the last few years, the four-stroke engine configuration remains unchanged. The need for high-efficiency engines is a reason to research alternative engine principles. A split-cycle engine is an ICE that has compression and expansion strokes in separate piston cylinders and operates on an open cycle, like conventional engines. The most noted benefit available with split-cycle engines is improved thermal efficiency over traditional engines [200]. Practical compromises or inherent architectural split-cycle engine design limitations may include why improved thermal efficiency is not realized practically, and thermal management has significant challenges when the expansion cylinder is subjected to high constant temperatures [200]. Due to the engine cycle being performed in two or more cylinders, the double compression-expansion engine (DCEE) idea belongs to the split-cycle engine family [201].

Several researchers have studied the effect of the DCEE on engine performance. Bhavani et al. [202] suggested that adopting an isobaric heat addition for a peak cylinder pressure (PCP) could have enabled a high BTE as any other heat addition process besides engine noise was lower. Lam et al. [203] simulated DCEE using the GT-power one-dimensional software, and they found that the DCEE with Lambda 3.0 could give a BTE of 56%, but decreasing the lambda to 1.2 could reach a BTE of 54.5%. This is mainly due to the higher overall heat transfer losses that would be close to the stoichiometric combustion. Recently, Lam et al. [204] reported that the growth in the load engine leads to increased efficiency due to decreased inter-cooling relative loss and improved mechanical efficiency. Additionally, engine tests reveal that a GIE of 47% was achieved in most operating conditions (98.2 to 310.4 mg/cycle of mass injecting). Furthermore, they found that a peak BTE of 52.8% was attained at a very high injection mass. Though the DCEE can achieve higher thermal efficiency, it suffers heat losses from the high-pressure method. Goyal et al. [205] analyzed the efficiency of the DCEE concept using one, two, and three-injector events. The benefits of these injector events are to minimize the convective heat losses. Therefore, GT-Power software has been employed to simulate this study for one and three-dimensional. The results reveal that the three-injector event minimized the heat transfer losses and enhanced the brake thermal efficiency, compared to the single and two-injector events. In particular, the three-injector event led to a high BTE and ITE of 54.2% and 58.5%, respectively.

3.4. Engine Knock Control

In SI engines, engine knock is an abnormal phenomenon that can restrain thermal efficiency and engine performance [206]. The conventional SI engines, which run at a high compression ratio, suffer from engine knock triggered by auto-ignition in the end-gas region at high loads [207][208]. Several methodologies are used to improve the thermal efficiency by suppressing engine knock. First, clarifying the inner mechanism between knocking characteristics [89] and auto-ignition [89][209]. Second, promoting SI flame propagation to vanish the end-gas auto-ignition [210]. Third, using advanced compression combustion approaches to govern auto-ignition [211].

There are several approaches to detect knock. The first is based on the direct measurement of in-cylinder parameters. The second approach is based on indirect measurements, such as cylinder block vibration and sound pressure [206][212][213][214]. Both are listed as followed.

- Heat transfer analysis.
- Temperature analysis.
- Cylinder block vibration analysis.
- In-cylinder pressure analysis.
- Acoustic emissions and light radiation analysis.
- Ion current analysis.

Furthermore, one of the significant challenges faced by the development of SI engines is suppressing engine knock. Therefore, some methods can efficiently repress knock, and each has its benefits and weaknesses. From the concept of increment in-cylinder turbulence, Hibi et al. [215] studied the impact of various compression flow fields on engine knock. The findings demonstrate that "end-gas auto-ignition" has been suppressed more evident under quick flame propagation conditions. Optical studies have recently shown that the auto-ignition does not necessarily cause engine knock when the auto-ignition flame is controllable [216]. Chen et al. [217] demonstrated that "end-gas auto-ignition" is an adequate condition of engine knock, and it is significantly associated with the peak HRR, particularly when auto-ignition occurs. In addition, under extreme knocking conditions, rapid turbulent flame propagation often leads to the advanced auto-ignition timing, resulting in concentrated heat release and thus severe auto-ignition. In other words, a higher flame speed may induce heavier engine knock at enhanced turbulent intensity conditions.

Recently, Duan et al. [218] studied the efficiency, combustion, and knocking characteristics of SI engines with a lean-burning engine fueled with n-butane liquefied methane gas mixtures. The results indicated that the energy contribution of n-butane increased with increased cylinder pressure, heat release rate, and accumulated heat release. The burning location was also increased by 50%, the burning time was decreased by 10–90%, and the knocking strength was increased. In addition, if the n-butane energy increased, the oscillation amplitude also increased, leading to more significant cycle-to-cycle variations. Nevertheless, the IMEP and the ITE first raised as the percentage of n-butane energy increased and then reduced. This is due to the increase in n-butane energy share which leads to shortened combustion duration (10–90%) and advanced 50% combustion location, thereby improving the ITE.

References

1. Pachiannan, T.; Zhong, W.; Rajkumar, S.; He, Z.; Leng, X.; Wang, Q. A literature review of fuel effects on performance and emission characteristics of low-temperature combustion strategies. Appl. Energy 2019, 251, 113380.
2. Polat, S.; Yücesu, H.S.; Uyumaz, A.; Kannan, K.; Shahbakhti, M. An experimental investigation on combustion and performance characteristics of supercharged HCCI operation in low compression ratio engine setting. Appl. Therm. Eng. 2020, 180, 115858.
3. Maurya, R.K.; Agarwal, A.K. Experimental study of combustion and emission characteristics of ethanol fuelled port injected homogeneous charge compression ignition (HCCI) combustion engine. Appl. Energy 2011, 88, 1169–1180.
4. Zheng, M.; Han, X.; Asad, U.; Wang, J. Investigation of butanol-fuelled HCCI combustion on a high efficiency diesel engine. Energy Convers. Manag. 2015, 98, 215–224.

5. Ganesh, D.; Nagarajan, G.; Ganesan, S. Experimental investigation of homogeneous charge compression ignition combustion of biodiesel fuel with external mixture formation in a CI engine. Environ. Sci. Technol. 2014, 48, 3039–3046.
6. Lu, X.; Qian, Y.; Yang, Z.; Han, D.; Ji, J.; Zhou, X.; Huang, Z. Experimental study on compound HCCI (homogenous charge compression ignition) combustion fueled with gasoline and diesel blends. Energy 2014, 64, 707–718.
7. Lü, X.; Hou, Y.; Zu, L.; Huang, Z. Experimental study on the auto-ignition and combustion characteristics in the homogeneous charge compression ignition (HCCI) combustion operation with ethanol/n-heptane blend fuels by port injection. Fuel 2006, 85, 2622–2631.
8. Nagarajan, G.; MillerJothi, N.K.; Renganarayanan, S. A New Approach for Utilisation of Lpg-Dee in Homogeneous Charge Compression Ignition (Hcci) Engine; SAE Technical Papers; SAE International: Warrendale, PA, USA, 2004.
9. Wang, S. Limitations of Partially Premixed Combustion. Ph.D. Thesis, Technische Universiteit Eindhoven, Eindhoven, The Netherlands, 2017.
10. Mathivanan, K.; Mallikarjuna, J.M.; Ramesh, A. Influence of multiple fuel injection strategies on performance and combustion characteristics of a diesel fuelled HCCI engine—An experimental investigation. Exp. Therm. Fluid Sci. 2016, 77, 337–346.
11. Çelebi, S.; Haşimoğlu, C.; Uyumaz, A.; Halis, S.; Calam, A.; Solmaz, H.; Yılmaz, E. Operating range, combustion, performance and emissions of an HCCI engine fueled with naphtha. Fuel 2021, 283, 118828.
12. Ganesh, D.; Nagarajan, G. Homogeneous charge compression ignition (HCCI) combustion of diesel fuel with external mixture formation. Energy 2010, 35, 148–157.
13. Qiu, L.; Cheng, X.; Liu, B.; Dong, S.; Bao, Z. Partially premixed combustion based on different injection strategies in a light-duty diesel engine. Energy 2016, 96, 155–165.
14. Liu, J.; Shang, H.; Wang, H.; Zheng, Z.; Wang, Q.; Xue, Z.; Yao, M. Investigation on partially premixed combustion fueled with gasoline and PODE blends in a multi-cylinder heavy-duty diesel engine. Fuel 2017, 193, 101–111.
15. Duan, X.; Lai, M.C.; Jansons, M.; Guo, G.; Liu, J. A review of controlling strategies of the ignition timing and combustion phase in homogeneous charge compression ignition (HCCI) engine. Fuel 2021, 285, 119142.
16. Lu, X.; Han, D.; Huang, Z. Fuel design and management for the control of advanced compression-ignition combustion modes. Prog. Energy Combust. Sci. 2011, 37, 741–783.
17. Urushihara, T.; Yamaguchi, K.; Yoshizawa, K.; Itoh, T. A Study of a Gasoline-fueled Compression Ignition Engine~ Expansion of HCCI Operation Range Using SI Combustion as a Trigger of Compression Ignition~. SAE Trans. 2005, 114, 419–425.
18. Haraldsson, G.; Tunestål, P.; Johansson, B.; Hyvönen, J. HCCI Combustion Phasing with Closed-Loop Combustion Control Using Variable Compression Ratio in a Multi Cylinder Engine; SAE Technical Papers; SAE International: Warrendale, PA, USA, 2003.
19. Aroonsrisopon, T.; Werner, P.; Waldman, J.O.; Sohm, V.; Foster, D.E.; Morikawa, T.; Iida, M. Expanding the HCCI operation with the charge stratification. SAE Trans. 2004, 113, 1130–1145.
20. Milovanovic, N.; Blundell, D.; Pearson, R.; Turner, J.; Chen, R. Enlarging the Operational Range of a Gasoline HCCI Engine by Controlling the Coolant Temperature; SAE Technical Papers; SAE International: Warrendale, PA, USA, 2005.
21. Calam, A.; Aydoğan, B.; Halis, S. The comparison of combustion, engine performance and emission characteristics of ethanol, methanol, fusel oil, butanol, isopropanol and naphtha with n-heptane blends on HCCI engine. Fuel 2020, 266, 117071.
22. García, A.; Monsalve-Serrano, J.; Roso, V.R.; Martins, M.E.S. Evaluating the emissions and performance of two dual-mode RCCI combustion strategies under the World Harmonized Vehicle Cycle (WHVC). Energy Convers. Manag. 2017, 149, 263–274.
23. Fang, W.; Kittelson, D.B.; Northrop, W.F. Optimization of reactivity-controlled compression ignition combustion fueled with diesel and hydrous ethanol using response surface methodology. Fuel 2015, 160, 446–457.
24. Kokjohn, S.L.; Hanson, R.M.; Splitter, D.A.; Reitz, R.D. Experiments and modeling of dual-fuel HCCI and PCCI combustion using in-cylinder fuel blending. SAE Int. J. Engines 2010, 2, 24–39.
25. Kokjohn, S.L.; Reitz, R.D. Reactivity controlled compression ignition and conventional diesel combustion: A comparison of methods to meet light-duty NOx and fuel economy targets. Int. J. Engine Res. 2013, 14, 452–468.
26. Li, J.; Yang, W.M.; An, H.; Zhou, D.Z.; Yu, W.B.; Wang, J.X.; Li, L. Numerical investigation on the effect of reactivity gradient in an RCCI engine fueled with gasoline and diesel. Energy Convers. Manag. 2015, 92, 342–352.

27. Kakaee, A.-H.; Rahnama, P.; Paykani, A. Influence of fuel composition on combustion and emissions characteristics of natural gas/diesel RCCI engine. J. Nat. Gas Sci. Eng. 2015, 25, 58–65.

28. Li, J.; Yang, W.; Zhou, D. Review on the management of RCCI engines. Renew. Sustain. Energy Rev. 2017, 69, 65–79.

29. Kokjohn, S.L.; Hanson, R.M.; Splitter, D.A.; Reitz, R.D. Fuel reactivity controlled compression ignition (RCCI): A pathway to controlled high-efficiency clean combustion. Int. J. Engine Res. 2011, 12, 209–226.

30. Benajes, J.; Molina, S.; García, A.; Belarte, E.; Vanvolsem, M. An investigation on RCCI combustion in a heavy duty diesel engine using in-cylinder blending of diesel and gasoline fuels. Appl. Therm. Eng. 2014, 63, 66–76.

31. Han, X.; Zheng, M.; Tjong, J.S.; Li, T. Suitability Study of n-Butanol for Enabling PCCI and HCCI and RCCI Combustion on a High Compression-Ratio Diesel Engine; SAE Technical Papers; SAE International: Warrendale, PA, USA, 2005.

32. Dempsey, A.B.; Walker, N.R.; Gingrich, E.; Reitz, R.D. Comparison of low temperature combustion strategies for advanced compression ignition engines with a focus on controllability. Combust. Sci. Technol. 2014, 186, 210–241.

33. Curran, S.; Prikhodko, V.; Cho, K.; Sluder, C.S.; Parks, J.; Wagner, R.; Kokjohn, S.; Reitz, R.D. In-Cylinder Fuel Blending of Gasoline/Diesel for Improved Efficiency and Lowest Possible Emissions on a Multi-Cylinder Light-Duty Diesel Engine; SAE Technical Papers; SAE International: Warrendale, PA, USA, 2010.

34. Heuser, B.; Ahling, S.; Kremer, F.; Pischinger, S.; Rohs, H.; Holderbaum, B.; Körfer, T. Experimental Investigation of a RCCI Combustion Concept with In-Cylinder Blending of Gasoline and Diesel in a Light Duty Engine; SAE Technical Papers; SAE International: Warrendale, PA, USA, 2015.

35. Leermakers, C.A.J.; Van den Berge, B.; Luijten, C.C.M.; Somers, L.M.T.; de Goey, L.P.H.; Albrecht, B.A. Gasoline-Diesel Dual Fuel: Effect of Injection Timing And Fuel Balance; SAE Technical Papers; SAE International: Warrendale, PA, USA, 2011.

36. Ickes, A.; Wallner, T.; Zhang, Y.; De Ojeda, W. Impact of cetane number on combustion of a gasoline-diesel dual-fuel heavy-duty multi-cylinder engine. SAE Int. J. Engines 2014, 7, 860–872.

37. Splitter, D.; Wissink, M.; Delvescovo, D.; Reitz, R. RCCI Engine Operation towards 60% Thermal Efficiency; SAE Technical Papers; SAE International: Warrendale, PA, USA, 2013; Volume 2.

38. Splitter, D.; Hanson, R.; Kokjohn, S.; Reitz, R.D. Reactivity Controlled Compression Ignition (RCCI) Heavy-Duty Engine Operation at Mid- and High-Loads with Conventional and Alternative Fuels; SAE Technical Papers; SAE International: Warrendale, PA, USA, 2011.

39. Reitz, R.D.; Duraisamy, G. Review of high efficiency and clean reactivity controlled compression ignition (RCCI) combustion in internal combustion engines. Prog. Energy Combust. Sci. 2015, 46, 12–71.

40. Soloiu, V.; Gaubert, R.; Moncada, J.; Wiley, J.; Williams, J.; Harp, S.; Ilie, M.; Molina, G.; Mothershed, D. Reactivity controlled compression ignition and low temperature combustion of Fischer-Tropsch Fuel Blended with n-butanol. Renew. Energy 2019, 134, 1173–1189.

41. Benajes, J.; García, A.; Monsalve-Serrano, J.; Lago Sari, R. Fuel consumption and engine-out emissions estimations of a light-duty engine running in dual-mode RCCI/CDC with different fuels and driving cycles. Energy 2018, 157, 19–30.

42. Pan, S.; Li, X.; Han, W.; Huang, Y. An experimental investigation on multi-cylinder RCCI engine fueled with 2-butanol/diesel. Energy Convers. Manag. 2017, 154, 92–101.

43. Gross, C.W.; Reitz, R. Investigation of Steady-State RCCI Operation in a Light-Duty Multi-Cylinder Engine Using “Dieseline”; SAE Technical Papers; SAE International: Warrendale, PA, USA, 2017; Volume 2017.

44. Charitha, V.; Thirumalini, S.; Prasad, M.; Srihari, S. Investigation on performance and emissions of RCCI dual fuel combustion on diesel—bio diesel in a light duty engine. Renew. Energy 2019, 134, 1081–1088.

45. Ebrahimi, M.; Najafi, M.; Jazayeri, S.A.; Mohammadzadeh, A.R. A detail simulation of reactivity controlled compression ignition combustion strategy in a heavy-duty diesel engine run on natural gas/diesel fuel. Int. J. Engine Res. 2018, 19, 774–789.

46. Han, J.; Somers, B. Effects of Butanol Isomers on the Combustion and Emission Characteristics of a Heavy-Duty Engine in RCCI Mode; SAE Technical Papers; SAE International: Warrendale, PA, USA, 2020.

47. Pan, S.; Han, W.; Liu, X.; Cai, K.; Li, X.; Li, B. Experimental study on combustion and emission characteristics of iso-butanol/diesel and gasoline/diesel RCCI in a heavy-duty engine under low loads. Fuel 2020, 261, 116434.

48. Eyal, A.; Thawko, A.; Baibikov, V.; Tartakovsky, L. Performance and pollutant emission of the reforming-controlled compression ignition engine—Experimental study. Energy Convers. Manag. 2021, 237, 114126.

49. Rahnama, P.; Paykani, A.; Reitz, R.D. A numerical study of the effects of using hydrogen, reformer gas and nitrogen on combustion, emissions and load limits of a heavy duty natural gas/diesel RCCI engine. Appl. Energy 2017, 193, 182–198.

50. Molina, S.; García, A.; Pastor, J.M.; Belarte, E.; Balloul, I. Operating range extension of RCCI combustion concept from low to full load in a heavy-duty engine. Appl. Energy 2015, 143, 211–227.
51. Jia, M.; Dempsey, A.B.; Wang, H.; Li, Y.; Reitz, R.D. Numerical simulation of cyclic variability in reactivity-controlled compression ignition combustion with a focus on the initial temperature at intake valve closing. Int. J. Engine Res. 2015, 16, 441–460.
52. Noehre, C.; Andersson, M.; Johansson, B.; Hultqvist, A. Characterization of Partially Premixed Combustion; SAE Technical Papers; SAE International: Warrendale, PA, USA, 2006.
53. Shankar, V. Double Compression Expansion Engine: Evaluation of Thermodynamic Cycle and Combustion Concepts. Ph.D. Thesis, King Abdullah University of Science and Technology, Thuwal, Saudi Arabia, 2019.
54. Manente, V.; Zander, C.-G.; Johansson, B.; Tunestal, P.; Cannella, W. An Advanced Internal Combustion Engine Concept for Low Emissions and High Efficiency from Idle to Max Load Using Gasoline Partially Premixed Combustion; SAE Technical Papers; SAE International: Warrendale, PA, USA, 2010.
55. Tuner, M.; Johansson, B.; Keller, P.; Becker, M. Loss Analysis of a HD-PPC Engine with Two-Stage Turbocharging Operating in the European Stationary Cycle; SAE Technical Papers; SAE International: Warrendale, PA, USA, 2013.
56. Paykani, A.; Kakaee, A.H.; Rahnama, P.; Reitz, R.D. Progress and recent trends in reactivity-controlled compression ignition engines. Int. J. Engine Res. 2016, 17, 481–524.
57. Kalghatgi, G.T.; Hildingsson, L.; Harrison, A.J.; Johansson, B. Autoignition quality of gasoline fuels in partially premixed combustion in diesel engines. Proc. Combust. Inst. 2011, 33, 3015–3021.
58. Kalghatgi, G.T.; Risberg, P.; Ångström, H.-E. Partially Pre-Mixed Auto-Ignition of Gasoline to Attain Low Smoke and Low NOx at High Load in a Compression Ignition Engine and Comparison with a Diesel Fuel; SAE Technical Papers; SAE International: Warrendale, PA, USA, 2007.
59. An, Y.; Jaasim, M.; Raman, V.; Im, H.G.; Johansson, B. In-cylinder combustion and soot evolution in the transition from conventional compression ignition (CI) mode to partially premixed combustion (PPC) mode. Energy Fuels 2018, 32, 2306–2320.
60. Ilango, T.; Natarajan, S. Effect of compression ratio on partially premixed charge compression ignition engine fuelled with methanol diesel blends-an experimental investigation. Int. J. Mech. Prod. Eng. 2014, 2, 41–45.
61. Najafabadi, M.I.; Dam, N.; Somers, B.; Johansson, B. Ignition Sensitivity Study of Partially Premixed Combustion by Using Shadowgraphy and OH* Chemiluminescence Methods; SAE Technical Papers; SAE International: Warrendale, PA, USA, 2016.
62. An, Y.; Vallinayagam, R.; Vedharaj, S.; Masurier, J.-B.; Dawood, A.; Najafabadi, M.I.; Somers, B.; Johansson, B. Analysis of Transition from HCCI to CI via PPC with Low Octane Gasoline Fuels Using Optical Diagnostics and Soot Particle Analysis; SAE Technical Papers; SAE International: Warrendale, PA, USA, 2017.
63. Vedharaj, S.; Vallinayagam, R.; An, Y.; Dawood, A.; Najafabadi, M.I.; Somers, B.; Chang, J.; Johansson, B. Fuel Effect on Combustion Stratification in Partially Premixed Combustion; SAE Technical Papers; SAE International: Warrendale, PA, USA, 2017.
64. Manente, V.; Tunestal, P.; Johansson, B.; Cannella, W.J. Effects of Ethanol and Different Type of Gasoline Fuels on Partially Premixed Combustion from Low to High Load; SAE Technical Papers; SAE International: Warrendale, PA, USA, 2010.
65. Han, X.; Yang, Z.; Wang, M.; Tjong, J.; Zheng, M. Clean combustion of n-butanol as a next generation biofuel for diesel engines. Appl. Energy 2017, 198, 347–359.
66. Zincir, B.; Shukla, P.; Shamun, S.; Tuner, M.; Deniz, C.; Johansson, B. Investigation of effects of intake temperature on low load limitations of methanol partially premixed combustion. Energy Fuels 2019, 33, 5695–5709.
67. Yin, L.; Turesson, G.; Tunestål, P.; Johansson, R. Evaluation and transient control of an advanced multi-cylinder engine based on partially premixed combustion. Appl. Energy 2019, 233–234, 1015–1026.
68. Leermakers, C.A.J. Efficient Fuels for Future Engines; Technische Universiteit Eindhoven: Eindhoven, The Netherlands, 2014; ISBN 9789038635545.
69. Liu, B.; Cheng, X.; Liu, J.; Pu, H. Investigation into particle emission characteristics of partially premixed combustion fueled with high n-butanol-diesel ratio blends. Fuel 2018, 223, 1–11.
70. Valentino, G.; Corcione, F.E.; Iannuzzi, S.; Serra, S. An Experimental Analysis on Diesel/n-Butanol Blends Operating in Partial Premixed Combustion in a Light Duty Diesel Engine; SAE Technical Papers; SAE International: Warrendale, PA, USA, 2012.

71. Cheng, X.; Shuai, L.I.; Yang, J.; Dong, S.; Bao, Z. Effect of N-Butanol-Diesel Blends on Partially Premixed Combustion and Emission Characteristics in a Light-Duty Engine; SAE Technical Papers; SAE International: Warrendale, PA, USA, 2014.

72. Zhang, M.; Derafshzan, S.; Richter, M.; Lundgren, M. Effects of different injection strategies on ignition and combustion characteristics in an optical PPC engine. Energy 2020, 203, 117901.

73. Mao, B.; Chen, P.; Liu, H.; Zheng, Z.; Yao, M. Gasoline compression ignition operation on a multi-cylinder heavy duty diesel engine. Fuel 2018, 215, 339–351.

74. Aziz, A.; Garcia, A.; Dos Santos, C.P.; Tuner, M. Impact of Multiple Injection Strategies on Performance and Emissions of Methanol PPC under Low Load Operation; SAE Technical Papers; SAE International: Warrendale, PA, USA, 2020.

75. Dimitrakopoulos, N.; Tuner, M. Investigation of the Effect of Glow Plugs on Low Load Gasoline PPC; SAE Technical Papers; SAE International: Warrendale, PA, USA, 2020.

76. Manofsky, L.; Vavra, J.; Assanis, D.N.; Babajimopoulos, A. Bridging the Gap between HCCI and SI: Spark-Assisted Compression Ignition; SAE Technical Papers; SAE International: Warrendale, PA, USA, 2011.

77. Olesky, L.M.; Martz, J.B.; Lavoie, G.A.; Vavra, J.; Assanis, D.N.; Babajimopoulos, A. The effects of spark timing, unburned gas temperature, and negative valve overlap on the rates of stoichiometric spark assisted compression ignition combustion. Appl. Energy 2013, 105, 407–417.

78. Cupo, F. Virtual Fuel Design for SACI Operation Strategy. In Modeling of Real Fuels and Knock Occurrence for an Effective 3D-CFD Virtual Engine Development; Springer: Berlin/Heidelberg, Germany, 2021; pp. 97–110.

79. Kalian, N.; Standing, R.; Zhao, H. Effects of Ignition Timing on CAI Combustion in a Multi-Cylinder DI Gasoline Engine; SAE Technical Papers; SAE International: Warrendale, PA, USA, 2005.

80. Wang, Z.; Wang, J.; Shuai, S.; He, X.; Xu, F.; Yang, D.; Ma, X. Research on Spark Induced Compression Ignition (SICI); SAE Technical Papers; SAE International: Warrendale, PA, USA, 2009.

81. Szybist, J.P.; Nafziger, E.; Weall, A. Load expansion of stoichiometric HCCI using spark assist and hydraulic valve actuation. SAE Int. J. Engines 2010, 3, 244–258.

82. Weall, A.J.; Szybist, J.P. The effects of fuel characteristics on stoichiometric spark-assisted HCCI. In Proceedings of the ASME 2011 Internal Combustion Engine Division Fall Technical Conference, Morgantown, WV, USA, 2–5 October 2011; pp. 243–259.

83. Xie, H.; Li, L.; Chen, T.; Yu, W.; Wang, X.; Zhao, H. Study on spark assisted compression ignition (SACI) combustion with positive valve overlap at medium–high load. Appl. Energy 2013, 101, 622–633.

84. Chiodi, M.; Kaechele, A.; Bargende, M.; Wichelhaus, D.; Poetsch, C. Development of an Innovative Combustion Process: Spark-Assisted Compression Ignition. SAE Int. J. Engines 2017, 10, 247–256.

85. Ortiz-Soto, E.A.; Lavoie, G.A.; Wooldridge, M.S.; Assanis, D.N. Thermodynamic efficiency assessment of gasoline spark ignition and compression ignition operating strategies using a new multi-mode combustion model for engine system simulations. Int. J. Engine Res. 2019, 20, 304–326.

86. Yun, H.; Wermuth, N.; Najt, P. Extending the High Load Operating Limit of a Naturally-Aspirated Gasoline HCCI Combustion Engine. SAE Int. J. Engines 2010, 3, 681–699.

87. Verma, G.; Sharma, H.; Thipse, S.S.; Agarwal, A.K. Spark assisted premixed charge compression ignition engine prototype development. Fuel Process. Technol. 2016, 152, 413–420.

88. Zhou, L.; Dong, K.; Hua, J.; Wei, H.; Chen, R.; Han, Y. Effects of applying EGR with split injection strategy on combustion performance and knock resistance in a spark assisted compression ignition (SACI) engine. Appl. Therm. Eng. 2018, 145, 98–109.

89. Chen, L.; Zhang, R.; Pan, J.; Wei, H. Effects of partitioned fuel distribution on auto-ignition and knocking under spark assisted compression ignition conditions. Appl. Energy 2020, 260, 114269.

90. Hunicz, J.; Mikulski, M.; Koszałka, G.; Ignaciuk, P. Detailed analysis of combustion stability in a spark-assisted compression ignition engine under nearly stoichiometric and heavy EGR conditions. Appl. Energy 2020, 280, 115955.

91. Biswas, S.; Ekoto, I. Spark Assisted Compression Ignition Engine with Stratified Charge Combustion and Ozone Addition. SAE Int. J. Adv. Curr. Pract. Mobil. 2019, 2, 385–400.

92. Robertson, D.; Prucka, R. A Review of Spark-Assisted Compression Ignition (SACI) Research in the Context of Realizing Production Control Strategies; SAE Technical Papers; SAE International: Warrendale, PA, USA, 2019.

93. Li, Z.L.; Qian, Y.; Huang, G.; Zhao, W.B.; Zhang, Y.Y.; Lu, X.C. Gasoline-diesel dual fuel intelligent charge compression ignition (ICCI) combustion: Conceptual model and comparison with other advanced combustion modes. Sci. China Technol. Sci. 2021, 64, 719–728.

94. Caton, J.A. On the importance of specific heats as regards efficiency increases for highly dilute IC engines. Energy Convers. Manag. 2014, 79, 146–160.
95. Yun, H.; Idicheria, C.; Najt, P. The effect of advanced ignition system on gasoline low temperature combustion. Int. J. Engine Res. 2019, 22, 417–429.
96. Yu, S.; Zheng, M. Future gasoline engine ignition: A review on advanced concepts. Int. J. Engine Res. 2021, 22, 1743–1775.
97. Dale, J.D.; Checkel, M.D.; Smy, P.R. Application of high energy ignition systems to engines. Prog. Energy Combust. Sci. 1997, 23, 379–398.
98. Dale, J.D.; Smy, P.R.; Clements, R.M. Laser ignited internal combustion engine—An experimental study. SAE Trans. 1978, 87, 1539–1548.
99. McIntyre, D.L. A Laser Spark Plug Ignition System for a Stationary Lean-Burn Natural Gas Reciprocating Engine; National Energy Technology Lab. (NETL): Morgantown, WV, USA; West Virginia University: Morgantown, WV, USA, 2007.
100. McMillian, M.H.; Woodruff, S.D.; Richardson, S.W.; McIntyre, D.L. Laser spark ignition: Laser development and engine testing. In Proceedings of the ICEF04 2004 Fall Technical Conference of the ASME Internal Combustion Engine Division, Long Beach, CA, USA, 24–27 October 2004.
101. Patane, P.; Nandgaonkar, M. Review: Multipoint laser ignition system and its applications to IC engines. Opt. Laser Technol. 2020, 130, 106305.
102. Morsy, M.H. Review and recent developments of laser ignition for internal combustion engines applications. Renew. Sustain. Energy Rev. 2012, 16, 4849–4875.
103. Weinrotter, M.; Kopecek, H.; Tesch, M.; Wintner, E.; Lackner, M.; Winter, F. Laser ignition of ultra-lean methane/hydrogen/air mixtures at high temperature and pressure. Exp. Therm. Fluid Sci. 2005, 29, 569–577.
104. Ryu, S.K.; Won, S.H.; Chung, S.H. Laser-induced multi-point ignition with single-shot laser using conical cavities and prechamber with jet holes. Proc. Combust. Inst. 2009, 32, 3189–3196.
105. Phuoc, T.X. Single-point versus multi-point laser ignition: Experimental measurements of combustion times and pressures. Combust. Flame 2000, 122, 508–510.
106. Nakaya, S.; Iseki, S.; Gu, X.; Kobayashi, Y.; Tsue, M. Flame kernel formation behaviors in close dual-point laser breakdown spark ignition for lean methane/air mixtures. Proc. Combust. Inst. 2017, 36, 3441–3449.
107. Lyon, E.; Kuang, Z.; Cheng, H.; Page, V.; Shenton, T.; Dearden, G. Multi-point laser spark generation for internal combustion engines using a spatial light modulator. J. Phys. D Appl. Phys. 2014, 47, 475501.
108. Saito, T.; Suzuta, Y.; Takahashi, E.; Furutani, H. Performance of internal combustion engine using multi-point laser ignition under nitrogen dilution conditions. In Proceedings of the 4th Laser Ignition Conference, Yokohama, Japan, 17–15 May 2016; p. LIC6-5.
109. Grzeszik, R. Impact of Turbulent In-Cylinder Air Motion and Local Mixture Formation on Inflammation in Lean Engine Operation: Is Multiple Point Ignition a Solution? In Proceedings of the Laser Ignition Conference 2017, Bucharest, Romania, 20–23 June 2017; p. LFA3-1.
110. Kuang, Z.; Lyon, E.; Cheng, H.; Page, V.; Shenton, T.; Dearden, G. Multi-location laser ignition using a spatial light modulator towards improving automotive gasoline engine performance. Opt. Lasers Eng. 2017, 90, 275–283.
111. Yamaguchi, S.; Takahashi, E.; Furutani, H.; Kojima, H.; Inami, S.; Miyata, J.; Kashiwazaki, T.; Nishioka, M. Two-point laser ignition for stable lean burn operation of gas engine. In Proceedings of the 2nd Laser Ignition Conference 2014, Yokohama, Japan, 22–24 April 2014.
112. Bihari, B.; Gupta, S.B.; Sekar, R.R.; Gingrich, J.; Smith, J. Development of advanced laser ignition system for stationary natural gas reciprocating engines. In Proceedings of the ASME 2005 Internal Combustion Engine Division Fall Technical Conference, Ottawa, ON, Canada, 11–14 September 2005; Volume 47365, pp. 601–608.
113. Pal, A.; Agarwal, A.K. Comparative study of laser ignition and conventional electrical spark ignition systems in a hydrogen fuelled engine. Int. J. Hydrogen Energy 2015, 40, 2386–2395.
114. Prasad, R.K.; Mustafi, N.; Agarwal, A.K. Effect of spark timing on laser ignition and spark ignition modes in a hydrogen enriched compressed natural gas fuelled engine. Fuel 2020, 276, 118071.
115. Gunther, M.; Sens, M. Ignition Systems for Gasoline Engines. In Proceedings of the 3rd International Conference, Berlin, Germany, 3–4 November 2016; Springer: Cham, Switzerland, 2017. ISBN 3319455036.
116. Cimarello, A.; Cruccolini, V.; Discepoli, G.; Battistoni, M.; Mariani, F.; Grimaldi, C.; Dal Re, M. Combustion Behavior of an RF Corona Ignition System with Different Control Strategies; SAE Technical Papers; SAE International: Warrendale,

PA, USA, 2018; Volume 2018, pp. 1–19.

117. Burrows, J.; Mixell, K.; Reinicke, P.B.; Riess, M.; Sens, M. Corona ignition-assessment of physical effects by pressure chamber, rapid compression machine, and single cylinder engine testing. In Proceedings of the 2nd International Conference on Ignition Systems for Gasoline Engines, Berlin, Germany, 24–25 November 2014.

118. Cimarello, A.; Grimaldi, C.N.; Mariani, F.; Battistoni, M.; Dal Re, M. Analysis of RF Corona Ignition in Lean Operating Conditions Using an Optical Access Engine; SAE Technical Papers; SAE International: Warrendale, PA, USA, 2017; Volume 2017.

119. Cruccolini, V.; Discepoli, G.; Cimarello, A.; Battistoni, M.; Mariani, F.; Grimaldi, C.N.; Dal Re, M. Lean combustion analysis using a corona discharge igniter in an optical engine fueled with methane and a hydrogen-methane blend. Fuel 2020, 259, 116290.

120. Federal-Mogul Advanced Corona Ignition System (ACIS) Shows Up to 10% Reduced Fuel Consumption in Testing. 2021, pp. 1–12. Available online: https://www.greencarcongress.com/2011/09/acis-20110914.html (accessed on 14 September 2011).

121. Agneray, A.; Jaffrezic, X.; Mispreuve, L. Radio Frequency Ignition System, Breakthrough Technology for the Future Spark Ignition Engine; SAI: Strasbourg, France, 2009.

122. Mariani, A.; Foucher, F. Radio frequency spark plug: An ignition system for modern internal combustion engines. Appl. Energy 2014, 122, 151–161.

123. Hampe, C.; Bertsch, M.; Beck, K.W.; Spicher, U.; Bohne, S.; Rixecker, G. Influence of High Frequency Ignition on the Combustion and Emission Behaviour of Small Two-Stroke Spark Ignition Engines; SAE Technical Papers; SAE International: Warrendale, PA, USA, 2013.

124. Biswas, S.; Ekoto, I.; Singleton, D.; Mixell, K.; Ford, P. Assessment of Spark, Corona, and Plasma Ignition Systems for Gasoline Combustion. In Proceedings of the ASME 2020 Internal Combustion Engine Division Fall Technical Conference, Virtual, 4–6 November 2020.

125. Ricci, F.; Petrucci, L.; Cruccolini, V.; Discepoli, G.; Grimaldi, C.N.; Papi, S. Investigation of the Lean Stable Limit of a Barrier Discharge Igniter and of a Streamer-Type Corona Igniter at Different Engine Loads in a Single-Cylinder Research Engine. Multidiscip. Digit. Publ. Inst. Proc. 2020, 58, 11.

126. Hua, J.; Zhou, L.; Gao, Q.; Feng, Z.; Wei, H. Influence of pre-chamber structure and injection parameters on engine performance and combustion characteristics in a turbulent jet ignition (TJI) engine. Fuel 2021, 283, 119236.

127. MAHLE Turbulent Jet Ignition Pre-Chamber Initiated Combustion System Supports High Efficiency and Near Zero Engine-Out NOx in Naturally Aspirated PFI Engine. 2021, pp. 1–16. Available online: https://www.greencarcongress.com/2010/10/tji-20101027.html (accessed on 27 October 2010).

128. Toulson, E.; Schock, H.J.; Attard, W.P. A Review of Pre-Chamber Initiated Jet Ignition Combustion Systems; SAE Technical Papers; SAE International: Warrendale, PA, USA, 2010.

129. Attard, W.P.; Fraser, N.; Parsons, P.; Toulson, E. A Turbulent Jet Ignition Pre-Chamber Combustion System for Large Fuel Economy Improvements in a Modern Vehicle Powertrain; SAE Technical Papers; SAE International: Warrendale, PA, USA, 2010; Volume 3, pp. 20–37.

130. Alvarez, C.E.C.; Couto, G.E.; Roso, V.R.; Thiriet, A.B.; Valle, R.M. A review of prechamber ignition systems as lean combustion technology for SI engines. Appl. Therm. Eng. 2018, 128, 107–120.

131. Bianco, A.; Millo, F.; Piano, A. Modelling of combustion and knock onset risk in a high-performance turbulent jet ignition engine. Transp. Eng. 2020, 2, 100037.

132. Ghorbani, A.; Steinhilber, G.; Markus, D.; Maas, U. Ignition by transient hot turbulent jets: An investigation of ignition mechanisms by means of a PDF/REDIM method. Proc. Combust. Inst. 2015, 35, 2191–2198.

133. Gholamisheeri, M.; Wichman, I.S.; Toulson, E. A study of the turbulent jet flow field in a methane fueled turbulent jet ignition (TJI) system. Combust. Flame 2017, 183, 194–206.

134. Biswas, S.; Qiao, L. Ignition of ultra-lean premixed hydrogen/air by an impinging hot jet. Appl. Energy 2018, 228, 954–964.

135. Attard, W.P.; Parsons, P. A normally aspirated spark initiated combustion system capable of high load, high efficiency and near zero NOx emissions in a modern vehicle powertrain. SAE Int. J. Engines 2010, 3, 269–287.

136. Bueschke, W.; Szwajca, F.; Wislocki, K. Experimental Study on Ignitability of Lean CNG/Air Mixture in the Multi-Stage Cascade Engine Combustion System; SAE Technical Papers; SAE International: Warrendale, PA, USA, 2020.

137. Hua, J.; Zhou, L.; Gao, Q.; Feng, Z.; Wei, H. Effects on Cycle-to-Cycle Variations and Knocking Combustion of Turbulent Jet Ignition (TJI) with a Small Volume Pre-Chamber; SAE Technical Papers; SAE International: Warrendale,

PA, USA, 2020.

138. Distaso, E.; Amirante, R.; Cassone, E.; De Palma, P.; Sementa, P.; Tamburrano, P.; Vaglieco, B.M. Analysis of the combustion process in a lean-burning turbulent jet ignition engine fueled with methane. Energy Convers. Manag. 2020, 223, 113257.

139. Zwitserlood, J.G.; Hofman, T.; Erickson, P.A. Hydrogen Enrichment of an Internal Combustion Engine via Closed Loop Thermochemical Recuperation; Eindhoven University of Technology: Eindhoven, The Netherlands, 2013.

140. Bari, S.; Mohammad Esmaeil, M. Effect of H2/O2 addition in increasing the thermal efficiency of a diesel engine. Fuel 2010, 89, 378–383.

141. Deheri, C.; Acharya, S.K.; Thatoi, D.N.; Mohanty, A.P. A review on performance of biogas and hydrogen on diesel engine in dual fuel mode. Fuel 2020, 260, 116337.

142. Akansu, S.O.; Kahraman, N.; Çeper, B. Experimental study on a spark ignition engine fuelled by methane–hydrogen mixtures. Int. J. Hydrogen Energy 2007, 32, 4279–4284.

143. Kahraman, N.; Ceper, B.; Akansu, S.O.; Aydin, K. Investigation of combustion characteristics and emissions in a spark-ignition engine fuelled with natural gas–hydrogen blends. Int. J. Hydrogen Energy 2009, 34, 1026–1034.

144. Saravanan, N.; Nagarajan, G.; Dhanasekaran, C.; Kalaiselvan, K.M. Experimental investigation of hydrogen port fuel injection in DI diesel engine. Int. J. Hydrogen Energy 2007, 32, 4071–4080.

145. Karim, G.A.; Wierzba, I.; Al-Alousi, Y. Methane-hydrogen mixtures as fuels. Int. J. Hydrogen Energy 1996, 21, 625–631.

146. Ji, C.; Wang, S. Experimental study on combustion and emissions performance of a hybrid hydrogen-gasoline engine at lean burn limits. Int. J. Hydrogen Energy 2010, 35, 1453–1462.

147. Zareei, J.; Haseeb, M.; Ghadamkheir, K.; Farkhondeh, S.A.; Yazdani, A.; Ershov, K. The effect of hydrogen addition to compressed natural gas on performance and emissions of a DI diesel engine by a numerical study. Int. J. Hydrogen Energy 2020, 45, 34241–34253.

148. Alrazen, H.A.; Abu Talib, A.R.; Adnan, R.; Ahmad, K.A. A review of the effect of hydrogen addition on the performance and emissions of the compression—Ignition engine. Renew. Sustain. Energy Rev. 2016, 54, 785–796.

149. Sagar, S.M.V.; Agarwal, A.K. Knocking behavior and emission characteristics of a port fuel injected hydrogen enriched compressed natural gas fueled spark ignition engine. Appl. Therm. Eng. 2018, 141, 42–50.

150. Qiao, J.; Li, Y.; Wang, S.; Wang, P.; Liu, J. Experimental investigation and numerical assessment the effects of EGR and hydrogen addition strategies on performance, energy and exergy characteristics of a heavy-duty lean-burn NGSI engine. Fuel 2020, 275, 117824.

151. Chakravarthy, V.K.; Daw, C.S.; Pihl, J.A.; Conklin, J.C. Study of the theoretical potential of thermochemical exhaust heat recuperation for internal combustion engines. Energy Fuels 2010, 24, 1529–1537.

152. Verhelst, S.; Wallner, T. Hydrogen-fueled internal combustion engines. Prog. Energy Combust. Sci. 2009, 35, 490–527.

153. Verhelst, S. Recent progress in the use of hydrogen as a fuel for internal combustion engines. Int. J. Hydrogen Energy 2014, 39, 1071–1085.

154. Popov, S.K.; Svistunov, I.N.; Garyaev, A.B.; Serikov, E.A.; Temyrkanova, E.K. The use of thermochemical recuperation in an industrial plant. Energy 2017, 127, 44–51.

155. Pashchenko, D.; Gnutikova, M.; Karpilov, I. Comparison study of thermochemical waste-heat recuperation by steam reforming of liquid biofuels. Int. J. Hydrogen Energy 2020, 45, 4174–4181.

156. Brinkman, N.D.; Stebar, R.F. A comparison of methanol and dissociated methanol illustrating effects of fuel properties on engine efficiency—Experiments and thermodynamic analyses. SAE Trans. 1985, 94, 62–85.

157. Poran, A.; Tartakovsky, L. Energy efficiency of a direct-injection internal combustion engine with high-pressure methanol steam reforming. Energy 2015, 88, 506–514.

158. Tartakovsky, L.; Baibikov, V.; Veinblat, M. Comparative Performance Analysis of SI Engine Fed by Ethanol and Methanol Reforming Products; SAE Technical Papers; SAE International: Warrendale, PA, USA, 2013.

159. Poran, A.; Tartakovsky, L. Performance and emissions of a direct injection internal combustion engine devised for joint operation with a high-pressure thermochemical recuperation system. Energy 2017, 124, 214–226.

160. Tartakovsky, L.; Sheintuch, M. Fuel reforming in internal combustion engines. Prog. Energy Combust. Sci. 2018, 67, 88–114.

161. Hwang, J.T.; Kane, S.P.; Northrop, W.F. Hydrous Ethanol Steam Reforming and Thermochemical Recuperation to Improve Dual-Fuel Diesel Engine Emissions and Efficiency. J. Energy Resour. Technol. Trans. ASME 2019, 141, 112203.

162. Mohan, B.; Yang, W.; Chou, S.K. Fuel injection strategies for performance improvement and emissions reduction in compression ignition engines—A review. Renew. Sustain. Energy Rev. 2013, 28, 664–676.

163. Kendlbacher, C.; Müller, P.; Bernhaupt, M.; Rehbichler, G. Large engine injection systems for future emission legislations. Sh. Offshore 2010, 3, 12.

164. Xin, Q.; Pinzon, C.F. Improving the Environmental Performance of Heavy-Duty Vehicles and Engines: Key Issues and System Design Approaches; Woodhead Publishing: Sawston, UK, 2014; pp. 225–278. ISBN 9780857095220.

165. Zhao, J.; Grekhov, L.; Ma, X.; Denisov, A. Specific features of diesel fuel supply under ultra-high pressure. Appl. Therm. Eng. 2020, 179, 115699.

166. Gumus, M.; Sayin, C.; Canakci, M. The impact of fuel injection pressure on the exhaust emissions of a direct injection diesel engine fueled with biodiesel-diesel fuel blends. Fuel 2012, 95, 486–494.

167. Lee, S.; Park, S. Experimental study on spray break-up and atomization processes from GDI injector using high injection pressure up to 30 MPa. Int. J. Heat Fluid Flow 2014, 45, 14–22.

168. Payri, R.; García-Oliver, J.M.; Xuan, T.; Bardi, M. A study on diesel spray tip penetration and radial expansion under reacting conditions. Appl. Therm. Eng. 2015, 90, 619–629.

169. Wang, X.; Huang, Z.; Zhang, W.; Kuti, O.A.; Nishida, K. Effects of ultra-high injection pressure and micro-hole nozzle on flame structure and soot formation of impinging diesel spray. Appl. Energy 2011, 88, 1620–1628.

170. Zhang, W.; Nishida, K.; Gao, J.; Miura, D. An experimental study on flat-wall-impinging spray of microhole nozzles under ultra-high injection pressures. Proc. Inst. Mech. Eng. Part D J. Automob. Eng. 2008, 222, 1731–1741.

171. Shinohara, Y.; Takeuchi, K.; Herrmann, O.E.; Laumen, H.J. Common-Rail-Einspritzsystem mit 3000 bar. MTZ—Mot. Z. 2011, 72, 10–15.

172. Meek, G.A.; Williams, R.; Thornton, D.; Knapp, P.; Cosser, S. F2E—Ultra High Pressure Distributed Pump Common Rail System; SAE Technical Papers; SAE International: Warrendale, PA, USA, 2014; Volume 1.

173. Li, X.; Pei, Y.Q.; Qin, J.; Zhang, D.; Wang, K.; Xu, B. Effect of ultra-high injection pressure up to 50 MPa on macroscopic spray characteristics of a multi-hole gasoline direct injection injector fueled with ethanol. Proc. Inst. Mech. Eng. Part D J. Automob. Eng. 2018, 232, 1092–1104.

174. Wintrich, T.; Krüger, M.; Naber, D.; Zeh, D.; Uhr, C.; Köhler, D.; Hinrichsen, C. Bosch Common Rail Solutions for High Performance Diesel Power Train. In Proceedings of the 25th Aachen Colloquium Automobile and Engine Technology, Aachen, Germany, 10–12 October 2016.

175. Aoyagi, Y.; Yamaguchi, T.; Osada, H.; Shimada, K.; Goto, Y.; Suzuki, H. Improvement of thermal efficiency of a high-boosted diesel engine with focus on peak cylinder pressure. Int. J. Engine Res. 2011, 12, 227–237.

176. Tao, F.; Bergstrand, P. Effect of Ultra-High Injection Pressure on Diesel Ignition and Flame under High-Boost Conditions; SAE Technical Papers; SAE International: Warrendale, PA, USA, 2008; pp. 776–790.

177. Kim, H.Y.; Ge, J.C.; Choi, N.J. Effects of fuel injection pressure on combustion and emission characteristics under low speed conditions in a diesel engine fueled with palm oil biodiesel. Energies 2019, 12, 3264.

178. Şen, M. The effect of the injection pressure on single cylinder diesel engine fueled with propanol–diesel blend. Fuel 2019, 254, 115617.

179. Nishida, K.; Zhu, J.; Leng, X.; He, Z. Effects of micro-hole nozzle and ultra-high injection pressure on air entrainment, liquid penetration, flame lift-off and soot formation of diesel spray flame. Int. J. Engine Res. 2017, 18, 51–65.

180. Zhai, C.; Jin, Y.; Nishida, K.; Ogata, Y. Diesel spray and combustion of multi-hole injectors with micro-hole under ultra-high injection pressure—Non-evaporating spray characteristics. Fuel 2021, 283, 119322.

181. Ewphun, P.-P.; Otake, M.; Nagasawa, T.; Kosaka, H.; Sato, S. Combustion Characteristic of Offset Orifice Nozzle Under Multi Pulse Ultrahigh Pressure Injection and PCCI Combustion Conditions. SAE Int. J. Adv. Curr. Pract. Mobil. 2020, 2, 1002–1012.

182. Asthana, S.; Bansal, S.; Jaggi, S.; Kumar, N. A Comparative Study of Recent Advancements in the Field of Variable Compression Ratio Engine Technology; SAE Technical Papers; SAE International: Warrendale, PA, USA, 2016.

183. Yang, S.; Lin, J. A theoretical study of the mechanism with variable compression ratio and expansion ratio. Mech. Based Des. Struct. Mach. 2018, 46, 267–284.

184. Rabhi, V.; Beroff, J.; Dionnet, F. Study of a Gear-Based Variable Compression Ratio Engine; SAE Technical Papers; SAE International: Warrendale, PA, USA, 2004.

185. Wos, P.; Balawender, K.; Jakubowski, M.; Kuszewski, H.; Lejda, K.; Ustrzycki, A. Design of Affordable Multi-Cylinder Variable Compression Ratio (VCR) Engine for Advanced Combustion Research Purposes; SAE Technical Papers; SAE

International: Warrendale, PA, USA, 2012.

186. Shaik, A.; Moorthi, N.S.V.; Rudramoorthy, R. Variable compression ratio engine: A future power plant for automobiles—An overview. Proc. Inst. Mech. Eng. Part D J. Automob. Eng. 2007, 221, 1159–1168.

187. Hariram, V.; Vagesh Shangar, R. Influence of compression ratio on combustion and performance characteristics of direct injection compression ignition engine. Alex. Eng. J. 2015, 54, 807–814.

188. Muralidharan, K.; Vasudevan, D.; Sheeba, K.N. Performance, emission and combustion characteristics of biodiesel fuelled variable compression ratio engine. Energy 2011, 36, 5385–5393.

189. Mohanraj, T.; Mohan Kumar, K.M. Operating characteristics of a variable compression ratio engine using esterified tamanu oil. Int. J. Green Energy 2013, 10, 285–301.

190. Bora, B.J.; Saha, U.K.; Chatterjee, S.; Veer, V. Effect of compression ratio on performance, combustion and emission characteristics of a dual fuel diesel engine run on raw biogas. Energy Convers. Manag. 2014, 87, 1000–1009.

191. Pan, M.; Shu, G.; Wei, H.; Zhu, T.; Liang, Y.; Liu, C. Effects of EGR, compression ratio and boost pressure on cyclic variation of PFI gasoline engine at WOT operation. Appl. Therm. Eng. 2014, 64, 491–498.

192. Sharma, A.; Murugan, S. Potential for using a tyre pyrolysis oil-biodiesel blend in a diesel engine at different compression ratios. Energy Convers. Manag. 2015, 93, 289–297.

193. Bora, B.J.; Saha, U.K. Experimental evaluation of a rice bran biodiesel–biogas run dual fuel diesel engine at varying compression ratios. Renew. Energy 2016, 87, 782–790.

194. Babu, A.R.; Amba Prasad Rao, G.; Hari Prasad, T. Experimental investigations on a variable compression ratio (VCR) CIDI engine with a blend of methyl esters palm stearin-diesel for performance and emissions. Int. J. Ambient Energy 2017, 38, 420–427.

195. Hosamani, B.R.; Katti, V.V. Experimental analysis of combustion characteristics of CI DI VCR engine using mixture of two biodiesel blend with diesel. Eng. Sci. Technol. Int. J. 2018, 21, 769–777.

196. Kalbfleisch, P.; Darbani, A. A Literature Review ME 540: Advanced IC Engine Systems & Modeling. 2018. Available online: https://engineering.purdue.edu/online/sites/default/files/sites/default/files/documents/SU2018Syllabus/ME540Syllabus-Fall2016.pdf (accessed on 22 August 2022).

197. Suresh, M.; Jawahar, C.P.; Richard, A. A review on biodiesel production, combustion, performance, and emission characteristics of non-edible oils in variable compression ratio diesel engine using biodiesel and its blends. Renew. Sustain. Energy Rev. 2018, 92, 38–49.

198. Zhang, Y.; Kumar, P.; Tang, M.; Pei, Y.; Merritt, B.; Traver, M.; Popuri, S. Impact of Geometric Compression Ratio and Variable Valve Actuation on Gasoline Compression Ignition in a Heavy-Duty Diesel Engine. In Proceedings of the ASME 2020 Internal Combustion Engine Division Fall Technical Conference, Virtual, 4–6 November 2020.

199. Rosha, P.; Mohapatra, S.K.; Mahla, S.K.; Cho, H.M.; Chauhan, B.S.; Dhir, A. Effect of compression ratio on combustion, performance, and emission characteristics of compression ignition engine fueled with palm (B20)biodiesel blend. Energy 2019, 178, 676–684.

200. Finneran, J.; Garner, C.P.; Bassett, M.; Hall, J. A review of split-cycle engines. Int. J. Engine Res. 2020, 21, 897–914.

201. Nhut, L. Double Compression-Expansion Engine Concepts: Experimental and Simulation Study of a Split-cycle Concept for Improved Brake Efficiency. Ph.D. Thesis, Lund University, Lund, Sweden, 2019.

202. Bhavani Shankar, V.S.; Lam, N.; Andersson, A.; Johansson, B. Optimum Heat Release Rates for a Double Compression Expansion (DCEE) Engine; SAE Technical Papers; SAE International: Warrendale, PA, USA, 2017; Volume 2017.

203. Lam, N.; Tuner, M.; Tunestal, P.; Andersson, A.; Lundgren, S.; Johansson, B. Double Compression Expansion Engine Concepts: A Path to High Efficiency. SAE Int. J. Engines 2015, 8, 1562–1578.

204. Lam, N.; Tunestal, P.; Andersson, A. Simulation of System Brake Efficiency in a Double Compression-Expansion Engine-Concept (DCEE) Based on Experimental Combustion Data; SAE Technical Papers; SAE International: Warrendale, PA, USA, 2019.

205. Goyal, H.; Nyrenstedt, G.; Moreno Cabezas, K.; Panthi, N.; Im, H.; Andersson, A.; Johansson, B. A Simulation Study to Understand the Efficiency Analysis of Multiple Injectors for the Double Compression Expansion Engine (DCEE) Concept; SAE Technical Papers; SAE International: Warrendale, PA, USA, 2021; pp. 1–18.

206. Zhen, X.; Wang, Y.; Xu, S.; Zhu, Y.; Tao, C.; Xu, T.; Song, M. The engine knock analysis—An overview. Appl. Energy 2012, 92, 628–636.

207. Chen, L.; Wei, H.; Chen, C.; Feng, D.; Zhou, L.; Pan, J. Numerical investigations on the effects of turbulence intensity on knocking combustion in a downsized gasoline engine. Energy 2019, 166, 318–325.

208. Wang, Z.; Liu, H.; Reitz, R.D. Knocking combustion in spark-ignition engines. Prog. Energy Combust. Sci. 2017, 61, 78–112.

209. De Bellis, V. Performance optimization of a spark-ignition turbocharged VVA engine under knock limited operation. Appl. Energy 2016, 164, 162–174.

210. Livengood, J.C.; Wu, P.C. Correlation of autoignition phenomena in internal combustion engines and rapid compression machines. Symp. (Int.) Combust. 1955, 5, 347–356.

211. Kawahara, N.; Kim, Y.; Wadahama, H.; Tsuboi, K.; Tomita, E. Differences between PREMIER combustion in a natural gas spark-ignition engine and knocking with pressure oscillations. Proc. Combust. Inst. 2019, 37, 4983–4991.

212. Corti, E.; Forte, C. Statistical Analysis of Indicating Parameters for Knock Detection Purposes; SAE Technical Papers; SAE International: Warrendale, PA, USA, 2009.

213. Worret, R.; Bernhardt, S.; Schwarz, F.; Spicher, U. Application of different cylinder pressure based knock detection methods in spark ignition engines. SAE Trans. 2002, 111, 2244–2257.

214. Millo, F.; Ferraro, C.V. Knock in SI engines: A comparison between different techniques for detection and control. SAE Trans. 1998, 107, 1091–1112.

215. Hibi, T.; Kohata, T.; Tsumori, Y.; Namiki, S.; Shima, K.; Katsumata, M.; Tanabe, M. Study on knocking intensity under in-cylinder flow field in SI engines using a rapid compression machine. J. Therm. Sci. Technol. 2013, 8, 460–475.

216. Gerty, M.D.; Heywood, J.B. An Investigation of Gasoline Engine Knock Limited Performance and the Effects of Hydrogen Enhancement; SAE Technical Papers; SAE International: Warrendale, PA, USA, 2006.

217. Chen, L.; Zhang, R.; Wei, H.; Pan, J. Effect of flame speed on knocking characteristics for SI engine under critical knocking conditions. Fuel 2020, 282, 118846.

218. Duan, X.; Liu, J.; Yao, J.; Chen, Z.; Wu, C.; Chen, C.; Dong, H. Performance, combustion and knock assessment of a high compression ratio and lean-burn heavy-duty spark-ignition engine fuelled with n-butane and liquefied methane gas blend. Energy 2018, 158, 256–268.

Retrieved from https://encyclopedia.pub/entry/history/show/65819