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Review

Key Technologies to 50% Brake Thermal Efficiency for Gasoline Engine of Passenger Car

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Abstract: As fuel consumption and emissions regulations become increasingly stringent, various advanced strategies have been proposed to achieve higher efficiency in internal combustion engines. This paper reviews the advancements in thermal efficiency of gasoline engines and analyzes the key technological methods to achieve over 50% brake thermal efficiency (BTE). The technological routes proposed for high-efficiency gasoline engine are primarily focused on high compression ratios and lean combustion combined with novel combustion technologies. Supporting technologies mainly include Atkinson/Miller cycles, intake boosting, exhaust gas re-circulation (EGR), water injection, thermal barrier coatings, friction reduction, structural optimization, and combustion diagnostics and control.

Keywords: thermal efficiency; gasoline engine; combustion technologies

1. Introduction

Climate change has increasingly drawn global attention and concern. In 2015, The Paris Agreement was adopted by 196 parties at the UN Climate Change Conference (COP21). The countries and regions voluntarily established energy efficiency and emission reduction targets. The central aim of the Paris Agreement is to hold "the increase in the global average temperature to well below 2 °C above pre-industrial levels" and pursue efforts "to limit the temperature increase to 1.5 °C above pre-industrial levels" [1]. At the Leaders Summit on Climate in 2021, participants announced ambitious climate targets ensuring that nations accounting for half of the world's economy have now committed to the emission reductions needed globally. The European Union (EU) has stated a target of reducing net greenhouse gas (GHG) emissions by at least 55% by 2030 and a net zero target by 2050, while the United States (US) has pledged to reduce emissions 50% below 2005 levels by 2030 [2]. China has set the "3060 goal", striving to peak carbon emissions by 2030 and to achieve carbon neutrality by 2060 [3].

Transportation is the second largest source of carbon emissions globally, surpassed only by electricity and heat production, which are categorized as a single source in industrial. According to the statistical results of the International Energy Agency (IEA) [4], the global transportation sector emitted 7.63 billion tons of carbon dioxide (CO_2) in 2021, which accounted for 22.7% of the carbon emissions from energy activities. It is evident that to achieve carbon dioxide reduction targets, it is crucial to reduce carbon emissions from transportation. There is an urgent need for the automotive industry to transition towards cleaner, low-carbon technologies. Consequently, many regions around the world have implemented stringent fuel consumption and emission regulations for vehicles. In Europe, major light-duty vehicle (LDV) markets are targeting 95 g/km CO_2 by 2020. In the US, the average reduction rate of CO_2 emissions for 2017 through 2021 is 3.5 percent per year and 5 percent per year for 2022 through 2025. In China, the fuel consumption standard is 6.9 L/100 km for domestically produced passenger cars, which will be lowered to 4.0 in 2025 and 3.2 in 2030 [5].

In the foreseeable future, energy-saving vehicles are expected to remain the dominant force in the market, with approximately 60% of vehicles predicted to still equipped with internal combustion engines by

2030 [6]. Therefore, improving the efficiency and reducing the emissions of internal combustion engines remains a top priority at this stage, whether for traditional fuel vehicles or hybrid vehicles. The High-Quality Development Plan of Internal Combustion Engine Industry (2021 – 2035) issued by China Internal Combustion Engine Industry Association aims to set ambitious targets for the industry. One of the key goals is to achieve a brake thermal efficiency (BTE) of 50% for the new generation of gasoline powertrains by 2030 [7].

Over the past decade, the application of various advanced combustion technologies has increased the BTE of gasoline engines from 30–36% [8] to over 45%. Fuel blending is a crucial technology for improving the thermal efficiency of internal combustion engines (ICE). Significant progress has been made in blending gasoline with different fuels such as diesel [9–12], n-heptane [13, 14], ethanol [15–18], polyoxymethylene dimethyl ethers (PODE) [19–23], hydrogen [24], natural gas [25], and coal to liquid (CTL) [26]. However, this review article focuses solely on research related to gasoline as a fuel. It highlights recent advancements in gasoline engine efficiency and the key technologies used.

2. Advances in High Thermal Efficiency Gasoline Engines

Table 1 summarizes the recent researches on the thermal efficiency of gasoline engines, where the number in the bracket represents the effective compression ratio (ε_e). The maximum BTE expected for slider-crank engines is about 60% [27]. Yu et al. [28] proposed a technological route to achieve 60% BTE in gasoline engines through numerical simulation and theoretical calculation. However, due to cost constraints, achieving this goal under realistic situations seems quite challenging. In 2019, Japan's Strategic Innovation Promotion (SIP) Program achieved a BTE of 51.5% for gasoline engine [29]. In the same year, Mazda announced that it had successfully developed a gasoline engine with an indicated thermal efficiency (ITE) of 56% [30].

Table 1. Summary of recent researches on the thermal efficiency of gasoline engines.

	ITE	BTE	$\varepsilon(\varepsilon_e)$	λ	EGR Rate	Displacement /L	Cylinder Number	Combustion Method
Yu et al. [28]/2019		60% (sim)	17 (14.2)	1.9	54%	1.933	1	HCCI
Ichiro et al. [30]/2019	56%		17.3	1.8	40%			SPCCI
Zhao et al. [31]/2024	53% (sim)		17	2.5		0.56	1	APC
Addepalli et al. [32]/2023	53%	46.1%	17			12.4	6	GCI
Hu et al. [33]/2023	52.5%		16	2.4		0.5	1	APC
Zhao et al. [34]/2024	51.6% (sim)		17	2.5		0.56	1	APC
SIP [29]/2019		51.5%	14~17	2				HEI
Our Research Group/2024	51.34%	47%	16.8	2.4		0.5	1	APC
Wang et al. [35]/2023	51%		12.28~16.4	2.24		0.5	1	APC
Li et al. [36]/2020	51%		18		40%	5.3	4	GCI
Zhao et al. [37]/2023	50.3%	46.3%	15.5	2		0.375	1	APC
Liu et al. [38]/2024	50.3%		17	1.9		0.563	1	HEI
Chen et al. [39]/2024	50.1%		12.48~16.4	2.8		0.5	1	APC
Du et al. [40]/2024	50%	46.3%	16.5	2.1		0.5	1	APC
Qian et al. [41]/2023	50%		18			5.3	4	GCI

Table 1. Cont.

	ITE	BTE	$\varepsilon(\varepsilon_e)$	λ	EGR Rate	Displacement /L	Cylinder Number	Combustion Method
Peethambaram et al. [42]/2024	49.85% (sim)		16.64	2.23		1.5	1	APC
Dernotte et al./2017	49.70%		16	3.13~3.33		5.886	6	GCI
Wang et al. [43]/2021	49.50%		16	2.25		0.5	1	Corona Ignition
Yu et al. [44]/2017	49.3% 48.5%		17	2.38~3.13		0.498	4	DICI HCCI
Wu et al. [45]/2024	48.5%		18		38%	5.3	4	GCI
Cai et al. [46]/2020	48.2%		17	1.94		0.5	1	Corona Ignition
Sellnau et al. [47]/2016	48.00%		15			1.8	4	GDCI
Wu et al. [48]/2023	48%		18			5.3	4	GCI
Meng et al. [49]/2022	47.62% (sim)	45.05% (sim)	9.48	2		1.8	4	HEI
Gainey et al. [50]/2023	47.60%		16		33%	1.7	4	GCI
Zhang et al. [51]/2023	47.46% (sim)		17.5		40%	0.5	1	SI
Yan et al. [52]/2023	47.4% (sim)		17			0.65	1	PPCI
Pei et al. [53]/2022	47.09%		17 (9.3~12.8)	1.9		0.563	1	HEI
Serrano et al. [54]/2019	47%		13~15	2		0.408	1	APC
Jiang et al. [55]/2019	47%		18			5.3	4	GCI
Vedula et al. [56]/2017	46.8%		12	1.85		0.709	1	APC (DM-TJI)
Zhang et al. [57]/2021	46.8% (sim)		11		20%	6.49	4	GCI
Li et al. [58]/2023	46.28%		17	1.9		0.563	1	HEI
Yuan et al. [59]/2024		46.14%	17	1.5~2.0		0.466	1	APC
Dec et al. [60]/2024		45.5%	16			5.9	6	LTGC-AMFI
Cung et al. [61]/2021	45.3%		22		18%	13	1	GCI
Zheng et al. [62]/2022	45%		12.5~15	1.5		0.5	1	SI
Ikeya et al. [63]/2015		45% (sim)	17 (12.5)		30%	0.626	1	HEI
Xu et al. [20]/2023	45%		16.7			2	4	PPCI
O'Donnell et al. [64]/2023		45%	16 (14.9)	2.38~3.13		5.9	6	HCCI

Table 1. Cont.

	ITE	BTE	$\varepsilon(\varepsilon_e)$	λ	EGR Rate	Displacement /L	Cylinder Number	Combustion Method
Lago Sari et al. [65]/2024		44.7%				14.9	6	GCI
Li et al. [66]/2024		44%	15	1.7		2	4	APC
Liu et al. [67]/2024	43.8%		16.5		10%	1.5	4	Passive Pre-Chamber
Bunce et al. [68]/2021		43.6%	13~15	1.7		1.5	3	APC
Sellnau et al. [69]/2019		43.50%	17			2.2	4	GDCI
Li et al. [70]/2023	43.21%		20.3			7.7	6	GCI
Ye et al. [71]/2024	43.1%		13.9~15.8	1		0.375	1	SI
Lee et al. [72]/2017		42.2% (sim)	12.6~15		35%	2	4	Twin Spark Plugs
Mao et al. [73]/2017		42%	16.8	~1.35		8.42	6	PCC
Osborne et al. [74]/2021		42%	11	1.7		2	4	HEI
Zhang et al. [75]/2021	41%		17	1		0.563	1	SI
Sok et al. [76]/2022	41%		13.1	0.95~1.61		0.343	4	HCCI
Hakariya et al. [77]/2017		40%	13		25%	2.5	4	HEI
Yang et al. [78]/2023	40%		10.5			1.5	4	SI
Zhu [79]/2021	40.5%		16	1.4		1.4	4	HEI
Chao [80]/2019		39.53%	12		15%	1	3	SI
Wang [81]/2022	39.1%		16	2		2	4	APC
Krajnović et al. [82]/2024	37.7% (sim)		12.8	1.6		0.67	1	APC
Lv et al. [83]/2024	37.29%		11.2	1		1.6	4	Passive Pre-Chamber

According to the data in Table 1, the effect of compression ratio ε and λ on thermal efficiency is shown in Figure 1. It is evident that a high compression ratio combined with lean combustion technology is the main technical route for efficient gasoline engines. Toyota's Hakariya et al. [77] increased the compression ratio of a 2.5 L naturally aspirated direct injection engine from 10.3 to 13.0, achieving high swirl ratio and high flow coefficient targets by increasing the stroke-to-bore (S/B) ratio and optimizing the intake port design. This resulted in faster combustion and an increase in maximum BTE from 35% to 40%. Similarly, Hyundai's Lee et al. [72] utilized analogous techniques to raise the compression ratio of a gasoline engine to 14, enhance the intake port design to increase the swirl ratio, and combined dual spark plug ignition with exhaust gas recirculation (EGR), boosting BTE from 38.3% to 42.2%.

Honda's Ikeya et al. [63] employed a higher S/B ratio, Miller cycle, EGR, high-energy ignition (HEI), which is typically defined as ignition energy exceeding 100 mJ, with 450 mJ applied in this study. Combined with an optimized combustion chamber shape which significantly increased combustion speed and reduced knocking tendency. This approach achieved an effective thermal efficiency of 45% at an engine speed of 2000 r/min, with an S/B ratio of 1.5, a geometric compression ratio of 17, and an effective compression ratio of 12.5. Niizato [84] extended the lean combustion limit using pre-chamber ignition, achieving a maximum λ of 2.7 and a peak ITE of 47.2%.

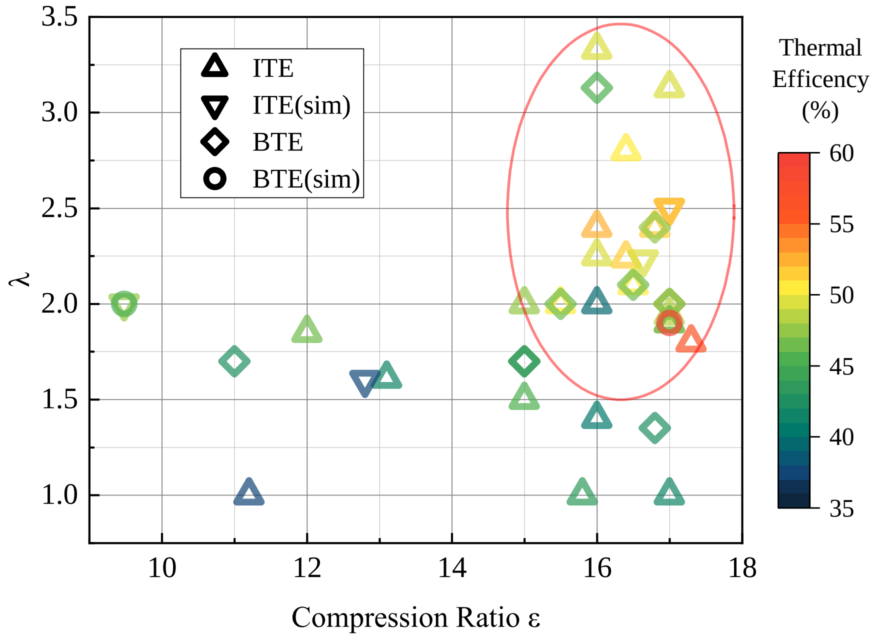

Figure 1. Effect of compression ratio ε and λ on thermal efficiency.

Geely's Wang et al. [43] applied high compression ratio technology (ε = 16), high swirl ratio intake ports, small overlap angle intake camshaft, lean combustion technology (λ = 2.0), and a corona ignition system. At 2000 r/min, the engine's ITE reached 49.5%. Hu et al. [33] extended the lean combustion limit using active pre-chamber (APC) ignition, achieving a peak ITE of 52.5% at λ of 2.4.

In addition to spark-ignition (SI) modes, gasoline compression ignition (GCI) under high compression and lean burn conditions also warrants attention. Delphi's Sellnau et al. [47, 69] developed the second-generation Gasoline Direct Injection Compression Ignition (GDCI) engine with a compression ratio of 15, using an EGR strategy to achieve partial premixed compression ignition across all operating conditions, reaching a maximum ITE of 48%. The third-generation GDCI engine, with a compression ratio of 17, achieved stable combustion with an BTE of 43.5%. The Sandia National Laboratories' Dernotte et al. [85] achieved a maximum ITE of 49.7% using a double direct-injection (D-DI) strategy to realize low-temperature stratified compression ignition with $\lambda > 3.0$ in an engine with a compression ratio of 16.

The SIP Program optimized the combustion system by integrating various technologies, including increasing the engine's compression ratio and stroke/bore ratio, ultra-lean combustion ($\lambda > 2.0$), an HEI system, and in-cylinder water injection, raising the BTE of gasoline engines from 38.5% to 48%. Building on this, they further increased BTE to 51.5% through thermoelectric conversion, improved turbocharging efficiency, and reduced friction losses as shown in Figure 2 [29]. Mazda's approach primarily involved high compression ratios, lean combustion (λ = 1.8), intake boosting, adiabatic combustion, and spark-controlled compression ignition (SPCCI). Utilizing cylinder pressure sensors for cycle-based in-cylinder combustion diagnostics and control, they boosted the thermal efficiency from 44% to 56% as shown in Figure 3 [30]. Our research group has recently achieved maximum ITE of 51.34% and BTE of 47% at 2800 r/min on a high compression ratio (ε = 16.8) single-cylinder engine. This was accomplished using active pre-chamber (APC) ignition technology for ultra-lean combustion (λ = 2.4) combined with intake boosting and the Miller cycle.

Summarize the technologies from Table 1 that achieve an ITE of over 50% for gasoline engines, as presented in Table 2. It highlights the key advancements that enable engines to achieve over 50% brake thermal efficiency (BTE), with an emphasis on the synergies between combustion methods and supporting technologies. High compression ratios, lean combustion, and intake boosting emerge as foundational elements across various modes such as HCCI, GCI, APC, and SPCCI, while technologies like EGR, variable effective compression ratio, thermal barrier coatings, water injection play complementary roles in addressing challenges like knock suppression, heat loss, and combustion stability. In addition, friction reduction is a technique that increases the efficiency without changing the combustion in the cylinder. By systematically analyzing the Table 2, it becomes evident that these technologies form an essential framework for achieving future efficiency targets.

Table 2. The main technologies on the high thermal efficiency of gasoline engines.

Combustion Method	HCCI [28]	GCI [32,36,41]	SPCCI [30]	HEI [29,38]	APC [31,33–35, 37,39,40]
High Compression Ratio	√	√	√	√	√
Lean Combustion	√	√	√	√	√
Intake Boosting	√	√	√	√	√
Exhaust Gas Recirculation	√	√	√		
Variable Effective Compression Ratio (e.g., Atkinson/Miller cycle)	√		√		√
Enhanced Air Flow			√	√	√
Thermal Barrier Coatings	√		√	√	√
Friction Reduction			√	√	
Water Injection				√	
High Pressure Injection			√		
Enhanced Mechanical Strength	√				

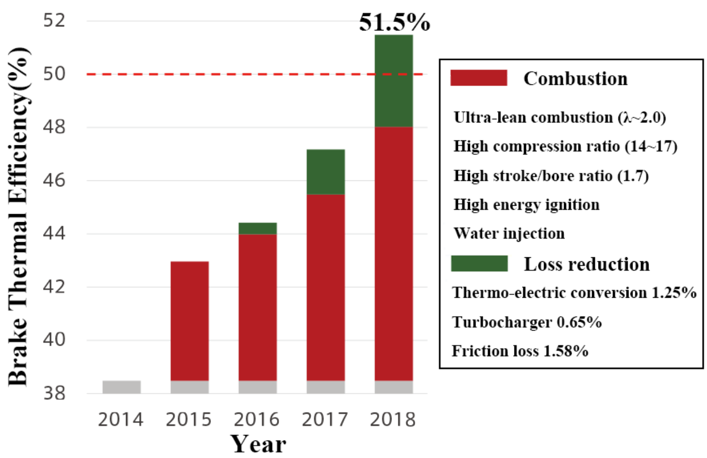

Figure 2. Technical route to achieve 51.5% BTE in the SIP Program (Adapted with permission from Ref. [29], 2019, SIP Program).

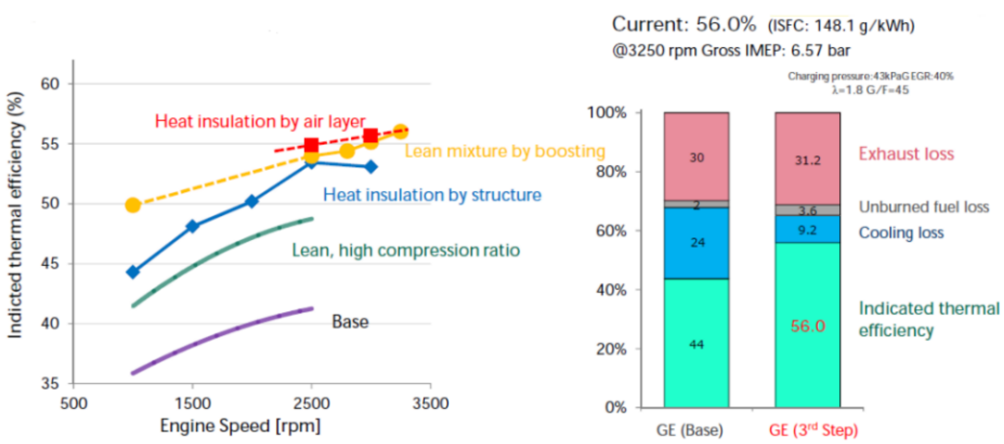

Figure 3. Technical route for Mazda to achieve 56% ITE (Reprinted with permission from Ref. [30], 2019, Mazda).

3. Key Technologies for High Thermal Efficiency Gasoline Engines

3.1. Theoretical Analysis

The actual combustion process in an engine is complex, but theoretical/numerical analysis can provide suitable pathways toward assessing the performance boundaries of the engine and provide optimized directions for subsequent design and research. The main energy transfer losses are summarized in Equation (1) to describe the relationship between various efficiencies of the internal combustion engine (ICE).

$$\eta_{\text{Brake}} = \eta_{\text{Combustion}} \cdot \eta_{\text{Thermodynamic}} \cdot \eta_{\text{GasExchange}} \cdot \eta_{\text{Mechanical}} \tag{1}$$

where η_{Brake} refers to the brake thermal efficiency, $\eta_{\text{Combustion}}$ refers to the combustion efficiency, $\eta_{\text{Thermodynamic}}$ refers to the thermodynamic efficiency, $\eta_{\text{GasExchange}}$ refers to the gas exchange efficiency and $\eta_{\text{Mechanical}}$ refers to the mechanical efficiency.

In a conventional ICE, $\eta_{\text{Combustion}}$, $\eta_{\text{GasExchange}}$, and $\eta_{\text{Mechanical}}$ are usually higher than 90%, reflecting their relatively high performance under typical conditions. However, further improvements in these areas, such as optimizing combustion processes or reducing mechanical losses, can still contribute meaningfully to achieving maximum BTE. Among these efficiencies, $\eta_{\text{Thermodynamic}}$ is typically the lowest, with a theoretical limit of about 60%. Therefore, in the theoretical analysis, a notable focus is placed on improving $\eta_{\text{Thermodynamic}}$ due to its significant potential for enhancing overall efficiency. Meanwhile, to maintain the universality of the calculation results, the heat transfer loss and time loss in $\eta_{\text{Thermodynamic}}$ are not considered in the theoretical analysis. Equation (2) represents the calculation of η_{Otto}, which corresponds to the theoretical $\eta_{\text{Thermodynamic}}$ of gasoline engines:

$$\eta_{\text{Otto}} = 1 - \frac{1}{\varepsilon^{\gamma-1}} \tag{2}$$

where η_{Otto} refers to the Otto cycle efficiency, γ refers to the specific heat ratio, and ε refers to the compression ratio. Equation (2) clearly reveals the effects of γ and ε on η_{Otto}. Figure 4 presents the curves illustrating Equation (2).

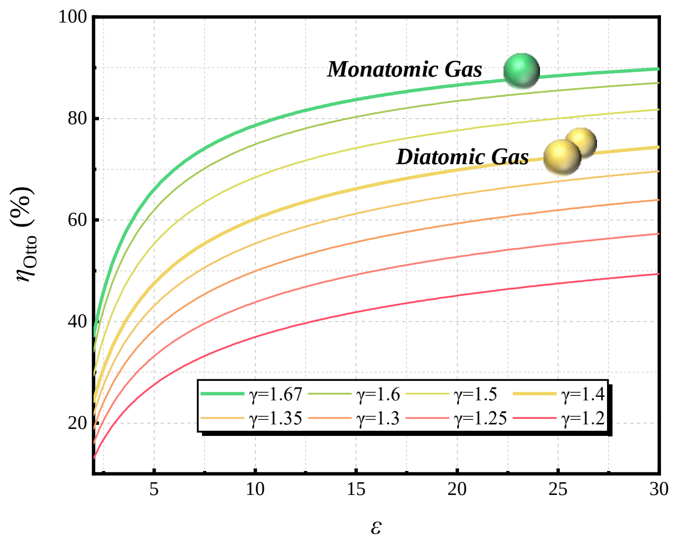

Figure 4. The curves of Otto cycle thermal efficiency.

Moreover, an appropriate combustion phase and a shorter combustion duration can enhance $\eta_{\text{Thermodynamic}}$, bringing it closer to the theoretical limit of η_{Otto} [85].

From a thermodynamic perspective, improving $\eta_{\text{Thermodynamic}}$ can primarily be approached in three ways:

(1) Maximizing the engine's compression ratio as much as possible.

(2) Ensuring the working fluid has a high specific heat ratio.

(3) Organizing combustion efficiently to enhance the isochoric heat addition, thus approaching the

theoretical cycle efficiency.

3.2. Technical Routes

Theoretical analysis indicates that the higher the compression ratio, the higher the theoretical thermal efficiency of a gasoline engine. However, as the compression ratio increases, the temperature and pressure at the end of compression also increase, which leads to a greater tendency for knocking. To mitigate knocking, it is necessary to employ technologies such as lean combustion, exhaust gas recirculation (EGR), and water injection [66,86] into the engine to lower the in-cylinder temperature. At the meantime, lean combustion can increase the specific heat ratio γ by increasing the excess air coefficient λ, thus further improving thermal efficiency. For example, studies have shown that in an engine with a compression ratio of 16, increasing λ from 1.0 to 1.4 can result in an approximate 3% absolute improvement in thermal efficiency, considering the variation of γ with temperature [87].

In light of recent studies, the combination of high compression ratios and lean combustion emerges as the most prominent and effective technological strategy for achieving high thermal efficiency in gasoline engines. However, as the air-fuel mixture becomes increasingly lean, ignition difficulties, misfiring, and combustion instability can arise. Therefore, to support lean combustion at high compression ratios, it is necessary to explore novel combustion modes.

Combustion modes are principally categorized into spark ignition and compression ignition technologies. Compression ignition technologies encompass homogeneous charge compression ignition (HCCI) [44,64], partially premixed compression ignition (PPCI) [20,21,52], reactivity-controlled compression ignition (RCCI) [14,26], stratified charge compression ignition (SCCI) [13] and intelligent charge compression ignition (ICCI) [88,89]. Spark ignition technologies are further subdivided into thermal plasma ignition and non-thermal plasma ignition. Thermal plasma ignition methods include HEI [24, 38], multiple spark ignition [72, 90], multi-electrode ignition [91,92], pre-chamber ignition [93,94], and laser ignition [95], whereas non-thermal plasma ignition techniques involve corona ignition [96, 97], microwave-assisted ignition [98, 99], and nanosecond pulse ignition [100,101]. The advantages and disadvantages of the main ignition technologies are compared in Table 3. Among them, pre-chamber ignition technology, particularly active pre-chamber ignition, not only effectively increases the ignition energy compared to other ignition methods but also enhances in-cylinder turbulence, making lean combustion ignition leaner and more stable. Significant progress has been made in recent years [33,42,54].

Table 3. Characteristics of the main ignition technologies.

Spark Ignition Technologies		Ignition Ability	Reliability	Complexity	Cost
Thermal Plasma	High Energy Ignition	Moderate	High	Moderate	Moderate
	Multiple Spark Ignition	Low	High	Low	Low
	Multi-electrode Ignition	Low	High	Low	Low
	Pre-chamber Ignition	High	High	Moderate	Moderate
	Laser Ignition	High	Low	High	Very High
Non-thermal Plasma	Corona Ignition	Moderate	Moderate	Moderate	High
	Microwave-assisted Ignition	Low	High	High	High
	Nanosecond Pulse Ignition	Low	High	Moderate	High

When the effective compression ratio cannot be further increased due to limitations such as knock tendency, the Atkinson/Miller cycle [78,102] can be used to improve the engine's thermal efficiency. This is achieved by using variable valve timing to create a higher expansion ratio while maintaining an effective compression ratio suitable for stable operation. Additionally, research into thermal barrier coatings technologies [50,103] can make the actual combustion cycle closer to the ideal cycle. Some studies have also used monatomic gases, such as argon [104,105], as the working medium to increase the specific heat ratio and thus improve efficiency. However, such approaches face significant challenges in practical applications due to the cost and complexity of using monatomic gases as the intake charge.

Beyond improving thermodynamic efficiency, mechanical efficiency can be enhanced through friction reduction technologies [106, 107]. Optimizing intake and exhaust systems [74, 108] and employing intake boosting technologies [109] can increase gas exchange efficiency. Furthermore, besides using novel combustion technologies, optimizing combustion chamber design [110] and utilizing combustion diagnostics and control technologies [111,112] can enhance combustion efficiency.

In summary, as shown in Figure 5, the main technological routes to achieve a BTE of over 50% include the following steps: designing engines with a geometric compression ratio not exceeding 20 and optimizing the intake and combustion chamber structures. Implementing Miller cycles through Variable Valve Timing (VVT). Utilizing intake boosting technologies in conjunction with novel combustion technologies, such as with an active pre-chamber ignition, to achieve ultra-lean combustion with a lambda greater than 2. Further enhancing efficiency with thermal barrier coatings and low-friction lubrication technologies. Finally, ensuring stable and reliable combustion through advanced combustion diagnostics and control technologies.

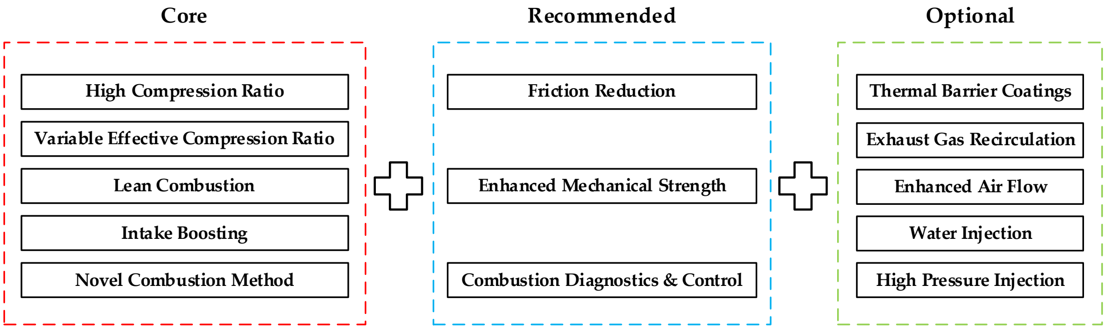

Figure 5. The main technological routes to achieve a BTE of over 50%.

4. Conclusions and Perspectives

This paper presents a review on the advancements in thermal efficiency of gasoline engines and analyzes the key technological methods to achieve over 50% brake thermal efficiency (BTE). Based on existing research and theoretical analysis, the feasible technological routes for achieving high thermal efficiency in gasoline engines has been proposed.

The technological routes involve high compression ratios with optimizing geometric structures, implementing Miller cycles with VVT, utilizing intake boosting and novel combustion technologies for ultra-lean combustion ($\lambda > 2.0$), enhancing efficiency with thermal barrier coatings and low-friction lubrication, and ensuring reliable combustion through advanced diagnostics and control technologies.

However, issues related to material strength, emission control, cost, and reliability still require ongoing research and development.

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