

Engine Performance Technology and Applications

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Abstract: The aim of this paper is to summarize and consolidate the optimization and improvements in engine types, new technologies, and existing technologies over the past few years. Additionally, it effectively analyzes the impact of improved engines on automotive performance and driving experience. Regarding direct-injection technology, this paper primarily highlights the new technology in the field of natural gas direct-injection engines. Among these, high-pressure direct-injection natural gas engines excel in improving fuel economy and emissions, effectively suppressing the limitations of knocking on such engines' output power. On the other hand, low-pressure direct-injection natural gas engines exhibit lower injection pressures when the engine is in the intake stroke. Concerning variable valve timing technology, the study investigates parameters such as the angle adjustment of the variable valve timing mechanism, unlocking methods, and unlocking pressures. Furthermore, the dual VVT-I technology enhances intake efficiency, ensuring ample torque output within the low and mid-range RPMs, guaranteeing sufficient power performance in various operating conditions. In today's rapidly advancing industrial technology landscape, many technologies have made significant progress. However, the current societal trend is moving towards energy conservation and carbon reduction, gradually phasing out traditional engines from the historical stage. The future development trend will be new energy engines, such as new energy materials like pure electric, hydrogen, and natural gas. Additionally, artificial intelligence will rapidly emerge in various industries.

Keywords: Engine, Performance, Direct Injection, Variable Valve Timing, New Energy, Intelligent.

1. Introduction

In today's rapidly evolving industrial landscape, numerous technologies have made substantial advancements, and among them is engine technology. Engines find applications in various sectors, including automotive, power generation, mechanical, and aerospace industries. The swift progress in these industrial domains demands higher levels of propulsion, imposing elevated requirements on engines. Engines, as critical components, have undergone extensive research, encompassing improvements, optimizations, and diverse designs. However, despite progress in various aspects, challenges persist.

Whether it's in racing or everyday transportation, both employ reciprocating four-stroke engines with fundamentally similar operating principles, undergoing four cyclic processes: intake, compression, power, and exhaust. Nevertheless, their design preferences differ significantly. Racing engines seek high-speed power bursts to attain unparalleled velocity, focusing on a singular objective. On the other hand, civilian engines lean toward torque applications at lower speeds, considering various other factors as well.

As a result, racing engines feature short stroke lengths and large bore diameters, allowing pistons to swiftly complete a work cycle. This enables rapid increases in engine speed, resulting in instantaneous acceleration. Racing engines can idle at speeds exceeding 12,000 RPM or even higher. In contrast, civilian engines have longer stroke lengths and smaller bore diameters, allowing pistons to move relatively slowly through each cycle, enhancing stability and enabling more efficient fuel utilization. Consequently, their operating speeds remain lower, with five to six thousand RPM already considered high.

Hence, despite the significant advancements in engine technology, not all new techniques and optimizations can be universally applied to all mechanical devices equipped with

engines. Selective equipment choices must be made based on the ultimate use-case scenario and driving experience considerations.

2. Direct Injection Technology

2.1. Principle

Direct injection involves the installation of fuel nozzles inside the engine cylinder, allowing fuel to be directly injected into the cylinder and mixed with the intake air. This process increases injection pressure, achieving finer fuel atomization and precise control of the fuel-to-air ratio. It eliminates the drawbacks of previous external intake manifold injection methods. Special designs, including nozzle placement, spray pattern, intake air control, and piston crown shape, ensure thorough and uniform fuel-air mixing within the entire cylinder. This results in more complete fuel combustion and higher energy conversion efficiency.

2.2. New Developments in Direct Injection

Direct injection natural gas engines can address the carbon soot emissions issues associated with direct-injection gasoline engines while improving fuel economy and power output. The supply of gas through direct injection into the cylinder offers several advantages:

- Significant reduction or elimination of volumetric efficiency losses associated with gaseous fuels.

- Prevention of fuel losses during the scavenging phase.

- Effective suppression of knock, allowing for higher compression ratios.

- Synergistic optimization of parameters such as fuel injection timing, air-fuel ratio, and ignition advance, enhancing control over the combustion process [1].

For cylinder-internal gas supply natural gas engines, they can be categorized into two types based on injection pressure

and injection timing: high-pressure direct injection natural gas engines and low-pressure direct injection natural gas engines [2].

2.2.1. High-Pressure Direct Injection Natural Gas Engine

High-pressure direct injection natural gas engines are not limited by knocking, and they offer improved fuel economy and emissions compared to diesel engines with equivalent power.

To further enhance the thermal efficiency and reduce emissions of high-pressure direct injection natural gas engines, researchers worldwide have studied their combustion characteristics, emission characteristics, and combustion models using various methods to boost engine performance.

McTaggart-Cowan conducted experimental analysis on the impact of fuel injection pressure and injection rate on the combustion and emission characteristics of HPDI engines. The results showed that higher injection pressure and controlled fuel injection rates can promote combustion, enhance thermal efficiency, and reduce particulate emissions[3].

Patychuk examined the influence of valve timing on the emission performance of HPDI engines under various loads. The results indicated a 70% reduction in methane emissions at loads below 50%, a 19% reduction in NOX emissions at 75% load, and good emissions at 10% load, albeit with increased exhaust temperatures[4].

Chen Changjun used STAR-CD software to simulate the injection and combustion processes in HPDI engine cylinders and analyzed the impact of injection timing and injection pressure on emissions. The results revealed that delaying injection timing improved NOX emissions but increased CO, HC, and particulate emissions. Increasing injection pressure reduced HC emissions but increased NO emissions[5].

2.2.2. Low-Pressure Direct Injection Natural Gas Engine

In the case of low-pressure direct injection natural gas engines, the injection pressure of natural gas is lower when the engine is in the scavenging stroke due to the lower cylinder pressure.

Researchers both domestically and internationally have primarily focused on the reaction mechanisms under dual-fuel modes, flame jet behavior inside the engine, and the knocking conditions of low-pressure direct injection natural gas engines.

Lounici conducted extensive research on the knocking characteristics of dual-fuel engines, analyzing the periodic variations of this phenomenon. They proposed a knocking indicator related to in-cylinder pressure for evaluating knock occurrences. Additionally, they delved into the impact of knock on heat release, cylinder wall temperature, engine performance, and emissions. Experiments demonstrated that increasing the injection quantity of pilot diesel fuel helps mitigate engine knocking[6].

Ye Ying initially established a three-dimensional CFD model for a low-pressure direct injection natural gas engine and analyzed various sub-models used in the model. They calibrated and validated the model based on research into various pre-chamber systems. By summarizing the rules of parameter design and designing multiple pre-chamber system solutions with different orifice structures, they identified an optimal pre-chamber system. Experimental results indicated that flame jet impingement on the wall or piston crown leads to reduced engine performance and increased emissions. The study also analyzed the effects of different injection strategies and EGR on engine combustion and emissions. The research

revealed that improving pre-chamber pre-injection can mitigate diesel stratification and reduce NOX emissions but may decrease the main chamber's combustion rate. Furthermore, under conditions of lean natural gas combustion, EGR can improve engine emissions[7].

2.3. Variable Valve Timing

2.3.1. Principle

Variable Valve Timing (VVT) technology is the prevailing method to enhance the flexibility of valve timing mechanisms in modern engines. It utilizes engine hydraulic fluid or electrical power as a power source to dynamically adjust the phase of the intake and exhaust camshafts in real-time, optimizing the valve overlap angle for various driving conditions.

Variable Valve Timing systems are commonly referred to as VVT or Variable Camshaft Timing (VCT). Engines equipped with VVT technology can increase the intake charge, resulting in higher volumetric efficiency, and further enhance engine torque and power.

The mainstream VVT system currently in use is the side-mounted OCV-type (Oil Control Valve) VVT system. It primarily consists of a phaser and an OCV oil control valve. Auxiliary components include camshaft position sensors, crankshaft position sensors, an Engine Control Unit (ECU), camshaft signal wheels, crankshaft signal discs, check valves, and a central bolt. Its basic structure is as follows:

Traditional engine valve timing systems feature fixed mechanical systems where the timing of valve opening and closing remains constant. Such systems struggle to meet the varying valve timing requirements of engines under different operating conditions and cannot satisfy the demand for consistent power output across different engine speeds. In contrast, Variable Valve Timing systems are electronically controlled systems that adjust the timing and duration of valve opening or closing. They match the engine's requirements under different speeds, enhancing torque balance and power output across various driving conditions while reducing fuel consumption.

2.3.2. Current Optimization Status

Currently, certain optimizations have been carried out in the field of Variable Valve Timing.

Liu Cheng, in conjunction with a Dongfeng Motor engine, proposed and effectively conducted the design optimization of the VVT system. The focus was on improving the development process of the Variable Valve Timing mechanism, enhancing development efficiency and quality, and boosting product competitiveness. The primary research involved setting critical parameters related to the Variable Valve Timing mechanism, such as adjustment angles, unlocking methods, and unlocking pressures. It also included the development and application of a dynamic VVT simulation model and the establishment and testing of a dynamic engine ignition test bench[8].

Additionally, Tang Zhenzhen utilized Toyota's dual VVT-I technology as an example. VVT-I stands for Intelligent Variable Valve Timing Control System. This system enhances intake efficiency, achieves ample torque output within the low and mid-speed range, and ensures sufficient power performance under various conditions. The research concluded that Toyota's dual Variable Valve Timing system, controlled by the Engine Control Module (ECM), can dynamically adjust the valve timing of the intake camshaft based on different engine conditions to obtain optimal valve

timing. This improves torque at low speeds, power at medium to high speeds, and reduces fuel consumption and tailpipe emissions. During fault diagnosis and maintenance, instrument-based diagnostics supplemented by manual inspection can quickly diagnose and rectify faults in the dual VVT-I system using the self-diagnostic system[9].

3. Impact on Automotive Performance and Driving Experience

Variable Valve Timing (VVT) technology primarily improves driving performance by controlling the opening and closing times of an automobile engine's valves effectively. It enhances engine power and fuel economy, reduces harmful emissions in engine exhaust, and improves idle stability and low-speed smoothness. Specifically:

By altering the valve timing, the engine's low-speed torque can be adjusted, allowing it to operate at lower engine speeds where friction losses are reduced, thereby improving fuel economy.

Within a significant range, changes in the intake valve closing angle can replace conventional throttle control for load adjustment. This reduces pumping losses associated with throttle-based load control, leading to lower fuel consumption and reduced NOx and HC emissions.

High-speed gasoline engines typically have valve timing settings that favor high RPMs, resulting in a large intake valve closing angle. This can cause air-fuel mixture to reverse flow into the intake manifold, leading to unstable combustion, reduced power, and unstable idling at idle and low speeds. With a variable valve timing mechanism, the intake valve closing angle automatically decreases at low speeds, eliminating this issue and improving low-speed and idle performance[10].

Performance is a significant advantage of direct injection into the cylinder, and it is the decisive factor in adopting cylinder-internal direct injection technology. Cylinder-internal direct injection involves injecting fuel directly into the combustion chamber, where gasoline absorbs heat during atomization, reducing the temperature inside the combustion chamber and lowering the risk of knocking. Furthermore, cylinder-internal direct injection allows for various injection strategies, such as stratified combustion and multiple injections. For example, injecting additional fuel just before the compression top dead center immediately lowers the combustion chamber temperature, allowing for more advanced ignition timing and improved performance. Even under medium to high loads, thermal efficiency is higher. In summary, cylinder-internal direct injection allows for more precise control of fuel injection quantity, resulting in fuel savings. Additionally, it enhances power to some extent, as engines with cylinder-internal direct injection typically have higher compression ratios, resulting in higher power output. Finally, cylinder-internal direct injection provides greater flexibility in fuel injection, contributing to advancements in engine technology.

Today, most performance vehicles use cylinder-internal direct injection technology. The primary reason is to ensure performance and increase engine power and torque. Cylinder-internal direct injection offers better controllability, ensuring that the engine operates as engineers intend in the electrified era. It also performs exceptionally well in terms of fuel consumption and emissions under the WLTC (Worldwide

Harmonized Light Vehicles Test Cycle) conditions, making it the mainstream choice.

4. Conclusion

In today's rapidly advancing industrial landscape, many technologies have made significant progress, and engines are no exception. Engines are now applied in various fields and have seen substantial improvements. This article has focused on new technologies related to cylinder-internal direct injection and intelligent variable valve timing. These advancements have been built upon the foundation of traditional engines. However, the current global trend is moving toward energy efficiency and carbon reduction, aiming to reduce the consumption of non-renewable energy sources and mitigate the environmental impact of vehicle exhaust emissions. This implies that traditional engines will gradually take a backseat in history.

The future direction of engine development will revolve around new energy sources. New energy engines will be equipped with alternative fuels, such as pure electric, hydrogen, natural gas engines, hybrid powertrains, and range-extender engines. Take turbocharging as an example; its principle involves utilizing the kinetic and thermal energy carried by exhaust gases to compress intake air. Therefore, whether it's traditional fossil fuels like petroleum or new energy sources like hydrogen or natural gas, they can all generate equivalent heat to sustain a turbocharging system.

In conclusion, the automotive industry is in a transitional phase, evolving from traditional engines to new energy engines, and embracing more sustainable and environmentally friendly technologies. The development of these new energy engines will not only reduce carbon emissions but also redefine the future of mobility, with a focus on energy efficiency, reduced environmental impact, and enhanced performance.

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