Current situation and looking-forward advancement of internal combustion engine

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Abstract. With a history of over 100 years, the internal combustion engine has undergone continuous technological advancements, making it widely utilized in various sectors such as industry, agriculture, and transportation. This is due to its high thermal efficiency and broad power range. However, the rapid growth of the global economy has led to a significant increase in the number of internal combustion engines, resulting in heightened energy consumption and environmental pollution concerns. Consequently, new technical requirements have been imposed on internal combustion engines. One key focus for researchers in this field has been improving the fuel economy of internal combustion engines. Through relentless efforts, remarkable progress has been made in producing economy cars with fuel consumption as low as 3 liters per 100 Km. Additionally, the growing demand for environmental protection has sparked increased attention toward reducing harmful emissions from internal combustion engines, which has become a topic of shared concern. In this article, the researcher will delve into the developmental journey of traditional internal combustion engines and explore the advantages and disadvantages of each engine type.

Keywords: internal combustion engine, homogeneous charge compression ignition, sustainability.

1. Introduction

The traditional combustion method of internal combustion engines is generally divided into two categories: compression ignition engines, such as diesel engines, and spark ignition engines, such as gasoline engines. Diesel engines primarily rely on diffusion combustion, while gasoline engines typically employ pre-mixed combustion [1]. Improving fuel efficiency in internal combustion engines has been a long-standing goal for researchers in this field. Continuous efforts have led to the development of economy cars that consume as little as 3 liters of fuel per 100 km [2]. Moreover, with the increasing demand for environmental protection, a growing focus is on reducing harmful emissions from internal combustion engines.

Researchers have concentrated their efforts on in-machine purification technologies. This involves using electronically controlled high-pressure common rail injection technology for diesel engines, optimizing the combustion system, and improving the intake and exhaust systems. These advancements have greatly improved the overall emission performance of diesel engines. Similarly, off-board purification technologies, such as three-way catalytic converters, have successfully controlled the emissions of NO_x and CO in gasoline engines, achieving very low levels. It is important to note that combustion technology is at the heart of improving power output, fuel efficiency, and emission reduction in internal combustion engines. Numerous researchers have devoted their studies to understanding combustion technology, providing technical support to enhance engine performance and reduce emissions. Based on this, this article aims to delve into the details of traditional internal combustion engine combustion theory and compare it with the combustion theory employed in newer hybrid internal combustion engines.

2. Types of conventional internal combustion engines

2.1. Diesel engine

The diesel engine is a typical compression ignition engine, where the air-fuel mixture is compressed within the cylinder to a specific temperature and pressure, resulting in spontaneous ignition. In diesel engines, there is a greater emphasis on pre-mixed combustion, leading to higher initial heat release and peak excitation rates. Consequently, this leads to higher maximum combustion temperatures and increased NO_x emissions. Then, diffusion combustion occurs, where the fuel is mixed with air and burned. Therefore, conventional diesel engines require high injection pressure and adequate air vortex strength to ensure complete diffusion combustion and reduce exhaust smoke. The main advantages and disadvantages of this combustion method are as follows:

i) High thermal efficiency and good fuel economy: Higher compression ratios improve thermal efficiency and fuel economy. CO emissions are generally better than gasoline engine emissions. ii) High vibration noise: Heterogeneous pre-mixed combustion in the initial stage, prior to reaching the top dead center, results in a higher rate of pressure rise, leading to increased vibration noise compared to gasoline engines. iii) High NO_x and particulate matter emissions: Pre-mixed combustion in diesel engines leads to higher combustion temperatures and a richer air-fuel mixture in the combustion chamber, contributing to increased NO_x emissions. Moreover, incomplete mixture combustion during diffusion combustion can produce higher PM emissions than gasoline engines.

Figure 1 demonstrates the heat release rate curve of a typical diesel engine. The curve shows a peak heat release rate zone at the beginning, caused by the delayed ignition from fuel injection to combustion. The shape of the heat release rate is determined by the amount of fuel injected during the pre-mixing phase and the resulting combustible mixture. A higher volume of this mixture results in a higher peak initial exothermic rate, maximum combustion temperature, and increased NO_x emissions. Diffusion combustion follows, where the fuel is mixed with air and burned. Traditional diesel engines necessitate high injection pressure and proper air vortex strength to ensure complete diffusion combustion and minimize exhaust smoke.

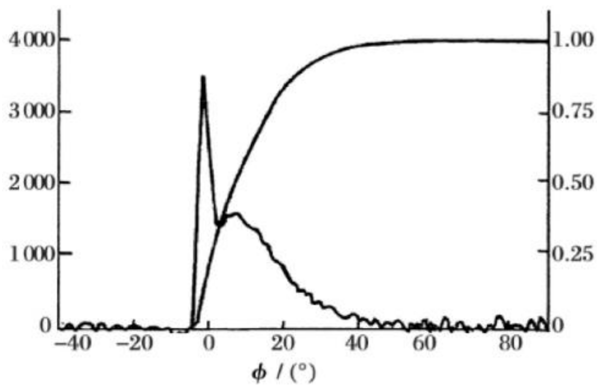

Figure 1. Diesel engine heat release rate curve [3].

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2.2. Gasoline engines

Gasoline engines are known for their characteristic pre-mixed combustion, which results in a smooth heat release rate curve without the prominent pulse peaks observed in the initial stage of diesel engines. This combustion method's main advantages and disadvantages can be summarized as follows.

Gasoline engines are designed with lower compression ratios to prevent knocking. This lower compression ratio leads to lower thermal efficiency and poorer fuel economy than diesel engines. Additionally, gasoline engines tend to have higher emissions of hydrocarbons and CO than diesel engines. During the intake process, fuel is injected into the intake pipe, allowing ample time for thoroughly mixing the fuel and air before combustion. This leads to a more uniform and readily combustible mixture, resulting in a smoother operation of gasoline engines than diesel engines, with reduced vibration noise. However, it should be noted that this injection process can cause some fuel to adhere to the intake pipe walls, which may result in higher emissions of HC and CO compared to diesel engines. Due to the predominantly homogeneous pre-mixed combustion in gasoline engines, particulate matter emissions are generally low. Furthermore, gasoline engines operate at lower ignition temperatures, resulting in lower NO_x emissions than diesel engines; due to the lower ignition temperature, NO_x emissions are also lower than diesel engines [4].

2.3. Natural gas engines

Natural gas, consisting primarily of methane, is a gaseous fuel wherein methane constitutes more than 90% of its composition. Additionally, it contains combustible gases such as hydrogen, hydrogen sulfide (H_2S), and CO, making up roughly 1% to 5% of the total composition. Inert gases like N_2, CO_2, and He are also present in natural gas, accounting for approximately 1% to 3%. Natural gas possesses distinctive characteristics that distinguish it from liquid fuels.

Natural gas exhibits a high octane number, enabling the modification of internal combustion engines to utilize higher compression ratios in gasoline engines. When employed in internal combustion engines converted from diesel engines, natural gas presents difficulties in the self-ignition of the mixture. Hence, diesel ignition or an additional ignition system is necessary to initiate combustion. Natural gas, a gaseous fuel, readily blends with air at ambient temperature, promoting thorough combustion within the internal combustion engine. Optimizing the engine's operational processes can minimize emissions of noxious substances. With its low density, natural gas poses potential challenges if the external mixing method is employed, resulting in a reduction in the amount of air entering the cylinder. Additionally, the lower calorific value of natural gas mixtures may encompass a decrease in engine power and performance. Natural gas internal combustion engines exhibit inferior lubrication capabilities, necessitating appropriate measures for critical components such as the fuel injection system to ensure the reliable operation of the engine. As an alternative fuel for automobiles, natural gas has a shorter driving range than traditional liquid fuels and demands an independent storage, transportation, and distribution network distinct from the existing infrastructure.

3. New developments in combustion technology for internal combustion engines

In response to energy and environmental concerns, researchers and engineers in the field of internal combustion engines worldwide are actively pursuing new advancements in engine technology to meet evolving requirements. Current notable technologies include electronically controlled high-pressure common rail injection for diesel engines, direct injection in the cylinder for gasoline engines, and inlet injection technology, all of which fall under lean combustion [5].

3.1. High-pressure common rail injection technology for diesel engines

The electronically controlled high-pressure common rail system comprises components such as a high-pressure pump, rail, injector, control solenoid valve, various sensors, and an electronic control unit (ECU). The system pressurizes fuel using the high-pressure pump and delivers it to the injector through the rail via high-pressure pipes. The injector is equipped with a solenoid valve controlled by the ECU based on sensor feedback to regulate the timing and amount of fuel injection [6].

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Recent advancements in high-pressure common rail injection technology have enabled the maintenance of consistently high injection pressure, unaffected by changes in load and speed. This feature allows diesel engines to deliver enhanced performance, maintaining high injection pressure even during low-speed and low-load conditions. Flexible pre-injection and post-injection techniques can be realized when combined with electronic control technology, meeting stringent emission performance requirements.

3.2. Gasoline engine direct injection (GDI)

Traditional gasoline engines employ throttle valves, increasing pumping losses and reducing mechanical efficiency. Research has focused on direct injection technology within the cylinder to overcome these limitations. Fuel is directly injected into the cylinder, akin to diesel engines, rather than in the intake manifold. The main advantages of GDI engines are as follows:

Engine fuel economy is significantly improved, particularly achieving a 30% to 35% improvement in certain load conditions. Enhanced performance during transient working conditions, reducing the requirements for aggressive acceleration. Quick engine starting, typically within 12 cycles, with low stiffening requirements during startup. Improved emission indicators for HC and CO_2 [7].

3.3. Homogeneous charge compression ignition (HCCI)

HCCI engines employ a homogeneous mixture, distinguishing them from conventional gasoline engines that rely on single-point ignition. The temperature and pressure of the mixture in the cylinder are elevated by optimizing the compression ratio and utilizing techniques such as exhaust gas recirculation, intake heating, and pressurization. This promotes spontaneous combustion, forming multiple ignition cores within the cylinder, ensuring stable ignition and combustion, and reducing flame propagation distance and combustion duration. Unlike diesel engines that rely on partially evaporated and mixed fuel at the time of ignition, HCCI combustion involves homogeneous pre-mixed combustion. Consequently, HCCI engines combine the advantages of both gasoline and diesel engines. HCCI offers the following advantages:

High power and fuel economy: Utilizing a homogeneous mixture enables the retention of conventional gasoline engines' high specific power characteristics. The reduced throttling losses and adoption of high compression ratios facilitate high energy release rates, approaching the ideal constant volume combustion process hence exhibiting high thermal efficiency, particularly under partial load conditions. Reduced NO_x and soot emissions: Using lean air-fuel ratios and exhaust gas recirculation, combustion temperatures are controlled below 1850 K, effectively suppressing NO_x formation and achieving virtually smoke-free combustion [8-10].

4. Conclusions

In the long run, internal combustion engine vehicles are expected to play a significant role in road transportation due to their well-established technology, reliability, and durability. While there is growing interest in electric vehicles, they still face technical limitations such as poor power performance and limited driving range, preventing them from completely replacing internal combustion engine vehicles. Fuel cell vehicles also encounter obstacles related to high costs and challenges in hydrogen fuel production and storage, making them unlikely to become mainstream vehicles in the near future. As a result, hybrid vehicles are seen as a viable alternative, combining the benefits of internal combustion engines and electric motors.

Researchers are exploring new combustion methods that combine the advantages of compression ignition and spark ignition engines to further enhance fuel efficiency and reduce emissions of internal combustion engines. One notable approach is diesel engine pre-mixed combustion, which has garnered significant attention and research efforts worldwide. Researchers aim to understand the mechanisms of mixture formation, ignition, combustion, and pollution control through theoretical and practical investigations of pre-mixed combustion systems. This research provides a promising avenue for achieving breakthroughs in reducing harmful emissions, particularly NO_x and PM emissions from diesel

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engines. Ultimately, it aims to address the global challenges in diesel engine emission control and work towards achieving ultra-low emissions from diesel engines.

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