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The influence of different fuels on engine combustion and emission characteristics

Li Zhipeng[1]

(1. Collegeof Traffic and Transportaion,Chongqing JiaotongUniversity,Chongqing,China)

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ABSTRACT: With global climate change, environmental problems are becoming increasingly severe. Sustainable development has become crucial, therefore studying the impact of different fuels on engine performance and emission characteristics has become a research hotspot. This article analyzes and summarizes the effects of different fuel types (gasoline, diesel, biofuels, synthetic fuels, hydrogen fuels, etc.) on the combustion mechanism, efficiency, and emission characteristics of internal combustion engines. Comparisons were made on the different chemical and physical properties of different fuels, and how their properties affect their combustion behavior in engines were analyzed. Qualitative and quantitative comparisons were also made on emission components such as NOx, CO, HC, PM, CO2. Finally, the current research findings were summarized, shortcomings were identified, and future research prospects were discussed.

KEYWORDS: Fuel, Combustion characteristics, engine, Pollution emissions

I. INTRODUCTION

[1]With the rapid development of the automotive industry and the acceleration of urbanization, the number of urban transportation vehicles, especially family cars, has increased sharply. The pollution generated by car engine emissions has become one of the main sources of atmospheric pollution. [2]To solve the problem of environmental pollution, China strives to achieve carbon peak before 2030 and carbon neutrality before 2060. Therefore, how to improve the combustion efficiency of internal combustion engines and reduce pollution emissions has become an increasingly hot research topic today. [3]Internal combustion engines, as the main source of power for motor vehicles and mechanical equipment, play a crucial role in industrial production and daily life. [4]The exhaust emissions generated by the combustion of traditional fuels have become a serious environmental problem, and the dependence on fossil fuels has also brought about uncertainty in energy supply.

An efficient and environmentally friendly engine largely depends on the type of fuel used. [5]At present, there are various fuels used in internal combustion engines, in addition to traditional gasoline and diesel, there are also environmentally friendly alternative fuels such as biofuels, synthetic fuels, and hydrogen fuels , the latter of which has great application prospects. Each fuel has its unique chemical and physical properties, which affect the combustion process and the types and quantities of emissions generated. [6]Through a comprehensive evaluation of fuel performance and engine combustion processes, we can further understand the impact of different fuel types on internal combustion engines , as well as how to optimize fuel selection to meet the needs of environmental protection and sustainable development.

II. PRINCIPLES OF ENGINE COMBUSTION

2.1 WORKING PRINCIPLE OF INTERNAL COMBUSTION ENGINE

The working principle of an internal combustion engine is to release energy by burning fuel, which then drives the piston to move and convert it into mechanical energy. [7]The process of work involves a series of highly controlled chemical reactions and consists of several main stages: intake, compression, combustion, and exhaust. It is commonly referred to as the engine cycle, as shown in Figure 1.

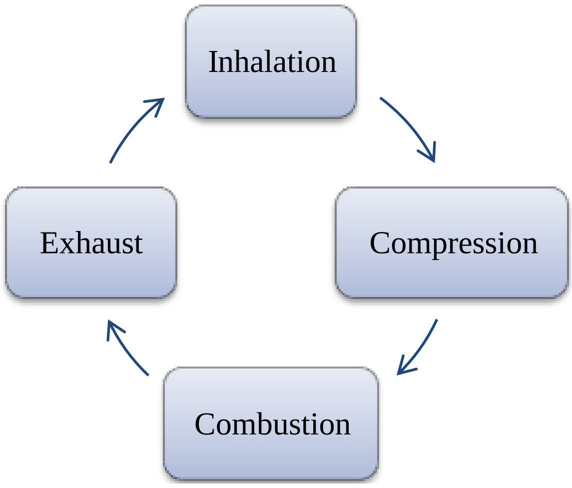

FIGURE 1.ENGINE CYCLE

During the intake phase, the engine's intake valve opens, allowing air or air-fuel mixture to flow into the engine cylinder. For naturally aspirated engines, air is pushed into the cylinder through atmospheric pressure; In turbocharged engines, turbochargers or mechanical superchargers are used to improve intake efficiency. During the inhalation phase, it is necessary to ensure maximum increase in the air volume of the cylinder to provide sufficient oxidizer for the next stage of compression.

In the compression stage, during the upward movement of the piston inside the cylinder, the inhaled air or air-fuel mixture is compressed, and its temperature and pressure increase, creating optimal conditions for ignition and combustion.

During the combustion phase, the spark plug ignites the mixed gas, and in diesel engines, fuel is injected into hot compressed air for spontaneous compression ignition. Combustion spreads in a spherical shape from the ignition source, and the chemical energy of the fuel mixture is rapidly converted into heat energy through combustion, which drives the piston to do work. Under ideal conditions, combustion is uniform and well controlled, capable of generating maximum power output while minimizing unburned fuel and harmful emissions.

During the exhaust phase, after completing the conversion of thermal energy to mechanical energy, the piston begins to move downwards, the exhaust valve opens, and the burned gas is discharged into the atmosphere. An efficient exhaust process is crucial for the overall efficiency of the engine cycle, as it ensures the minimization of cylinder pressure and provides optimal conditions for the next intake cycle.

2.2BASIC PRINCIPLES AND PROCESSES OF COMBUSTION

[8]Combustion is a chemical reaction in which fuel reacts with oxygen to produce energy. The process involves complex chemical reaction chains, including premixed combustion and diffusion combustion stages. The chemical composition and reactions of fuel determine the combustion rate, flame stability, and combustion products. The performance of fuel is evaluated by various indicators such as octane number (gasoline), cetane number (diesel), volatility, combustion rate, calorific value, and oxygen content. By evaluating various indicators, the combustion performance and emission characteristics of different fuels can be assessed.

III. DIFFERENT FUEL TYPES AND THEIR CHARACTERISTICS

In the context of environmental and energy crises, the development of traditional internal combustion locomotives faces enormous challenges and urgently needs to find clean and efficient alternative fuels. [9-11]Currently, the alternative fuels suitable for internal combustion engines mainly include methanol, ethanol, biodiesel, dimethyl ether, and natural gas. These alternative fuels are carbon based fuels that also produce a large amount of $CO2$ during combustion, and there is still a need to find clean and carbon free fuels.

3.1 CHARACTERISTICS OF TRADITIONAL FUELS

Gasoline is a common traditional fossil fuel, a refined petroleum product, a light liquid fuel mainly composed of hydrocarbons. Mainly used for spark ignition engines. Chemical properties include high octane rating and volatility, allowing gasoline

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to burn at relatively low temperatures and pressures. It performs excellently in terms of ignition performance, combustion efficiency, and power output. The combustion of gasoline produces a series of hydrocarbons and energy, as well as pollutants such as carbon monoxide, nitrogen oxides, and unburned hydrocarbons.
Diesel is a heavy liquid fuel composed of long-chain hydrocarbon compounds. Mainly used for compression ignition (diesel) engines. Diesel has a higher calorific value and viscosity, and its cetane number is also higher than gasoline, making it more prone to spontaneous combustion at higher pressures. Due to its high compression ratio and high energy density, diesel engines perform well in terms of economy and durability. When diesel is burned, it can provide higher combustion efficiency, but it also produces more particulate matter (PM) and nitrogen oxides (NOx). The comparison of traditional fuel characteristics is shown in Table 1.

TABLE 1. CHARACTERISTICS OF TRADITIONAL FUELS

	Gasoline	Diesel
Composition	Hydrocarbon	Long chain hydrocarbon compounds
Characteristics	Low density, volatile, easily oxidizable, and high octane rating	High density, less volatile, difficult to self ignite, high compression ratio, and high power performance
Applications	Light vehicles, motorcycles, and small ships	Heavy duty vehicles, large ships, generators

3.2 CHARACTERISTICS OF RENEWABLE ENERGY FUELS

Renewable energy fuels include biofuels, hydrogen fuels, etc., which have many differences and obvious advantages and disadvantages compared to traditional fuels.
Biofuels are renewable energy sources extracted from plants, animals, or other organic matter. It has the characteristics of wide source, renewable, low-carbon emissions, and engine protection. Biofuels can replace traditional petroleum fuels, reduce carbon emissions, and protect the environment. Common biofuels include biodiesel, ethanol, and methanol.

[12-13]Hydrogen, as an energy source, is abundant, clean and zero carbon, with high quality, low calorific value, rapid flame propagation during combustion, and good resistance to explosions. It is an excellent alternative fuel for spark ignition internal combustion engines. Hydrogen fuel produces only water vapor during combustion and has no other direct emissions, making it an extremely environmentally friendly energy source. However, there are still technical and cost challenges in the storage and transportation of hydrogen, and the production of hydrogen fuel also requires energy consumption, indirectly generating emissions. The comparison of advantages and disadvantages between renewable energy fuels and traditional fossil fuels is shown in Table 2.

TABLE 2. ADVANTAGES AND DISADVANTAGES OF RENEWABLE ENERGY VERSUS CONVENTIONAL ENERGY

	Renewable energy fuels	Traditional fossil fuels
Name	Biofuels (biodiesel, ethanol), hydrogen fuel	Gasoline, diesel
Advantages	Generate less greenhouse gases; Reduce dependence on imported oil and increase national energy security; Higher sustainability, theoretically endless supply	The density is usually much higher than most renewable energy fuels; The infrastructure for mining, processing, distribution, and retail is complete and mature; Economies of scale and mature technology make fossil fuels typically cheaper than renewable energy fuels
Disadvantages	Production and processing costs are more expensive; There is no complete generation and distribution system and infrastructure; Low production efficiency	Burning produces a large amount of greenhouse gases and other pollutants; The difficulty of extracting limited resources is increasing day by day; Energy security is easily affected by major oil producing countries

3.3 CHARACTERISTICS OF NEW FUELS

The new fuels are mainly synthetic fuels, liquefied natural gas, etc. Synthetic fuel is the process of converting different raw materials into fuel that can be used for combustion through various chemical processes. Synthetic fuels can be made from raw materials such as biomass, coal, and natural gas. Compared to traditional petroleum fuels, synthetic fuels have higher flexibility, and the production process of synthetic fuels can be adjusted according to demand to obtain the desired products, such as gasoline, diesel, or jet fuel. There are lower greenhouse gas emissions, and the production process of synthetic fuels can adopt carbon capture and storage technology to reduce greenhouse gas emissions and have higher renewability. Synthetic fuels can also use biomass as raw materials to achieve the utilization of renewable energy.

Liquefied natural gas (LNG) is the process of cooling natural gas to extremely low temperatures (approximately -162 ° C) to condense it into liquid form. [14]Compared with traditional natural gas, liquefied natural gas has a higher energy density and is more convenient for storage and transportation. Its carbon emissions are also lower compared to ordinary natural gas.

IV. THE IMPACT OF FUEL ON ENGINE COMBUSTION

4.1 THE IMPACT OF DIFFERENT FUELS ON COMBUSTION EFFICIENCY

The physical and chemical properties of fuel directly affect the efficiency of the combustion process, determining the interaction between fuel and oxygen, the power output of combustion in the engine, and the emission characteristics. The influence of different physical and chemical properties on combustion efficiency is shown in Table 3.

TABLE 3. INFLUENCE OF FUEL PHYSICOCHEMICAL PROPERTIES ON COMBUSTION EFFICIENCY

	Energy density	Oxidation stability	Volatility	Octane number
definition	The energy that can be released per unit mass or volume of fuel	The ability to resist chemical oxidation during fuel storage	The speed at which fuel changes from liquid to gas	The ability of gasoline to resist detonation
influence	The higher the energy density, the more energy is released during combustion	The better the oxidation stability, the higher the combustion efficiency	The higher the volatility, the higher the uniformity, completeness, and efficiency of combustion	The higher the octane rating, the higher the combustion efficiency

The energy density of fuel refers to the amount of energy that can be released per unit mass or volume of fuel. Fuel with higher energy density can release more energy during combustion, directly affecting combustion efficiency. Traditional fossil fuels such as gasoline and diesel have relatively high energy density and are more efficient in transportation and power generation than many renewable energy fuels.

Oxidative stability refers to the ability of a fuel to resist chemical oxidation during storage. Poor oxidation stability can lead to a decrease in the quality of stored fuel and affect combustion efficiency. As mentioned earlier, renewable fuels generally require the addition of antioxidants to extend their storage life and improve their combustion efficiency.

[15]Volatility is also another important factor affecting fuel combustion efficiency. The volatility of fuel determines its degree of gasification in the combustion chamber. Good volatility helps fuel mix better with air, improving the uniformity and completeness of combustion. Gasoline has high volatility, so spark ignition engines are chosen. But diesel has lower volatility, making it suitable for high-pressure injection compression ignition engines.

[16]Finally, the octane rating of fuel also has a significant impact on combustion efficiency. Octane number refers to the ability of gasoline to resist detonation. High octane gasoline allows the engine to operate at higher compression ratios without producing engine knock, thereby increasing combustion efficiency and output power. Diesel has a higher octane rating, which allows it to provide

higher energy output during combustion and achieve higher combustion efficiency.

4.2 THE INFLUENCE OF DIFFERENT FUELS ON COMBUSTION RATE

The combustion rate refers to the rate at which fuel releases energy during the combustion process. The physical and chemical properties of fuel have a significant impact on the combustion rate, and the oxidizability of fuel determines the rate at which it can be oxidized, which affects the combustion rate. Fuel with high volatility can evaporate faster to form a mixture, which can accelerate the combustion process. The combustion process of fuels with higher octane values is relatively slower, so it takes longer to ignite and burn. Each factor can affect the combustion rate, which directly affects the power output and emissions of the engine. [17]In an ideal situation, fuel should burn rapidly near the apex of the piston to maximize the pressure acting on the piston, but there may also be ignition delays. The following are methods to increase combustion rate for different fuels.

In diesel engines, the combustion rate depends on the way fuel is injected into the combustion chamber and the degree of turbulence inside the cylinder. The higher eddies and turbulence of diesel can accelerate combustion speed, but incomplete combustion may also occur if the fuel is not injected and mixed properly.

In spark ignition engines, improving the uniformity and aerodynamic conditions of the mixture can increase the combustion rate of gasoline. Gasoline with higher octane ratings can also burn stably at higher compression ratios.

Renewable fuels such as ethanol and methanol burn slower than gasoline, but they have a higher oxygen content, which facilitates complete combustion of the fuel and reduces pollutant emissions.

4.3 THE INFLUENCE OF FUEL ON COMBUSTION STABILITY AND ANTI KNOCK CAPABILITY

The stability of fuel is mainly related to volatility, boiling point, octane number, etc.

Highly volatile fuels have faster evaporation rates and can mix with air to form combustible mixtures, providing better combustion stability and reducing the risk of flame instability or flickering.

The boiling point of fuel determines the temperature range within which it evaporates to form a combustible mixture. Fuels with lower boiling points can evaporate at lower temperatures, forming flammable mixtures that provide better combustion stability. Compared to high boiling point fuels, it can reduce incomplete combustion or local flameout, and lower combustion stability.

There are two types of combustion in nature, namely slow burning combustion and detonation combustion, with the main difference being the mode of flame propagation. [18]Explosive combustion is a combustion method that couples shock waves and reaction zones, essentially a supersonic combustion wave. Octane number refers to the maximum pressure that a fuel can withstand when mixed with iso octane in a compressor. Fuels with high octane ratings have higher resistance to detonation and can withstand higher pressures without spontaneous combustion. Fuel with strong anti knock ability also helps improve the reliability and stability of the engine. The effects of different fuels on combustion stability and anti knock ability are as follows:

Using high octane gasoline prevents premature self ignition during compression and prevents engine knocking. Octane value enhancers such as MTBE and ethanol can be added to gasoline to enhance its knock resistance.

The cetane number in diesel is more important than the octane number, as it reflects the self ignition temperature and combustion performance of diesel. High cetane number diesel contributes to combustion stability.

The combustion stability and anti knock ability of biofuels depend on their specific composition. Biodiesel has high combustion stability, while ethanol and methanol have high anti knock ability.

V. THE INFLUENCE OF FUEL ON ENGINE EMISSION CHARACTERISTICS

Different fuels can have a significant impact on engine emissions. Zhang et al. [19] found that increasing the content of aromatic hydrocarbons can increase the particulate matter emissions of gasoline engines. Yang et al. [20-21] also found similar results, and the total aromatic hydrocarbons in gasoline significantly increase the emissions of non methane hydrocarbons, THC, formaldehyde, and monocyclic aromatic hydrocarbons such as benzene and toluene. [22]Shen found that increasing the olefin content of gasoline from 10% to 25% can reduce THC emissions by about 15%, while increasing the aromatic content from 35% to 45% can increase NOx emissions by 4%. Andrae et al. [23] found that olefins help increase the reactivity of fuel. Zhao et al. [24] studied the effect of olefins on the emission characteristics of gasoline engines, and

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the results showed that olefins help reduce gasoline engine soot emissions. He et al. [25] found that isoparaffins, cycloalkanes, and aromatics have a significant impact on gasoline engine CO and NOx emissions, while alkanes, olefins, aromatics, and alkynes have a significant impact on gasoline engine volatile organic compound emissions.

5.1 COMPONENTS OF EXHAUST GASES FROM DIFFERENT FUELS

The fuel composition has a significant impact on the exhaust gas composition and emission concentration. The content of hydrocarbons and oxygen in fuel directly affects the generation and emission of hydrocarbons, carbon monoxide, and carbon dioxide in exhaust gas, as shown in Table 4.

TABLE 4. EXHAUST GAS FRACTION OF FUEL

	Content of hydrocarbons	Aromatic hydrocarbon content	oxygen content
Fuel	High content	High content	Low content
exhaust gas	High HC emission concentration	High HC emission concentration	High CO2 emissions

[26]The content of hydrocarbons in fuel directly determines the generation and emission of HC during combustion. A higher content of hydrocarbons will lead to more HC generation, increasing the emission concentration of HC. Saturated hydrocarbon fuels produce less HC compared to unsaturated hydrocarbon fuels. [27]Aromatic hydrocarbon fuels also produce more HC compared to non aromatic hydrocarbon fuels.

The content of hydrocarbons in fuel directly affects the generation and emission of CO during combustion. [28]A higher content of hydrocarbons will lead to more CO generation, increasing the concentration of CO emissions. [29]Lower fuel oxygen content can lead to incomplete combustion and increase the generation of CO. [30]The oxygen content of fuel also affects the generation and emission of CO_2. Lower fuel oxygen content can lead to incomplete combustion and increase the generation of CO_2.

5.2 EMISSIONS OF PARTICULATE MATTER AND NITROGEN OXIDES

With the continuous increase of car ownership, exhaust pollution has become one of the main sources of urban air pollution. Particulate matter and nitrogen oxides are two important components in exhaust gas, which have serious impacts on the environment and human health. [31]A higher content of hydrocarbons in fuel can also lead to more nitrogen oxides in combustion products, thereby increasing the generation and emission concentration of nitrogen oxides.

Previous studies have shown that automobile exhaust particulate matter is mainly composed of highly condensed solid carbonaceous substances, inorganic ash, sulfides, volatile organic compounds, and so on. [32]Among them, carbon black agglomerates are most common in particle sizes<0.5 μ m and 1.5-3 μ m, while inorganic ash content is mainly concentrated in 0.2-2 μ m.

The higher sulfur content, aromatic compounds, and polycyclic aromatic hydrocarbons in fuel can lead to the production of more sulfur dioxide, further promoting the generation and emission of particulate matter.[33]The emission of particulate matter can be reduced by adding specific fuel additives, which can promote the full combustion of particulate matter, thereby reducing the generation and emission of particulate matter. In addition, the successful research on additives that can adsorb emitted particles has further reduced particulate matter emissions.

5.3 GREENHOUSE GAS EMISSIONS

[34]The main greenhouse gases after combustion of different fuels typically include carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). Traditional fossil fuel combustion produces more carbon dioxide, while biofuels can absorb the corresponding carbon dioxide through the regrowth process of biomass, reducing net emissions. Natural gas combustion produces less CO_2, while hydrogen combustion only produces water and is considered a cleaner fuel.

The sulfur content in fuel can increase the emission of sulfur dioxide from combustion, thereby posing a threat to air quality and human health. Sulfur dioxide can be further converted into sulfates, causing a greater impact on the environment. The oxygen content in fuel directly affects the efficiency of the combustion process and the level of greenhouse gas emissions. At the same carbon to hydrogen ratio, the higher the oxygen content, the more carbon dioxide is produced during combustion, leading to an increase in greenhouse gas emissions.

VI. CONCLUSION

This article analyzes and compares the effects of different fuels on engine combustion and emission characteristics. By comparing traditional fuels such as gasoline and diesel with renewable energy and new fuels, the impact of different chemical compositions and physical properties on the combustion process and emission results was revealed. The following conclusion can be drawn:

Although traditional fuels perform outstandingly in terms of performance, they lead to higher pollutant emissions, while alternative fuels help reduce certain emissions, but still face technological and cost challenges. With the advancement of corresponding combustion technologies in the future, the application of new and renewable fuels will become more widespread, which can further reduce pollutant emissions.

In summary, there is an urgent need to find a balance between fuel performance and environmental impact. Environmental protection and sustainable development are the requirements of the times, and technological innovation in fuel is an urgent need for the industry. Future research should focus on reducing the extraction costs and usability of renewable and alternative energy sources.

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