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Current Status of Research on Biodiesel as an Alternative Fuel for Internal Combustion Engines

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In this paper, the research on biodiesel or blending with other fuels is reviewed. Based on the current status of biodiesel research, this paper introduces the current research progress, combustion and emission characteristics, blending with other fuels, and development direction of biodiesel. The combustion, emission, and spray of biodiesel are not exactly the same as diesel, so it is not suitable to be used directly in diesel engines. Biodiesel can be blended with diesel, ethanol, ammonia and other fuels to improve its power performance and reduce harmful emissions. This review can serve as an important reference for those who want to engage in biodiesel research, and a quick understanding of biodiesel research before.

Keywords: Renewable Energy; Alternative fuels; Biodiesel; Combustion; Emission; Spraying characteristics

Introduction

With the development of society, the total energy consumption is increasing. At present, the primary energy used in the world mainly includes fossil energy such as crude oil, coal and natural gas, among which crude oil accounts for more than one-third of the total global energy consumption [1] (as shown in Fig.1). China's limited oil reserves and heavy reliance on overseas imports have become an important issue affecting China's energy security. In the field of transportation, such as automobiles, ships and aviation, oil consumption accounts for more than 50% of the total consumption [2]. According to the statistical analysis of the China Association of Automobile Manufacturers [3], the production and sales of automobiles increased by 4.15~5.57 % year-on-year. Among them, commercial vehicles which mainly use diesel engines, increased by 9.41~10.58 % year-on-year. With the further improvement of China's economic level, China's fuel consumption will continue to grow in the coming period. Figure 1 shows the graph of crude oil consumption and crude oil production in China in recent years, which shows that China's fuel energy gap is gradually expanding.

The internal combustion engine will remain the primary source of power in automobiles for the foreseeable future, and the growth in vehicle sales has increased the consumption of oil [4]. The huge production of automobiles also increases the burden on the environment, which is more obvious in commercial vehicles. Diesel engines have high power and durability and are widely used in trucks and medium to large buses. However, the diffusion combustion method of diesel as a heavy oil makes the fuel

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unevenly distributed in space, forming a considerable proportion of combustion-rich areas and leading to the generation of large amounts of particulate matter. In addition, the uneven distribution of fuel also makes the formation of higher temperature peaks in the combustion chamber, generating more NO_x, and the combustion emissions of diesel engines also generate CO, hydrocarbons (THC), etc. To cope with these problems, countries around the world have developed strict emission regulations [5]. For example, Europe began to implement Euro V vehicle emission standards in 2009. In 2019, China began to implement national V vehicle emission standards nationwide. Technological innovations in internal combustion engines also contribute to the reduction of pollutant emissions and oil consumption, and are divided into three main categories [6]. The first type is to change the internal combustion method of the engine, such as the use of exhaust gas recirculation system in diesel engines to re-burn the exhaust gas and thus reduce the NO_x in the exhaust gas. The second type of pollutant purification technology is the addition of catalysts to the exhaust process to achieve the purpose of purification, such as the three-way catalytic technology already used in gasoline engines, which greatly reduces NO_x and THC emissions. The third category is the search for green and renewable alternative fuels for internal combustion engine fuel, including ethanol, dimethyl ether, biodiesel, etc. The development of alternative fuels for internal combustion engines and the establishment of a diversified energy supply system will not only help to improve engine emissions, but also further reduce dependence on petroleum.

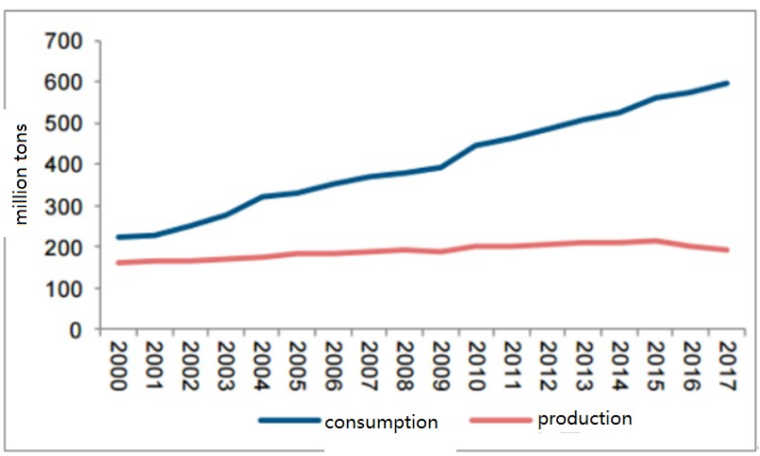


Fig. 1. China's oil consumption and production in recent years [1]

As a renewable green energy, biodiesel is widely valued in all countries around the world. Based on the current status of biodiesel research, this paper introduces the current research progress, combustion and emission characteristics of biodiesel, blending with other fuels, and development direction of biodiesel. This paper is an important reference for those who want to engage in biodiesel research and a quick understanding of biodiesel research.

Physical and Chemical Properties of Biodiesel

Biodiesel is a methyl ester or ethyl ester fuel made from oilseed crops, wild oilseed plants, aquatic plant oils (like engineered microalgae), animal fats and grease, and restaurant waste oil, etc. This fuel can be synthesized through an ester exchange process.

There are more than 30 kinds of vegetable oil-based biodiesels known to be used in internal combustion engines, and their main characteristics are as follows [7].
(1) The calorific value of biodiesel is lower than diesel. But the density is higher than diesel, and the volumetric calorific value is similar to diesel. So, the engine oil supply system almost does not need to be changed.
(2) The viscosity of biodiesel is higher than diesel, which affects the spraying characteristics and cold starting performance. But the viscosity of vegetable oil decreases faster with the increase of temperature.
(3) The cetane number of biodiesel is lower than diesel. The flash point and ignition temperature of biodiesel are worse than diesel. When used in diesel engine, it generally needs to increase the injection advance angle.
(4) Biodiesel generally contains oxygen, which is good for combustion.
(5) Biodiesel can be mixed with diesel in any ratio.
(6) Biodiesel contains small amount of water, ash, carbon residue and impurities.
(7) The main component of biodiesel is unsaturated fatty acid, which is easy to oxidize and deteriorate easily.

Combustion, Spraying, Power Economy and Emission Characteristics of Biodiesel

Combustion Characteristics

The physical parameters of biodiesel are close to those of conventional diesel. Biodiesel and diesel have good miscibility, so it can be blended with conventional diesel in any ratio and used directly in existing engines. However, the combustion characteristics of biodiesel and diesel in engines are very different, which depends on the physical and chemical properties of biodiesel and blending concentration. Many scholars have conducted a lot of related researches. In terms of the output power, the maximum output power of biodiesel is slightly lower than that of diesel, because the calorific value of biodiesel is lower than that of diesel. Sinha and Agarwal [8] reported that when using lower concentrations of rice bran biodiesel (B5, B10 and B20), the maximum engine output was equal to or slightly higher than that of the diesel engine. The evaporative characteristics of the fuel, the viscosity, and the oxygen content of the biodiesel all affected the exothermic rate of the combustion process, especially at high rpm. The lower biodiesel concentration increased the output power of the tested engine, and the degree of influence is shown in Figure 2.

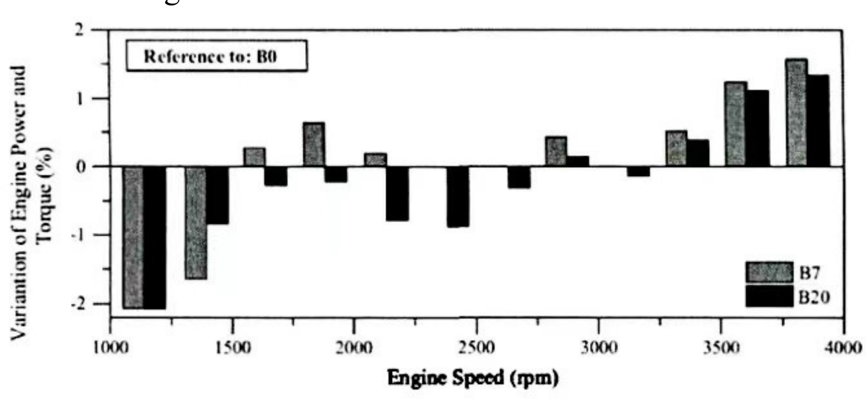


Fig. 2. Effect of biodiesel blends on engine output power and torque [8]

In terms of engine thermal efficiency, most studies reported that the thermal efficiency of biodiesel and its blends is higher than that of diesel, mainly related to the blending ratio, fuel oxygen content, fuel viscosity and density. For example, *Mahanta et al.* [9] reported that the thermal efficiency of B20 biodiesel was higher than that of diesel fuel due to the oxygen atoms of biodiesel that contributed to more adequate combustion of the fuel in the combustion chamber. Agarwal [10] tested the effect of different blending ratios of biodiesel relative to diesel fuel on the peak engine thermal efficiency (as shown in Figure 3) and found that the B20 blend had the highest thermal efficiency. Du *et al.* [11] pointed out that the thermal efficiency of biodiesel, biodiesel-ethanol and biodiesel-methanol blends were higher than that of diesel at all operating conditions. This is due to the small amount of ethanol in the fuel blend that improves the combustion characteristics of the fuel. In addition, the use of higher injection pressure can improve the atomization characteristics of biodiesel droplets and increase the thermal efficiency of the fuel.

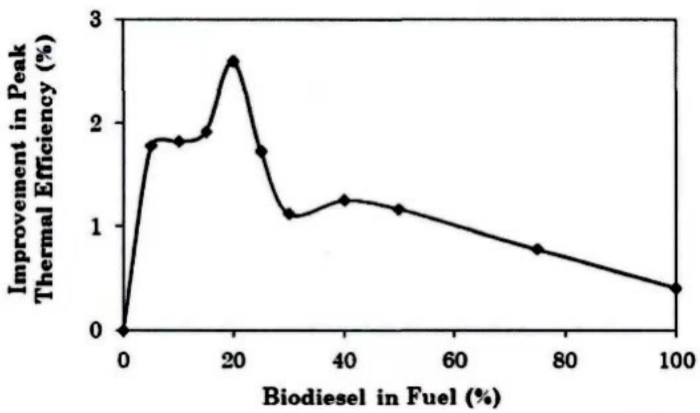


Fig. 3. Effect of biodiesel blending ratio on the improvement of peak thermal efficiency [10]

Emission Characteristics

China's latest National VI standard makes further restrictions on pollutant emissions, in which the emission requirements for CO and THC (Total Hydro Carbons) are reduced by one-third compared to National V, and the overall pollutant limits are 40-50% stricter compared to National V [12]. For biodiesel, the emissions of THC, CO, and PM decreased with the increase of blending ratio, while NO_x increased slightly [13-16]. Grimaldi *et al.* [17] reported that the CO emissions of biodiesel were similar to those of diesel at 2500 rpm of the engine, and the CO emissions of biodiesel decreased significantly at 4000 rpm of the engine speed. Gumus *et al.* [18] observed that CO emissions decreased as the biodiesel blend percentage increased, and that CO emissions decreased with increasing injection pressure in the engine for all biodiesel blends. THC emissions are affected by feedstock and fuel properties such as oxygen content, cetane number, engine injection pressure, fuel injection time delay, etc. Su *et al.* [19] showed that biodiesel blends emit significantly lower THC emissions at full load compared to diesel. Gumus *et al.* also [18] studied the THC emissions of biodiesel at different blending ratios and injection pressures and found that the THC emissions decreased with increasing biodiesel blending ratio and fuel injection pressure (as shown in Figure 4).

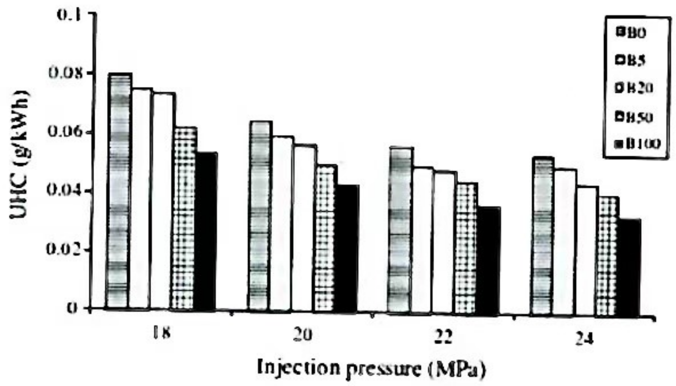


Fig. 4. Variation of THC emission with injection pressure [18]

Most relevant studies have shown that biodiesel produces higher NO_x than diesel in unmodified engines. Gimuis *et al.* [20] concluded that NO_x emissions increase with increasing engine load due to higher peak combustion chamber temperatures. Sharp *et al.*[21] investigated the relationship between NO_x emissions and fuel performance, showing that NO_x emissions decreased with increasing fuel oxygen content in the test fuel and increased with increasing carbon chain length. Mueller *et al.* [22] concluded that the increase in NO_x in biodiesel engines cannot be quantified by changes in a single fuel performance. Rather, it is the result of many coupled mechanisms whose effects enhance or cancel each other under different conditions.

In terms of particulate matter (PM) emissions (e.g., Figure 5), Lapuerta *et al.* [23] tested PM emissions from four biodiesels in a 2.2 L turbo diesel engine and showed that all four biodiesels emitted substantially less PM than diesel. The Dhar and Agarwal [24] study noted that PM emissions from both B20 and B50 were lower than those from diesel, and that as injection pressure increased, particulate matter particle size decreased.

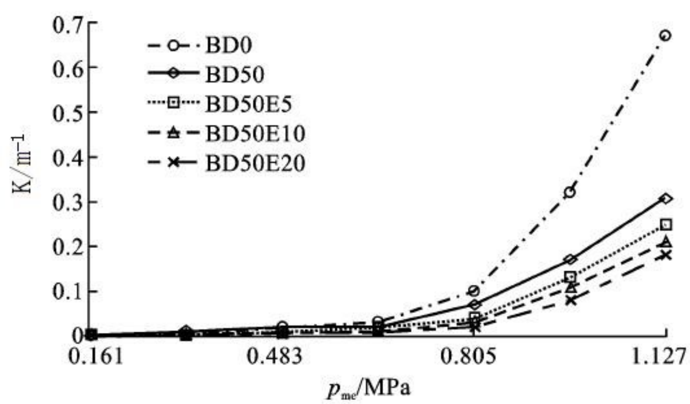
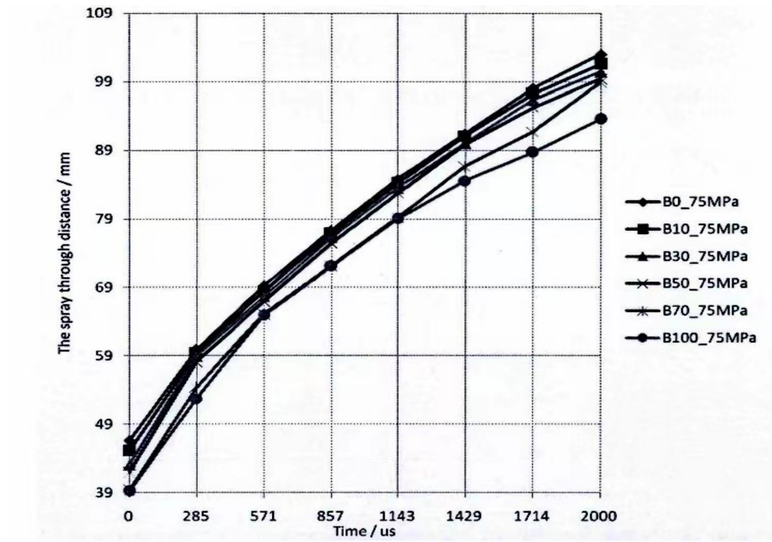


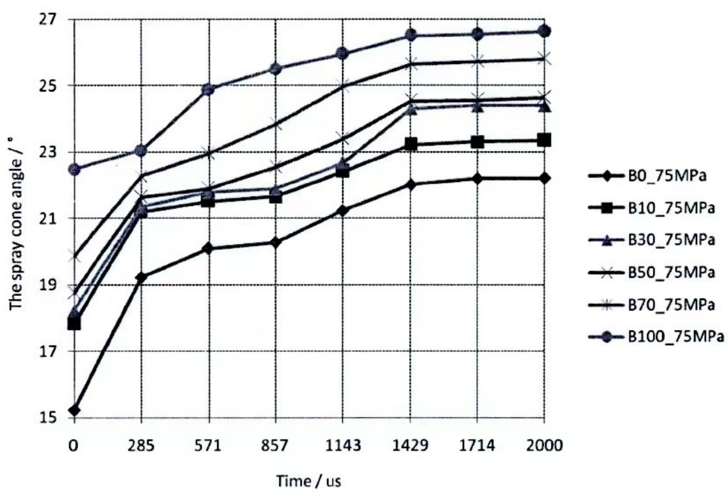
Fig. 5. Variation of the PM emission [23]

Spraying Characteristics

The most important factor affecting engine combustion is the quality of the in-cylinder fuel-air mixture. The formation of the mixture is closely related to the in-cylinder environment, the spray characteristics of the fuel, and the atomization effect. The spray characteristics of biodiesel are an important factor affecting its operation and emission in the engine [25]. From the above review, it can be seen that the engine injection pressure, atomization method and the physical parameters of biodiesel itself will directly affect the combustion and working characteristics of the fuel in the engine, which in turn determines the fuel economy and emission performance of the engine. Therefore, the spray characteristics of biodiesel in diesel engines are the key factors affecting the efficient and clean combustion of the engine. Compared with diesel fuel, the density, viscosity and surface tension of biodiesel are larger, which will directly affect the spray characteristics of biodiesel in engines. Among them, the viscosity affects the fuel flow at different temperatures and the spray parameters when the fuel is injected into the combustion chamber, which may eventually lead to deposits in the engine, especially at higher viscosities. Many studies in the literature have shown that the viscosity of biodiesel tends to decrease non-linearly with increasing temperature, but remains higher than that of diesel [26]. Density is also an important physical parameter of biodiesel and has a more significant effect on the macroscopic spray characteristics of the fuel. During the spraying process, denser fuels have higher momentum and tend to produce larger spray penetration and collision with the piston, so the density of biodiesel needs to be controlled in practical use. For example, the density of biodiesel at room temperature is limited to the range of 860~900 kg/m^3 in Europe. Knothe *et al.* [27] studied the density variation trend of biodiesel in the range of 15~40°C and derived the correlation equation. In addition, the surface tension of the liquid affects the droplet formation and fragmentation during the spraying process, which in turn affects the atomization characteristics of the fuel. The surface tension of biodiesel is higher than that of diesel, which is not conducive to the breaking into fine droplets during the spraying process and affects the atomization characteristics of biodiesel. Lee *et al.* [28] investigated the spray penetration, soot mean diameter (SMD) and mean velocity distribution of biodiesel blends. The results showed that the biodiesel blends had similar spray development trends as diesel, but were larger due to the higher viscosity and surface tension of biodiesel. Han *et al.* [29] studied the spray characteristics of three components of biodiesel, methyl laurate, methyl oleate and ethyl oleate, and the results showed that methyl oleate and ethyl oleate produced larger spray penetration distances due to their higher viscosity and surface tension (as shown in Figure 6). Cao *et al.* [30] investigated the spray characteristics of biodiesel blends with non-edible oils, and the results showed that the spray penetration and spray velocity increased and the spray cone angle decreased as the percentage of biodiesel in the blends increased. The macroscopic spray characteristics of biodiesel-diesel blends with different blending ratios were investigated by Xie *et al.* [31]. The results indicated that the spray cone angle increased and the spray penetration and peak tip velocity decreased with increasing ambient pressure. It was also found that the higher viscosity and surface tension of biodiesel inhibited the fragmentation of the liquid jet.



(a)



(b)

Fig. 6. Comparison of different biodiesel macro spray parameters with diesel [27]

Blending and Combustion of Biodiesel with Other Fuels

Biodiesel has the characteristics of higher viscosity and lower calorific value [32]. This makes the fuel consumption of engines burning biodiesel higher than that of diesel. And the thermal efficiency is reduced. Therefore, many researchers have used biodiesel blended with other fuels to improve the fuel properties of biodiesel [33].

Qiu *et al.* [34] blended biodiesel with different proportions of ammonia for combustion simulation. Their simulation results show that biodiesel blended with a certain amount of ammonia can promote combustion, which can improve engine performance and reduce harmful emissions. However, the engine power is slightly reduced with the addition of ammonia. Zuo *et al.* [35] conducted experiments on biodiesel-diesel blends. They found that the ignition point of biodiesel-diesel blends was earlier than diesel at full load. Due to the advanced ignition point, the maximum cylinder pressure and peak exothermic rate of biodiesel-diesel blends are lower than that of diesel during the main combustion phase. Geng *et al.* [36] experimented the addition of 5%, 10% and 20% ethanol to biodiesel-diesel blends. The results show that the maximum in-cylinder pressure and the maximum instantaneous heat release rate of the blended fuel are higher than those of diesel fuel at small loads. With the increase of ethanol blending ratio, the NO_x and HC emissions of biodiesel-diesel-ethanol blends increased slightly. But they were lower than the emission level of diesel.

CONCLUSIONS

In summary, several conclusions can be drawn as follow:
1) The combustion, emission, and spray of biodiesel are not exactly the same as diesel, so it is not suitable to be used directly on diesel engines.
2) Biodiesel can be blended with diesel, ethanol, ammonia and other fuels to improve its power performance and reduce harmful emissions.
3) The current studies on biodiesel are mostly based on the external conditions of combustion and the blending combustion between different fuels. There is a relative lack of studies to describe the combustion process from the chemical reaction kinetics perspective. The study of the combustion process of fuels from the chemical reaction kinetics point of view allows to obtain the fundamental reactions that play an important role in in-cylinder combustion. Therefore, the study of the combustion process from the chemical reaction kinetics point of view is a new direction.

CONFLICTS OF INTEREST

The author declares that there is no conflict of interests regarding the publication of this paper.

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