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Recent Studies on Alternative Fuel of Dimethyl Ether

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With the development of industrialization, a large number of non-renewable fuels (such as coal and crude oil) are consumed, and the harmful substances produced in the combustion process of a large number of fossil fuels have caused serious pollution to the atmosphere, and the harmful gases produced by combustion have caused disastrous damage to the ecological balance. Therefore, finding clean energy and exploring alternative fuels are very important in today's society. This paper mainly reviews the studies on the alternative fuels of dimethyl ether (DME). Firstly, the types of alternative fuels currently researched by society and their respective advantages and disadvantages are analyzed, and the preparation of dimethyl ether and its advantages and disadvantages are analyzed in detail. In addition, the physicochemical properties, combustion and emission characteristics of dimethyl ether and diesel are compared and analyzed. The conclusion is that the injection delay angle of dimethyl ether is larger than that of diesel, the ignition delay period is shorter than that of diesel, and the maximum explosion pressure, maximum pressure rise rate and combustion noise of dimethyl ether are lower than that of diesel. The diffusion combustion speed of DME is faster than that of diesel, and the combustion duration is shorter than that of diesel. At the same time, as an alternative energy, dimethyl ether engine has a significant reduction in NOx emission, a very low level of HC and CO emission, and zero soot emission. In conclusion, the DME engine has good performance and emission characteristics.

Keywords: Dimethyl ether; Diesel engine; Alternative fuel; Clean fuel

Introduction

A good ecological environment is not only the basis for human survival, but also the prerequisite for the sustainable and stable development of society. With the rapid development of global industry and economy, the main energy sources of human society, such as coal, crude oil and natural gas, have been irreversibly depleted after hundreds of years of over exploitation and huge consumption. As a populous country, China's per capita reserves of major fossil energy are far below the world's per capita level. In addition, the rough economic development model consumes a lot of energy, resulting in low production efficiency. Moreover, China has always been dependent on major fossil energy sources. It is a major problem that China's development is constrained by the energy problem. The implementation of sustainable development strategy, energy security and stable economic development must first solve the energy problem.

In addition, with the continuous increase of the total energy consumption, a large number of harmful substances generated during the burning of fossil fuels have caused

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serious pollution to the atmosphere, and the harmful gases generated during the burning have caused catastrophic damage to the ecological balance. These damages may include a series of chain reactions (such as climate warming, glacier melting, and sea level rise), and some coastal areas are in danger of being submerged. The above problems are threatening the survival of mankind and have already aroused great concern and concern of our government [1]. Under the dual pressure of energy pressure and environmental pressure, it is urgent for our government and researchers to work together to accelerate the development and utilization of new, cleaner and more environmentally friendly alternative energy.

Table 1. Main Components and Hazards of Automobile Exhaust

Component	Main hazards
CO	If CO in the atmosphere enters the human body, it will quickly combine with hemoglobin, weakening the ability of blood to provide for human tissues, causing chronic poisoning such as headache and dizziness caused by hypoxia, and making the reaction function, sensory function, memory function, etc. unable to work normally.
HC	Olefins have anesthetic effect and irritation to mucous membrane. HC will react with NO_2 to generate photochemical smoke. Aromatic hydrocarbons are harmful to blood, liver and nervous system. Polycyclic aromatic hydrocarbons and their derivatives have certain carcinogenic effect, and aldehydes are harmful to eye mucous membrane, respiratory tract and blood.
NO_x	It slowly oxidizes NO_2 in the atmosphere and combines with water to form nitric acid after being inhaled by the human body, causing cough, asthma, even emphysema and myocardial damage. NO_x is one of the main factors to form chemical smog.
PM	The main component is carbon, which can be suspended in the atmosphere for a long time without sedimentation. It will penetrate deep into human lungs, causing mechanical overload, damage the self purification devices of various channels in the lungs, and promote the toxic effect of other pollutants.

Automobile is an indispensable means of transportation in modern social life. With the continuous increase of car ownership, the exhaust emissions of traditional gasoline and diesel vehicles have an increasing impact on the environment. Among them, the pollution caused by automobile exhaust accounts for 60%~70% of the total air pollution. Due to multiple reasons such as automobile exhaust emissions and the environment, most parts of China are almost covered by a thick haze every day, which also makes the words "air quality" and "PM2.5" become frequently used words "smog" attacking the city. Under the heavy fog, automobile exhaust emissions become the culprit causing smog, and become the target of public criticism for a time. Among them, the hazards of the main components of exhaust gas from automobile internal combustion engines are shown in Table 1 [2]. These ingredients will have more and more negative effects on the environment and human body as the number of cars increases.

From the perspective of long-term energy strategy, we should actively develop alternative clean fuels to reduce dependence on fossil fuels such as oil. Therefore, the

government should encourage and support the design, R&D and application of alternative fuel vehicles in policy, and give preferential policies in terms of taxation in the early stage of the development of alternative fuel vehicles, even for a period of time, to encourage the reduction of the consumption of fossil fuels such as oil, thus reducing environmental pollution [3].

Application of Alternative Fuels in Internal Combustion Engines

Common Alternative Fuels

At present, the most widely researched and applied alternative fuels mainly include liquefied/vaporized natural gas, liquefied petroleum gas, alcohol fuel, biofuel, hydrogen fuel, dimethyl ether (DME), mixed fuel, etc. [4-7]. A comparison of physical and chemical properties between traditional fuels and alternative clean fuels is shown in Table 2.

1) Liquefied/vaporized natural gas and liquefied petroleum gas

Liquefied/vaporized natural gas (LNG) and liquefied petroleum gas (LPG) have been widely used in urban public transport, and their outstanding feasibility has been confirmed. Liquefied/vaporized natural gas (LNG) and liquefied petroleum gas (LPG) have the following advantages: environmental protection, almost no black smoke in the emission, only a small amount of sulfur, and no benzene and lead, which greatly reduces the environmental pollution. With good antiknock property and much higher octane number than gasoline, the engine's power performance and thermal efficiency can be improved by appropriately increasing the compression ratio and adopting supercharging technology. With low vaporization temperature, it can enter the cylinder in the form of gas, with less carbon deposition, extending the engine overhaul cycle. It has high safety and adopts various structures and technologies to make the gas burn in a fully enclosed environment. The economy is good, and the price is lower than that of gasoline. However, since the natural gas is mainly stored in the west of China, and the application of natural gas is limited to local industries, the large-scale application of natural gas in China is limited [8].

2) Biodiesel

Biodiesel has many advantages, such as rich resources, which can be obtained by esterification of plant or animal fats, and it is a renewable resource. Besides, it has high energy density, excellent economic performance and emission performance. It can be directly used without changing the original structure of compression ignition engines. However, if it is used for a long time, it will produce carbon deposits inside the fuel injectors, and cause deterioration of lubricating oil and other problems [9]. In addition, it is necessary to ensure sufficient raw materials and high costs in the production process.

3) Alcohol fuel

The sources of methanol and ethanol in alcohol fuels are very rich. They can not only be extracted from coal, heavy oil and natural gas, but also from renewable resources such as sugar cane, sugar beet and plant fiber. Moreover, the technology is relatively mature. The biggest advantage of methanol and ethanol as alternative fuels is that there is almost no soot generated during combustion, which is very clean, and CO, HC and NO_X emissions are lower than those of compression ignition engines [10]. Therefore, alcohol fuel, one of the petroleum alternative fuels, has a great application prospect in the future.

4) Hydrogen

Hydrogen is an efficient and clean fuel. When burning hydrogen and gasoline of the same quality, the heat release of hydrogen is 3 times that of gasoline. The combustion product of hydrogen is only water, which will not lead to carbon deposition in the engine and will not pollute the environment. However, hydrogen is a secondary energy and needs to be produced by other energy sources, which leads to high production costs [11]. Moreover, the difficulties in storage and transportation of hydrogen also lead to the limitations of its wide application.

Table 2. Comparison of physical and chemical properties between traditional fuels and alternative clean fuels

Nature	Gasoline	Diesel	Hydrogen	Dimethyl ether	Methanol	Ethanol	CNG	LPG
Molecular formula	C_5-C_{12}	C_xH_y	H_2	CH_3OCH_3	CH_3OH	CH_3CH_2OH	CH_4	C_3H_8+C_4H_{10}
Octane number	90-106	20-30	0	-	111	111	130	107
Cetane number	13-17	40-55	0	55-60	<15	<8	Low	<10
Theoretical air fuel ratio A/F	14.8	14.6	34.3	8.9	6.5	9.0	17.2	15.53
Boiling point/℃	30-220	180-370	-253	25.1	65	78	-162	-35
Flash point/℃	-43	60	-252.8	-41.4	11	21	-187	-104
Autoignition temperature/℃	350-400	250	570	235	450	423	650	460
Liquid phase density/$kg \cdot L^{-1}$	0.72-0.75	0.84	0.169	0.66	0.79	0.79	0.47	0.52
Low calorific value/$MJ \cdot kg^{-1}$	44.5	42.5	10.8	28.8	19.9	27.6	50.1	46.0
Latent heat of vaporization/k$J \cdot kg^{-1}$	297	250	305	460	110	904	510	401
Vapor pressure/MPa	0.45-0.9	<0.01	10.67	0.5	0.2	0.18	-	0.1
20 ℃ dynamic viscosity/Pa·s	0.42	2.4	-	0.15	0.6	1.2	-	0.6
Volume ratio of combustible range/%	1.3-7.6	0.6-6.5	4.0-74.5	3.4-17	5.5-26	3.5-1.5	5-15	2.4-9.5
Mass fraction of oxygen atom/%	0%	0%	0%	34.8%	50%	34.8%	0%	0%
Mass fraction of carbon atom/%	85%-88%	86%	0%	52.2%	37.5%	52.2%	75%	82%

5) Dimethyl ether

In recent years, more and more countries around the world have studied dimethyl ether. The main reason is that dimethyl ether has a high cetane number, a low autoignition temperature and excellent compression characteristics. So it is suitable to

replace diesel in compression ignition engines. Research shows that the thermal efficiency of direct injection compression ignition engines using dimethyl ether is the same as that of diesel fuel. In addition, the running stability and combustion noise of the engine are almost at the same level as those of the gasoline engine [12], and the exhaust emissions are clean and clean. No auxiliary ignition device and exhaust catalytic post-treatment device are required, which greatly reduces NO_X emissions and realizes smokeless combustion.

Clean Alternative Fuel of Dimethyl Ether

In order to change the tense situation of energy supply and demand in China and reduce automobile exhaust pollution, an alternative fuel with extensive sources, mature production technology, good economy and low pollution emissions is urgently needed. Dimethyl ether, as a new alternative fuel for diesel engines in recent years [11-15], has aroused great interest, and related research is increasing and deepening.

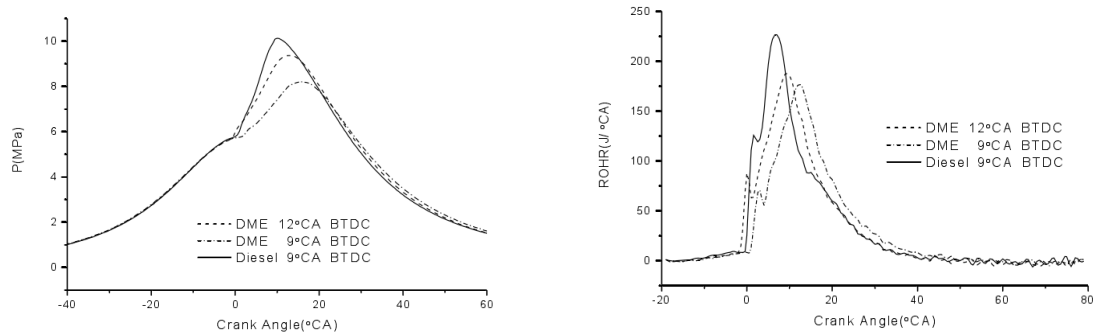
Preparation of Dimethyl Ether

Dimethyl ether fuel comes from a wide range of sources, and can be produced in large quantities from coal, natural gas, coalbed methane, biological organics, etc. [15-16]. The preparation of dimethyl ether can be divided into direct method and indirect method [17]. Direct method refers to the direct preparation of dimethyl ether from synthesis gas. The indirect method refers to the synthesis gas, which is first made into methanol, and then dehydrated from methanol. China is rich in coal resources, accounting for 11% of the world's total reserves, and the price is low, only about 1/3 of the world average price. Therefore, burning coal to produce dimethyl ether can not only effectively reduce environmental pressure and ease energy security problems, but also promote the development of clean coal combustion technology, which is a good way to do more with one action.

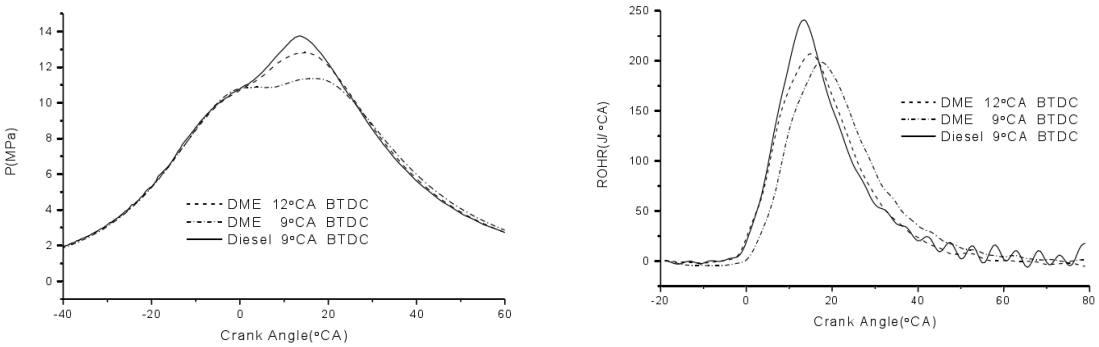
Comparison of Combustion and Emissions between Dimethyl Ether Engine and Diesel Engine

Comparison of Combustion Characteristics between Dimethyl Ether Engine and Diesel Engine

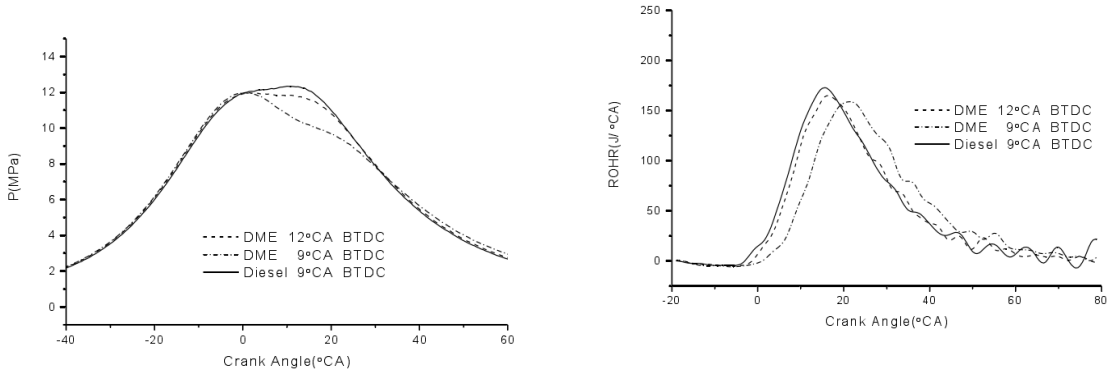
Figure 1 shows the comparison of indicator diagram and heat release rate of dimethyl ether engine and diesel engine. It can be seen from the figure that the cetane number of dimethyl ether is higher than that of diesel, and the ignition delay period is shorter than that of diesel. During the ignition delay period, the diesel engine accumulates more fuel in the cylinder and burns together after ignition, resulting in a higher maximum explosive pressure than that of the DME engine. The injection delay of dimethyl ether is larger than that of diesel. When the fuel injection advance angle is the same, the injection advance angle of dimethyl ether is smaller than that of diesel. The position corresponding to the maximum cylinder pressure of the dimethyl ether engine is later than that of the diesel engine [19].



a) 800 r/min Pe=0.87 MPa



b) 1400 r/min Pe=1.52 MPa



c) 2200 r/min Pe=1.21 MPa

Figure 1. Comparison of Cylinder Pressure and Heat Release Rate between DME Engine and Diesel Engine [19]

It can be seen from Figure 1 that the supercharged diesel engine has a high intake pressure and temperature, a short ignition delay period, less fuel to participate in premixed combustion, less heat released from premixed combustion, low premixed combustion heat release peak value, and high diffusion combustion heat release peak value. Due to the short ignition delay period of dimethyl ether, the heat released by premixed combustion is less, and the peak heat release of premixed combustion is lower than that of diesel engine.

To sum up, the injection delay angle of dimethyl ether is larger than diesel, the ignition delay period is shorter than diesel, and the maximum burst pressure, maximum pressure rise rate, and combustion noise are lower than diesel. The diffusion combustion

speed of dimethyl ether is faster than that of diesel, and the combustion duration is shorter than that of diesel.

Emission Comparison between DME engine and Diesel engine

In 2004, Japan Institute of Industrial Technology (AIST) and Japan National Oil Corporation (JNOC) jointly conducted tests with different injection advance angles and engine speeds on a tandem pump diesel engine fueled with dimethyl ether [20]. The results showed that the maximum power and torque of the engine when fueled with dimethyl ether were equal to or greater than the original engine. Under the condition that NOx emission is maintained at the same level as that of the original engine, the thermal efficiency of DME at low and medium speed is often lower than that of diesel, and the thermal efficiency at high speed is equivalent to that of the original diesel.

Table 3. Emission Test Results of Dimethyl Ether Engine under Japanese 13 mode [21]

				[g/kWh]
	CO	HC	NOx	PM
Japanese 2003 limits	2.22	0.87	3.38	0.18
Diesel fuel operation	3.17	0.89	4.26	0.17
DME operation	0.117	0.222	4.26	0.0102
(Japanese 2003 regulation)	(-95%)	(-74%)	(-27%)	(-94%)

In 2004, Shinichi Goto of the Japanese Institute of Industrial Technology and Shinichi Suzuk of the Japanese oil company conducted an experimental study on a modified naturally aspirated diesel engine [21] using exhaust gas recirculation (EGR) and oxidation after treatment (DOC) technologies to burn dimethyl ether. Table 3 shows the emission results measured according to the Japanese 13 operating mode. Compared with the emission limit of Japanese 2003 regulations, NOx emissions decreased by 27%, CO decreased by 95%, HC emissions decreased by 74%, and particles emissions decreased by 94%.

In conclusion, the power performance of DME engine is superior to that of diesel engine. Under external characteristics, the fuel consumption rate of DME engine is lower than that of diesel engine at medium and low speed, and slightly higher at high speed. The NO_x emission of DME engine is significantly lower than that of diesel engine, the HC emission is also lower than that of diesel engine, and the CO emission is slightly higher than that of diesel engine. The HC and CO emissions of DME engine are at a very low level. In all operating conditions of the engine, the soot emission of the DME engine is zero. Dimethyl ether engine shows good performance and emission characteristics.

Advantages and Disadvantages of Dimethyl Ether as Diesel Engine Fuel

Through the research on the physical and chemical properties of dimethyl ether and the comparison between dimethyl ether and diesel oil, the following advantages and disadvantages are found [22]:

1) In the molecular formula of dimethyl ether, there are only C – H and C – O bonds, but no C – C bonds. The oxygen content is very high. Therefore, compared with diesel fuel, combustion will not produce soot, but also has good combustion effect and high thermal efficiency.

2) The cetane number of fuel is an important indicator of engine efficiency. The higher the cetane number, the stronger the ignition of fuel. The good ignition performance of dimethyl ether is due to its high cetane number, which ranges from 55 to 66, while that of diesel is only 40 to 55.

3) Dimethyl ether is a non petroleum energy and does not exist in nature, but it can be prepared from coal, natural gas and various biomass with low difficulty and easy preparation.

4) Dimethyl ether is easy to corrode rubber products during use, so it can only contact metal products directly during use and storage.

5) Under normal temperature and pressure, dimethyl ether is usually kept in a gaseous state. Based on this, in order to prevent dimethyl ether from vaporizing during combustion and affecting fuel performance, dimethyl ether needs to be pressurized. Generally, pressurize to 1.5 to 3 MPa and store dimethyl ether in liquid state.

6) Dimethyl ether is a colorless, non-toxic, non corrosive, non carcinogenic gas fuel. Due to its characteristics, it will not corrode metals, and its physical and chemical properties are stable. Even if it is placed in an aerobic environment for a long time, it will not produce oxidation reactions, and there will be oxides. Compared with propane and butane, dimethyl ether is extremely safe to use.

7) The calorific value of dimethyl ether is lower than that of diesel fuel, so more dimethyl ether is needed to achieve the same heat release as diesel fuel.

CONCLUSIONS

1. Dimethyl ether has high cetane number, low autoignition temperature and excellent compression characteristics, so it is suitable to replace diesel in compression ignition engines

2. The injection delay angle of dimethyl ether is larger than that of diesel, the ignition delay period is shorter than that of diesel, and the maximum explosion pressure, maximum pressure rise rate and combustion noise are lower than that of diesel. The diffusion combustion speed of dimethyl ether is faster than that of diesel, and the combustion duration is shorter than that of diesel.

3. The power performance of DME engine is better than that of diesel engine. Under external characteristics, the fuel consumption rate of DME engine is lower than that of diesel engine at medium and low speed, and slightly higher at high speed. The NOx emission of DME engine is significantly lower than that of diesel engine, the HC emission is also lower than that of diesel engine, and the CO emission is slightly higher than that of diesel engine. The HC and CO emissions of DME engine are at a very low level. In all operating conditions of the engine, the soot emission of the DME engine is zero. Dimethyl ether engine shows good performance and emission characteristics.

CONFLICTS OF INTEREST

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

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