A Review of the Effect of Compressed Natural Gas (CNG) on Combustion and Emission Performance of Internal Combustion Engines

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In order to reduce the environmental pollution caused by conventional internal combustion engines, the application of natural gas in internal combustion engines and the combustion and emission performance of natural gas internal combustion engines have been widely studied by scholars. Because the physical and chemical properties of natural gas are different from those of conventional gasoline or diesel, the operating performance of natural gas internal combustion engines in practical applications is also different from that of conventional internal combustion engines. This paper presents the physicochemical properties of compressed natural gas, the two combustion modes (premixed combustion and non-homogeneous diffusion combustion) in internal combustion engines and the effect of compressed natural gas on the performance of internal combustion engines. Compared with gasoline engines, natural gas internal combustion engines have relatively lower power and higher effective power loss; lower effective fuel consumption rate in terms of economy; and lower CO and NO_x emissions than gasoline engines in terms of emissions.

Keywords: Clean Energy; Compressed Natural Gas (CNG); Combustion and Emission Performance; Improvement Methods

Introduction

Globally, 95% of transportation energy comes from fossil fuels [1-2]. To solve the energy crisis and reduce the environmental pollution caused by vehicle emissions, many countries are actively searching for alternative energy sources. The availability and environmental friendliness of compressed natural gas (CNG) as a clean energy source make it a preferred alternative fuel in internal combustion engines, and the application of natural gas in spark ignition (SI) and compression ignition (CI) engines has been widely studied.

The main component of natural gas is methane (CH_4) at 60 to 90%, which is followed by various other hydrocarbons. Compared with gasoline, there are certain deficiencies in automotive applications. To improve the performance of natural gas engines, many scholars have studied the combustion and emission performance of natural gas engines. Kontses *et al.* [3] conducted tests on diesel, gasoline, liquefied petroleum gas (LPG), and compressed natural gas (CNG) vehicles for particulate emissions. It was

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found that diesel and CNG engines had the lowest emissions with PN (number of particles) values as low as 7.8×10^9 and 2.4×10^{10} p/km, respectively. Yontar and Doğu [4] investigated the effect of gasoline and CNG fuels on the low and high load conditions of a two-phase relay ignition engine and showed that CNG reduced the maximum torque by 15.6 % and 19.6 % at a throttle opening of 75 % and 25 %, respectively, compared to gasoline. Overall, the use of CNG reduced the emissions of CO_2 and HC, but engine performance parameters such as torque and power were reduced. By studying the effect and optimization of EGR on natural gas engines, Guo *et al.* [5] concluded that exhaust gas recirculation (EGR) fluctuations in the intake manifold lead to differences in the EGR rate entering each cylinder during the intake process, and optimization can reduce the differences. Tahir *et al.* [6] selected a single cylinder spark ignition (SI) engine to study the effect of CNG on spark ignition engine, and showed that the in-cylinder pressure of CNG is 20% lower than that of gasoline. Liu *et al.* [7] improved the intake pipe to solve the problem of poor uniformity of natural gas engine operation. Han *et al.* [8] designed a new spark ignition compressed natural gas (CNG) engine and studied the combustion performance. The results showed that the torque of CNG engine increased from 5.2 % to 6.6 % when the compression ratio increased from 10.5 to 12, and increasing the compression ratio could improve the performance of CNG to some extent. Sahoo and Srivastava [9] studied the effect of compression ratio on effect of engine burst, performance, combustion and emission characteristics of dual-fuel CNG engine. The results showed that the peak burst of gasoline engine was significantly higher than that of CNG engine, and the fuel consumption and thermal efficiency of CNG were improved at higher speed compared to gasoline engine.

The performance of a natural gas engine depends mainly on the actual working process. The combustion process of the fuel entering the cylinder directly affects the thermal power conversion rate and exhaust gas composition of the engine, so the improvement of engine performance cannot be achieved without the improvement of the engine combustion process. This paper reviews the effect of compressed natural gas (CNG) fuel on the performance of internal combustion engines from the perspective of combustion and emission.

Physical and Chemical Properties of Natural Gas

Natural gas, as the first alternative fuel for vehicles implemented in China, has been widely used in public transportation in some cities with its favorable price and obvious emission reduction effect [10]. The basic physicochemical properties of natural gas are different from those of traditional gasoline diesel. As a gaseous fuel, its octane number is significantly higher than that of gasoline, and it shows a blue flame during combustion. The basic physicochemical properties of natural gas are as follows.

(1) Density. The density of natural gas is 0.78 kg/m^3 at atmospheric pressure, which is less than the density of air (1.293 kg/m^3).

(2) Low calorific value. The low calorific value of natural gas by mass is 50.0 MJ/kg, which is higher than the low calorific value of gasoline (43.9 MJ/kg). However, the theoretical mixture calorific value of natural gas is 3.39 MJ/m^3, which is lower than that of gasoline engine (3.73 MJ/m^3). So the theoretical mixture calorific value of natural

gas is relatively low.

(3) Boiling point. The boiling point of natural gas is -162℃, which is not easily liquefied and usually exists in a gaseous form.

(4) Ignition temperature. The ignition temperature of natural gas is about 537℃, which is significantly higher than the ignition temperature of gasoline (390~420 ℃). Therefore, when natural gas is used in engines, it is easy to use the ignition method due to its higher ignition temperature, and not suitable for the compression ignition mode.

(5) Octane number. Octane number is proportional to the explosive resistance. The octane number of natural gas is about 120, which is higher than that of gasoline (90 ~ 98). So, it has good anti-explosive performance, and is suitable for higher compression ratios.

(6) Ignition limit. The volume concentration of natural gas ignited in air ranges from 5% to 15%, and the calculated excess air coefficient ranges from 0.6 to 1.8. Therefore, the lean burn of natural gas in an internal combustion engine can improve its economy.

A comparison of the physical and chemical properties of natural gas, gasoline and diesel is given in Table 1 [11].

Table 1 Comparison of physical and chemical properties of natural gas with gasoline and diesel

Fuel	Mass fraction	Density/(kg·m^{-3})		Theoretical air-fuel ratio	
		Gas phase	Liquid phase	Volume ratio	Quality ratio
Natural Gas	C:75 H:25	0.715	424	9.5	17.3
Gasoline	C:85 H:15	—	720-737	8586.0	14.7
Diesel	C:86	—	840	9417.0	14.0

Low calorific value (MJ·kg^{-1})	Octane Number (RON)	Cetane number (CN)	Fire limit (Volume) /%	Ignition temperature /℃	Flame propagation rate /(cm·s^{-1})
47.6	108	—	5.0 ~15.0	645	34 ~37
43.9	80 ~99	0 ~10	1.3 ~7.6	392 ~421	38 ~45
42.5	20 ~30	35 ~60	1.5 ~8.2	230	39 ~47

Combustion Methods and Characteristics of CNG in Internal Combustion Engines

With the continuous development and progress in the automotive field, compressed natural gas is more widely used in automobiles. According to the classification of CNG fuel supply method, the combustion method of CNG internal combustion engine can be divided into two types: premixed combustion type and non-homogeneous diffusion combustion type.

Pre-mixed Combustion Type

Hybrid Gas Formation Characteristics

In a premixed combustion internal combustion engine, natural gas is mixed with air at the intake pipe or valve and enters the cylinder on the engine intake stroke. Before spark ignition or fuel ignition, a more homogeneous combustible mixture has formed in the cylinder.

Combustion Characteristics

Since the mixture in the cylinder is relatively uniform, a stable nucleus is formed by spark ignition or fuel ignition, and the mixture is burned in the form of flame propagation with the nucleus as the center. Pre-mixed combustion type natural gas engines include spark ignition and diesel-natural gas dual-fuel engine [12]. Homogeneous mixture combustion (HCCI) is a new combustion method in natural gas diesel engines. During HCCI combustion, uniformly mixed air-fuel and residual exhaust gases are compressed and ignited without any obvious flame propagation process, and the overall combustion temperature is relatively uniform [13]. In addition, spark ignition type engines with lean combustion technology can increase the average effective pressure and reduce the combustion temperature and NO_x emissions [14-16]. However, at low load, it is easy for the mixture to be too lean, resulting in misfire or incomplete combustion and increased CO and HC emissions. During the combustion process of the pilot-ignition engine, the air-fuel mixture gradually becomes leaner as the load decreases. The mixture is too lean, resulting in incomplete combustion and a significant increase in HC and CO emissions, which is not suitable for medium and low load operation. Based on analysis of the combustion and emission performance of premixed combustion natural gas engines, it can be seen that the mixture is formed before spark ignition or ignition. Combustion relies mainly on flame propagation, so the mixture is relatively dense, reducing fuel economy. In addition, it also leads to greater volumetric efficiency loss of natural gas engines, reducing the output power. For example, the use of lower compression ratio to suppress deflagration will reduce the thermal efficiency of the engine at all operating conditions. Zhang *et al.* [17] improved the performance and emissions of the micro-premixed combustion mode which were compared with those in the hybrid restricted combustion mode. The results showed that the brake thermal efficiency could be improved by 1.1-3.6 % with the micro-premixed combustion mode at different loads.

Non-Homogeneous Diffusion Combustion Type

Hybrid Gas Formation Characteristics

Non-homogeneous diffusion-combustion natural gas engines use in-cylinder direct injection of natural gas as the fuel supply method. In a direct injection natural gas engine, due to the lower density of natural gas compared to diesel and gasoline, the natural gas jet is still lower even with a higher jet velocity during the injection process, and the mixing velocity with air is lower. Therefore, it is more necessary to organize in-cylinder airflow moves to promote the mixing of natural gas and air.

Combustion Characteristics

There are two types of direct injection natural gas engines: low pressure injection and high pressure injection, and the low pressure in-cylinder injection natural gas engine is still a premixed combustion type. Non-homogeneous diffusion combustion is similar to conventional diesel combustion, allowing the gas to be burned at the same time as the injection. This method does not require much premixed combustion, keeps the pressure rise rate stable, and helps reduce NO_x emissions and particulate matter emissions. Among the performance and emissions of six CNG combustion modes including homogeneous compression ignition and non-homogeneous diffusion combustion, Wang *et al.* [13] mentioned that the non-homogeneous diffusion combustion mode of diesel natural gas has good overall performance, reaching the thermal efficiency level of conventional diesel engines while reducing NO_x and CO emissions. Direct in-cylinder injection (DIC) [18] is a high-pressure injection of natural gas before the compression upper stop, ignited by a small amount of diesel or an electric plug, to achieve diffusion of the non-homogeneous mixture, thus solving the problem of premixed combustion in natural gas engines. Compared with intake tract injection, direct in-cylinder injection natural gas engines can avoid the loss of volumetric efficiency and reduce the possibility of unburned hydrocarbons and deflagration.

The Effect of CNG on the Performance of Internal Combustion Engines

Natural gas as a clean energy source has been studied for the performance of internal combustion engines mainly in terms of power, economy and emission. Many studies have been done by experts and scholars on natural gas as an alternative fuel for automotive engines. CNG is extremely vaporizable and can be quickly mixed with other work gases to form a homogeneous combustible mixture, resulting in a better combustion process and improved emission and thermal efficiency. Therefore, engines using CNG as fuel can have better power, economy and emission performance [19]. Verma *et al.* **Error! Reference source not found.** studied the effect of different EGR rates on the combustion and emission of a high-pressure direct injection (HPDI) engine by building a three-dimensional computational fluid dynamics (CFD) diesel/natural gas dual fuel injection model. Natural gas dual fuel injection model is used to study the effect of different EGR rates on the combustion and emission characteristics of high pressure direct injection (HPDI) engines. The results showed that the high-temperature region is mainly formed by the combustion of natural gas jets ignited by diesel fuel, and NO is mainly generated in the high-temperature region generated by the combustion of natural gas jets. The combustion of ignited diesel fuel contributes less to NO generation. Zheng *et al.* [22] investigated the combustion and emission characteristics and economics of a heavy-duty natural gas engine blended with different ratios of reformed gas by selecting a suitable catalytic oxidizer in a natural gas engine, and improved the performance of the natural gas engine by oxidizing the catalytic reforming system. In the literature [23], a comparison of the power and economy of natural gas internal combustion engines and gasoline engines is shown in Figures 1 and 2.

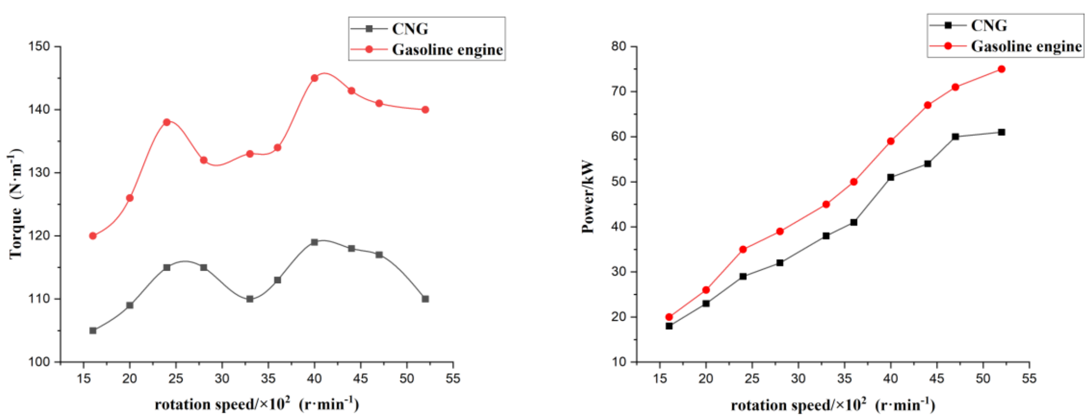
Dynamic Characteristics

Comparing the dynamics of the natural gas internal combustion engine with the gasoline engine (as shown in Figure 1), the CNG engine is lower than the gasoline engine in power and torque experimental data, and the torque gap is the largest at 5200 r/min, which is 21.93% lower than that of the gasoline engine. At this speed, the power gap is the largest, which is 19.37%. The CNG engine has an effective power loss. The causes of effective power loss include the following:

(1) Fuel flame propagation is slow. The main component of natural gas is methane, which has the slowest flame propagation speed when burned compared to conventional fuels such as gasoline and diesel. The characteristic of natural gas combustion is that the ignition temperature is high, which makes the total combustion cycle of the natural gas engine longer, and the peak gas pressure in the cylinder deviates from the top dead center, resulting in a slow rise in the pressure and temperature in the cylinder. Therefore, CNG engines require a larger ignition advance angle compared to gasoline [24]. Increasing the ignition advance angle results in a decrease in engine power. Theoretically, a unit mass of natural gas requires more air to burn than gasoline. For an engine with the same displacement, the combustion quality of natural gas is lower than that of gasoline, resulting in lower natural gas engine power. Mixing flammable and explosive hydrogen and natural gas can speed up the combustion.

(2) Volumetric efficiency loss. The density of CNG in the gas phase is lower than that of air, and relatively less air enters the cylinder during the intake process. Whereas in a gasoline engine, gasoline does not reduce the amount of air entering the cylinders. Therefore, the output power of the gasoline engine will be better than that of the CNG engine during the combustion process. To improve the power performance of the engine, the volumetric efficiency of the CNG engine can be improved using increasing the number of intake valves per cylinder, increasing valve timing and lift optimization, and using a supercharged CNG engine.

In order to improve the power performance of natural gas engines, different percentages of reformed gas could be blended [22], and the combustion characteristics of natural gas engines showed that the peak in-cylinder pressure and the cyclic variation of IMEP (The Indicates Mean Effective Pressure) were significantly reduced and the engine ran more smoothly.



(a)Torque (b)Tower

Figure 1. Comparison of CNG internal combustion engine and gasoline engine dynamics

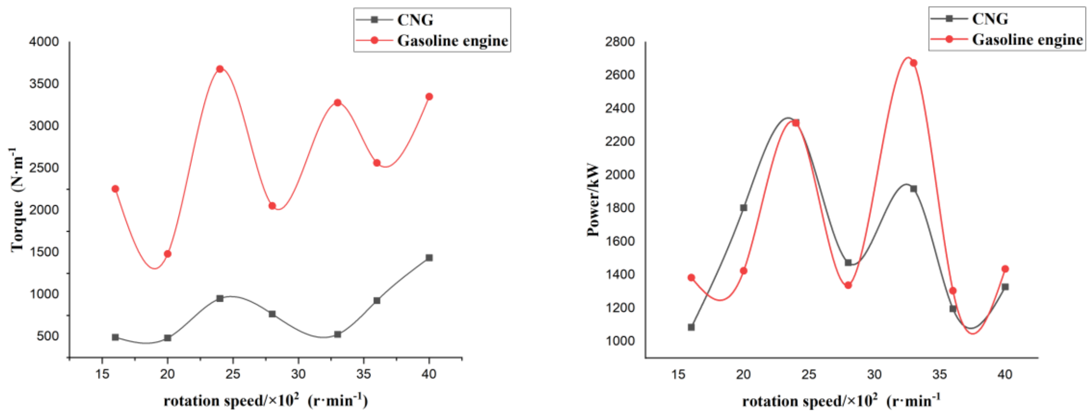
Economic Characteristics

Economy is mainly expressed through the fuel consumption rate, where higher effective fuel consumption rate represents better economy of internal combustion engines. Due to the higher low calorific value of CNG, less fuel is consumed at the same power output compared to gasoline engines. The effective fuel consumption rate with CNG fuel is 12% to 20%, which is lower than gasoline over the entire speed range. However, for CNG/diesel engines, the fuel consumption rate is lower at medium and high loads, and the fuel consumption rate is higher at low loads. And because the combustion efficiency is low, the thermal efficiency at low load is also low. To meet its economy, the combustion rate of gas should be increased to reduce fuel consumption. Due to the low effective fuel consumption rate and high CNG calorific value, the effective thermal efficiency of natural gas engines is 5-12% higher than that of gasoline engines. CNG/diesel dual-fuel engines are more suitable for working under medium and high loads, and have higher thermal efficiency and lower fuel consumption rates under medium and high loads [25].

Emission Characteristics

The emission performance of the engine is mainly analyzed through the control of CO, HC, NOx and solid particulate matter By comparing the emissions from burning CNG and burning gasoline (as shown in Figure 2), it can be concluded that NO_x emissions from CNG and gasoline have the same trend, and NO_x emissions from CNG are lower than those of gasoline at all RPMs. The NO_x emission reduction at 1600r/min is the largest, which is 81.66%. For CO emissions, the CO emissions trends for both fuels are also consistent, except for 2000 r/min and 2800 r/min. The CO emissions of the CNG engine at all speeds are lower than those of the gasoline engine, with a maximum decrease of 26.67% at 3200r/min.

CNG engines have the highest hydrogen-to-carbon ratio. Hydrogen-rich natural gas (HCNG) is an emerging alternative gas fuel, which has a higher low calorific value and relatively slow flame propagation compared to gasoline, resulting in a lower maximum temperature of its combustion chamber than ordinary gasoline engines. The main factors affecting NO_x emissions of a CNG engine are oxygen content, combustion temperature, etc. The longer the reaction time and the higher the temperature under adequate oxygen content, the higher the NO_x emissions. The overall NO_x emissions increase with the increase of the speed, because the increase in speed leads to an increase in the combustion rate and combustion temperature, which is favorable to NO_x production. The lower temperature is beneficial to reducing NOx generation, and CO generation is mainly due to the incomplete combustion of hydrocarbons caused by local oxygen deficiency, whose main influencing factor is the mixture concentration. At medium and high speeds, the stagnation period is long and the charge factor is low, so the combustion is inadequate and intensifies the generation of CO. In terms of improving emission characteristics, Sabri Kül and Orhan [27] added CNG to diesel fuel. Compared to pure diesel fuel, the CNG blends at 500, 1250 and 2000 g/h at 100 N-m load reduced NO_x emissions by 40.5, 59.4 and 68.2% (on average) and CO emissions by 8.8, 16.7 and 22.5% (average). Natural gas mixes more evenly with air in the same gas phase, so it burns more fully and therefore emits fewer emissions than gasoline.



(a)Torque (b)Tower

Figure 2. Emission comparison of CNG internal combustion engine and gasoline engine

CONCLUSIONS

Natural gas emits less pollutants than gasoline and is promising to solve the current serious environmental pollution problems. The following conclusions were drawn by the literature survey of the effects of combustion and emission characteristics of natural gas internal combustion engines：

(1) The power performance of natural gas engines is relatively low due to the low calorific value of the CNG combustible mixture, high ignition temperature and slow flame propagation speed. Increasing the ignition energy, at the same time properly increasing the ignition advance angle or using intake boost can improve its power performance.

(2) Compared with gasoline engines, CNG engines consume less fuel at the same power output, and injecting fuel at the optimal injection advance angle can improve the economic performance of the engine.

(3) Compared with gasoline fuel, the power performance of the engine is worse when CNG is used as fuel, the maximum difference of torque and power reaches 21.9% and 19.8%, respectively. But the emission is less, the results show that the emission of NO_x is reduced by up to 81.66% and the emission of CO is reduced by up to 26.67%.

Therefore, improving the power of natural gas internal combustion engines on the basis of ensuring their emissivity is the main content of current research in this field.

CONFLICTS OF INTEREST

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

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