Current Status of Research on Methanol as an Alternative Fuel to Conventional Fuels

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With the rapid development of China's economy and society, the domestic demand for automobiles is growing explosively. At the same time, the dependence of China's crude oil on foreign countries exceeds 65%. This is a great hidden danger to the sustainable development of China's economy and energy security. Automobile consumes a large amount of petroleum resources, and automobile exhaust is one of the main factors causing environmental pollution. In view of the dual pressure of energy saving and emission reduction, methanol has been favored by many researchers for its many advantages (such as cleanliness, environmental protection, renewable and high accessibility). In this paper, the resource extensibility of methanol, the physicochemical properties of methanol, the application characteristics of methanol in internal combustion engine and the comparison of the combustion performance of methanol with traditional fuels are summarized and analyzed.

Keywords: Energy crisis; Environmental pollution; Methanol; Combustion characteristic

Introduction

With the rapid development of China's economy, automobiles and engineering and transportation vehicles become explosive growth, which will bring energy crisis and environmental pollution and other problems [1-2]. According to the analysis of data released by “World Energy Statistical Yearbook 2022”, China's oil production will be equal to China's oil consumption in 2022. From Figure 1, it can be seen that China's oil production has not changed much, but its oil consumption has been rising [3]. Along with the growth of chemical energy consumption, the problem of environmental pollution has become more and more serious, according to the data from the Annual Report on Environmental Management of Mobile Sources in China in 2021, in 2020, the national emissions of carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NO_x), and particulate matter (PM) from automobiles are 6.938 million tons, 1.724 million tons, 6.137 million tons, and 6.4 million tons, respectively. It can be seen from Fig. 1 that diesel vehicles emit more than 80% of the total vehicle emissions of nitrogen oxides (NO_x) and more than 90% of the particulate matter (PM), while gasoline vehicles emit more than 80% of the total vehicle emissions of carbon monoxide (CO) and more than 70% of the hydrocarbons (HC) [4].

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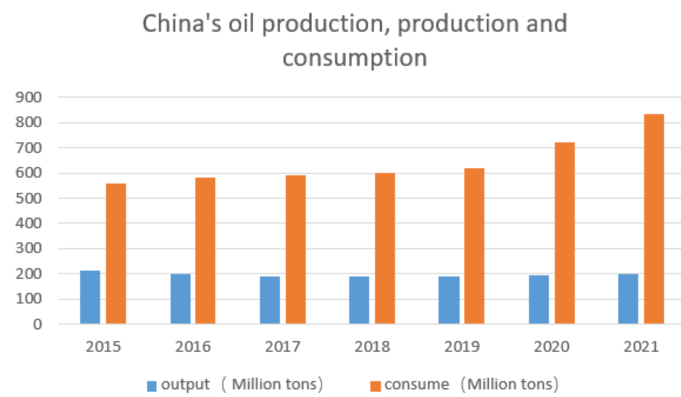

Fig. 1. China's oil production versus consumption [3]

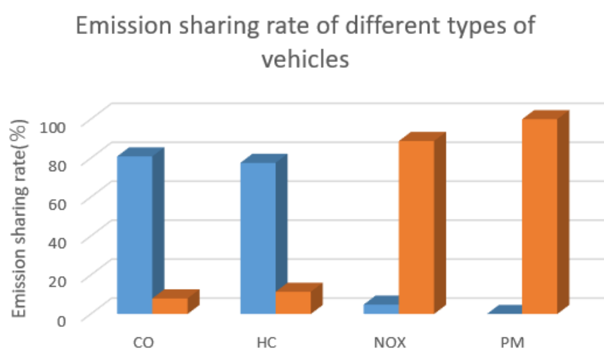

Fig. 2. Pollutant emission share of vehicles by fuel types [3]

In order to solve the problems of fossil energy shortage and environmental pollution, the search for clean and renewable energy has become an urgent need. Methanol, as one of many alternative fuels, has attracted a lot of attention in recent years by virtue of its wide source and versatility. Methanol has distinctive characteristics compared to traditional fossil fuels [5-6]. For example, it has high octane number and good anti-detonation property, which can increase the engine compression ratio to improve engine performance and reduce fuel consumption. It has high latent heat of vaporization and lower combustion temperature in the engine, which helps to reduce heat loss and NO_x emission [7-8]. However, the low cetane number of methanol makes it difficult for direct compression ignition in compression-ignition engines, and other auxiliary means are needed to help its ignition and combustion [9]. The high lower ignition concentration limit, low vapor pressure, and high latent heat of vaporization of methanol all make cold starting of methanol-fueled engines difficult and prone to formaldehyde and unburned methanol emissions. Although there are still many problems to be solved in burning methanol in internal combustion engines, methanol is still considered as one of the most promising alternative fuels [10-12].

Sources and Physicochemical Properties of Methanol

Sources of Methanol

Methanol feedstock comes from a wide range of sources and mature production processes, which is mainly through coal chemical and natural gas synthesis. The main sources include coal, natural gas, coal bed methane, and biomass [13]. Most of the coal used for methanol production in China is poor quality coal with high sulfur content, which has low production cost. Meanwhile, it can be desulfurized during the production process, which is conducive to environmental protection, and can also yield by-products such as sulfur and urea [14].

Physical and Chemical Properties of Methanol

Table 1 shows a comparison of some physical parameters of methanol with gasoline and diesel. It can be found that the latent heat of vaporization of methanol is four times higher than that of gasoline and diesel, and the evaporation process will absorb more heat and lower the average temperature in the cylinder. Methanol has a high auto-ignition temperature, so it is difficult to directly compress and ignite, and auxiliary means are needed to help methanol ignite. Methanol has a small molecular weight, a simple chemical structure, a low carbon to hydrogen ratio, and contains its own oxygen, so it is easier to burn completely, which helps to reduce CO and HC emissions. It is theoretically possible to burn methanol in diesel engines without generating carbon smoke [15-18].

Table 1. Comparison of the main property parameters of methanol with gasoline and diesel

Nature/Unit	Methanol	Petrol	Diesel
Chemical formula	CH_3OH	C16~C23	C16~C23
Freezing point (°C)	-96	-57	-1~-4
Boiling point (°C)	64.7	27~225	180~370
Flash point (°C)	12	45	75
Natural temperature (°C)	500	350~468	270~350
Latent heat of vaporization (kg/kJ)	1167	310	270
Low calorific value (kJ/kg)	19930	43030	42500
Octane number (MON)	94.6	81~84	-
Cetane number	3	0~10	45~55
Theoretical mass to air-fuel ratio	6.5	14.8	14.6

From Table 1, it is known that methanol as an alternative fuel for internal combustion engines has the following main characteristics.

(1) Compared with gasoline and diesel, methanol has a lower freezing point and can be used in lower climates.

(2) The high latent heat of vaporization of methanol, the lower vapor pressure and boiling point will make the cold start of the engine difficult. On the other hand, it will also lower the intake temperature and increase the charge factor of the engine [19].

(3) The oxygen content and ignition limit of methanol are higher, and the dilute combustion characteristics are better, so that the engine has a larger working condition coverage. Especially in gasoline engines, it will reduce the chance of misfire due to imprecise control of air-fuel ratio causing too lean combustible mixture. The laminar flame speed of methanol is faster, and the combustion rate in engines is higher than that of gasoline, which can improve the isotonicity of in-cylinder combustion [20].

(4) Methanol has a higher octane number and can be used as an additive and alternative fuel to increase the octane number of gasoline. The cetane number of methanol is much less than that of diesel, while the natural temperature is higher than that of diesel, making its compression ignition difficult. Therefore, to use methanol in

compression ignition engines, the spontaneous ignition performance of methanol needs to be improved or ignited by spark plugs, electric plugs, and by spraying in diesel fuel [21].

(5) Methanol is an oxygenated fuel with an oxygen content of up to 50%, and the self-oxygenation effect of the fuel facilitates fuller fuel combustion, high combustion efficiency, and no carbon soot generation, as well as reduced HC and CO emissions [22].

Combustion Characteristics of Methanol Internal Combustion Engines

Application of Methanol in Ignition Internal Combustion Engines

The application of methanol in ignition internal combustion engines can be divided into methanol-gasoline blended combustion, pure methanol combustion, and indirect utilization of methanol. By indirect utilization, it means that methanol is not directly allowed to be burned as a fuel in the engine, but the combustible gases (such as H_2 and CO), which are generated through the reforming cracking reaction of methanol, are fed into the cylinder for combustion [23].

Methanol Gasoline Blending and Combustion

Ling *et al.* [24] from Zhejiang University investigated the emission characteristics of methanol gasoline in an MR479q engine. Bench tests showed that adding methanol to gasoline reduced conventional emissions (such as NO_x, CO, and unburned HC), but unconventional emissions (such as formaldehyde and unburned methanol) increased significantly. When the proportion of methanol in the fuel was 70%, NO_x was reduced by 29%~54%, CO by 66%~71% and unburned HC by 71%~80% compared with gasoline engines. In terms of emission generation mechanism, the 3D simulation results show that HC, aromatic hydrocarbons and unburned methanol are mainly generated by factors such as in-cylinder gap effect and carbon accumulation, while CO and formaldehyde are mainly generated by complex chemical reaction processes. With the increase of compression ratio, CO emission decreases and NO_x emission increases.

Wang *et al.* [25] from the State Key Laboratory of Internal Combustion Engine, Tianjin University, investigated the emission characteristics of methanol engine based on an electronically controlled M85 methanol engine. The conventional and non-conventional emissions were investigated by exhaust gas analyzer and gas chromatograph, respectively. The test results showed that M85 methanol fuel can significantly reduce the conventional emissions, while the non-conventional emissions contain almost no methanol but high formaldehyde content, which is due to the fact that the three-way catalytic converter does not easily convert formaldehyde and the higher the load, the lower the purification efficiency, while the purification efficiency for methanol is almost 100%.

Wu *et al.* [26] conducted a bench test study on the engine performance of M10, M15, M50 methanol gasoline and 93# gasoline and found that compared to 93# gasoline, the power change of burning M10, M15 and M50 increased by -2%~6.25%, -2%~9.38% and 2%~12.5%, respectively, which shows that in terms of power performance, methanol gasoline fuel has little change compared to 93 # gasoline. As the methanol ratio increases, the power improvement changes, but in terms of overall operating conditions, the power improvement is not significant. Compared to 93# gasoline fuel consumption rate, M10, M15, and M50 converted to equivalent fuel consumption rate increased by 1.52%, 0.37%, and 15%, respectively. This shows that the change in fuel economy of methanol gasoline is not very obvious. The changes in HC emissions for all four fuels decreased with increasing speed. Among the three types of methanol gasoline, HC emissions decreased gradually with the increase of methanol proportion, and the highest decrease was 80%. CO emissions were significantly reduced compared with 93# gasoline, and CO emissions also decreased gradually with the increase of methanol content, and the highest decrease was 77.78%. With the increase of methanol blending ratio, the NO_X emission becomes lower and lower, with the highest reduction of 69.23%.

From the above studies, it can be concluded that methanol and gasoline have similar physicochemical properties, and methanol gasoline with low methanol ratio can be used directly in gasoline engines, while methanol gasoline with high ratio can also be used in ignition engines with simple adjustments. The improvement in economy and power over conventional fuels is small, but the emission characteristics are greatly improved, while the inherent characteristics of methanol fuels can cause cold start difficulties and unconventional pollutant emissions.

Pure Methanol Combustion

Zhu *et al.* [27] used a model of turbocharged inline 4-cylinder gasoline engine as a prototype to study the effect of methanol combustion on engine performance and emissions. Compared to gasoline combustion, the engine showed a significant improvement in power after switching to methanol, with a maximum increase of 5.22%. From the test results, the equivalent fuel consumption rate can be reduced by 10.53~ 18.52 % when switching to methanol burning, compared to the original engine burning gasoline at low to medium speed. At low and medium loads, CO emissions do not change much. But when at high loads, burning methanol can significantly reduce CO emission. CO is reduced by 29.6% at the highest load when compared to the original engine when burning methanol. At the average effective pressure of 0.4 MPa, 0.8 MPa and maximum load, HC emissions were 90.5%, 84.2% and 37.4% lower with methanol than with gasoline, respectively. Since the latent heat of vaporization of methanol is much higher than that of gasoline, this greatly reduces the mixture temperature and thus the maximum combustion temperature. Also, because methanol burns faster than gasoline, the high temperature reaction time is shortened, and the combined effect of these two conditions results in lower NO_X emissions. The test results showed that the NO_X in the exhaust gas was reduced by 95.6%, 16.4% and 14.8% when methanol was burned compared with gasoline at the average effective pressure of 0.2 MPa, 1.2 MPa and maximum load, respectively.

Wang *et al.* [28] from Jiangsu University conducted an experimental study on a four-cylinder EFI gasoline engine with a displacement of 2.0 L using pure methanol as fuel. The results showed that the maximum torque of the methanol engine was lower than that of the gasoline engine when the speed was below 2500 r/min, and higher than that of the original engine when the speed exceeded 2500 r/min. The equivalent fuel consumption was reduced by up to about 10% compared with the original engine. If the compression ratio increased from 10 to 11.5, the maximum torque of the engine increased by 3.4%~6.3%, and the equivalent fuel consumption of the methanol engine decreased by 2%~5%. For the problem of cold starting of the methanol engine, three additives, gasoline, isopentane and petroleum ether were added to the methanol fuel. When the ambient temperature was -20℃, the engine could be started smoothly within 4 s with these three additives.

From the above research analysis, it is concluded that burning pure methanol fuel is easier to achieve with less modification to the traditional internal combustion engine, and it can significantly improve the power of the engine in terms of combustion characteristics, improve the fuel economy of the engine under low load, and significantly improve the emission characteristics of the engine under high load.

Indirect Utilization of Methanol

Yao *et al.* [29] evaluated the impact of methanol cracked gas application technology on an ignition engine by studying the application of methanol cracked gas in a 477F engine. When methanol cracked gas was burned, the engine dynamics decreased, although it still remained above 95% of its original engine. The power performance of the methanol cracker engine with a palladium-based catalyst was better than that of the methanol cracker gas engine with a copper-based catalyst. Compared with the gasoline fuel consumption rate, the methanol-equivalent fuel consumption rate produced with the copper-based catalyst decreased by 22% to 26%. The methanol cracking gas-equivalent fuel consumption rate produced with the palladium-based catalyst decreased by 24% to 31%. Overall, the economic advantage of burning methanol cracked gas over gasoline is greater.

The HC emissions from the combustion of methanol cracked gas produced with copper-based and palladium-based catalysts, respectively, were relatively similar and consistent for the engine application, but the emissions were about 90% lower compared to gasoline combustion. The CO emissions from the combustion of methanol cracked gas with copper-based and palladium-based catalysts, respectively, are very similar, but the CO emissions from methanol cracked gas engines are reduced by about 90% compared to gasoline. Similarly, the NO_X emission patterns from methanol cracked gas combustion with the two different catalyst types are very similar and the NO_X emissions are relatively similar, but with significant reductions of up to 80% compared to virgin gasoline. From this study, it is concluded that methanol cracked gas as an engine fuel can effectively improve engine fuel economy and reduce HC, CO and NO_X emissions.

Application of Methanol in Compression-Ignition Internal Combustion Engines

The application of methanol in compression-ignition engines is more difficult than in ignition engines because of the large difference between the properties of methanol and diesel fuel. However, the diesel engine has the advantages of high thermal efficiency and high power compared to the ignition engine, so the research on methanol as its alternative fuel is also more valuable. Since it is difficult to achieve direct compression ignition of methanol, the application of methanol in compression-ignition internal combustion engines is concentrated on diesel ignition, diesel-methanol blended combustion and electric heating plug combustion methods.

Diesel Ignition

Fang et al. [30] from Jilin University conducted an experimental study on the performance and emissions of direct injection compression-ignition engines with dual injection system when burning diesel methanol, and found that the methanol engine showed a maximum decrease in smoke of up to 66% and a decrease in NO_x emissions of about 60%-70% compared to the original diesel engine, but CO and HC emissions increased more.

Shi *et al.* [31] conducted methanol injection tests in diesel engines in the intake tract. At low load conditions, injection of methanol reduced the dynamics by a maximum of 5%, which was due to the decrease in cylinder temperature caused by its high latent heat of vaporization. As the load increases, the engine dynamics increases when methanol is injected into the intake tract, and the maximum increase is 2.9%. However, as the amount of methanol injected increases, *i.e.*, as the percentage of total fuel increases, the power tends to increase and then decrease.

Zhang *et al.* [32] converted a supercharged intercooled engine into a diesel pilot-fired methanol dual-fuel engine by adding a methanol supply system for a bench test study. With the increase of methanol blending ratio, the HC emission of the dual-fuel engine also increased significantly, with a maximum increase of 2000%. At a certain blending ratio, HC emissions decreased as the load increased. The CO emissions of the dual-fuel engine increased significantly. The CO emissions of the dual-fuel engine increased continuously with the increase of methanol blending ratio. At the same blending ratio, the CO emission of dual-fuel engine tends to decrease with the increase of load. With the increase of methanol blending ratio, the NO_X emission of dual-fuel engine combustion decreases. For a certain blending ratio, the higher the load ratio, the more NO_X emissions. With the increasing of methanol blending ratio, the dual-fuel carbon soot emission decreases.

From the above study, the analysis concluded that the diesel priming method can reduce the smoke but the concentration of some pollutant emissions is high, and the existing diesel engine on the transformation is difficult and costly, it is difficult to implement the promotion.

Diesel-Methanol Blending and Combustion

Rao *et al.* [33] burned microemulsified methanol diesel in a D1110 diesel engine and found no significant difference in power and fuel consumption rate for burning pure diesel without making parameter adjustments to the engine, and NO_x, CO and carbon soot emissions were significantly reduced.

Soni *et al.* [34-35] investigated the effects of methanol blending ratio, swirl ratio, exhaust gas recirculation method and water blending method on emissions by numerical simulations and found that when the percentage of methanol in diesel fuel was increased from 10% to 30%. NO, CO and HC emissions were significantly reduced by 65%, 68% and 56%, respectively, and also indicating that blending the right amount of water in the fuel was beneficial to reduce NO, carbon soot, CO and HC emissions.

Duan *et al.* [36] showed that burning M15 increased the output power by 1.82%~7.14% compared to burning 0# diesel, but burning M30 decreased the power by burning M15 and M30, respectively. Compared to burning 0# diesel, burning M15 resulted in a 3.85% to 9.36% reduction in equivalent fuel consumption rate, and burning M30 resulted in a 5.14% to 15.26% reduction in equivalent fuel consumption rate. This shows that burning methanol blended fuel can significantly improve the economy. Compared with burning 0# diesel, when burning M15 and M30, CO emissions are reduced by 44.74~50 % and 50~68.97 %, HC emissions are reduced by 40.48~48.89 % and 48.89~70.59 %, respectively; NO_X emissions are reduced by 10.71%~33.33% and 25~35.71 %, respectively; and particulate matter emissions with smokiness were reduced by 57.14% and 64.29%, respectively.

From the above research analysis, it is concluded that methanol and diesel blending forms are methanol diesel and emulsified diesel, and both blended fuels are made of diesel, methanol, and additives in a certain ratio through a strict process of blending. Compression-ignition internal combustion engines using diesel-methanol blending combustion method can significantly improve the engine economy and can significantly improve the emission characteristics of internal combustion engines, but if we want to obtain the best power, there is an optimal methanol blending ratio.

Electric Heating Plug to Help Ignite

Electric thermal plugs can effectively improve the cold startability of the engine. Li *et al.* [37] investigated the reasons for successful diesel fuel ignition when the electric thermal plugs assisted combustion through an experimental study of a single-cylinder diesel engine with a compression ratio of 15.5 and a static combustion bomb, and concluded that the electric thermal plugs ignite the diesel fuel by increasing the local temperature to above 413°C.

Yang *et al.* [38] investigated the combustion characteristics of pure methanol combustion by direct injection compression ignition on a two-cylinder diesel engine. According to the characteristics of high latent heat of vaporization and high auto-ignition temperature of methanol fuel, measures such as increasing compression ratio and intake heating were adopted to successfully obtain stable operation of pure methanol in direct injection compression-ignition mode, and it can effectively reduce NO_x emission of diesel engine with fuel economy comparable to that of the original engine.

Wang *et al.* [39] studied a diesel engine burning pure methanol fuel by adding electric heating plugs, increasing the compression ratio and injection pump diameter to a 1115 single-cylinder diesel engine. They found that the power and economy of the methanol engine were better than the original diesel engine after the test. The NO_x emissions were reduced by 45% on average, and the HC and CO emissions were reduced by 70% on average at high loads, but higher than the original engine at low and medium loads.

From the above research and analysis, it is concluded that the electric heating plug combustion method can effectively improve the cold starting performance of internal combustion engines and effectively reduce the emission of NO_x, HC, CO and other pollutants at high load. But at low and medium loads, its emission performance is worse than that of the original engine.

Summary and Outlook

This paper reviews many technical means of methanol fuel combustion for internal combustion engines, analyzes its performance and emission characteristics, points out the difficulties and development prospects in the application process, and provides ideas and methods for the research field of methanol as an alternative fuel for internal combustion engines, taking into account the current situation of domestic and foreign research. The results show that the power, fuel economy and emission characteristics of internal combustion engines can be improved after using methanol.

For ignition internal combustion engines, the power of methanol can be maintained at more than 95% of the original engine, and the engine power can be improved under certain operating conditions. In terms of economy, when methanol blending technology is used, the improvement of economy is more obvious as the proportion of methanol increases, and the economy decreases when the proportion is smaller; when methanol cracking technology is used, the equivalent fuel consumption rate is reduced the most and the economy is the best. Especially from the emission performance, the emission of CO, HC and CO_2 can be significantly reduced.

For compression-ignition internal combustion engines, the use of methanol has a negative impact on diesel engine dynamics at low load conditions, while the combustion of methanol can improve dynamics as the load increases. From the economics point of view, all the technologies can improve the economy in general, except for the use of electric plug combustion, which can lead to higher equivalent fuel consumption rate under certain conditions. In terms of emission characteristics, both Soot and NOx emissions are significantly improved by burning methanol. The use of electric plug combustion and diesel ignition method will make HC and CO emissions worse, but will improve NO_x and carbon soot emissions, and the electric plug combustion method will improve NO_x and carbon soot more significantly, while the use of emulsification method can reduce HC, CO, carbon soot and NO_x emissions. Therefore, overall, the use of emulsification of methanol is the best technology for the application.

In summary, there are some problems in the current stage of methanol combustion in internal combustion engines, including poor cold start, high emission of non-conventional pollutants such as formaldehyde and methanol under low load, and poor fuel economy and power under some working conditions. In view of the various problems faced by the current methanol-fired technology for internal combustion engines, it is very beneficial to carry out the following researches to further improve the existing methanol-fired technology for internal combustion engines and promote the practical application of methanol in internal combustion engines:

(1) Mechanisms of emission generation and control methods. In addition to conventional pollutants, the study of non-conventional pollutant emissions such as formaldehyde and unburned methanol is also very important. To solve the emission problem of internal combustion engine when burning methanol, especially to make the high pollutant emission problem during cold start or low load operation.

(2) Research on the reaction mechanism of methanol, including research on the combustion mechanism of methanol mixed with other fuels and pure methanol combustion. To clarify the characteristics of methanol combustion to help solve the problems of difficult cold start and unstable ignition when internal combustion engines are burning methanol.

(3) The research of methanol additives, by adding additives to change the combustion characteristics and physical properties of methanol, reduce the difficulty of burning methanol in internal combustion engines, and improve the applicability of methanol alternative fuels.

CONFLICTS OF INTEREST

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

REFERENCES

[1] Singh, A. P., Sharma, N., Kumar, V., and Agarwal, A. K. (2021). Experimental investigations of mineral diesel/methanol-fueled reactivity controlled compression ignition engine operated at variable engine loads and premixed ratios. 22(7), 2375-2389. DOI: 10.1177/1468087420923451

[2] Singh, A. P., and Agarwal, A. K. (2021). Introduction to Novel Internal Combustion Engine Technologies for Performance Improvement and Emission Reduction. In: *Novel Internal Combustion Engine Technologies for Performance Improvement and Emission Reduction*, A. P. Singh, and A. K. Agarwal, eds., Springer Singapore, Singapore, pp: 3-6. DOI: 10.1007/978-981-16-1582-5_1

[3] Li, H., Zhang, J., Chen, J., Chen, W., Zhao, Y., Lin, M., Li, L., Zhang, X., and Dai, X. Global energy transition faces challenges in 2021 -Based on the bp Statistical Yearbook of World Energy (2022). *Natural Gas and Oil*, http://kns.cnki.net/kcms/detail/51.1183.TE.20221013.1732.002.html (accessed on 11/26/2022).

[4] Ministry of Ecology and Environment of the PRC. (2021). China Mobile Source Environmental Management Annual Report. Web: http://www.gov.cn/xinwen/2021-09/11/5636764/files/3ac6b9802f8b47fc8200403308a0d25d.pdf (accessed on 11/26/2022)

[5] Kovács, M., Papp, M., Zsély, I. G., and Turányi, T. (2021). Main sources of uncertainty in recent methanol/NOx combustion models. 53(7), 884-900. DOI: https://doi.org/10.1002/kin.21490

[6] Dierickx, J., Verbiest, J., Janvier, T., Peeters, J., Sileghem, L., and Verhelst, S. (2021). Retrofitting a high-speed marine engine to dual-fuel methanol-diesel operation: A comparison of multiple and single point methanol port injection. *Fuel Communications*, 7, 100010. DOI: https://doi.org/10.1016/j.jfueco.2021.100010.

[7] Chen, H., He, J., Chen, Z., and Geng, L. (2021). A comparative study of combustion and emission characteristics of dual-fuel engine fueled with diesel/methanol and diesel–polyoxymethylene dimethyl ether blend/methanol. *Process Safety and Environmental Protection*, 147, 714-722. DOI: https://doi.org/10.1016/j.psep.2021.01.007

[8] Kalwar, A., Singh, A. P., and Agarwal, A. K. (2020). Utilization of primary alcohols in dual-fuel injection mode in a gasoline direct injection engine. *Fuel*, 276, 118068. DOI: https://doi.org/10.1016/j.fuel.2020.118068

[9] Chen, Z., Chen, H., Wang, L., Geng, L., and Zeng, K. (2020). Parametric study on effects of excess air/fuel ratio, spark timing, and methanol injection timing on combustion characteristics and performance of natural gas/methanol dual-fuel engine at low loads. *Energy Conversion and Management*, 210, 112742. DOI: https://doi.org/10.1016/j.enconman.2020.112742

[10] Zhang, M., Hong, W., Xie, F., Liu, Y., Su, Y., Li, X., Liu, H., Fang, K., and Zhu, X. (2019). Effects of diluents on cycle-by-cycle variations in a spark ignition engine fueled with methanol. *Energy*, 182, 1132-1140. DOI: https://doi.org/10.1016/j.energy.2019.06.110

[11] Shao, Y., Sun, Q., Li, A., He, Z., Xu, Z., Qian, Y., Lu, X., Huang, Z., and Zhu, L. (2019). Effects of natural gas, ethanol, and methanol enrichment on the

performance of in-cylinder thermochemical fuel reforming (TFR) spark-ignition natural gas engine. *Applied Thermal Engineering*, 159, 113913. DOI: https://doi.org/10.1016/j.applthermaleng.2019.113913

[12] Sharma, N., Patel, C., Tiwari, N., and Agarwal, A. K. (2019). Experimental investigations of noise and vibration characteristics of gasoline-methanol blend fuelled gasoline direct injection engine and their relationship with combustion characteristics. *Applied Thermal Engineering*, 158, 113754. DOI: https://doi.org/10.1016/j.applthermaleng.2019.113754

[13] Chen, Z., Wang, L., and Zeng, K. (2019). A comparative study on the combustion and emissions of dual-fuel engine fueled with natural gas/methanol, natural gas/ethanol, and natural gas/n-butanol. *Energy Conversion and Management*, 192, 11-19. DOI: https://doi.org/10.1016/j.enconman.2019.04.011

[14] Prayogi, Y., Syaiful, and Sinaga, N. (2019). Performance and exhaust gas emission of gasoline engine fueled by gasoline, acetone and wet methanol blends. *IOP Conference Series: Materials Science and Engineering*, 535(1), 012013. DOI: 10.1088/1757-899X/535/1/012013

[15] Song Y. (2019).Experimental study on the effect of alcohol injection moment on the combustion and emission characteristics of methanol/diesel dual-fuel engine. Chang'an University, Thesis.

[16] Lian, R., Zhu, W., Xiao, C., Hu, Z., Pan, L. (2019) Research on promotion and value of DMCC heavy-duty trucks. *Automobile Applied Technology*, 2019(03), 10-12.

[17] Wu S. (2019). Prospect of military methanol vehicle application[J]. Development & Innovation of Machinery & Electrical Products, 32(01), 49-51.

[18] Hussein, M. R. A., Hassoon, M. A. S., and Al-Abbas, D. A. H. (2018). Experimental Study into Combustion Characteristics of IC Engines Operated with Blended Fuels. *IOP Conference Series: Materials Science and Engineering*, 433(1), 012053. DOI: 10.1088/1757-899X/433/1/012053

[19] Gupta, A., and Mishra, P. C. (2018). Emission and friction analysis of IC engine running in methanol blend. *Tribology in Industry*, *40*(1), 10.

[20] Yuan, Q. (2017). Effect of ignition moment on methanol engine combustion. *Technology Innovation and Application*, 2017(22), 181-182.

[21] Huang C.F., Hao C.X., Wang J.F., and Xie Q. (2017). Analysis of pollutant emissions from motor vehicles--Part II of the Annual Report on Environmental Management of Motor Vehicles in China. *Environmental Protection*, 45(13), 42-47.

[22] HAN, S. B., and PARK, J. Y. (2016). Performance and Emission Characteristics of Ethanol and Methanol Gasoline Blended Fuels in a Spark Ignition Engine. *Transactions of the Korean Hydrogen and New Energy Society*, *27*(4), 441-446. DOI: https://doi.org/10.7316/khnes.2016.27.4.441

[23] Kamil, M., and Nazzal, I. T. (2016). Performance evaluation of spark ignited engine fueled with gasoline-ethanol-methanol blends. *Journal of Energy and Power Engineering*, *10*(6), 343-351. DOI: 10.17265/1934-8975/2016.06.002

[24] Li, C. (2016). *Design and development of low emission methanol-diesel dual fuel intelligent combustion system*. Tianjin University, Thesis.

[25] Ling, X.C. (2015). *Simulation and experimental study of emission generation mechanism of engine burning methanol-gasoline fuel mixture*. Zhejiang University, Thesis.

[26] Wu, Z., Wang, Y., and Hou, G. (2014). Experimental study on the performance of different proportation methanol gasoline mixed burning. *Journal of Changchun Institute of Technology(Natural Sciences Edition)*, 15(02), 69-72.
[27] Zhu, J. (2017). *Comparative study on the performance of engine fueled gasoline and methanol*. Huazhong University of Science and Technology, Thesis.
[28] Wang, Y. (2016). *Experimental study on the combustion of M100 methanol in electronically controlled gasoline engine*. Jiangsu University,2016, Thesis.
[29] Yao, C., Li, X.C., Tang, C., Zang, R., and Wu, Y. (2013). Combustion Characteristic of Methanol Dissociated Gas Engine Through Cu/Pd-Based Catalysts. *Transactions of CSICE*, 30(6), 486-491.
[30] Fang, X., Liu, X., Jin, W., and Yan, S. (2003). A Study on a DI Compression Ignition Engine with Diesel-Methanol Injection by Dual Injection Systems. *Transactions of CSICE*, 21(6), 411-414. DOI:10.16236/j.cnki.nrjxb.2003.06.005.
[31] Shi, W., Wang, T., Liao, W., Wang, D., Wang, H., and Deng, Y. (2012). Effect of methanol injection at intake port on turbocharged and intercooled diesel engines. *Vehicle Engine*, 2012(06), 46-50.
[32] Li, G., Zhang, C., and Li, Y. (2017) Combustion cycle variation of electronically controlled common rail diesel engine fueled with methanol-diesel dual fuel. *Journal of Chang'an University (Natural Science Edition)*, 37(02), 107-114. DOI:10.19721/j.cnki.1671-8879.2017.02.013.
[33] Rao, H., Wang, T., Wang, K., and Zhu, J. (2008). Experimental Research on Methanol-diesel Micro-emulsified Fuel in DI Engine. *Vehicle Engine*, 2008(05), 89-92.
[34] Soni, D. K., and Gupta, R. (2016). Optimization of methanol powered diesel engine: A CFD approach. *Applied Thermal Engineering*, 106, 390-398. DOI: https://doi.org/10.1016/j.applthermaleng.2016.06.026
[35] Soni, D. K., and Gupta, R. (2016). Numerical investigation of emission reduction techniques applied on methanol blended diesel engine. *Alexandria Engineering Journal*, 55(2), 1867-1879. DOI: https://doi.org/10.1016/j.aej.2016.02.019
[36] Duan, M.W., Yang, W.C., Tan, S.B., Ma, K., Qiao, B.C., and Luo, Y. (2015). Study on the application of microemulsion methanol diesel in diesel engines. *Small Internal Combustion Engine and Vehicle Technology*, 44(05), 85-88+93.
[37] Li, J., Gong, C., Liu, B., Su, Y., Dou, H., and Liu, X. (2009). Combustion and Hydrocarbon (HC) Emissions from a Spark-Ignition Engine Fueled with Gasoline and Methanol during Cold Start. *Energy & Fuels*, 23(10), 4937-4942. DOI: 10.1021/ef900502e
[38] Yang, M.H., Wei, X.Y., and Hu, G.D. (1990). Experimental study of compression-ignition pure methanol engine. *Journal of Dalian University of Technology*, 1990(06), 697-704.
[39] Wang, J., Zhu, J., Wang, Y., Liu, L., and Gao, C.H. (2014). Performance and emission study of high compression ratio methanol engine. *Agricultural Mechanization Research*, 36(09), 229-232. DOI:10.13427/j.cnki.njyi.2014.09.052