EFFECTS OF INJECTION TIMING ON COMBUSTION PERFORMANCE AND EMISSIONS IN A DIESEL ENGINE BURNING BIODIESEL BLENDED WITH METHANOL

by

Jie RUAN[a], Helin XIAO[a*], Xiaolong YANG[b], Fengyun GUO[b], Jiaqi HUANG[b], and Hongling JU[b]

[a] Hubei Key Laboratory of Advanced Technology for Automotive Component, Wuhan University of Technology, Wuhan, China
[b] Hubei Collaborative Innovation Center for Automotive Components Technology, Wuhan University of Technology, Wuhan, China

Original scientific paper
https://doi.org/10.2298/TSCI191211202R

Currently, biodiesel has been received much attention from many researchers around the world due to its clean and renewable characteristics. In the present study, combustion and emissions characteristics have been studied on a modified four-cylinder, 4-stroke, water-cooled, direct injection compression internal engine equipped with a common rail fuel injection system fueled with methanol-biodiesel blends as well as pure biodiesel. The experiment was operated at a constant engine speed of 1800 rpm and injection timing from 2.5-22.5 ° crank angle before top dead center. With the injection timing advanced, peak in-cylinder pressure and maximum heat release rate increased while combustion start points were advanced. Ignition delay was shorten first and then prolonged while brake thermal efficiency was increased first and then decreased. With the injection timing in advance, NO_x emissions increased, 1,3-butadiene and benzene emissions decreased while hydrocarbon and acetaldehyde emissions decreased first and then increased, and soot emissions increased first and then decreased.

Key words: *biodiesel-methanol blends, combustion and emissions, Diesel engine, injection timing*

Introduction

With the rapid development of industrialization, supply of petroleum could not satisfy the excessive consumption in modern industry and emissions from petroleum could not fit for the stringent emission regulations. Among them, widespread application of internal combustion engines had led to increasing consumption of fossil fuels, resulted in significant energy crisis. Based on these reasons, it was necessary to search for advanced combustion techniques and alternative fuels to fulfill these challenges. Biodiesel has been widely used as an alternative fuel because of high cetane number (CN), renewability as well as good compatibility for internal combustion engine [1-5].

Biodiesel was derived from biological materials. Waste oils, animal fats and woody oils were conventional sources. It was considered to be an accessible and environmentally friendly fuel [6-9]. However, biodiesel also had some limitation for applying to Diesel engine.

* Corresponding author, e-mail: hlxiao_qcxy@whut.edu.cn

Biodiesel had different compressibility from diesel because of its higher viscosity than that of diesel fuel, resulted in significant changes in spray characteristics when directly used in Diesel engine, thus affected the quality of mixture formation and a series of evolution processes of soot, particles. In addition, although the addition of biodiesel could significantly reduce CO, soot and HC emissions, some unregulated emissions (acetaldehyde, benzene and 1,3-butadiene) were produced from biodiesel [10-14]. These emissions originated from the combustion of a small amount of alcohols contained in biodiesel. Thus, looking for superior diesel substitutes would be of significant importance in the field of energy development.

As a kind of renewable fuel, methanol had attracted worldwide attention because of its superior physicochemical performance, as shown in tab. 1. It had certain advantages over gasoline and diesel in terms of power, economy and environmental protection [15-20]. Firstly, the engine power could be greatly increased by reforming the fuel system due to the high octane number of methanol. Secondly, the production cost of methanol had a great advantage due to *multi-supply* Fraley [21] methanol production mode. Moreover, methanol had 50% oxygen content which could improve combustion process.

However, methanol could not apply to Diesel engine directly due to its high octane number. Several scholars had studied on the combustion and emissions of methanol in internal combustion engine. Yao *et al.* [22] explored combustion and emissions performance of high proportion methanol/diesel blends on Diesel engines. The results showed that HC and CO emissions increased while significantly decreased soot and NO_x emissions. Wei *et al.* [23] probed the influence of premixed ratio of methanol on combustion and emission characteristics of Diesel engine. Moreover, high premixed ratio of methanol prolonged ignition delay, NO_x and soot emissions declined while HC and CO emissions increased. Maurya and Agarwal [24] compared the combustion performance and emission characteristics of HCCI engine fueled with ethanol and methanol. The experiments highlighted that compared to gasoline and ethanol, methanol auto-ignited earlier and showed lower $IMEP_{max}$. These studies showed that methanol would be a promising alternative fuel for existing combustion systems.

In summary, methanol addition into biodiesel could improve its fuel atomization characteristics. Moreover, biodiesel-methanol blends could be applied to Diesel engine without much modification. Meanwhile, injection timing determined the combustion phase of diesel engine, so the suitable injection timing was conductive to improve combustion performance and emission characteristics of internal compression combustion engine. Advanced injection timing would make pressure rise rate raised sharply, resulting in rough combustion, cylinder knocking, deflagration. Meanwhile, delayed injection timing led to combustion deterioration which reducing power and economy [25, 26]. Therefore, it was of great importance to determine suitable injection timing for improving combustion and emission performance. In addition, this article explores the effect of methanol on improving the combustion and emission performance of biodiesel.

Experimental

Engine and instrumentation

The test was conducted on a modified four-cylinder, 4-stroke, water-cooled, direct injection compression internal engine mounted with a high pressure common rail fuel injection system as illustrated in fig. 1. Meanwhile, the relevant parameters were displayed in tab. 1. The engine was connected with an eddy current (EC) dynamometer to keep the speed constantly at 1800 rpm (±5 rpm) and adjust torque output. Moreover, using an electrical control module to control and monitor engine working parameters.

The in-cylinder pressure collected by Kistler 6025C pressure transducers mounted in the cylinder head. These measured signals were passed through a charge amplifier and then acquired by a CB-466 combustion analyzer. In-cylinder pressure acquisition was triggered at a 0.25° crank angle (CA) intervals for 100 successive cycles. Coolant temperatures was precisely maintained at 86 °C (±1 °C) by PID controller and oil temperature was maintained around 87 °C (±1 °C) in pace with variable engine loads. Moreover, intake air temperature was stabilized around 26 °C (±0.5 °C). The injection pressure is maintained at 120 MPa. Using an AVL gas analyzer to measure gaseous emissions while the accuracy of HC, CO as well as NO_x were 1 ppm, 1 ppm, and 0.1%, respectively. Various unregulated emissions were collected by sampling bag first and then gauged via a gas chromatograph which were accurate to 0.1 ppm. Soot emissions were measured through opacimeter with the accuracy of 0.1 [m^{-1}].

Table 1. Engine specification

Type of engine	Four-cylinder, 4-stroke
Bore	96 mm
Stroke	103 mm
Compression ratio	17.5
Displacement	2982 cc
Rated power	85 kW
Rated speed	3200 rpm
Type of ignition	Compression ignition
Method of starting	Electric start
Maximum torque	300 Nm

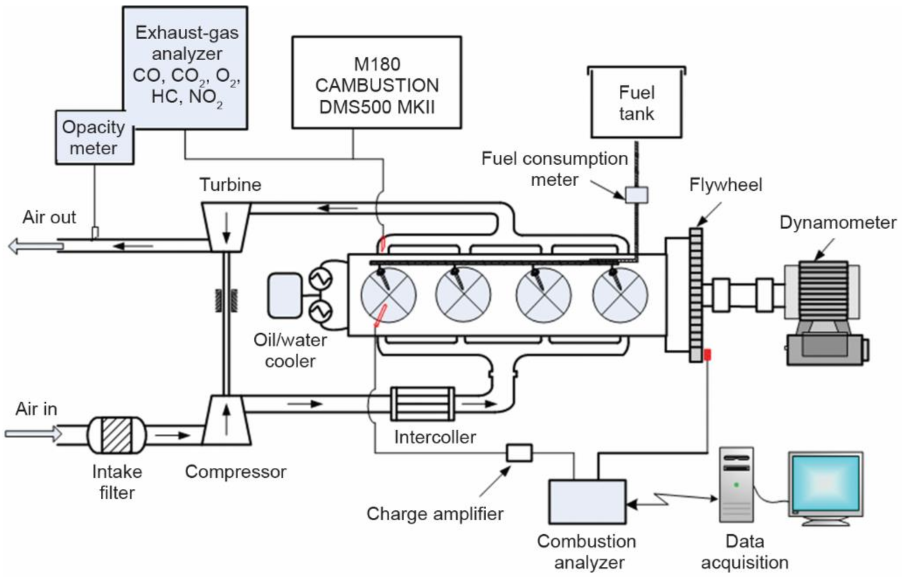

Figure 1. Schematic of engine and instrumentation set-up

Test fuels and experimental procedures

General properties of biodiesel and methanol were listed in tab. 2. Biodiesel, as the base fuel, was supplied by Longhai Biological Technology Co. Ltd. Methanol was provided by Jupeng Chemical Corporation at 99% purity. Mixtures of 0%, 10%, 15%, and 20% by mass fraction of methanol with biodiesel were evaluated, marked as BM0, BM10, BM15, and

BM20. This experiment was conducted to keep thermal value in every cycle consistent at 787.5 J to better investigate the impact of fuels properties on combustion performance and emissions. Therefore, this experiment needed to adjust injected fuel mass to keep the same energy input due to the different low heating values of various test fuels. In addition, the experiment was operated at various start of injection time which was adjusted from 2.5 to 22.5 ºCA bTDC with an increment of 5 ºCA. Meanwhile, all experimental conditions were conducted at a constant speed of 1800 rpm. In order to reduce experimental error, measurement data of each operating condition was acquired for 5 timings at least. Besides, the data of BM20 at 2.5 ºCA bTDC could not be measured due to serious combustion deterioration.

Table 2. Properties of diesel, biodiesel, methanol, and gasoline

Parameters	Diesel	Biodiesel	Methanol	Gasoline
Chemical formula	C_{12}-C_{25}	–	CH_3OH	C_4-C_{12}
Octane number	20-30	35-43	114	80-97
Cetane number	40-55	50-62	3	0-10
Oxygen content [%]	0	10.8	50	0
Density at 20 °C [kgm^{-3}]	826	881	796	744.6
Latent heating [kJkg^{-1}] at 25 °C	270-301	300	1109	373
Lower heating value [MJ kg^{-1}]	42.5	37.5	19.7	42.9
Auto-ignition temperature [°C]	270-350	280-456	470	390-410

Results and discussion

Analysis of in-cylinder combustion characteristics

Figure 2 displayed the curves of in-cylinder pressure and heat release rate (HRR) of the Diesel engine fueled with all the test fuels at variable injection timings. Figures 2(a) and 2(b) showed that the peak pressure in cylinder decreased with injection timing delayed. Moreover, the combustion tended to occur in expansion stroke, led to the decline of the peak pressure in the cylinder. As fig. 2(c) showed, when injection timing at 2.5 °CA bTDC, compared to BM0 and BM10, the combustion of BM15 had deteriorated. It could be explained by following reason. With methanol fraction increasing, biodiesel-methanol blends owned lower CN because CN of methanol was lower than biodiesel, caused BM15 more difficult to reach ignition condition compared to BM10. Therefore, the burning of BM15 mainly occurred at expansion stroke, thus led to combustion deterioration. The pre-mixed gas of biodiesel accumulated during the ignition delay was burned together, and the peak value of the HRR was high. At this time, the injection process had not stopped. Due to the poor atomization effect of the biodiesel, it took a certain time to reach the ignition conditions. There was a clear interval of HRR between the ignition delay and the combustion duration. The atomization effect of BM10 was better than biodiesel, so there was no obvious interval between the ignition delay and the combustion duration. As for BM15 and BM20, the higher latent heat of vaporization of methanol and the lower CN made it difficult for the fuel to reach the ignition condition. Therefore, the phenomenon of *double peaks* had appeared. According to fig. 2, it could be seen that the HRR peaks of BM20 appeared later than that of BM15. This was because methanol added into biodiesel could decline CN. From fig. 2(d), the in-cylinder pressure and HRR were not given when injection timing at 2.5 °CA bTDC because the combustion of BM20 appeared serious deterioration.

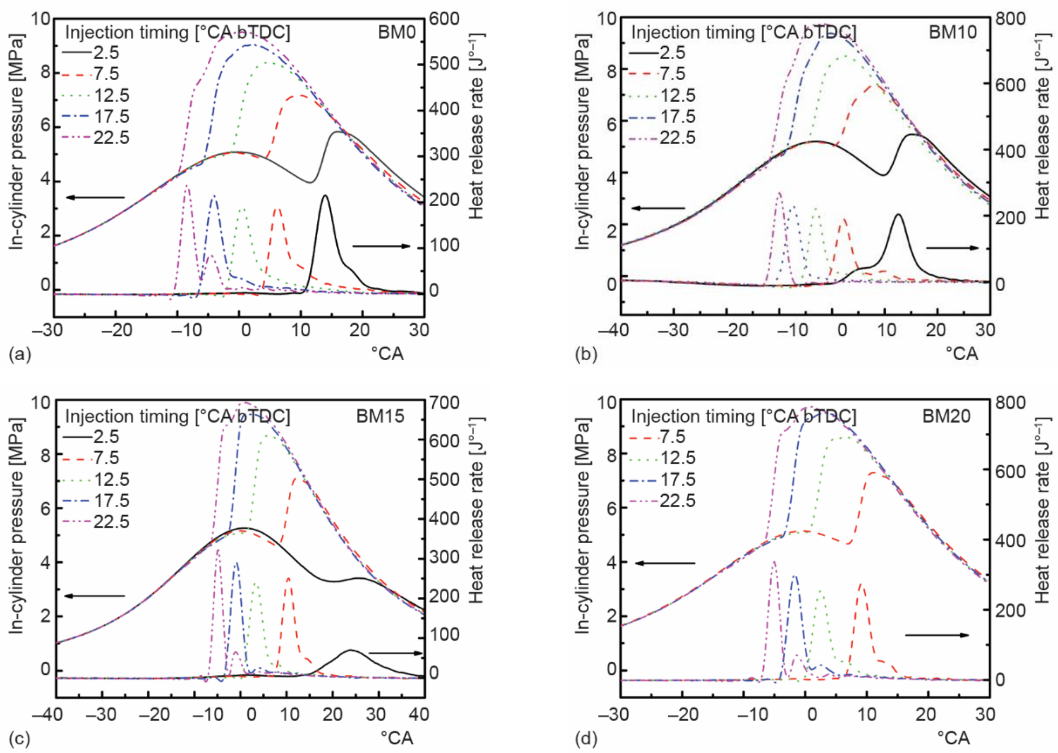

Figure 2. Pressure and HRR of four test fuels at different injection timings

Figure 3 showed ignition delay (defined as the CA interval from the start injection timing to 10% burning point) was prolonged with the increment of methanol ratio, which could be attribute to the properties of methanol. Firstly, the higher latent heat of vaporization for methanol declined in-cylinder temperature so as to prolong ignition delay. Secondly, both the lower CN and higher auto-combustion temperature for methanol made it more difficult to be ignited, thus prolonged ignition delay. When injection timing at 22.5 °CA bTDC, there was enough time forming uniform premixed gases. With injection timing in advance, higher temperature and pressure in the cylinder made it easier to reach ignition condition, thus shorten ignition delay. When injection timing near TDC, the burning mainly occurred in expand stage, due to the short duration in high temperature environment, the ignition delay was prolonged.

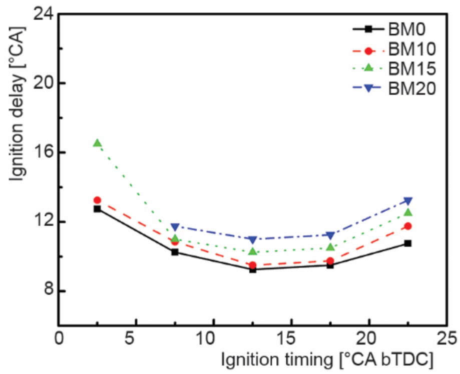

Figure 3. Variation of ignition delay *vs.* injection timings for different fuels

The combustion duration (defined as the CA interval from 10% burning point to 90% burning point) of the test fuels at different injection timings was shown in fig. 4. When injection timing at 2.5 ºCA bTDC, the combustion duration of BM15 was obviously higher than that of BM0 and BM10. This is because under the influence of short high temperature duration in cylinder when injection timing at 2.5 °CA bTDC, lower CN and higher latent heat of vaporization of fuel blends led to combustion deteriorates, so the combustion duration was prolonged. As injection timing was further advanced, the combustion duration decreased with the increase of methanol ratio. In addition to the effect of ignition delay, the rise of oxygen content in the fuel blends accelerated combustion process and thus shorten combustion duration.

Figure 5 showed brake thermal efficiency (BTE) of four test fuels at variable injection timing. With methanol faction increasing, BTE decreased gradually at all test injection timings. On one hand, methanol addition into biodiesel could improve combustion process due to its higher oxygen content than biodiesel, thus reduced BTE. On the other hand, the latent heating of methanol was lower than biodiesel so that more fuel mass should be injected at same condition, resulted in increasing BTE. Besides, BTE of BM15 had greatly decreased at 2.5 °CA bTDC due to combustion deterioration.

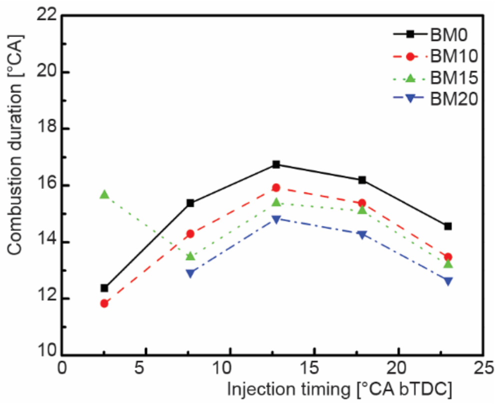

Figure 4. Variation of combustion duration *vs.* injection timings for different fuels

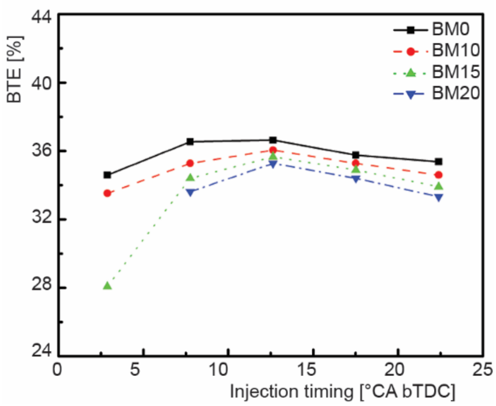

Figure 5. Variation of BTE *vs.* injection timings for different fuels

Regulated emission characteristics

The emissions of NO_x were shown in fig. 6. For the four test fuels, NO_x emissions significantly raised with the advance of injection timing. According to the research of Fernando *et al.* [27], the formation of NO_x was determined by high temperature, enough oxygen content as well as residence timing in cylinder. Therefore, advanced injection timing promoted sufficient premixed combustion and the pressure and temperature in the cylinder increased, which promoted the formation of NO_x. In the same injection timing, the fuel blends produced more NO_x with the increment of methanol expect 2.5 °CA bTDC, the higher oxygen content than biodiesel was one of the mainly reason of NO_x formation.

Figure 7 showed the HC emissions from the test fuels at different injection timings. With the injection timing in advance, HC emissions declined first and then increased. As injection timing near TDC, the former analysis showed ignition delay was prolonged and the mixture was easy to diffuse into the slit area, which produced a large amount of HC. As the injection timing was advanced, HC emissions reached minimum value at 12.5-17.5 °CA bTDC for both test fuels. However, as injection timing at 22.5 °CA bTDC, the fuel spray penetrated longer distance and was easy to inject into the cylinder wall, which led to wall quenching phenomenon and increases HC emissions. With methanol fraction increasing, HC emissions raised gradually. Methanol addition into biodiesel could decline CN of the blends and then prolonged ignition delay, promoting more fuel blends contacting the cylinder wall with lower temperature and the wall quenching effect Xiao *et al.* [28] was aggravated, which increased HC emissions.

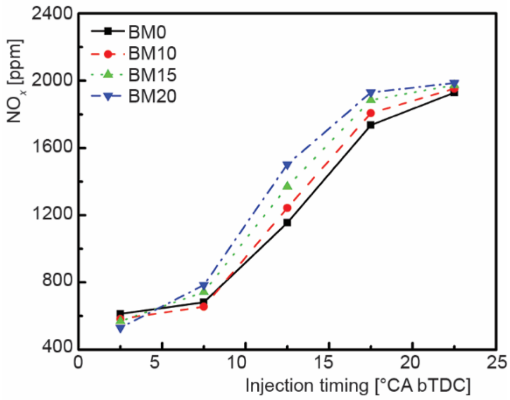

Figure 6. Variation of NO_x emissions with injection timings for different fuels

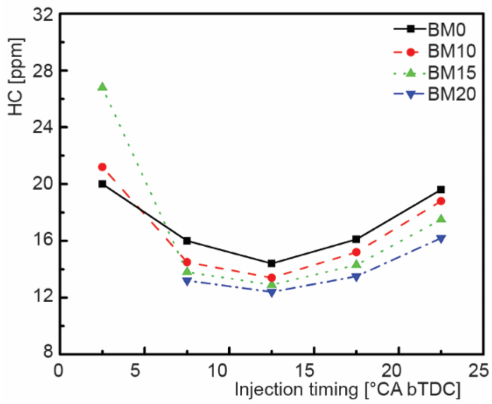

Figure 7. Variation of HC emissions with injection timings for different fuels

Figure 8 displayed the CO emissions for each test fuel at various injection timings. It was noticeable that fuel blends had advantages on CO emissions compared with biodiesel expect 2.5 °CA bTDC. The CO emissions reduced first and then almost remained unchanged with injection timing in advance. Under the condition of 2.5 °CA bTDC, the main burning occurred at expansion stroke, thus the lower combustion temperature and pressure in cylinder retarded the oxidation process of CO. With the injection timing advanced, considerable premixture was formed during ignition delay and burning together near TDC, which produced higher temperature and pressure in cylinder, thus promoted CO oxidation. Except for 2.5 °CA bTDC, adding methanol increased CO emissions but at other main injection timing promoted CO oxidation for fuel blends.

Figure 9 showed the variable tendency of soot emissions under various injection timings. Soot emissions of the test fuel raised first and then decreased with the main injection timing advanced except BM15. At 2.5 °CA bTDC, BM15 produced higher soot emissions due to the deterioration of combustion. With injection timing in advance, ignition delay was shorted first. On one hand, the proportions of diffusive combustion increased so the soot emissions increased. On the other hand, combustion was far from TDC and lower temperature in cylinder retarded soot formation. Therefore, the soot emissions of the test fuel varied slowly from 12.5° to 17.5 °CA bTDC, and the soot emissions decreased significantly when injection timing at 22.5 °CA bTDC.

Unregulated emission characteristics

Figure 10 indicated the influence of injection timing on 1,3-butadiene emissions of test fuel. The emissions of 1,3-butadiene from test fuel decreased with main injection timing

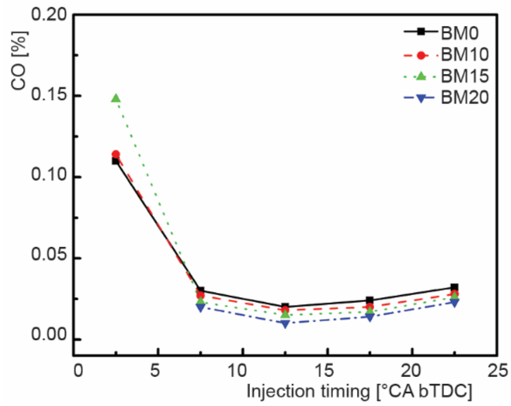

Figure 8. Variation of CO emissions with injection timings for different fuels

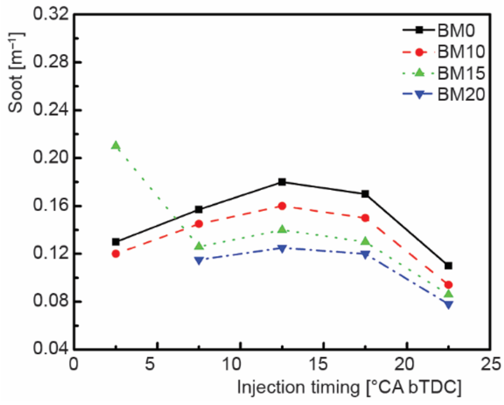

Figure 9. Variation of soot emissions with injection timings for different fuels

in advance. As Zhu Lei *et al.* [29] concluded, higher combustion temperature inhibited the formation of 1,3-butadiene. The high combustion temperature duration was prolonged with the injection timing away from TDC, which promoted the oxidation of 1,3-butadiene. For different test fuels, the emissions of 1,3-butadiene decreased with the addition of methanol except for 2.5 °CA bTDC at the same injection timing, as the reason mentioned above. However, 1,3-butadiene was hard to oxidize at low in-cylinder temperature and pressure due to the lag of combustion starting point at 2.5 °CA bTDC. The higher latent heat of methanol vaporization further declined the in-cylinder temperature, so considerable 1,3-butadiene emissions from BM15 was produced.

Figure 11 showed the variations on acetaldehyde emissions at various injection timings. acetaldehyde emissions first decreased and then increased with advance of injection timing. When main injection timing at 2.5 °CA bTDC, the starting point of combustion was too close to TDC, which resulted in the combustion mainly occurring in the expansion stroke, forming suitable condition for the formation of acetaldehyde. As injection timing at 12.5 °CA bTDC, the higher combustion temperature in cylinder improved the combustion efficiency, and promoted the post oxidation of acetaldehyde at exhaust stroke. However, when injection

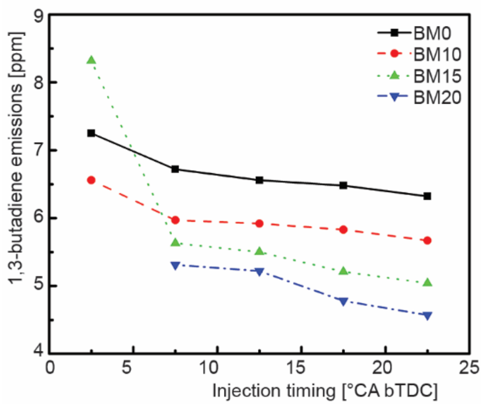

Figure 10. Variation of 1,3-butadiene emissions with injection timings for different fuels

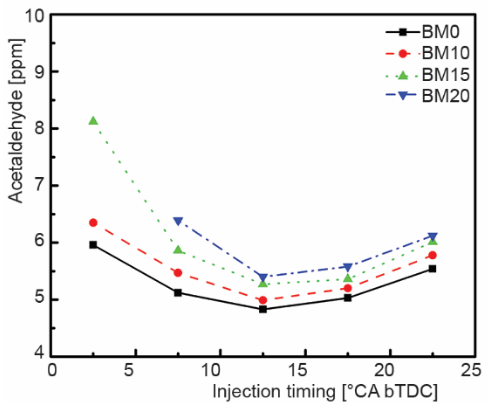

Figure 11. Variation of acetaldehyde emissions with injection timings for different fuels

timing at 22.5 °CA bTDC, acetaldehyde emissions increased because injection timing was too early and long injection penetration distance caused partial fuels injected into cylinder wall forming quenching layers, resulting in a large amount of acetaldehyde emissions, which increased the acetaldehyde emissions. Moreover, the addition of methanol also increased the acetaldehyde emissions at the same injection timing.

Figure 12 indicated the variation of benzene emissions at various injection timings. Benzene emissions of test fuel decreased gradually with injection timing in advance. It could be explained by that combustion temperature increased with the injection timing far away from TDC. On the one hand, the combustion duration prolonged, which promoted the oxidation process of benzene emissions. On the other hand, the benzene ring structure was easier to be broken and restrained the formation of benzene ring at higher temperature. In addition, benzene emissions decreased with the rise of methanol ratio under various injection timings, the reason had been discussed in the previous paper.

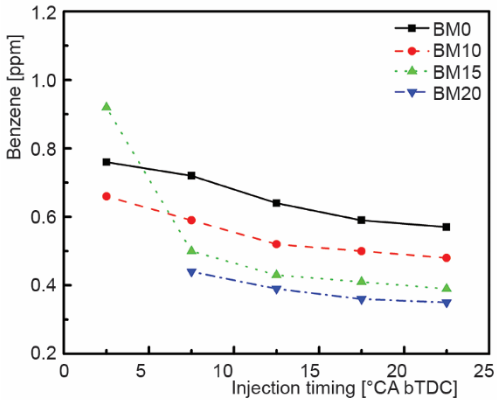

Figure 12. Variation of benzene emissions with injection timings for different fuels

Conclusion

In this paper, combustion performance and emission characteristics of methanol and biodiesel blends under various injection timings has been investigated in a Diesel engine. The main conclusions are extracted as follows.

With injection timing in advance, in-cylinder pressure and HRR of test fuels increased while combustion phase was advanced. The blending with methanol increased the in-cylinder pressure and HRR at advanced injection timing.

- The ignition delay was shorted first and then prolonged with the injection timing advanced. The change trends of the combustion duration of test fuels except BM15 were opposite to that of the ignition delay.
- Except for the main injection timing of 2.5 °CA bTDC, ignition delay was prolonged with methanol ratio increasing while combustion duration showed the opposite trend. Delayed injection timing was not fit to the fuel blends with higher methanol ratio.
- With the injection timing advanced, the BTE increased first and then decreased. The blending with methanol decreased BTE at the same injection timing.
- With injection timing in advance, NO_x emission increased, CO emission decreased, soot emissions first increased and then decreased, HC emission first decreased and then increased slightly.
- For unconventional emissions, 1,3-butadiene and benzene emissions reduced with injection timing advanced, but acetaldehyde emissions decreased first and then increased.
- Expect 2.5 °CA bTDC, the blending with methanol increased acetaldehyde and NOx emissions but decreased HC, CO, 1,3-butadiene and benzene emissions.

Acknowledgment

The authors would like to thank the National Natural Science Fund of China (No. 21377101), National Natural Science Fund of China (No. 51276132) and Wuhan University of Technology for financial support to this study.

Reference

[1] Tan, P. Q., *et al.*, Particle Number Emissions from a Light-Duty Diesel Engine with Biodiesel Fuels Under Transient-State Operating Conditions, *Applied Energy, 113* (2014), 113, pp. 22-31
[2] Tan, P., *et al.*, Particle Number Emission from a Vehicle Diesel Engine with Biodiesel Fuel, *Journal of Automotive Safety & Energy, 1* (2010), 1 pp. 83-88
[3] Fang, T. G., Lee, C. F., Biodiesel Effects on Combustion Processes in an HSDI Diesel Engine Using Advanced Injection Strategies, *Proceedings of the Combustion Institute, 32* (2009), 2, pp. 2785-2792
[4] Zheng, M., *et al.*, Low Temperature Combustion of Neat Biodiesel Fuel on a Common-Rail Diesel Engine, *SaeTransactions, 101* (1989), 3, pp. 465-472
[5] Deepak, A., *et al.*, Experimental Investigation of Control of NOx Emissions in Biodiesel-Fueled Compression Ignition Engine, *Renewable Energy, 31* (2006), 14, pp. 2356-2369
[6] Ramadhas, A. S., *et al.*, Use of Vegetable Oils as I. C. Engine Fuels – A Review, *Renewable Energy, 29* (2004), 5, pp. 727-42
[7] Rawat, I., *et al.*, Biodiesel from Microalgae: A Critical Evaluation from Laboratory to Large Scale Production, *Applied Energy, 103* (2013), 1, pp. 444-467
[8] Meller, E., *et al.*, Catalytic Deoxygenation of Castor Oil Over Pd/C for the Production of Cost Effective Biofuel, *Fuel, 133* (2014), 1. pp. 89-95
[9] Garcia-Davila, J., *et al.*, Jatropha Curcas L. Oil Hydro Conversion Over Hydrodesulfurization Catalysts for Biofuel Production, *Fuel, 135* (2014), Nov., pp. 380-386
[10] Millo, F., *et al.*, Effects of Different Biofuels Blends on Performance and Emissions of an Automotive Diesel Engine, *Fuel, 159* (2015), 1, pp. 614-627
[11] Manzetti, S., Andersen, O., A Review of Emission Products from Bioethanol and Its Blends with Gasoline.,Background for New Guidelines for Emission Control, *Fuel, 140* (2015), 2, pp. 293-301
[12] Zheng, M., *et al.*, Biodiesel Engine Performance and Emissions in Low Temperature Combustion, *Fuel, 87* (2008), 6, pp. 714-722
[13] Zheng, M., *et al.*, Low Temperature Combustion of Neat Biodiesel Fuel on a Common-rail Diesel Engine, SAE World Congress & Exhibition, Detroit, Mich., USA, 2008
[14] Aydin, H., Ilkiliç, C., Effect of Ethanol Blending with Biodiesel on Engine Performance and Exhaust Emissions in a CI Engine, *Applied Thermal Engine, 30* (2010), 10, pp. 1199-20
[15] Canakci, M., *et al.*, Exhaust Emissions and Combustion Characteristics of a Direct Injection (DI) Diesel Engine Fueled with Methanol-Diesel Fuel Blends at Different Injection Timings, *Energy & Fuels, 22* (2008), 6, pp. 3709-3723
[16] Suresh, R., *et al.*, Performance Analysis for Emission and Combustion of Methanol Blend Diesel Fuel in CI Engine Using Glow Plug, *Proceedings*, Frontiers in Automobile & Mechanical Engineering, Chennai, India, 2010
[17] Guo, Z., *et al.*, Combustion and Emission Characteristics of Blends of Diesel Fuel and Methanol-to-Diesel, *Fuel, 90* (2011), 3, pp. 1305-1308
[18] Hu, T, *et al.*, Improvement of Spark-Ignition (SI) Engine Combustion and Emission during Cold Start, Fueled with Methanol/Gasoline Blends, *Energy & Fuels, 21* (2007), 1, pp. 171-175
[19] Chun-De, Y., *et al.*, Characteristics of Particulate Matter Emission from a Diesel/Methanol Compound Combustion Engine, *Transactions of CSICE, 26* (2008), 4, pp. 302-306
[20] Wenkun, W., *et al.* Study on Combustion and Emission Characteristics of Methanol/Biodiesel/F-T Diesel Blends, *Renewable Energy Resources, 34* (2016), 1, pp. 131-135
[21] Fraley, L., Methanol Production Process and System, *Europe PMC, 54* (2012), 7, pp. 67-72
[22] Yao, C., *et al.* Effect of Diesel/Methanol Compound Combustion on Diesel Engine Combustion and Emissions, *Energy Conversion and Management, 49* (2008), 6, pp. 1696-1704
[23] Wei, L., *et al.*, Combustion and Emission Characteristics of a Turbocharged Diesel Engine Using High Premixed Ratio of Methanol and Diesel Fuel, *Fuel, 140* (2015), Jan., pp. 156-163

[24] Maurya, R. K., Agarwal, A. K., Experimental Investigations of Performance, Combustion and Emission Characteristics of Ethanol and Methanol Fueled HCCI Engine, *Fuel Processing Technology, 126* (2014), Oct., pp. 30-48
[25] Mani, M., Nagarajan, G., Influence of Injection Timing on Performance, Emission and Combustion Characteristics of a DI Diesel Engine Running on Waste Plastic Oil, *Energy, 34* (2009), 10, pp. 1617-1623
[26] Qi, D., *et al.,* Effect of EGR and Injection Timing on Combustion and Emission Characteristics of Split Injection Strategy DI-Diesel Engine Fueled with Biodiesel, *Fuel, 90* (2011), 5, pp. 1884-1891
[27] Fernando, S., *et al.,* NOx Reduction from Biodiesel Fuels, *Energy & Fuels, 20* (2006), 1, pp. 376-382
[28] Xiao, H. L., *et al.,* Combustion Performance and Emissions of 2-Methylfuran Diesel Blends in a Diesel Engine, *Fuel, 175* (2016), July, pp. 157-163
[29] Poulopoulos, S. G., *et al.,* Regulated and Unregulated Emissions from an Internal Combustion Engine Operating on Ethanol-Containing Fuels, *Atmospheric Environment, 35* (2001), 26, pp. 4399-4406

Paper submitted: December 11, 2019
Paper revised: April 8, 2020
Paper accepted: May 26, 2020