Combustion and Emission Characteristics of CI Engine fueled with Rapeseed Biodiesel, Diesel and Ethanol Blend

Hao Chen[*, 1], Lu Yang[*], Yapeng Li[+], Yong Ma[*], Penghui Zhang[*], Jiang Li[*]

www.rericjournal.ait.ac.th

Abstract – *Biodiesel and ethanol are the two important renewable fuels for automotives. They can mix with diesel and form the blended fuel. To study the combustion and emission characteristics of the blend fuels, experiments are done on a single cylinder CI engine. Compared with BD20, combustion of BD20E5 and BD20E10 starts later; at small loads the peak combustion pressures and the peak heat release rates of the two fuels are low and at middle and large loads they increase; at 1500r/min the smoke emissions decrease 20.78% and 39.59% averagely, the CO emissions decrease 28.6% and 49.3% averagely, the HC emissions increase 29.4% and 66.8%, and the* NO_X *emissions maintain the same level. Accordingly, diesel-biodiesel-ethanol blend is a kind of clean and environmentally friendly alternative fuel for automotives.*

Keywords – Combustion, combustion pressure, ethanol, emission, heat release rate, rapeseed biodiesel.

1. INTRODUCTION

In 2011 the ratio of fossil energy in the total energy consumption grows up to 87.1%, oil accounted for 33.1% and the shares of natural gas and coal are 23.7% and 30.3% [1]. On the one hand, fossil energy is non-renewable and is in continuous depletion; on the other hand, the use of fossil fuels will produce large amounts of greenhouse gases (mainly CO_2, a small amount of CH_4, N_2O and HFC_s) of [2], which is the main cause of climate change, and a serious threat to the global ecological environment. Bio-fuels refer to fuel ethanol and Biodiesel, and in the whole life cycle carbon emissions are significantly lower than fossil fuels, which is friendly to the environment [3]-[5]. The United States and Brazil have extensive use of fuel ethanol and bio diesel [6]-[7] as vehicle fuel.

Biodiesel refers to methyl or ethyl ester fuels obtained by transesterification process from the oil-bearing crops, wild oil-bearing crops, micro-algae and other aquatic plant oil, animal fats, waste food oil and other raw materials [8]-[11]. Biodiesel has extensive sources, and its physical properties are close to fossil diesel [12]. There are three generation feed stocks of Biodiesel: the first generation is edible oils, such as soybean oil, palm oil, rapeseed oil and so on, which has been restricted due to social threat to food security, cultivated land and environmental problems [13]; the second generation is non edible sources, such as Jatropha oil [14], the second generation is under unified planning of the government and raw material forest base is constructed; the third generation is micro-algae with high oil production rate, which is rich in sources. Industry of micro-algae biodiesel can be combined with coal power plant (absorbing CO_2) and sewage treatment plant (purifying sewage water), because photosynthesis rate of micro-algae is 2-3 times higher than common plants, and it can absorb CO_2 and converted into biomass [15]-[19]. Accordingly, micro-algae is considered as the best raw material for biodiesel production and it is helpful for easing global warming.

At present, the domestic and foreign research on biodiesel is very comprehensive and is in depth. The main contents focus on the following points: 1) combustion, power, economic and emission characteristics of diesel engine fueled with mixture fuel of diesel and biodiesel from different raw materials; 2) spray characteristics of biodiesel and its blend with diesel; 3) physicochemical properties of biodiesel and its blend with diesel. Study on the physicochemical properties showed: the main problem of biodiesel is its high viscosity and low temperature fluidity (high pour point). For example, freezing points of soybean oil and palm oil methyl esters are -4ºC and 12ºC [13]; kinematic viscosities at 40ºC are 4.08 and 4.71. Freezing point and viscosity at 20ºC of ethanol are -115ºC and $1.2mm^2 \cdot s^{-1}$ which means blending ethanol into diesel and biodiesel mixture is an effective way to reduce the viscosity and improve the low temperature fluidity. However, low heat value of ethanol is 26.9 MJ/Kg which is obviously lower than that of diesel and Biodiesel and this problem can be solved by injecting more fuels. Both Biodiesel and ethanol are renewable fuels and their utilization in diesel engines is friendly to the environment. Therefore, this paper chooses biodiesel from rapeseed oil and 0# standard diesel and adds different volume proportion of ethanol, to solve the low-temperature liquidity and high viscosity problems of biodiesel. Experiments on combustion and emission characteristics of diesel engine fueled with different proportions of biodiesel, diesel and ethanol blend have been studied.

2. TEST CONDITIONS

2.1 Device and Test

ZH1105W, a single cylinder diesel engine, is used for test. Its main parameters: the cylinder diameter is 105 mm, the piston stroke is 115 mm, the compression ratio is 16.5, the rated power is 11.03 kW, advanced angle of

*School of Automobile, Chang'an University, South Second Circle Road, 710064, Xi'an, Shaanxi Province, China.

[+]Department of Mechanical and Electrical Engineering, Dongguan Polytechnic.

Corresponding author: Tel: + 86 158 2975 7680, Fax: + 86 029 8233 4476.
E-mail: colen7680@126.com

fuel supply is 22 degrees before TDC. The emission test system includes an exhaust gas analyzer AVL Digas4000 and a smoke Opacimeter AVL Dismoke4000. Extinction coefficient K (m^{-1}) is chosen as smoke value. A dynamic system for combustion test includes a CB566 combustion analyzer, a pressure sensor, a charge amplifier, a photoelectric sensor and a crankshaft position generator. In a certain condition of engine operation, cylinder pressures of one hundred cycles are recorded and averaged. Based on the averaged pressure, the heat release ratios are calculated by using two-zone model. Fuel flow in thirty seconds is measured with the TP-244 flow sensor produced from Japanese company Onokazu and is recorded in a DF-313 digital flow meter. Then the effective fuel consumption is calculated for evaluating the economy characteristic. Figure 1 shows the arrangement of engine and test instruments.

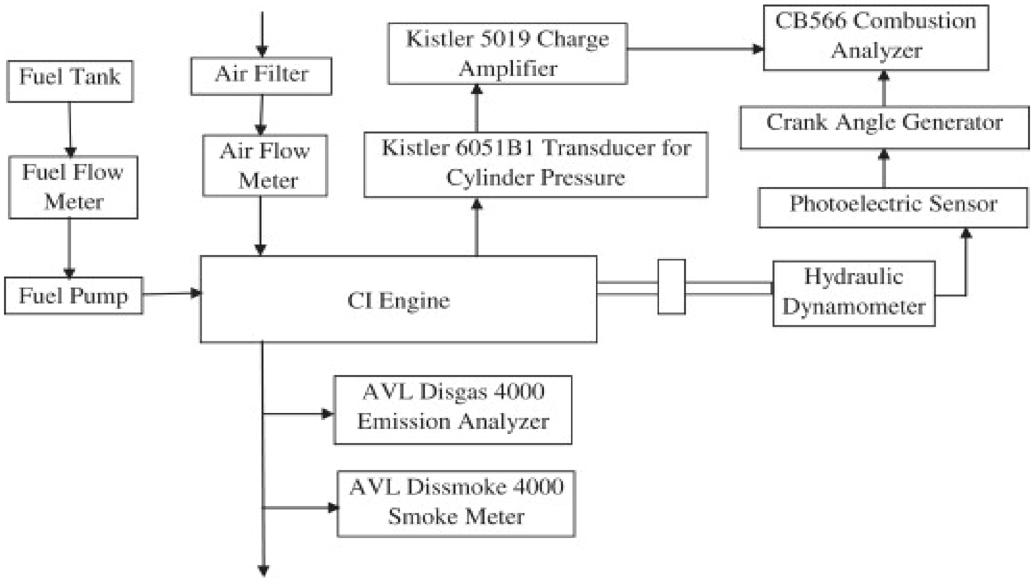

Fig. 1. Engine and test instruments.

Table 1. Properties of fuels.

Properties of fuels	Diesel	Biodiesel	Ethanol	BD20	BD20E5	BD20E10	Standard
Density at 20ºC/ g·cm^{-3}	0.835	0.882	0.789	0.844	0.842	0.840	GB/T1884-2000
Cetane number	51	52	8	51.2	49.1	46.9	ASTM D 4737-03
Viscosity at 20ºC/ mm^2·s^{-1}	3.9	5.9	1.2	4.3	4.2	4.0	GB/T265-1988
Low heat value/ MJ·kg^{-1}	42.5	38.7	26.9	41.7	40.9	40.2	GB/T 384-1981
Oxygen content/ %	0	10	34.78	2	3.74	5.48	/
Latent heat of vaporization/ kJ·kg^{-1}	254	254	904	254	287	319	/

2.2 Test Fuel

Biodiesel for blend is the product using rapeseed oil as the feed stock from the Chunguang grease factory in Hanzhoung, Shaanxi province. Three fuels for test are BD20 (20 vol.% of biodiesel with 80 vol.% of petroleum diesel), BD20E5 (20 vol.% of biodiesel, 75% of petroleum diesel and 5% of ethanol) and BD20E10 (20 vol.% of biodiesel, 70% of petroleum diesel and 10% of ethanol). Table 1 lists the major characteristics of the test fuels.

2.3 Engine Operation Condition

Engine operation condition is chosen as follows: 1500 and 1800r/min for engine speed; 0.0885, 0.177, 0.266, 0.354, 0.443, and 0.531MPa indicating the brake mean effective pressure (BMEP) for engine loads.

3. RESULTS AND DISCUSSION

3.1 Combustion characteristics

3.1.1 Combustion pressure

Figures 2 to 6 show the combustion pressure comparison of the three fuels at different conditions. 1) Compared with BD20, start points of combustion of BD20E5 and BD20E10 obviously delay reflected by the combustion pressure curves which leave away from TDC. On the one hand, cetane number of ethanol is 8 which is low leading to the relatively poor ignitability of BD20E5 and BD20E10. The other is that latent heat of vaporization of ethanol is 904 kJ/kg which is much higher than that of diesel or biodiesel. Accordingly, with the mixture of ethanol, the ignition delay period prolongs. 2) Compared with BD20E5, the delay effect of BD20E10 is obvious at small load and weakens with the loads. At small loads, the thermal and power condition in cylinder is poor and accordingly the poor ignitability of ethanol is prominent; at large loads, the condition improves and ethanol proportion has little influence on the delay effect. 3) Compared with 1500r/min, the effect of combustion delay becomes more obviously when the speed increases to 1800r/min.

Table 2 gives the peak pressure of the fuels at different conditions and their corresponding crank angle. 1) Compared with BD20, at 1500r/min and 0.086MPa, the peak pressures of both BD20E5 and BD20E10 are much lower, mainly due to the poor ignitability of ethanol and low heat value of ethanol; at 1500r/min and 0.354MPa the peak pressures are in the same level which are only 0.04 and 0.05MPa lower; at 1500r/min and 0.531MPa, the peak pressures are 0.08 and 0.09MPa higher, because on the one hand the prolonged ignition delay period increases the quantity of combustible mixed gas and on the other hand in the improved thermal and power condition ethanol can play positive effect on combustion. When the speed increases to 1800r/min, the discipline is similar and the difference is that when the load increases to 0.354MPa the peak pressures of BD20E5 and BD20E10 are already 0.09 and 0.24MPa higher than that of BD20. 2) Compared with BD20E5, the peak pressure of BD20E10 decreases at 0.086MPa and increases at middle and large loads. For example, at 1800r/min and 0.531MPa, the combustion delay effect almost disappears and high oxygen content of BD20E10 (5.48%) accelerates the combustion speed and promotes the complete combustion which leads to the high peak pressure. 3) Compared with BD20, at small loads the corresponding angles of peak pressures of BD20E5 and BD20E10 leave away from TDC, and with the load increasing the angles are close to TDC which indicates that ethanol accelerate the combustion speed due to the high oxygen content.

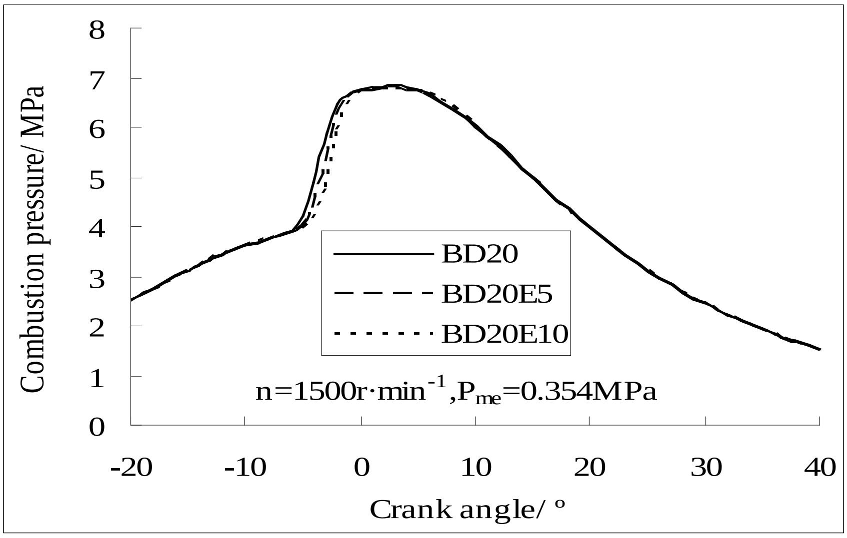

Fig. 2. Combustion pressure at 1# condition.

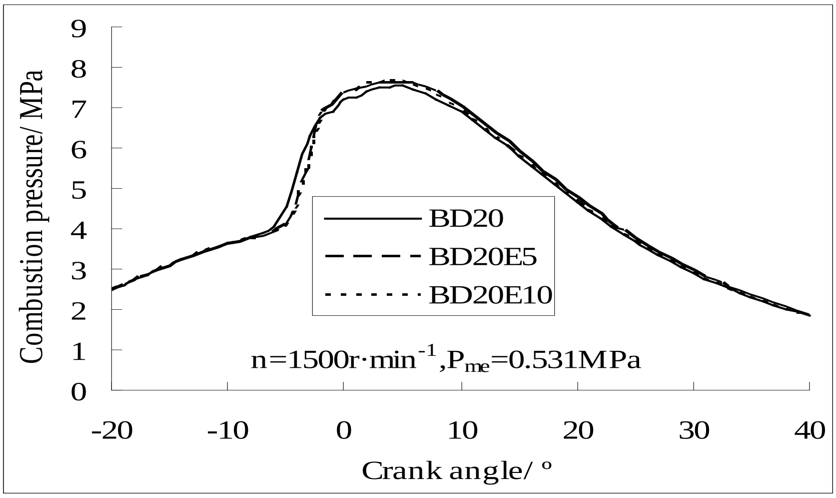

Fig. 3. Combustion pressure at 2# condition.

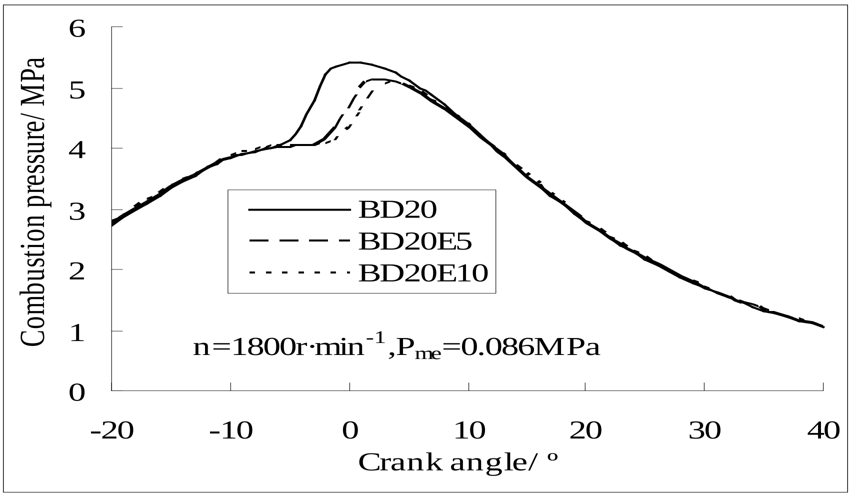

Fig. 4. Combustion pressure at 3# condition.

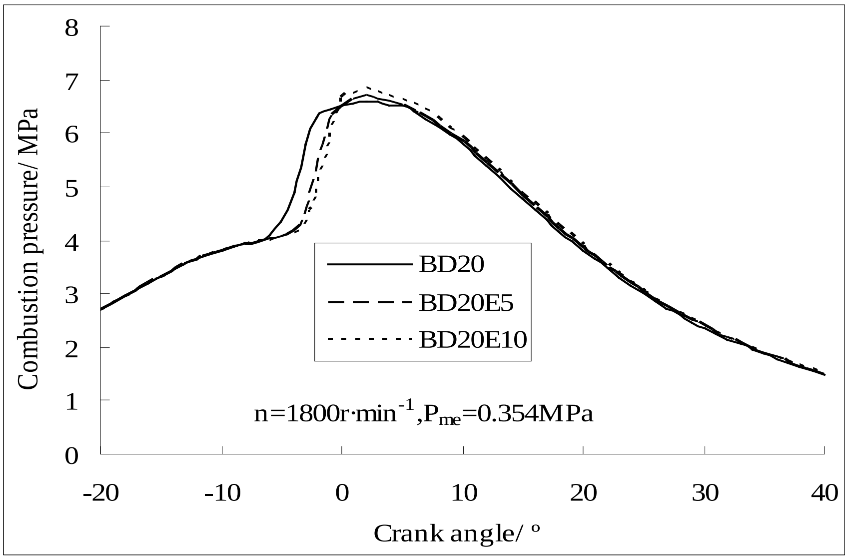

Fig. 5. Combustion pressure at 4# condition

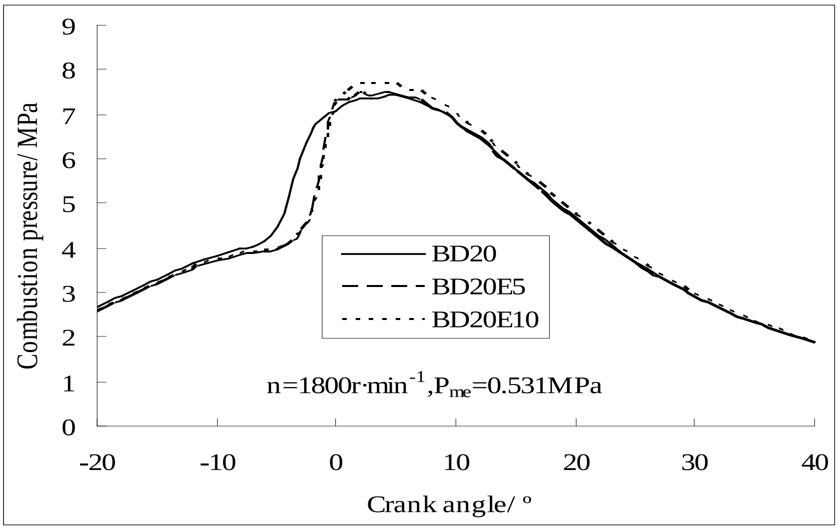

Fig. 6. Combustion pressure at 5# condition

Table 2. Peak combustion pressure and corresponding angles at different conditions.

Speed (r/min), P_{me} (MPa)	BD20		BD20E5		BD20E10	
	Peak pressure/ MPa	Angle/ °CA	Peak pressure/ MPa	Angle/ °CA	Peak pressure/ MPa	Angle/ °CA
1500, 0.086	5.50	0	5.38	1	5.33	1
1500, 0.354	6.83	3	6.79	3	6.78	3
1500, 0.531	7.54	5	7.62	4	7.63	4
1800, 0.086	5.40	1	5.13	3	5.07	4
1800, 0.354	6.59	3	6.68	2	6.83	2
1800, 0.531	7.42	5	7.48	4	7.70	2

Note 1: "Angle" indicates the corresponding angle after top dead center

3.1.2 Instantaneous Heat Release Rate

Figures 7 to 11 show the instantaneous heat release rate comparison of the three fuels at different conditions. Table 3 gives the peak rates of the fuels at different conditions. 1) Compared with BD20, at 1500r/min and 0.086MPa, the peak heat release rates of both BD20E5 and BD20E10 are obviously lower, mainly due to the poor ignitability of ethanol and low heat value of ethanol; at 1500r/min and 0.354MPa the peak rates are 0.002 and 0.024 kJ·(°CA)$^{-1}$ higher; at 1500r/min and 0.531MPa, the peak rates are 0.027 and 0.039 kJ·(°CA)$^{-1}$ higher, because the prolonged ignition delay period increases the quantity of combustible mixed gas and ethanol accelerates the combustion speed which makes the heat releases more concentrated. When the speed increases to 1800r/min, the discipline is similar. 2) Compared with BD20E5, the peak heat release rate of BD20E10 decreases at 0.086MPa and increases with the load, because better thermal and power condition is helpful for ethanol to play the promotion effect on combustion process.

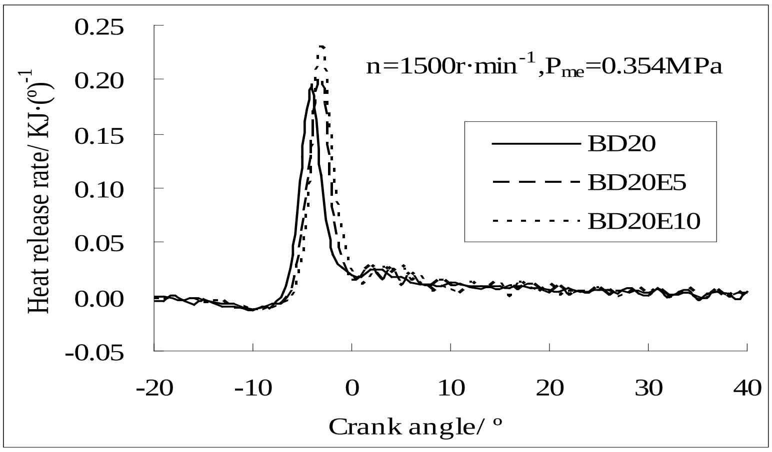

Fig. 7. Heat release rate at 1# condition.

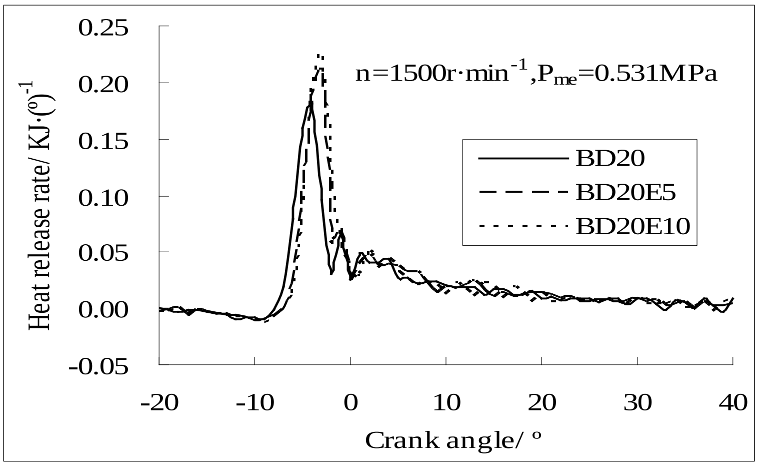

Fig. 8. Heat release rate at 2# condition.

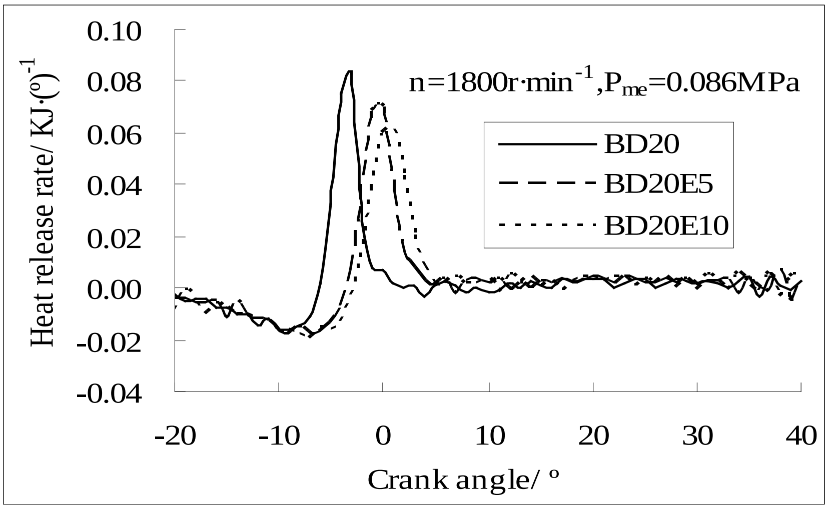

Fig. 9. Heat release rate at 3# condition.

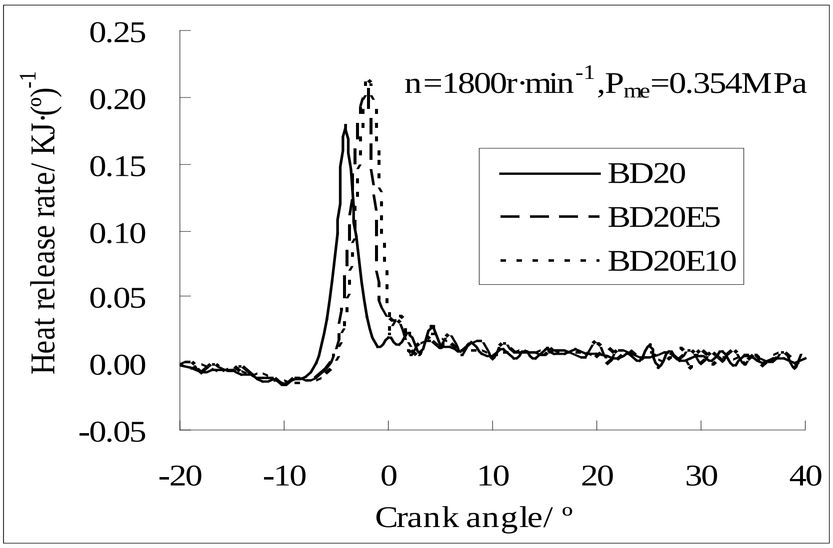

Fig. 10. Heat release rate at 4# condition.

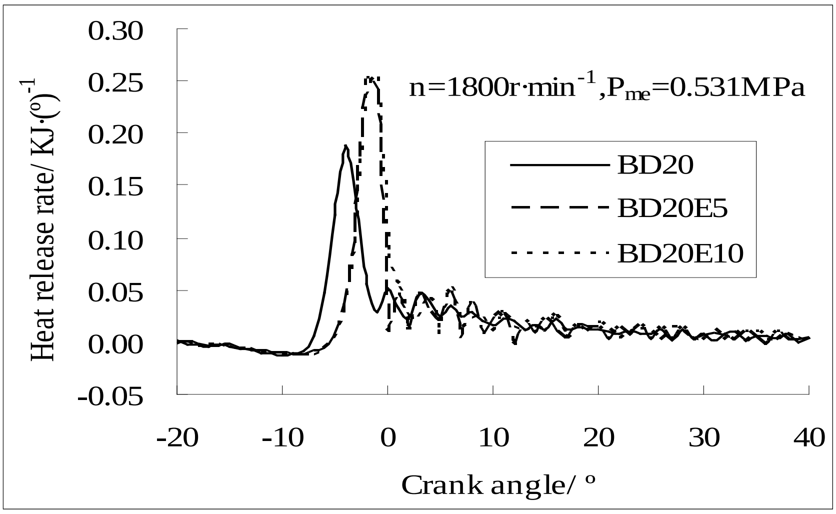

Fig. 11. Heat release rate at 3# condition.

Table 3. Peak heat release rate and corresponding angles at different conditions.

Speed (r/min), BMEP (MPa)	BD20	BD20E5	BD20E10
	Peak heat release rate/ kJ·(°CA)$^{-1}$	Peak heat release rate/ kJ·(°CA)$^{-1}$	Peak heat release rate/ kJ·(°CA)$^{-1}$
1500, 0.086	0.109	0.077	0.077
1500, 0.354	0.196	0.198	0.22
1500, 0.531	0.181	0.208	0.22
1800, 0.086	0.083	0.070	0.062
1800, 0.354	0.180	0.204	0.211
1800, 0.531	0.188	0.251	0.254

3.2 Emission Characteristics

Figures 12 and 13 indicate the smoke emission characteristic at 1500r/min and 1800r/min. 1) Compared with BD20, smoke emissions of BD20E5 and BD20E10 decreased by 20.78% and 39.59% averagely at 1500r/min. Smoke is easy to form in the high temperature and anoxic environment. On the one hand, the oxygen content in the fuel increase with the ethanol proportion, which contributes to the complete combustion of fuel and results that in the combustion process the self-sufficient oxygen is helpful for improving local hypoxia condition of oil beam. On the other hand, when blended with ethanol, high volatility and low viscosity improve the spray quality of the two fuels and therefore improve the local hypoxia condition in the mixed zone. 2) At small loads, the smoke reductions of BD20E5 and BD20E10 are especially slight because in the cylinder the heat status is poor which weakens the effect of ethanol due to its poor ignitability and the temperature is low which is unhelpful for the form of smoke. The reductions increase with the load and at high loads they increase dramatically, because in the high temperature and the hypoxia condition ethanol can effectively promote the combustion and improve the hypoxia condition.

Figures 14 and 15 show the NOx emission characteristic at 1500r/min and 1800r/min. 1) Both at 1500r/min and 1800r/min, there is no apparent variable regulation for the NOx emission. NOx emission is mainly determined by the oxygen content and the combustion temperature. First of all, 34.78% oxygen content of ethanol improves the content of blend fuels which may increase the NOx emission. Secondly, the latent heats of vaporization of BD20E5 and BD20E10 are 287 and 319 kJ/kg which are higher than that of BD20, consequently when the fuels are injected into the chamber, they absorb the heat and trend to reduce the temperature which may decrease the NOx emission. Thirdly, promotion effect of ethanol on combustion and high heat release rate may improve the combustion temperature which may increase the NOx emission. As a result, NOx emission is in non-regular variation. 2) At 0.531MPa of the load, NOx emissions of BD20E5 and BD20E10 are higher than that of BD20. In this condition effect of increasing NOx emission is stronger than the opposite effect.

Figures 16 and 17 indicate the HC emission characteristic at 1500r/min and 1800r/min. Although HC is not the main pollutant in emission of diesel engine, compared with BD20 HC emissions of BD20E5 and BD20E10 are averagely 29.4% and 66.8% higher than that of BD20 at 1500r/min. Duration time of diesel fuel in combustion chamber is much shorter than that of gasoline, so the influences of cold shock effect of cylinder wall, narrow gap effect, adsorption of oil film and adsorption of the sediments are very small. Due to the poor ignitability of ethanol, unburned HC increases in the combustion process, however the emission quantity is very little.

Figures 18 and 19 show the CO emission characteristic at 1500r/min and 1800r/min. Compared with BD20, CO emissions of BD20E5 and BD20E10 averagely decrease 28.6% and 49.3% at 1500r/min. High oxygen contents make the combustion more complete, as an incomplete combustion product, CO emissions significantly reduce.

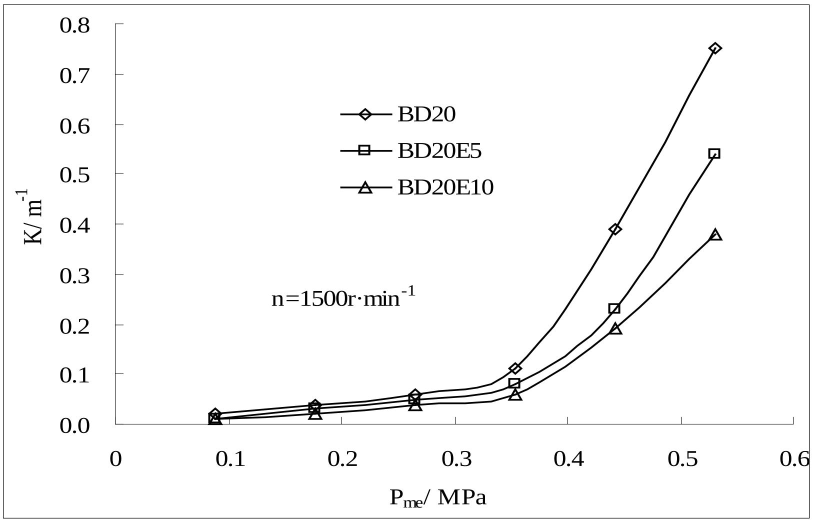

Fig. 12. Smoke emission at 1500r/min.

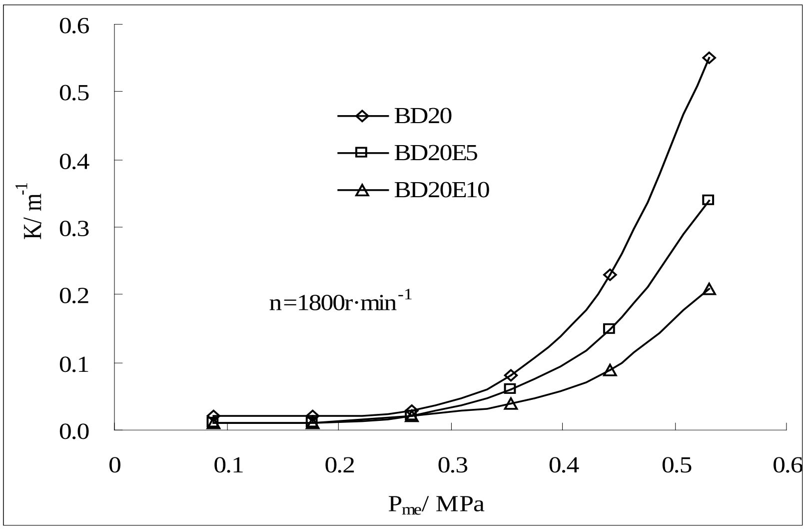

Fig. 13. Smoke emission at 1800r/min.

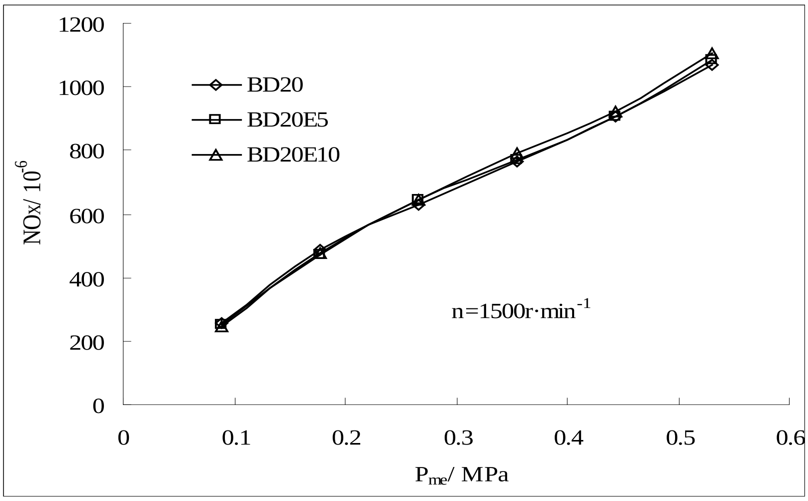

Fig. 14. NOx emission at 1500r/min.

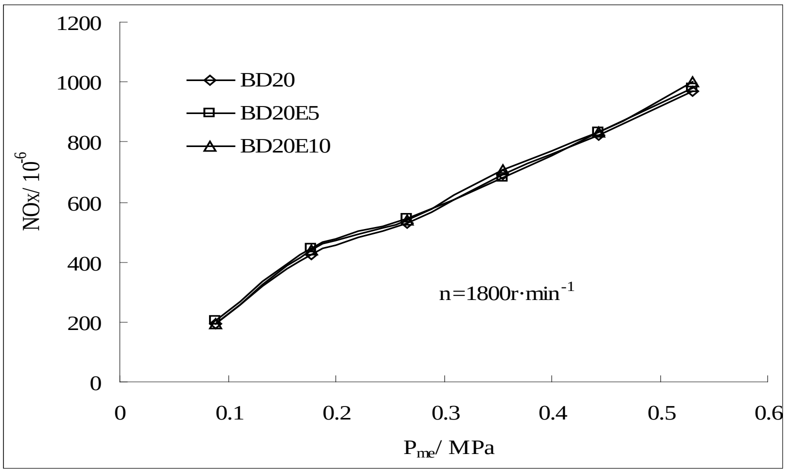

Fig. 15. NOx emission at 1800r/min.

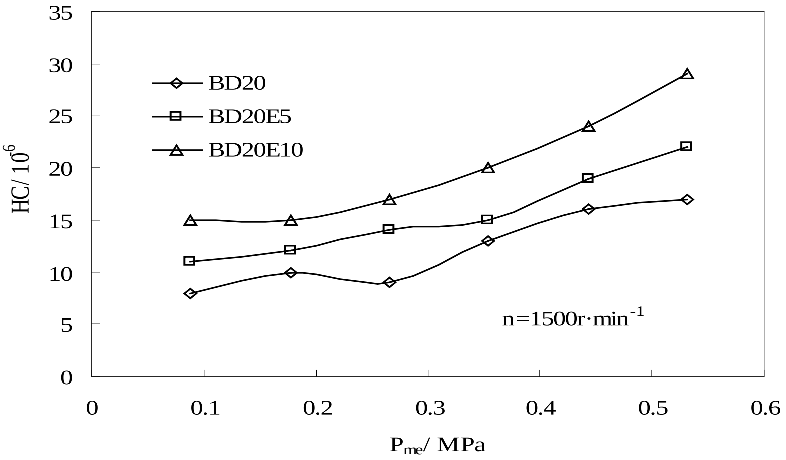

Fig. 16. HC emission at 1500r/min.

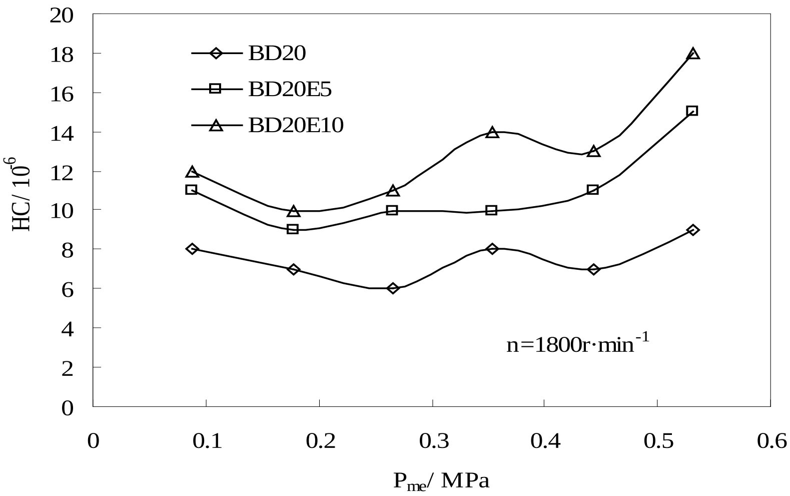

Fig. 17. HC emission at 1800r/min.

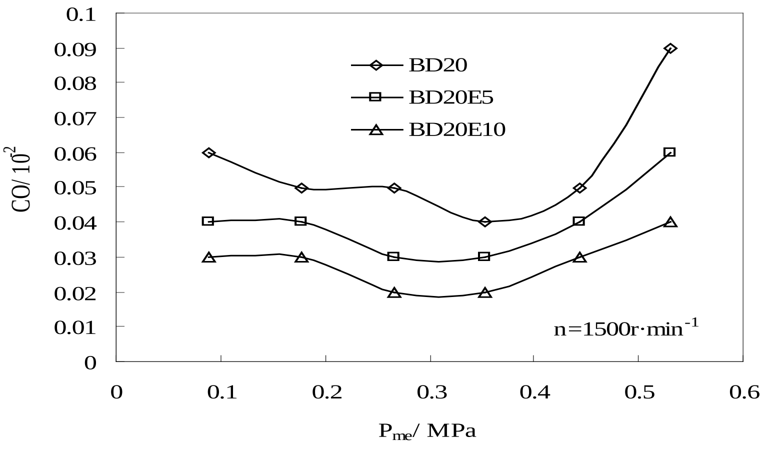

Fig. 18. HC emission at 1500r/min.

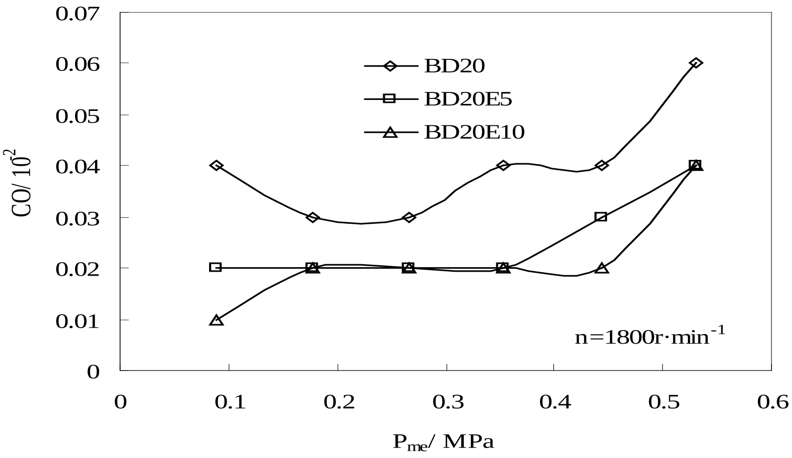

Fig. 19. HC emission at 1800r/min.

4. CONCLUSION

Biodiesel is a kind of clean and renewable energy, which has been applied within a certain scale in China. High viscosity and poor low temperature fluidity restrain further development and application of Biodiesel. Ethanol also belongs to renewable energy and it has several advantages such as higher oxygen content and low viscosity. In this premise, ethanol is helpful for improving the fuel characteristics of biodiesel and diesel mixture and accordingly the combustion process can be promoted.

To sum up, high latent heat of vaporization and poor ignitability of ethanol can delay the combustion, accelerate the combustion speed and promote the complete combustion. At small load peak combustion pressure and peak heat release rate decrease and at middle and large loads they increase obviously, with the blending of ethanol. Combustion characteristics directly affect the emissions, and as a result, compared with BD20, the smoke and CO emissions of BD20E5 and BD20E10 reduce, HC emissions increase and NOx emissions are basically unchanged.

ACKNOWLEDGMENT

This project is supported by the Natural Science Basic Research Plan in Shaanxi Province of China (Program No. 2014JQ7268) and Special Fund for Basic Scientific Research of Central Colleges, Chang'an University (2013G1221018, 2013G1221028, 2013G3222004).

REFERENCES

[1] BP P.L.C., 2012. BP Statistical Review of World Energy 2012. Retrieved January 31, 2013 from the World Wide Web: http://www.bp.com/content/dam/bp/pdf/statistical-review/statistical_review_of_world_energy_2013.pdf.

[2] Atabani A.E., Silitonga A.S., Badruddin I.A., Mahlia T.M.I., Masjuki H.H. and Mekhilef S., 2012. A comprehensive review on biodiesel as an alternative energy resource and its characteristics. *Renewable and Sustainable Energy Reviews* 16: 2070-2093.

[3] Lozada I., Islas J., and Grande G., 2010. Environmental and economic feasibility of palm oil biodiesel in the Mexican transportation sector.

Renewable and Sustainable Energy Reviews 14: 486-492.

[4] Sánchez J.A.G., Martínez J.M.L., Martín J.L. and Holgado M.N.F., 2012. Comparison of life cycle energy consumption and GHG emissions of natural gas, biodiesel and diesel buses of the Madrid transportation system. *Energy* 47: 174-198.

[5] Wang Z., Calderon M.M. and Lu Y., 2011. Lifecycle assessment of the economic, environmental and energy performance of Jatropha curcas L. biodiesel in China. *Biomass and Bioenergy* 35: 2893-2902.

[6] Yan X.Y. and R.J. Crookes. 2009. Reduction potentials of energy demand and GHG emissions in China's road transport sector. *Energy Policy* 37: 658–668.

[7] Ong H.C., Mahlia T.M.I. and Masjuki H.H., 2012. A review on energy pattern and policy for transportation sector in Malaysia. *Renewable and Sustainable Energy Reviews* 16: 532-542.

[8] Hao C., Qi. D.-H., and Bian Y.-Z., 2010. Study on performance of diesel engine fuelled with biodiesel-ethanol-water micro-emulsion fuel. *China Internal Combustion Engine Engineering* 31(1): 21-26.

[9] Qi D.-H, Chen H., Matthews R.D. and Bian Y.-Z., 2010. Combustion and emission characteristics of ethanol–biodiesel–water micro-emulsions used in a direct injection compression ignition engine. *Fuel* 89(5): 958- 964.

[10] Qi D.H., Chen H., Lee C.F., Geng L.M., Bian Y.Z., 2010. Experimental studies of a naturally aspirated, DI diesel engine fuelled with ethanol-biodiesel-water microemulsions. *Energy and Fuel* 24(1): 652-663.

[11] Xue J.L., Grift T.E, and Hansen A.C., 2011. Effect of biodiesel on engine performances and emissions. *Renewable and Sustainable Energy Reviews* 15(2): 1098–1116.

[12] Szulczyk K.R. and B.A. McCarl. 2010. Market penetration of biodiesel. *Renewable and Sustainable Energy Reviews* 14: 2426-2433.

[13] Lin L., Cunshan Z., Vittayapadung S., Xiangqian S., Mingdong D., 2011. Opportunities and challenges for biodiesel fuel. *Applied Energy* 88: 1020-1031.

[14] Kongkasawan J. and S. Capareda. 2012. Jatropha oil refining process and biodiesel conversion: mass and energy balance. *International Energy Journal* 13(4): 169-176.

[15] Demirbas A., 2011. Biodiesel from oilgae, biofixation of carbon dioxide by microalgae: A solution to pollution problems. *Applied Energy* 88: 3541–3547.

[16] Sorguven E. and M. Ozilgen, 2010. Thermodynamic assessment of algal biodiesel utilization. *Renewable Energy* 35: 1956–1966.

[17] Pruvost J., Van Vooren G., Le Gouic B., Couzinet-Mossion A. and Legrand J., 2011. Systematic investigation of biomass and lipid productivity by microalgae in photobioreactors for biodiesel application. *Bioresource Technology* 102: 150–158.

[18] Roleda M.Y., Slocombe S.P., Leakey R.J.G., Day J.G., Bell E.M. and Stanley M.S., 2013. Effects of temperature and nutrient regimes on biomass and lipid production by six oleaginous microalgae in batch culture employing a two-phase cultivation strategy. *Bioresource Technology* 129: 439–449.

[19] Chen H., Yang L., Zhang P.H. and Li J., 2012. Related policies to energy saving and GHG emission reductions in China and the US. *International Energy Journal* 13(4): 189-200.