

Article

Experimental Study of the Effect of Intake Oxygen Concentration on Engine Combustion Process and Hydrocarbon Emissions with N-Butanol-Diesel Blended Fuel

Wei Tian¹, Yunlu Chu¹, Zhiqiang Han², Xiang Wang³, Wenbin Yu^{4,*} and Xueshun Wu¹

- ¹ Fluid and Power Machinery Key Laboratory of Ministry of Education, Xihua University, Chengdu 610039, China; tianviv@hotmail.com (W.T.); chuyunlu713@126.com (Y.C.); xueshunwu08@163.com (X.W.)
- ² Vehicle Measurement, Control and Safety Key Laboratory of Sichuan Province, Xihua University, Chengdu 610039, China; hanzq@mail.xhu.edu.cn
- ³ Institute of Engineering Thermophysics, Chinese Academy of Sciences, Beijing 100190, China; wangxiang@iet.cn
- ⁴ Department of Mechanical Engineering, National University of Singapore, 9 Engineering Drive 1, Singapore 117576, Singapore
- * Correspondence: mpeyuw@nus.edu.sg; Tel.: +65-843-75-901

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Abstract: This paper summarizes a study based on a modified, light, single-cylinder diesel engine and the effects of the physicochemical properties for n-butanol-diesel blended fuel on the combustion process and hydrocarbon (HC) emissions in the intake at a medium speed and moderate load in, an oxygen-rich environment (Coxy = 20.9-16%), an oxygen-medium environment (Coxy = 16-12%), and an oxygen-poor environment (Coxy = 12-9%). The results show that the ignition delay period is the main factor affecting the combustion process and it has a decisive influence on HC emissions. In an oxygen-medium environment, combustion duration affected by the cetane number is the main reason for the difference in HC emissions between neat diesel fuel (B00) and diesel/n-butanol blended fuel (B20), and its influence increases as the intake oxygen concentration decreases. In an oxygen-poor environment, in-cylinder combustion temperature affected by the latent heat of vaporization is the main reason for the difference in HC emissions between B00 and B20 fuels, and its influence increases as the intake oxygen concentration decreases. By comparing B20 fuel with diesel/n-butanol/2-ethylhexyl nitrate blended fuel (B20 + EHN), the difference in the ignition delay period caused by the difference in the cetane number is the main reason for the difference in HC emissions between B20 and B20 + EHN fuels in oxygen-poor environment, and the effect of this influencing factor gradually increases as the intake oxygen concentration decreases.

Keywords: cetane number; latent heat of vaporization; combustion temperature; combustion duration; change of influencing factors

1. Introduction

When a low-reactivity fuel [1] is blended with a high reactivity fuel such as diesel [2], the fuel's alcohol properties are modified, which improves efficiency and clean combustion, and therefore it has attracted attention. However, such methods inevitably bring an increase in HC emissions, and some believe that the latent heat of vaporization of fuel is one of the main factors affecting HC emissions. Siwale et al. [3] conducted a study on the emissions of n-butanol-diesel blended fuel (by mixing pure diesel and n-butanol with volume fractions of 5%, 10%, and 20%, respectively) in a modified



turbocharged diesel engine. The results showed that the addition of n-butanol produces more HC emissions as compared with the pure diesel because of the slow evaporation and the high latent heat of vaporization of n-butanol blends over a 25% load at 3000 r/min. Rajesh Kumar et al. [4] studied the effects of the mixing iso-butanol, n-pentanol, n-hexanol, and n-octanol with diesel on the engine performance of a single-cylinder, four-stroke, naturally aspirated diesel engine. The results showed that the high HC emissions of iso-butanol-diesel blends was attributed to the dominative effect of the latent heat of evaporation over its cetane number. Using a turbocharged in-cylinder direct injection diesel engine, Ileri [5] studied the influence of adding 2-ethylhexyl nitrate (EHN) on the combustion and emission of a diesel-sunflower, oil-n-butanol blended fuel and diesel-sunflower, oil-1-pentanol blended fuel. The test results showed that, at all engine loads, the higher latent heat of vaporization of n-butanol and 1-pentanol leads to an increase in HC emissions compared to diesel. Armas et al. [6] investigated pollutant emissions from the New European Driving Cycle (NEDC) using ethanol- and butanol-diesel blends. The result showed that the latent heat of vaporization is an important factor in HC emissions, but the high combustion temperatures during the development of NEDC weakened the effect of the latent heat of vaporization as compared with the combustion in cold engine conditions. Atmanli, Ying, and others [7–11] have also drawn similar conclusions.

However, some believe that the cetane number is also one of the important factors affecting HC emissions. Doğan et al. [10] conducted a study on pure diesel and n-butanol-diesel blended fuel in a single-cylinder, four-stroke, naturally aspirated diesel engine. The results showed that at 3.3, 6.6, 9.8, and 13.1 N·m engine loads, the HC emissions of n-butanol-diesel fuel was higher than that of diesel fuel. One explanation for this was that the lower cetane number prolonged the ignition delay period and increased the time for fuel to evaporate, resulting in an increase in HC emissions. Imdadul et al. [12] studied the effect of adding EHN to a biodiesel-n-butanol-diesel blended fuel on the engine performance of a single-cylinder naturally aspirated engine. The results showed that EHN improved the cetane number and accelerated the blending of gas air-fuel, so the mixture became inhomogeneous in the diffusion combustion zone and emitted high HC. Choi et al. [9] conducted a diesel-n-butanol dual fuel test using a turbocharged, four-cylinder diesel engine with cylinder pressure common rail. The results showed that the THC of 20% n-butanol fuel is higher than that of diesel fuel, mainly because of the decrease of the cetane number of n-butanol-diesel fuel blends. Studies by López, Tutak, and others [2,13–18] have also shown that the cetane number has a significant effect on HC emissions.

Further research has indicated that the main cause of the change in HC emissions is the latent heat of vaporization and the cetane number of the fuel effects on the combustion temperature and combustion duration during the combustion process. Atmanli [7] conducted a studies on pure diesel, diesel-hazelnut oil-n-butanol blended fuel, diesel-hazelnut oil-1-pentanol blended fuel, and EHN in a four-cylinder, heavy-duty diesel engine. The studies have shown that the addition of n-butanol has a high latent heat of vaporization that causes combustion temperature drops, flame quenching, and cooling regions, which increase HC emissions. Rakopoulos et al. [19] conducted a study on pure diesel and n-butanol-diesel blended fuel with n-butanol volume fractions of 8%, 16%, and 24%, respectively, in a four-cylinder, high-speed, direct-injection diesel engine. The results showed that the temperature lowering effect, caused by heat of evaporation and low calorific value, had a dominant influence over the low cetane number and possibly led to a high temperature during the premixed part of combustion at 1.4, 2.57, and 5.37 bar brake mean effective pressure (BMEP). Zheng et al. [20] studied the influence of biodiesel-n-butanol, biodiesel-ethanol and biodiesel-2,5-dimethylfuran (DMF) blended fuels on the combustion and emission characteristics with different EGR rates, loads, and fuel blending ratios based on a single-cylinder diesel engine. The studies have shown that with a decrease in the cetane number, the ignition delay period is significantly increased and the premixed combustion is more rapid, resulting in shorter combustion and a higher-pressure rate. In addition, the latent heat of vaporization of the fuel can reduce the local temperature. Sathiyamoorthi et al. [21] conducted a diesel-lemongrass oil-ethanol blended fuel test in a single-cylinder, four-stroke naturally aspirated engine. The results showed that adding ethanol with a volume ratio of 5% increased HC. The main

reasons for this increase were that the cetane number of the blended fuel decreased after the addition of ethanol fuel, the combustion duration increased, and the lean flame out (LFO) area increased. Studies by Zhang, Guisheng, Chen, and others [17,22–24] have also confirmed the important role of combustion temperature and combustion duration on the effects of the latent heat of vaporization and the cetane number on HC emissions.

In summary, the cetane number and the latent heat of vaporization are two important factors affecting the generation of HC. Additionally, the combustion duration and the in-cylinder combustion temperature result caused by these two factors play a decisive role in the HC emission value. However, the promotion and inhibition of the coupling effect between the cetane number and the latent heat of vaporization for the combustion process, and the resulting variation relationship between combustion duration and in-cylinder combustion temperature at different intake oxygen concentrations have not been systematically studied. Using a modified, single-cylinder, light, diesel engine, this study focuses on the influence of the coupling effect of the cetane number and the latent heat of vaporization on key parameters of the combustion process and HC emissions in oxygen-rich, oxygen-medium, and oxygen-poor environments. The results provide a theoretical basis and data support for the rational organization of a combustion heat release process and a combustion path control in the later stage.

Moreover, in our previous experimental study, we investigated the effects of physicochemical properties of fuels on HC emissions under low intake pressure (lower than 120 kPa). A change of intake pressure causes enormous diversity on in-cylinder absolute oxygen content and this affects the engine combustion process, which causes different critical values of combustion process parameters and HC emissions. Therefore, it is necessary to investigate the effects of physicochemical properties of fuels on HC emissions under higher intake pressure, which is also one of the highlights of this study.

2. Materials and Methods

2.1. Research Idea and Research Scheme

To study the influence of cetane number and latent heat of vaporization at different intake oxygen concentrations on the combustion process parameters and HC emissions of a n-butanol-diesel blended fuel, this study coordinated the organization of fuel components and in-cylinder gas components based on the in-cylinder mixing process and the chemical reaction process, as shown in Figure 1. The diesel's cetane number and the latent heat of vaporization are adjusted via the addition of n-butanol or cetane improver to cause the change in the fuel's physical and chemical properties. The exhaust gas recirculation rate was also adjusted to control the gas temperature, pressure, and oxygen concentration in the cylinder. Finally, the coupling influence of fuel's physical and chemical properties on HC generation was explored.



Figure 1. General research approach and scheme.

2.2. Test Engine

As shown in Figure 2, the engine used in the test was originally a four-stroke, turbocharged diesel engine. The specific parameters of the engine are shown in Table 1. On the basis of the original engine, the engine's intake system, exhaust system, and the electronic control system were modified to build the required test environment. The intake and exhaust system of the original machine were removed. The first cylinder was transformed into a test cylinder with independent intake and exhaust system, while the other three cylinders were naturally aspirated. The test cylinder adopted the air compressor to simulate the boost pressure, and the surge tanks were added in the air intake and exhaust pipe, respectively, to stabilize the air quantity and mixture. The exhaust gas recirculation (EGR) pipeline was installed between the test cylinder's exhaust pipe and the surge tank to adjust the EGR rate by changing the opening of the back-pressure valve and EGR valve. A one-way valve was used to prevent backwards air flow. The electronic control unit (ECU) of the original engine controlled the rail pressure, throttle, EGR valve opening, and the fuel injection of the remaining three cylinders. The fuel injection of the test cylinder was controlled by the open ECU developed by our laboratory.



Figure 2. Engine test system.

Table 1	Main	narameters	of original	diesel	engine
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Item	Parameter
Type of diesel engine	Water-cooled, four-stroke, in-line, OHV
Bore/(mm)	93
Stroke/(mm)	102
Displacement/(mL)	2771
Compression ratio	17.5:1
Intake type	Turbocharged
Oil supply system	High-pressure common rail
Maximum power (kW)/(r/min)	80/3600
Maximum torque $(N \cdot m)/(r/min)$	280/(1800-2400)
Intake advance angle (°CA After Top Dead Center (ATDC))	351
Intake lag angle (°CA Before Top Dead Center (BTDC))	161
Exhaust advance angle (°CA ATDC)	117
Exhaust lag angle (°CA BTDC)	352

2.3. Test Fuel and Supply System

In this test, China V diesel oil and n-butanol were used as the benchmark fuel, and n-butanol was mixed with China V diesel according to the mass fraction of 20:80 to obtain the n-butanol-diesel blended fuel with the mass fraction for n-butanol of 20%, named B20. The China V diesel was named B00. A suitable proportion of 2-ethylhexyl nitrate (EHN), the ignition delay period improver, was added to B20 to adjust the ignition delay period of B20 to be consistent with that of B00. The B20 fuel with the ignition delay period improver EHN was named B20 + EHN. The main physicochemical property parameters of the test fuels are shown in Table 2.

Property	B00	B20 + EHN	B20
Cetane number	45-55	45-55	37.6-45.6
Low heat value (MJ/kg)	42.8	40.86	40.86
Latent heat of vaporization (kJ/kg)	0.27-0.301	0.332-0.357	0.332-0.357
Density (g/mL)	0.8265	0.825	0.8235

Table 2. Comparison of main physical properties of blended fuels.

The fuel supply system consisted of fuel tank, filter, fuel consumption meter, high-pressure oil pump, high-pressure common rail, pressure regulator, fuel injector, and electronic control system. Among them, the high-pressure common rail adopted the BOSCH (BOSCH Co., Ltd.) three-generation high- pressure common rail system and the electronic control system adopted the open WIT (WIT Electronic Fuel System Co., Ltd.) ECU.

2.4. Data Acquisition System

The signal acquisition system used was composed of an air flowmeter, fuel consumption meter, photoelectric encoder, signal conditioning circuit, in-cylinder pressure sensor, charge amplifier, pressure sensor, temperature sensor, NI data acquisition card, and PC. The photoelectric encoder and the signal conditioning circuit were responsible for the capture and synchronization of the crankshaft signal; the cylinder pressure sensor and charge amplifier were responsible for the acquisition of the in-cylinder pressure; the pressure and temperature sensor collected the steady-state pressure and temperature of the engine; the data of the air flowmeter and fuel consumption meter were sent to the PC through 485 communication. The main instruments and equipment of the acquisition system are shown in Table 3.

Name of Equipment	Model		Specifications	Precision	Manufacturer
Intake flow meter	Toceil20N80		0 (15)–750 kg/h	0.1 kg/h	Shanghai ToCeiL
In-cylinder pressure sensor	6125C		0–30 MPa	$\pm 1\%$	Switzerland Kistler
Fuel consumption meter	CMFG010		0–60 kg/h	$\pm 0.12\%$	Shanghai ToCeiL
Constant temperature system of engine coolant	ET4900-LQY		45–110 °C	±2 °C	Sichuan Chengbang
Electric eddy current dynamometer	DW110		110 kW 400 N∙m/2800 r/min 8000 r/min	$\pm 0.4\%$ FS, ± 1 r/min	Sichuan Chengbang
Gas analyzer	MEXA-7100DEGR	CO HC NOx	0–5000 ppm 0–50000 ppm 0–10000 ppm	1 ppm 1 ppm 1 ppm	Japan HORIBA
Pressure sensor	CYYZ11-Z-46-V5-07-B-G		-100-500 kPa	0.1% FS	Beijing Star Sensor
Temperature sensor	WZPK-191		−50–400 °C	1 °C	Shanghai Yijia
Acquisition card NI-USB6353		-10 v-10 v	16-bit resolution	America NI	

Table 3. Specifications and precision of measuring equipment.

On the basis of the in-cylinder pressure data collected, the instantaneous heat release rate and the average in-cylinder temperature were calculated using the off-line combustion analysis system written

by LabVIEW. In the process of combustion, high-frequency oscillations occurred when the combustion pressure was propagated in a narrow combustion chamber, and external electromagnetic interference caused jagged fluctuation of the measured in-cylinder pressure [25]. Therefore, the smoothing process of the measured in-cylinder pressure was required. At present, there are three methods for curve smoothing: the cubical smoothing algorithm with seven-point approximation [26], the orthogonal polynomial algorithm [27] and the cubical smoothing algorithm with five-point approximation [28]. The combustion analysis system adopted the cubical smoothing algorithm with five-point approximation for the smoothing process of the cylinder pressure data.

The instantaneous heat release rate was calculated according to the first law of thermodynamics. The calculation methods for instantaneous heat release rate and in-cylinder average temperature were referred to in previous studies [29–32].

Gas emissions were analyzed using a HORIBA's MEXA-7100DEGR (HORIBA, Kyoto, Japan) analyzer and THC was measured using a heated hydrogen flame lionization detector in HORIBA's MEXA-7100DEGR (HORIBA, Kyoto, Japan). The unit of THC was converted from (ppm) to (g/(kW·h)) [33].

The intake oxygen concentration (Coxy) was determined by the EGR rate and the oxygen concentration in the exhaust gas, as shown in Equation (1):

$$C_{\text{oxy}} = \left[\left(1 - \frac{a\%}{100} \right) \times 0.209 + a\% \times b\% \right] \times 100 \tag{1}$$

where a% is the EGR rate, b% is the O₂ concentration in the exhaust, and a% is shown in Equation (2):

$$a\% = \frac{CO_{2in} - CO_{2air}}{CO_{2exh} - CO_{2air}}$$
(2)

where CO_{2in} is CO_2 concentration of the intake air, CO_{2exh} is the CO_2 concentration of exhaust gas, and CO_{2air} is the CO_2 concentration in the air. Both a and b are measured directly using a HORIBA's MEXA-7100DEGR analyzer (HORIBA, Kyoto, Japan).

2.5. Test Conditions

The test conditions for the test engine were as follows: speed of 1500 r/min, cyclic fuel heating value of 642 J/cycle, break mean effective pressure of 0.5 MPa, fuel injection pressure of 100 MPa, fuel injection timing of -7 °CA ATDC, cooling water temperature of 85 °C, intake pressure of 180 kPa, and intake air temperature of 17 °C. The main parameters of the test conditions are shown in Table 4.

Item	Parameter
Engine speed	1500 r/min
Fuel type	B0/B20/B20 + EHN
Cyclic fuel heating value	642 J/cycle
Injection timing	-7 °CA ATDC
Injection pressure	100 MPa
Intake air pressure	180 kPa
Intake air temperature	17 °C
Cooling water temperature	85 °C

Table 4. Test conditions of engine.

2.6. Parameter Definition

The difference in HC emissions or combustion process parameters for two fuels (ΔA) was calculated as follows:

$$\Delta A = A_1 - A_2 \tag{3}$$

where A is HC emission, T_{max} , CD or ID, A_1 and A_2 are the corresponding values of A in two fuels at the same intake oxygen concentration. The specific definitions of Δ HC, Δ Tmax, Δ CD, and Δ ID under different comparative analyses are shown in Table 5.

Comparative Analysis of	Object of A	A_1 is the Value of	A ₂ is the Value of
	HC	B20	B00
	T _{max}	B20	B00
B00 and B20 fuels	CD	B00	B20
	ID	B20	B00
	HC	B20 + EHN	B00
	T _{max}	B20 + EHN	B00
B00 and B20 + EHN fuels	CD	B00	B20 + EHN
	ID	B00	B20 + EHN
	HC	B20	B20 + EHN
	T _{max}	B20 + EHN	B20
B_{20} and B_{20} + EHIN fuels	CD	B20 + EHN	B20
	ID	B20	B20 + EHN

Table 5. Parameters in the definitions of Δ HC, Δ T_{max}, Δ CD, and Δ ID.

3. Results and Discussion

To analyze the influence of the physicochemical properties of n-butanol-diesel blended fuel on HC emissions based on the intake oxygen concentration, the intake oxygen concentration was divided into an oxygen-rich environment, an oxygen-medium environment, and an oxygen-poor environment according to the trend of HC generation at different intake oxygen concentrations. The intake oxygen concentration in the oxygen-rich environment was 20.9–16%, in the oxygen-medium environment it was 16–12%, and in the oxygen-poor environment it was 12–9%.

3.1. Influence of Cetane Number and Latent Heat of Vaporization on Combustion Process and HC Emission at Different Intake Oxygen Concentrations

3.1.1. Oxygen-Rich Environment

As shown in Figure 3a, in an oxygen-rich environment with the oxygen concentration of 20.9–16% in the intake, the HC emission values of the two fuels are slightly reduced as the intake oxygen concentration decreases and the overall variation quantity is less as compared with the oxygen-medium and oxygen-poor environments. At the same oxygen concentration, the HC value generated by B20 fuel is slightly greater than that by B00 fuel, and as the intake oxygen concentration decreases, the difference in HC emissions of the two fuels varies from 0.13 g/(kW·h) to 0.31 g/(kW·h). Compared with the oxygen-poor environment, the difference in HC emissions does not change much. This is because the B20 fuel has a higher maximum in-cylinder temperature and shorter combustion duration in the oxygen-rich environment, and the combustion difference between the two fuels changes less. As shown in Figure 3b,c and Figure 4a, as the intake oxygen concentration decreases, the difference in maximum in-cylinder temperature for the two fuels is maintained in the range of 10.3 K to 16.6 K, and the difference in combustion duration for the two fuels is maintained in the range of 1.5 °CA to 2 °CA, so the difference in HC emissions between the two fuels is only slightly reduced.



Figure 3. HC emissions and the difference (**a**), maximum in-cylinder temperatures and the difference (**b**), combustion durations and the difference (**c**), and ignition delay periods and the difference (**d**) for B00 and B20 fuels.



Figure 4. Average in-cylinder temperature and heat release rate at 18% (**a**), 15% (**b**), and 10% (**c**) intake oxygen concentrations.

3.1.2. Oxygen-Medium Environment

As shown in Figure 3a, in an oxygen-medium environment with the oxygen concentration of 16–12% in the intake, the HC emissions value of B00 fuel increases from 0.65 g/(kW·h) to 2.69 g/(kW·h)

and the HC emissions value of B20 fuel increases from $1.27 \text{ g/(kW \cdot h)}$ to $3.52 \text{ g/(kW \cdot h)}$ as the intake oxygen concentration decreases. At the same intake oxygen concentration, the difference in HC emissions between the two fuels increases from $0.62 \text{ g/(kW \cdot h)}$ to $0.83 \text{ g/(kW \cdot h)}$. This is due to the fact that in the oxygen-medium environment, the B20 fuel has a higher maximum in-cylinder temperature and shorter combustion duration as compared with the B00 fuel, as shown in Figure 3b,c and Figure 4b. As the intake oxygen concentration decreases, the difference in maximum in-cylinder temperature between the two fuels increases from 6.8 K to 33.2 K and the difference in combustion duration between the two fuels increases from 1 °CA to 3 °CA. This indicates that the main reason for the higher HC emissions of B20 fuel in the oxygen-medium environment is the shorter combustion duration. In addition, the main reason for the increase in the difference in HC emissions between the two fuels increases with the decrease of the intake oxygen concentration while the in-cylinder combustion temperature has little effect on the difference in HC.

The addition of n-butanol to diesel fuel increases the latent heat of vaporization of the fuel and lowers the cetane number of the fuel, thereby increasing the ignition delay period. However, these two factors exert completely opposite effects on the in-cylinder combustion temperature and combustion duration. On the one hand, after the addition of n-butanol fuel to diesel fuel, the latent heat of vaporization becomes greater, the ignition delay period becomes longer, and the temperature of the mixture gas decreases before ignition. These effects are beneficial due to the reduction in the combustion temperature and flame propagation speed of the entire combustion process and the increase in the combustion duration. On the other hand, when n-butanol fuel is added to diesel fuel, the cetane number becomes less, the ignition delay period becomes longer, the mixture gas is mixed more homogeneously, the heat release rate becomes faster after ignition, and the in-cylinder temperature rise becomes faster, which are favorable due to the increase in the combustion duration [20].

As shown in Figure 3d, it is evident from the comparison of the ignition delay period of the two fuels in the oxygen-medium environment that the ignition delay period of the B20 fuel is greater, and the difference in the ignition delay period between the two fuels is in the range of 0.5–1 °CA, which is almost unchanged. In an oxygen-medium environment, B20 fuel has a longer ignition delay period, higher combustion temperature, and shorter combustion duration at the same intake oxygen concentration, which indicates that the lower cetane number of B20 fuel is the main factor affecting combustion. When the intake oxygen concentration decreases, the difference in the ignition delay period is almost constant, the difference in the in-cylinder combustion temperature and the difference in the combustion duration increase, which indicates that the cetane number plays a main role in increasing the difference in combustion duration for the two fuels. Therefore, the cetane number is the main factor affecting the generation of HC in the medium oxygen environment, and its influence increases as the intake oxygen concentration decreases.

3.1.3. Oxygen-Poor Environment

As shown in Figure 3a, in an oxygen-poor environment with an intake oxygen concentration of 12% to 9%, the HC emissions value of the two fuels increases significantly as the intake oxygen concentration decreases. The HC emissions value of B00 fuel increases from 2.69 g/(kW·h) to 10.51 g/(kW·h), and of B20 fuel increases significantly from 3.52 g/(kW·h) to 21.03 g/(kW·h). Furthermore, the difference in HC emissions between the two fuels increases from 0.83 g/(kW·h) to 10.52 g/(kW·h) at the same intake oxygen concentration. That is, in an oxygen-poor environment, the in-cylinder temperature and the combustion duration of the B20 fuel are lower than those of the B00 fuel, as shown in Figure 3b,c and Figure 4c. As the intake oxygen concentration decreases, the maximum in-cylinder temperature of the B00 fuel increases from 973.8 K to 997.7 K, while that of the B20 fuel decreases from 1007 K to 911.9 K, and the difference in the maximum in-cylinder temperature of changes from 33.2 K to -85.8 K. As the intake oxygen concentration decreases, the difference in combustion duration between the two fuels decreases from 3 °CA to

1.5 °CA. Therefore, one of the main reasons for the higher HC emissions of B20 fuel in an oxygen-poor environment is its lower combustion temperature and shorter combustion duration. Another reason is the oxygen in B20 fuel that contributes to the oxidation process of HC. The increased difference in HC emissions between B20 fuel and B00 fuel with the decrease of the intake oxygen concentration is mainly caused by the increase in the difference in the in-cylinder combustion temperature. The influence of the in-cylinder combustion temperature on the HC emissions increases, and the influence of the combustion duration decreases, when the intake oxygen concentration decreases.

There is a need to further analyze the influence of the relationship between the latent heat of vaporization and the cetane number on HC generation. As seen in Figure 3d in an oxygen-poor environment, as the intake oxygen concentration decreases, the difference in the ignition delay period is maintained in the range of 0.5 °CA to 1.5 °CA, which is almost constant. Meanwhile, the difference in the maximum increase in-cylinder temperature and the combustion duration decreases. This demonstrates that when the intake oxygen concentration decreased, the B20 fuel with a higher latent heat of vaporization causes a further decrease of the in-cylinder combustion temperature, so the difference in combustion temperature between the two fuels continues to increase. In addition, the latent heat of vaporization of the B20 fuel causes the combustion duration to be prolonged, reducing the difference in combustion duration between the two fuels. It is proven that in an oxygen-poor environment, the main factor influencing the difference in HC emissions between B20 fuel and B00 fuel is the latent heat of vaporization, and as the intake oxygen concentration lowers, the influence of latent heat of vaporization will be more obvious.

3.2. Influence of Ignition Delay Period on Combustion Process and HC Emission at Different Intake Oxygen Concentrations

As mentioned in Section 2.1, the ignition delay period is an important intermediate influencing factor, and both the cetane number and the latent heat of vaporization affect the in-cylinder combustion temperature and the combustion duration through the ignition delay period. To further analyze the effects of latent heat of vaporization on the combustion process and HC generation at different intake oxygen concentrations, 0.7% EHN was added to B20 fuel to adjust the ignition delay period of this B20 + EHN fuel so that it was the same as the ignition delay period of B00 fuel.

Oxygen-Rich, Oxygen-Medium, and Oxygen-Poor Environments

As shown in Figure 5a, as the intake oxygen concentration decreases from 20.9% to 9%, the HC emissions of the two fuels first decrease slightly and then increase. The HC emissions value of B00 fuel increases from $0.52 \text{ g/(kW \cdot h)}$ to $10.51 \text{ g/(kW \cdot h)}$, and the HC emissions value of B20 fuel increases from $1.07 \text{ g/(kW \cdot h)}$ to $13.68 \text{ g/(kW \cdot h)}$. The difference in HC emissions between the two fuels is maintained in the range of 0.13 to 1.28 g/(kW·h), within the range of the intake oxygen concentration of 20.9% to 10%, and only when the intake oxygen concentration is 9%, the difference in HC emissions reaches $3.17 \text{ g/(kW \cdot h)}$. This is because as the intake oxygen concentration decreases from 20.9% to 10%, the difference in the ignition delay period of the two fuels is maintained in the range of 0.5 °CA to 1 °CA and the difference in maximum in-cylinder temperature of the two fuels is reduced from 50.2 K to 3.3 K, as shown in Figure 5b. As shown in Figure 5c, the difference in combustion duration of the two fuels varies from -0.5 °CA to 1 °CA. As shown in Figure 6, when the ignition delay periods of the two fuels is adjusted to be the same, the difference in the in-cylinder combustion temperature and the difference in combustion duration is slight, resulting in a slight HC difference between the two fuels at different intake oxygen concentrations. When the intake oxygen concentration is 9%, since the B20 + EHN fuel is 2.5 °CA lower than that of the B00 fuel in terms of the ignition delay period, the mixing process of the B20 + EHN fuel is less homogeneous, the heat release during the descent of the piston is slower, and its maximum in-cylinder temperature is 63.6 K lower than that of B00 fuel, which ultimately results in a large difference in HC emissions between the two fuels.



Figure 5. HC emissions and the difference (**a**), maximum in-cylinder temperatures and the difference (**b**), combustion durations and the difference (**c**), and ignition delay periods and the difference (**d**) for B00 and B20 + EHN fuels.



Figure 6. Average in-cylinder temperature and heat release rate at 18% (**a**), 15% (**b**), and 10% (**c**) intake oxygen concentrations.

3.3. Influence of Cetane Number on Combustion Process and HC Emission at Different Intake Oxygen Concentrations

In this study we compared the difference between B20 and B20 + EHN fuels at different intake oxygen concentrations to further analyze the influence relation of the cetane number on HC emissions.

3.3.1. Oxygen-Rich and Oxygen-Medium Environments

In the oxygen-rich and oxygen-medium environments, as the intake oxygen concentration decreases, the HC emissions value of B20 fuel increases from $0.83 \text{ g/(kW \cdot h)}$ to $3.52 \text{ g/(kW \cdot h)}$, the HC emissions value of B20 + EHN fuel increases from $1.07 \text{ g/(kW \cdot h)}$ to $3.04 \text{ g/(kW \cdot h)}$, and the difference in HC emissions between the two fuels increases from $-0.24 \text{ g/(kW \cdot h)}$ to $0.48 \text{ g/(kW \cdot h)}$, with a slight change in difference, as shown in Figure 7a. This is because the difference in maximum in-cylinder temperature of the two fuels is maintained in the range of -14.4 K to 34.1 K (Figure 7b) and the difference in combustion duration of the two fuels is maintained in the range of 1 °CA to 2.5 °CA (Figure 7c) as the intake oxygen concentration decreases. As seen in Figure 8, in the oxygen-rich and oxygen-medium environments, although the intake oxygen concentration is reduced, the greater intake pressure causes the absolute oxygen content in the cylinder to be sufficient at this time, and the small change in the combustion difference results in a slight change in the HC difference.



Figure 7. HC emissions and the difference (**a**), maximum in-cylinder temperatures and the difference (**b**), combustion durations and the difference (**c**), and ignition delay periods and the difference (**d**) for B20 and B20 + EHN fuels.



Figure 8. Average in-cylinder temperature and heat release rate at 18% (**a**), 15% (**b**), and 10% (**c**) intake oxygen concentrations.

3.3.2. Oxygen-Poor Environment

In an oxygen-poor environment, as the intake oxygen concentration decreases, the HC emissions value of the two fuels increases significantly. The HC emissions value of the B20 fuel is greater than that of the B20 + EHN fuel and the difference in HC emissions between the two fuels is increased from 0.48 g/(kW·h) to 7.35 g/(kW·h), as shown in Figure 7a. This is because as the intake oxygen concentration decreases, the in-cylinder combustion temperatures of both fuels decrease, and the difference in maximum in-cylinder temperature between the two fuels increases from -14.4K to 22.2K, as shown in Figures 7b and 8. Meanwhile, the combustion duration of the B20 + EHN fuel is greater than that of the B20 fuel, and the difference in combustion duration between the two fuels is reduced from 2.5 °CA to 1.5 °CA (Figure 7c). Therefore, the main reason for the lower HC emissions value of B20 + EHN fuel as compared with that of B20 fuel in an oxygen-poor environment is because the combustion duration of B20 + EHN fuel as compared with that of B20 fuel in an oxygen concentration decreases, the gradual increase of the difference in the average in-cylinder temperature is another reason for the increases of the difference in HC emissions between the two fuels, and the influence of the in-cylinder combustion temperature on the HC generation is increased while the influence of the combustion duration on HC generation is decreased.

It is necessary to further analyze the effect of the cetane number on HC generation. As shown in Figure 7d, as the intake oxygen concentration decreases, the ignition delay period of the B20 fuel increases from 11 °CA to 14 °CA, the ignition delay period of the B20 + EHN fuel increases slightly from 10 °CA to 11 °CA, and the difference in the ignition delay period between the two fuels is increased from 1 °CA to 3 °CA. This demonstrates that as the intake oxygen concentration decreases, the combustion phase of the two fuels is further away from the top dead center, and compared with the B20 + EHN fuel, the mixing of the B20 fuel with a longer ignition delay period is more homogeneous,

but its combustion phase is more lagging. In the case of heat release, the heat release rate of combustion is not significantly increased, and the heat release process is slowed down significantly, resulting in a greater decrease in the in-cylinder combustion temperature and a faster growth rate in the combustion period, as shown in Figure 8c. It can be seen that in an oxygen-poor environment, the difference in HC emissions between the two fuels is caused by the difference in the ignition delay period resulting from the difference in the cetane number, and as the intake oxygen concentration decreases, the effect of this influencing factor gradually increases.

4. Conclusions

In this paper, the effects of cetane number and latent heat of vaporization on the combustion characteristics and HC emissions of n-butanol/diesel blended fuel were studied at different intake oxygen concentrations. The results of the study are summarized as follows:

- (1) By adjusting the ignition delay periods of B00 and B20 + EHN fuels to the same and comparing the two fuels, it was shown that the ignition delay period is the main factor affecting the combustion duration and the in-cylinder combustion temperature, and the ignition delay period, which is dominated by cetane number and latent heat of vaporization, has a decisive influence on HC emissions.
- (2) In an oxygen-rich environment, although the intake oxygen concentration is reduced, the greater intake pressure makes the absolute oxygen content in the cylinder still sufficient, and the small change in the combustion difference results in less variation of the difference in HC emissions.
- (3) In an oxygen-medium environment, the combustion duration is the main factor causing the difference in HC emissions between the B00 and B20 fuels. Moreover, as the intake oxygen concentration decreases, the effect of this factor increases. Meanwhile, the cetane number in the fuel is the main factor causing the difference in combustion duration of the two fuels and its effect increases as the intake oxygen concentration decreases.
- (4) In an oxygen-poor environment, the in-cylinder combustion temperature is the main cause of the difference in HC emissions in two fuels and the influence of this factor increases as the intake oxygen concentration decreases, while the influence of the combustion duration decreases.
- (5) In an oxygen-poor environment, the latent heat of vaporization is the main factor affecting the difference in HC emissions between B20 and B00 fuels, and as the intake oxygen concentration decreases, the effect of this factor increases.
- (6) In an oxygen-poor environment, the difference in the ignition delay period caused by the difference in the cetane number is the main reason for the difference in HC emissions between B20 and B20 + EHN fuels, and as the intake oxygen concentration decreases, the effect of this influencing factor gradually increases.

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Nomenclature

ATDC	after top dead center
BMEP	brake mean effective pressure
CA	crank angle
CD	combustion duration
Coxy	intake oxygen concentration
ECU	electric control unit
EGR	exhaust gas recirculation
EHN	2-Ethylhexyl nitrate
HC	hydrocarbon
HRR	heat release rate
ID	ignition delay
IT	in-cylinder temperature
THC	total hydrocarbon
T _{max}	maximum in-cylinder temperature
ΔCD	difference of combustion duration in two fuels
ΔID	difference of ignition delay in two fuels
ΔHC	difference of hydrocarbon in two fuels
ΔT_{max}	difference of maximum in-cylinder temperature in two fuels

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