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EXPERIMENTAL STUDY ON THE EFFECT OF INJECTION PARAMETERS ON COMBUSTION AND PARTICULATE SIZE DISTRIBUTION OF PARTIALLY PREMIXED COMBUSTION FUELED WITH N-BUTANOL

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ABSTRACT

In this paper, the effects of injection parameters on combustion and particulate size distribution of partially premixed combustion (PPC) fuel with n-butanol were investigated experimentally. High concentrations of particle emission for the n-butanol PPC combustion are observed. The particle sizes are primarily concentrated within 64nm. With the advance of the start of injection (SOI) timing, more particles are formed and the particulate size distribution curve shifts towards right (larger size). In addition, the pilot-main injection strategy can effectively reduce the maximum pressure rise rate (MPRR). Furthermore, through adopting appropriate injection parameters, the MPRR and particle number can be reduced simultaneously, while still maintaining a comparable indicated thermal efficiency compared to the single injection strategy.

Keywords: Partially premixed combustion, n-Butanol, Injection strategy, Particulate Size Distribution

NONMENCLATURE

Abbreviations	
SOI	Start of injection
PPC	Partially premixed combustion
MPRR	Maximum pressure rise rate
CA50	Crank angle when 50% of the total heat has been released
SOF	Soluble organic fraction

1. INTRODUCTION

In recent years, the partially premixed combustion (PPC) strategy has gained much attention due to its potentially high thermal efficiency and low emissions [1,2]. However, high soot emission can be a problem for the diesel PPC combustion, especially at the high-load condition. As a result, the fuel with high octane number and volatility should be considered to further control the soot emission, such as gasoline. With the increasing concerns on the shortage of fossil fuel resources, however, the biofuels may also be a good choice.

N-butanol is a promising biofuel [3]. These years, the production technology of n-butanol has been improved significantly, which gains the worldwide attention. Due to its high oxygen content and octane number, n-butanol is suitable for the PPC combustion strategy [4]. In the previous studies, n-butanol is typically served as blended fuel with gasoline or diesel in order to reduce the soot emission [4, 5-9]. In addition, n-butanol can also be adopted as a single alternative fuel [10-14]. It is indicated that the n-butanol PPC combustion has the potential to obtain low NOx and soot emissions, as well as high thermal efficiency. However, because of the high octane number of n-butanol, the maximum pressure rise rate (MPRR) for the n-butanol PPC combustion is extremely high, which may limit the high-load operation [10, 14]. As a result, many works recommended to adopt the double injection strategy [15, 16].

Particle emission is a major issue for the internal combustion engines. According to the EURO-VI emission standard, the particle number should be less than 6.0×10^{11}#/Km. By definition, the particles with a diameter lower than 30 nm are classified as nucleation mode and those larger than 30 nm are classified as accumulation mode. Typically, the total particles are consisted of about 90% of nucleation particles. However, due to the smaller sizes, the mass of the nucleation particles is typically less than the 20% of the total particle mass. Especially for the PPC combustion, the premixed combustion can result in a high concentration of nucleation particles, which contains many soluble organic fraction (SOF) contents. As a consequence, it is more preferable to measure the particle size distributions for the PPC combustion strategy [17-19]. Particularly for the n-butanol PPC combustion, it has a high proportion of premixed combustion due to the high octane number and volatility of n-butanol. Therefore,

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this paper tends to explore the effects of the injection strategy on the combustion performance and particulate size distribution for the n-butanol PPC combustion.

2. EXPERIMENTAL SETUP AND METHODOLOGY

2.1 Test bench

The experiment was conducted on a single-cylinder diesel engine, which is modified from a six-cylinder engine equipped with a common-rail direct injection system. The engine specifications are presented in Table 1. Figure 1 shows the schematic of the experimental setup.

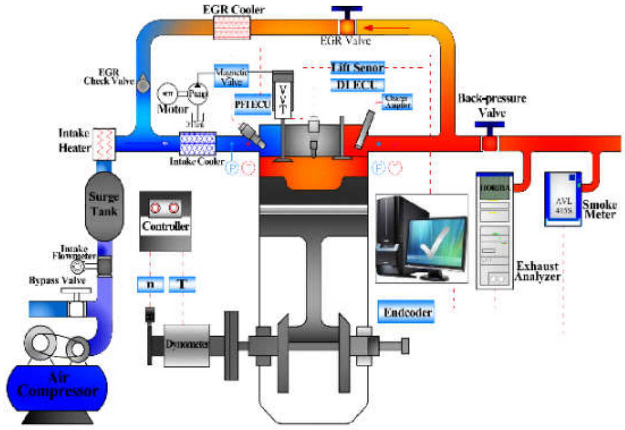


Figure 1. *Schematic of the experimental setup*

Table 1. *Engine specifications*

Engine speed (r·min-1)	2500
Bore × Stroke (mm)	105 ×125
Connecting rod length (mm)	210
Compression ratio	16:1
Displacement (L)	1.0818
Combustion chamber	Reentrant type
Injection system	Common rail
Injection pressure (MPa)	80
Number of injector holes	8
Injector hole diameter (mm)	0.15
Included spray angle (deg)	150

2.2 Test conditions

The engine speed is maintained at 1500 r/min. The intake temperature and pressure are maintained at 50±1 °C and 0.24 MPa, respectively. In order to ensure the repeatability and comparability of the testing results, the temperature of the cooling water and lubricating oil are controlled at 85±1 °C and 95±1 °C, respectively. In addition, a double injection strategy was adopted and the pilot injection rate is defined as the ratio of the pilot injection pulse-width to the total injection pulse-width, as illustrated in Figure 2. And the total cycle fuel injection quantity keeps at 70mg/cyc.

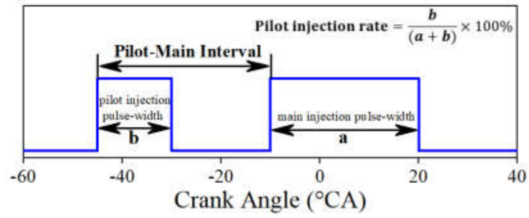
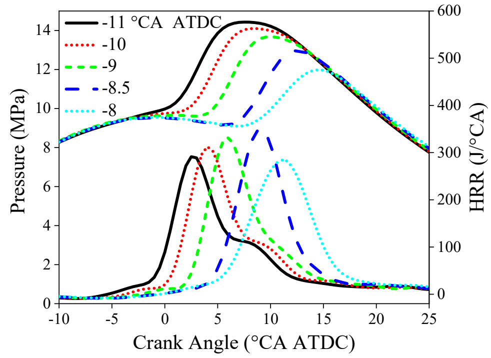


Figure 2. *Definition of the pilot injection rate*

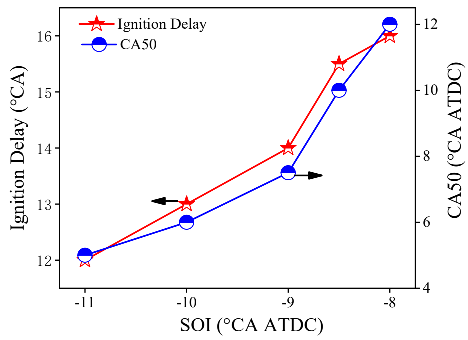
3. RESULTS AND DISCUSSION

3.1 The Effect of Injection Timing on Combustion and Particulate Size Distribution for the n-Butanol PPC Combustion

The EGR rate of this section is kept at 10%. Figure 3 shows the in-cylinder pressure, heat release rate, CA50, and ignition delay at different SOI (start of injection) timings. As shown in Figs. 3(a) and 3(b), with the advance of SOI timing, the peak heat release rate firstly increases and then decreases. In addition, the ignition delay gets shorter and the combustion changes from the premixed combustion mode to the two-stage combustion mode. It is noticed that when the SOI timing is changed from -8 to -9 °CA ATDC, the combustion is dominated by the premixed combustion process, similar to the homogenous charge compression ignition combustion mode, of which the ignition is quite sensitive to the temperature.



(a) In-cylinder pressure and heat release rate



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(b) Ignition delay and CA50

Figure 3. *The in-cylinder pressure and heat release rate, ignition delay, and CA50 at different injection timings*

Figure 4 shows the MPRR and indicated thermal efficiency at different injection timings. The MPRR increases abruptly as the SOI timing is advanced from -8 to -9 °CA ATDC, primarily due to the more intense premixed combustion process. As shown in Fig. 3(b), the CA50 is reduced sharply with the sharp increase of MPRR, which also leads to the higher thermal efficiency. However, with the further advance of SOI timing from -9 to -11 °CA ATDC, the combustion speed slows down while the heat transfer loss increases, owing to the diffusion combustion process.

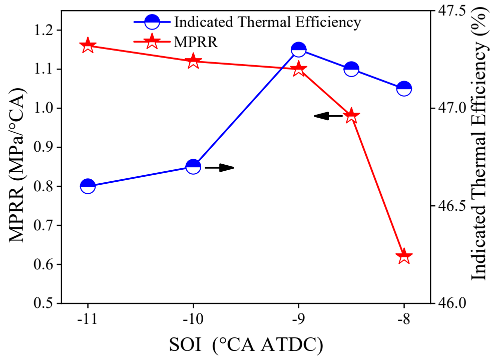
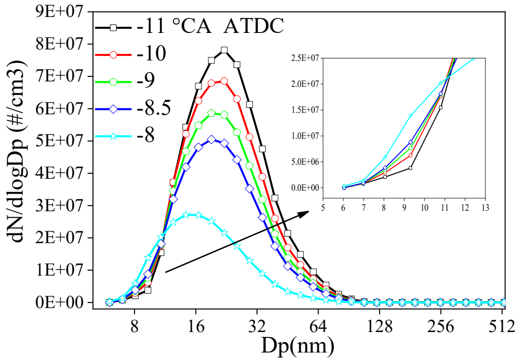


Figure 4. *The MPRR and indicated thermal efficiency at different SOI*

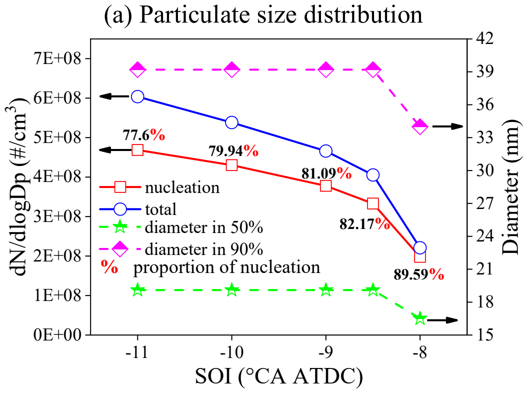
Figure 5 shows the particulate size distribution and statistics of particle emissions at different SOI. The 'diameter in 50%' and 'diameter in 90%' in Fig. 5(b) are defined as the diameters corresponding to the 50% and 90% of the total particles number when calculated from the smallest diameter to larger diameter. In some degree, the 'diameter in 50%' and 'diameter in 90%' can both stand for the size of total particles.

Overall, the particulate size distribution curves at different SOI timings show a unimodal feature. In addition, the peak particle concentration increases with the advance of SOI, and the particulate size distribution curve tends to shift towards the larger size with a higher concentration. However, for the particles smaller than 12 nm, a decreasing tendency is observed with the advance of SOI timing. Figure 5(b) shows that the 'diameter in 90%' is smaller than 40 nm at different SOI timings. Besides, almost no changes for the 'diameters in 50%' and 'diameters in 90%' are observed at different SOI timings, except at -8 °CA ATDC.

Due to the longest ignition delay and latest combustion phasing at the SOI of -8 °CA ATDC, the mixture is much leaner, which refrains the particle formation. However, with the advance of SOI timing, the air-fuel mixing period is shorter and more diffusion combustion process is observed, which are beneficial for the particle formation.



(a) Particulate size distribution



(b) The statistics of particle emissions

Figure 5. *The particle number and size distribution and statistics of particle emissions*

3.2 The Effect of Pilot-Main Injection Strategy on Combustion and Particulate Size Distribution for the n-Butanol PPC Combustion

As shown in the previous section, the single injection strategy for the n-butanol PPC combustion meets the problem of high MPRR. As a result, this section investigated the effect of pilot-main injection parameters (pilot injection timing and ratio) on the n-butanol PPC combustion. During the experiment, the main injection timing is kept at -6 °CA ATDC and no EGR is adopted. In addition, the experimental results for the single injection strategy with a SOI timing of -9.5 °CA ATDC are also presented for comparison.

Figure 6 shows the in-cylinder pressure and heat release rate with different pilot injection parameters. Overall, compared to the single injection strategy, the peak heat release rate can be effectively reduced when adopting the double injection strategy. It is also seen from Fig. 6(a) that the peak heat release rate decreases firstly and then increases with the increase of the pilot-main injection interval. In addition, the ignition timing is

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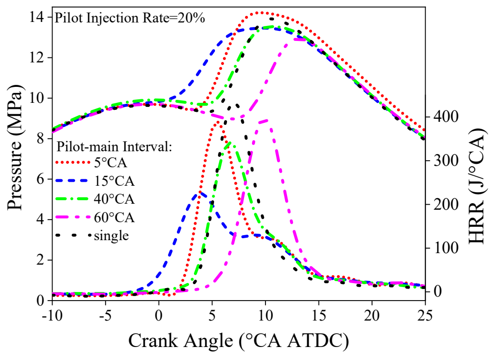
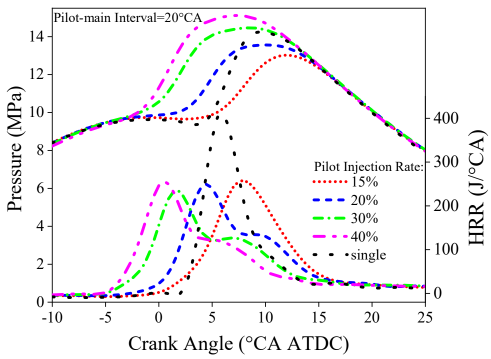
advanced initially and then retarded. Besides, the proportion of premixed combustion decreases firstly and then increases. Figures 6(b) and 6(c) show that the ignition timing is advanced with the higher pilot injection rate, due to the higher mixture reactivity before ignition. However, the peak heat release rates at different pilot injection rates are similar when the pilot-main injection interval is fixed at 20 °CA. However, a decreasing trend is observed at the higher pilot injection rate when the pilot-main injection interval is fixed at 50 °CA.

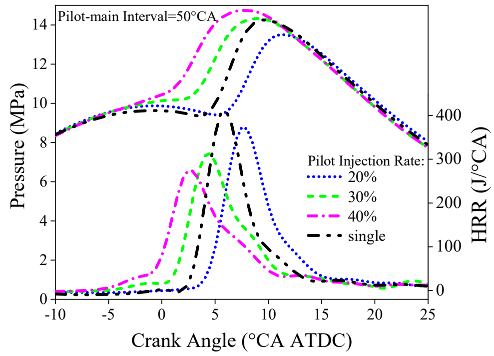
The effect of pilot-injection fuel on promoting ignition is the interactive effect of pilot injection mass and pilot-main injection interval. The too short reaction time for pilot-injection fuel will weaken the effect on promoting ignition since the inadequate low-temperature reaction, and it is the same effect for too long reaction time because the mixture of pilot-injection gets too lean. In addition, the pilot injection rate has a positive correlation with the effect on promoting ignition. Taking comprehensively consideration of pilot-main injection interval, pilot injection rate, the combustion is showed as Fig.6.



(a) The effect of different pilot-main injection intervals



(b) The effect of different pilot injection rates with a 20 °CA interval

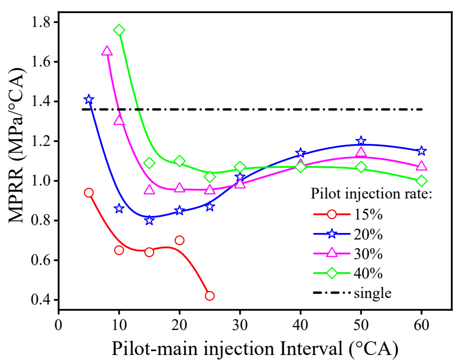


(c) The effect of different pilot injection rates with a 50 °CA interval

Figure 6. *The in-cylinder pressure and heat release rates with different pilot-injection parameters*

Figure 7 shows the MPRR and indicated thermal efficiency at different pilot injection parameters. As shown in Fig. 7(a), compared to the single injection strategy, the pilot-main injection strategy can effectively reduce the MPRR. With the increase of the pilot-main injection interval, the MPRR is reduced rapidly and then increased slightly, closely related to the peak heat release rate. In addition, when the pilot-main injection intervals are smaller than 30 °CA, the MPRR is increased with the higher pilot injection rate. However, when the pilot-main injection intervals are higher than 30 °CA, the MPRR is reduced with the increase of pilot injection rate.

It is observed from Fig. 7(b) that the indicated thermal efficiency is reduced with the increase of pilot-main injection interval. In addition, the indicated thermal efficiency is also reduced with the increase of pilot injection rate when the pilot-main injection interval is higher than 20 °CA, owing to the higher THC and CO emissions. However, when the pilot-main injection interval is lower than 20 °CA, the indicated thermal efficiency is increased with the pilot-main injection increase, due to the advanced CA50. Furthermore, it can be noticed that the low MPRR and acceptable indicated thermal efficiency can be obtained simultaneously when the pilot-main injection interval is about 20 °CA.



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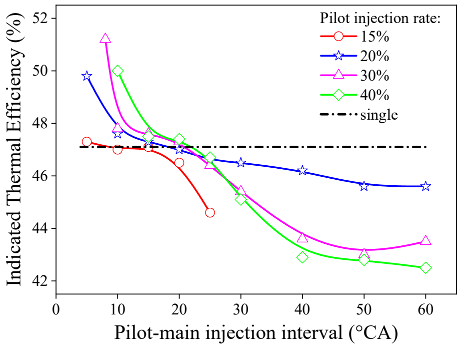
(a) MPRR



(b) Indicated thermal efficiency

Figure 7. *The MPRR and indicated thermal efficiency with different pilot injection parameters*

Figure 8 shows the indicated thermal efficiency and MPRR using different injection strategies. For the double injection strategy, the pilot-main injection interval is kept at 20 °CA. Obviously, compared to the single injection strategy, the pilot-main injection strategy can effectively reduce the MPRR. As the pilot injection rate is increased from 15% to 40%, the MPRR can be reduced by 0.66 to 0.25MPa/°CA, respectively. However, owing to the retarded combustion process, the indicated thermal efficiency is reduced for the double injection strategy.

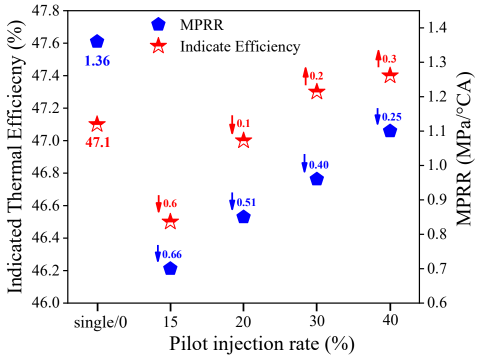
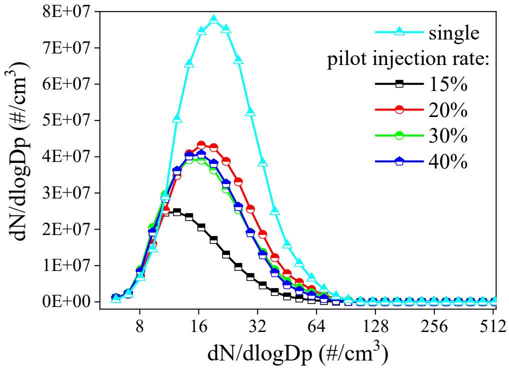
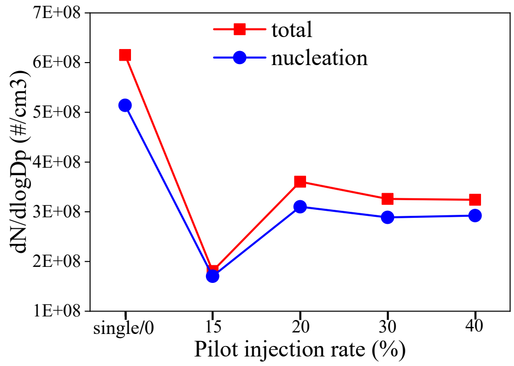


Figure 8. *The indicated thermal efficiency and MPRR of different injection strategies*

Figure 9 shows the particulate size distribution and total and nucleation particle number for different injection strategy. As seen from Fig. 9(a), the particle sizes are primarily lower than 64 nm. Clearly, the peak particle concentration for the single injection strategy is significantly higher than the pilot-main injection strategy. However, the number of the particles smaller than 12 nm for the single injection strategy are lower than the pilot-main injection strategy. In addition, similar particulate size distribution curves for the pilot-main injection strategy can be observed, except for the 15% pilot injection rate, due to its more retarded combustion. On one hand, the proportion of diffusion combustion, peak heat release rate are similar for different pilot injection rate as can be seen from Fig.6 (b), on the other hand, the concentration of the mixture from the main injection is higher than the mixture from pilot injection, and the quantity of mixture from the main injection is larger for the lower pilot injection rate since the longer ignition delay, so the quantity of mixture and its mean concentration are may similar for different pilot injection rate.



(a) Particulate size distribution



(b) Total and nucleation particle number

Figure 9. *The particulate size distribution, total and nucleation particle number of different injection strategies*

4. CONCLUSION

In this paper, the effects of injection parameters on combustion and particulate size distribution for the n-butanol PPC combustion were investigated experimentally. The main conclusions can be summarized as follows:

1. High concentrations of particle emissions for the n-butanol PPC combustion strategy are observed and the particles are mainly smaller than 64 nm. In addition, the particulate size distribution curve tends to shift towards the larger size and higher concentration with the advance of SOI.

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2. Pilot-main injection strategy can effectively reduce the MPRR. With the increase of pilot-main injection interval, the MPRR is reduced sharply and then increased slowly. Besides, the MPRR is also increased with the higher pilot injection rate when the pilot-main interval is below 30 °CA.

3. Compared to the single injection strategy, acceptable MPRR, particle emission, and indicated thermal efficiency can be obtained for the double injection strategy.

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