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Experimental investigation about effect of double-spark plug ignition on cyclic variation and knocking for SI engine

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Abstract. In order to analyze the effect of the double-spark plug ignition (DSI) on the heat release rate, cyclic variation in combustion and engine knocking, four different single- and double-spark plug ignition strategies are used for testing. Combustion diagnosis results show that when the DSI strategy is used, it can effectively promote the combustion process, increase the maximum combustion pressure, shorten the combustion duration and reduce the coefficient of cyclic variation (COV). Under low load condition, the effects are more pronounced. Test data reveals the following phenomenon. With the DSI strategy, both the cyclic variation in the early period of rapid-burning and in the later period of rapid-burning are reduced, especially in the early period of rapid-burning. Then, the cyclic variation rate of the combustion duration is significantly reduced. Since the burning rate in the early period of rapid-burning is greatly accelerated, knocking tendency of the DSI engine is more obvious than that of the single-spark SI engine. The potential to improve engine performance and fuel economy by the DSI strategy largely depends on the optimization of the spark advance. Based on the optimization of the ignition timing of the DSI strategy $S_{28\&28}$, the break mean effective pressure (BMEP) is improved by about 5%-6% compared to the original 158FMI engine.

Keywords. Gasoline engine; double-spark plug ignition; cyclic variation; heat release rate; indicated mean effective pressure; knocking.

1. Introduction

Cyclic variation in combustion is a major feature in the case of spark ignition (SI) engines, and it is also a unique phenomenon of irregular combustion of the SI engine [1, 2]. Double-spark plug ignition (DSI) can shorten the flame propagation distance, which is beneficial to ignition and rapid combustion, and thus improving the combustion characteristics of the SI engine [3, 4]. Studies have shown that using the DSI strategy can significantly reduce combustion cyclic variation, especially in a very lean mixture or with a significantly large amount of exhaust gas recirculation (EGR). It can produce a more robust and repeatable combustion pattern without misfire [5–10]. However, detailed studies on the process of reducing combustion cyclic variation with the DSI strategy have rarely been reported.

In addition, the effects of the double-spark plug ignition on engine performance and fuel economy vary from one researcher to another. Some scholars believe that in the absence of a misfire, if the location and ignition timing of the single-spark plug are already in an optimum state, using double-spark plug ignition does not improve engine performance [11–14]. As for the effect of the double-spark plug ignition on the characteristics of knocking combustion, there are few targeted studies, and the views of different researchers are different [15, 16].

In order to make contribution in this field, a double-spark plug configuration is used on the 158FMI engine, which is an SI engine with single-spark plug ignition (SSI), to investigate the effects of the DSI strategy on the combustion process in the cylinder. Four different single- and double-spark plug ignition strategies were used for testing. The results show that with DSI strategy, the burning rate in the early period of rapid-burning is greatly accelerated, which has an important effect on reducing the cyclic variation in combustion. However, under the same spark advance condition, the knocking tendency of DSI strategy is more obvious than that of SSI strategy. In addition, the results also show that the potential of DSI strategy to improve engine performance highly depends on the optimization of spark advance. Therefore, based on the optimization of the ignition timing of the DSI strategy $S_{28\&28}$,

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the thermal efficiency of the 158FMI DSI engine is again improved.

2. Experimental engine and method

The DSI engine used in this work is modified from the 158FMI engine, which is a four-stroke, air cooled, single-cylinder, single spark plug gasoline engine with a carburetor fuel supply system. Characteristic dimensions of the 158FMI engine are as follows: cylinder bore 58.8 mm, stroke 49 mm, geometric compression ratio 9.2. Table 1 shows the engine technical specifications. Based on the structure of 158FMI engine, a new mounting hole is designed in the cylinder head to install another spark plug, as shown in figure 1. The add spark plug is considered to be symmetrically arranged with the original spark plug on the cylinder head. The spark plug installation point of the original engine is 14 cm offset from the center of the combustion chamber, and its maximum spark advance is set to 35°CA BTDC (before top dead center).

A pressure sensor (Kistler Type 6052B) and a crank angle encoder (Kistler Type 2613B) are used to carry out combustion diagnosis for the DSI engine. The data acquisition system of DEWE-2010 is utilized to process electrical signals from the pressure sensor and the crank angle encoder. Combustion parameters as well as their statistical characteristics can be calculated in real time by the DEWESOFT combustion analysis package which uses a well-established thermodynamic methodology for cylinder pressure data analysis and combustion process characterization. During the combustion diagnoses, sampling resolution of pressure signal is set to 0.1 °CA. Each test action continuously samples 120 cycles, and arithmetic average of the 120 test cycles is used to calculate the combustion characteristic parameters for the test action.

In order to investigate the effect of DSI strategy on the heat release rate in the cylinder, cyclic variation in combustion and knocking, four different single- and double-spark plug ignition strategies were used on this modified engine for testing. The four ignition strategies are SSI strategy S_{28}, DSI strategy $S_{28\&28}$, SSI strategy S_{35} (original ignition strategy of the 158FMI engine) and DSI strategy $S_{35\&35}$ respectively, as shown in Table 2.

In Table 2, it shows the spark advances of these different ignition strategies at various speeds. Here, 28 represents SSI strategy S_{28}, whose spark advance increases linearly from 18.3°CA BTDC at 4000 r/min to 23.7°CA BTDC at

Table 1. Engine specifications.

Type	four-stroke, air cooled, single-cylinder, single spark plug gasoline engine with a carburetor fuel supply system
Bore×Stroke	58.8 mm×49 mm
Comp. Ratio	9.2
Displ.	133 cm^3
Rated power	7.8 kw @ 8000 r/min
Rated torque	10 Nm @ 7000 r/min

Table 2. Spark advance of the four different single- and double-spark plug ignition strategies at various speeds.

Speed r/min	28 °CA	28&28 °CA	35 °CA	35&35 °CA
4000	18.3	18.3/18.3	35	35/35
4500	19.3	19.3/19.3	35	35/35
5000	20.5	20.5/20.5	35	35/35
5500	21.5	21.5/21.5	35	35/35
6000	22.5	22.5/22.5	35	35/35
6500	23.7	23.7/23.7	35	35/35

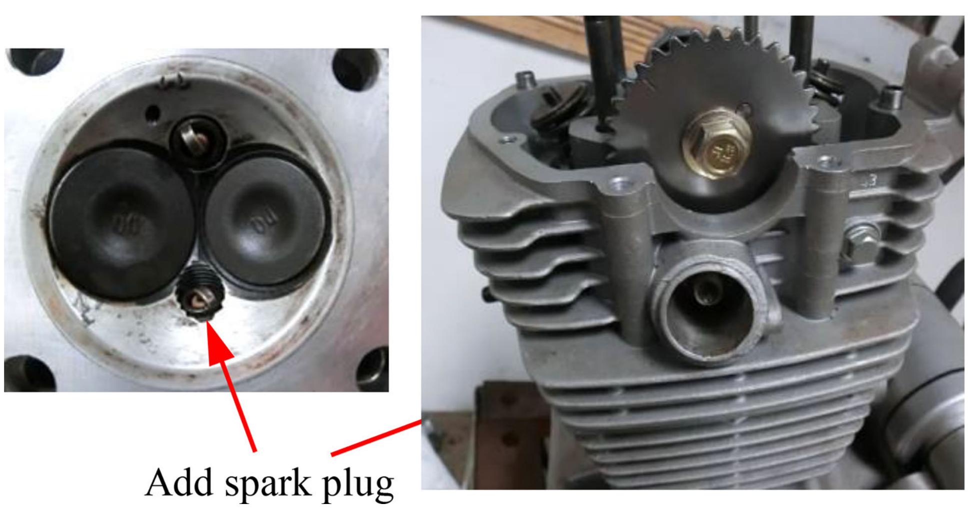

Figure 1. Cylinder head of the double-spark SI engine.

6500 r/min, and reaches the maximum spark advance of 28°CA BTDC at 8500 r/min. 28 and28 represent DSI strategy $S_{28\&28}$, which has the same spark advance as SSI strategy S_{28}. 35 represents SSI strategy S_{35}, its spark advance is 35°CA BTDC from 4000 r/min to 6500 r/min. 35 and35 represent DSI strategy $S_{35\&35}$, which has the same spark advance as SSI strategy S_{35}.

3. Results and discussion

3.1 *Effect of DSI on combustion characteristics*

Figure 2 shows the curves of maximum combustion pressure (p_{max}) and indicated mean effective pressure (p_{mi}), which were calculated by averaging the continuously sampled 120 test cycles under full load condition of 4000 r/min, 4500 r/min, 5000 r/min and 20% partial load condition of 4000 r/min (4000-20 in the figure). Under full load condition, the fuel/air equivalence ratio is 1.2, and the corresponding torque of the engine at full load condition of 4000 r/min, 4500 r/min, and 5000 r/min is 8.1 Nm, 8.7 Nm and 9.0 Nm respectively.

In figure 2(a), under different speed and load conditions, the sequence of ignition strategy corresponding to the p_{max} value from high to low is: $S_{35\&35}$, S_{35}, $S_{28\&28}$ and S_{28}. p_{max} value of the DSI strategy $S_{35\&35}$ is the largest. Although the data of p_{max} for the DSI strategy $S_{28\&28}$ is lower than the SSI strategy S_{35}, the value of p_{max} for the DSI strategy is significantly higher than the SSI strategy at the same spark advance. In figure 2(b), under full load condition, data of p_{mi} for the DSI strategy $S_{28\&28}$ is the largest, which has a 2%-4% higher than the SSI strategy S_{28}. Compared with the DSI strategy $S_{35\&35}$, data of p_{mi} for the SSI strategy S_{35} is higher. DSI strategy $S_{35\&35}$ has the lowest p_{mi} value under full load condition. This is mainly because after adopting DSI strategy, the burning rate is accelerated, the combustion duration is shortened, and the ignition timing needs to be delayed. The excessive ignition advance will increase the negative compression work and reduce the p_{mi} value. However, under low load condition, data of p_{mi} for the DSI strategy $S_{35\&35}$ is the largest.

Figure 3 shows the curves of heat release rate under different load condition of 4000 r/min, which were calculated by averaging the continuously sampled 120 test cycles. It can be seen that when the DSI strategy is adopted, the burning rate is significantly accelerated. The combustion duration is shortened, the maximum heat release rate is greatly improved, and the crank angle of the highest heat release rate is significantly advanced. Although the heat release rate of the DSI strategy $S_{28\&28}$ is delayed compared to the SSI strategy S_{35}, its maximum heat release rate is significantly higher than the SSI strategy S_{35}, which embodies the remarkable effect of DSI strategy to accelerate the heat release rate in the cylinder.

Figure 4 shows the crank angle corresponding with the burned mass fraction of 5% (E05), 10% (E10), 50% (E50) and 90% (E90) respectively. It is shown that with the DSI strategy, the main combustion stage (interval between E05 and E90) is shortened by 8-10°CA. The rapid-burning period (interval between E10 and E90) is shortened by about 8°CA and that occurs mainly during the early period of rapid-burning (interval between E10 and E50).

The shortening of the combustion duration is beneficial to the improvement of the thermal efficiency. For example, under full load condition of 4000 r/min, 4500 r/min, and 5000 r/min, the brake-specific fuel consumption (BSFC) of the original 158FMI SSI engine (which using the SSI strategy S_{35}) is 356 g/(kW·h), 340 g/(kW·h) and 329 g/(kW·h), the corresponding thermal efficiency is 23.0%, 24.1% and 24.8% respectively. When using the DSI strategy $S_{28\&28}$, its BSFC is reduced to 350 g/(kW·h), 335 g/

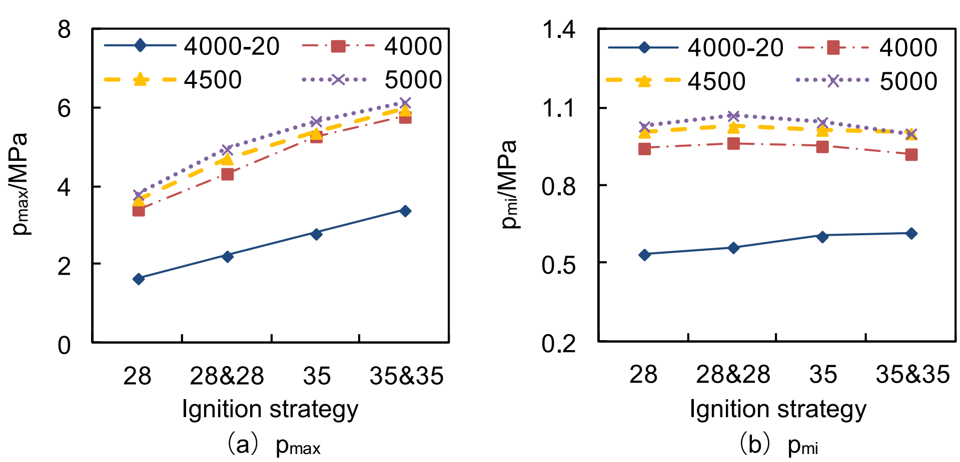

Figure 2. Comparison of p_{max} and p_{mi} under different ignition strategy condition.

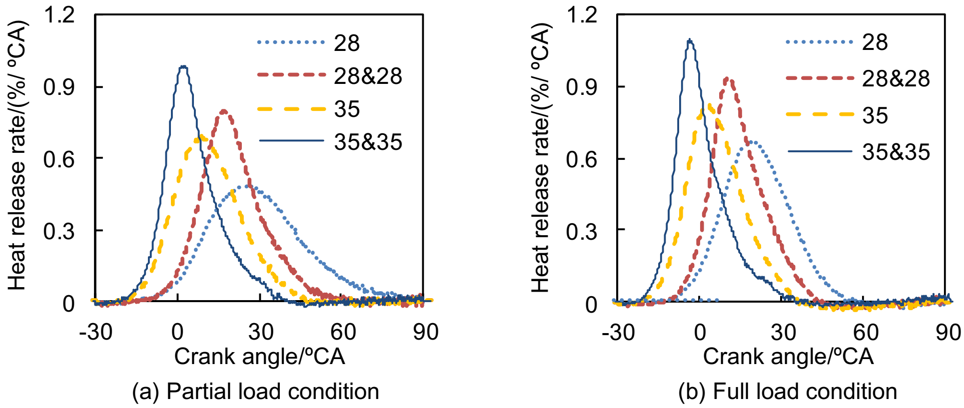

Figure 3. Heat release rate under different ignition strategy condition of 4000 r/min.

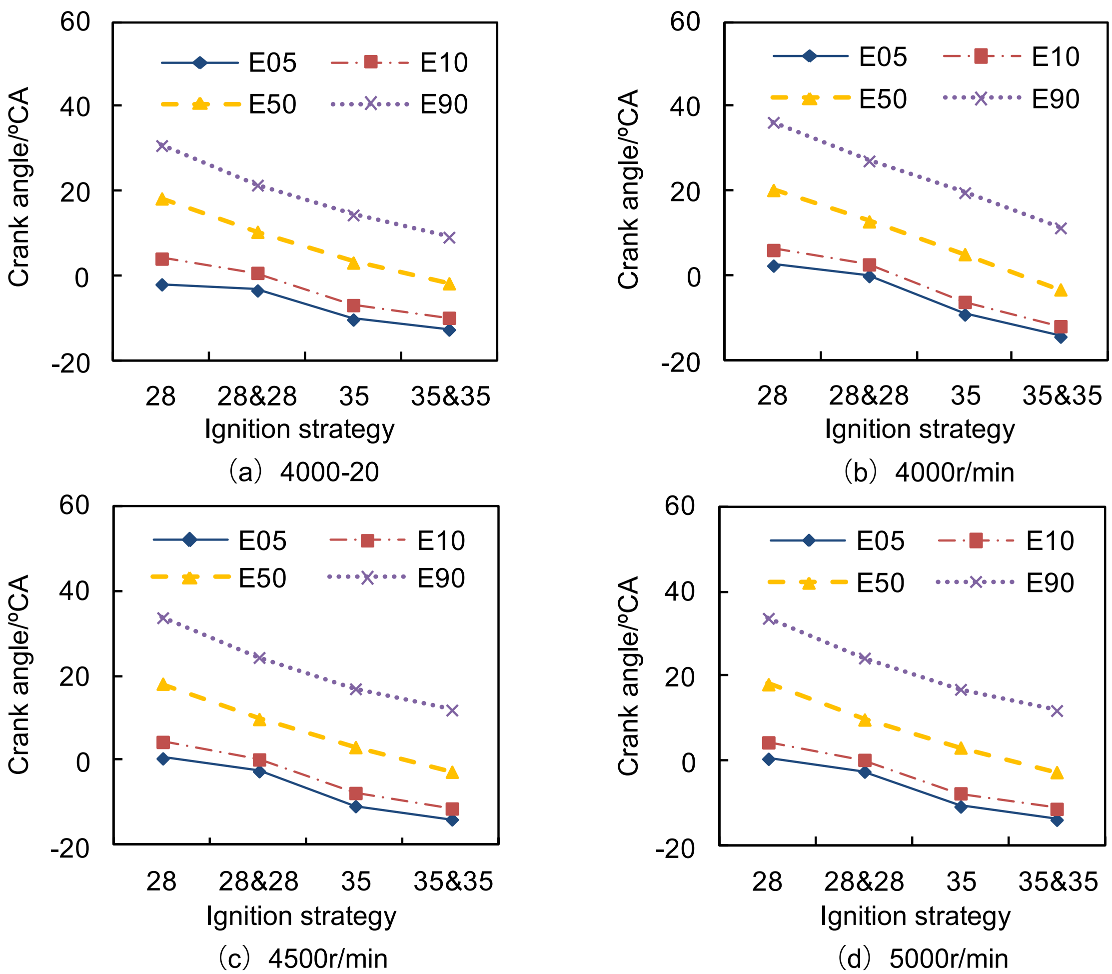

Figure 4. Comparison of combustion parameters under different ignition strategy condition.

(kW·h) and 320 g/(kW·h) respectively. The corresponding thermal efficiency is 23.4%, 24.4% and 25.6% respectively. The thermal efficiency of the latter is about 2%-3% higher than the former.

Under low load condition, the DSI strategy, especially for the DSI strategy $S_{28\&28}$, is more effective in shortening the combustion duration and accelerating the burning rate in the cylinder.

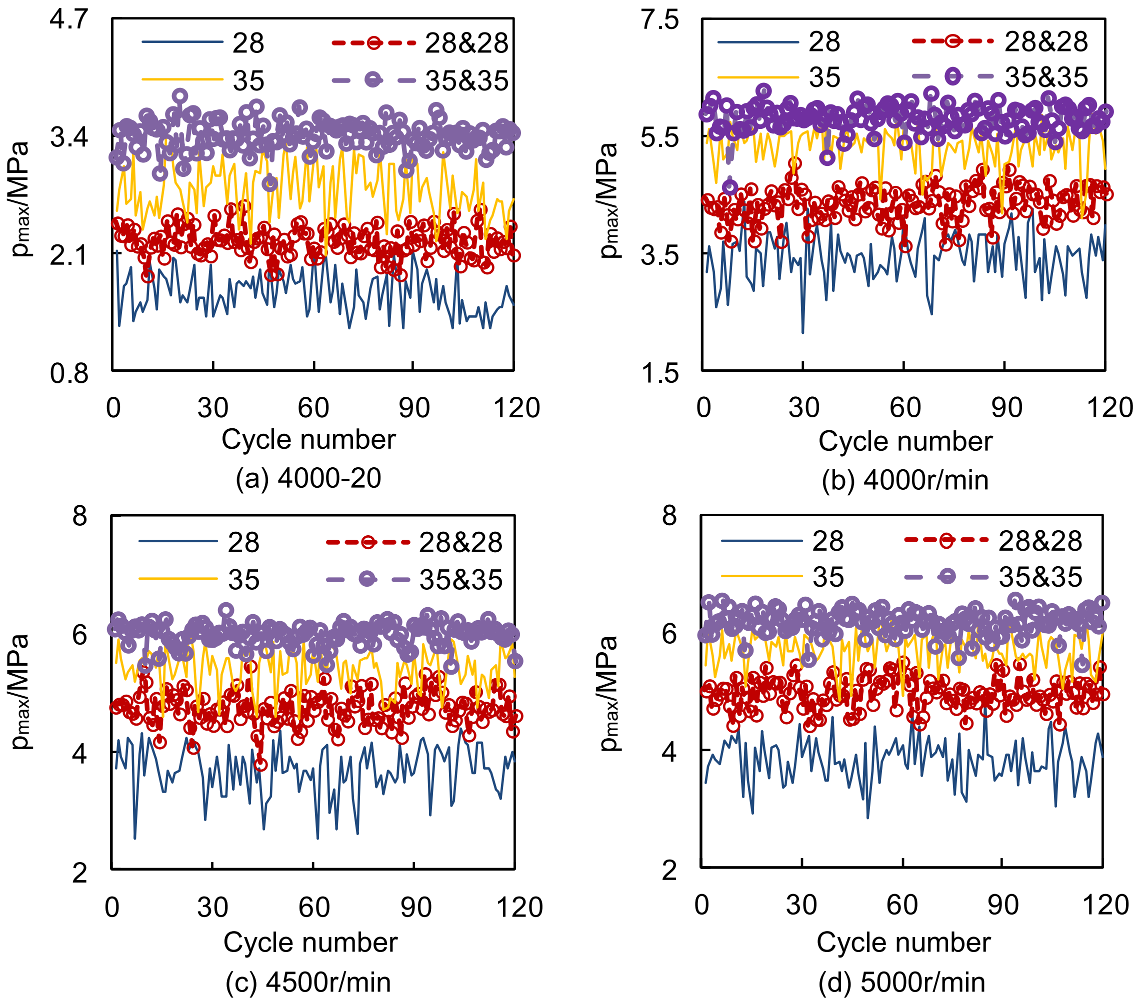

Figure 5. p_{max} for the continuously sampled 120 cycles under different ignition strategy condition.

3.2 *Effect of DSI on cyclic variation*

Figure 5 shows p_{max} for the individual-cycles of the continuously sampled 120 test cycles under different speed and load conditions. In figure 5(a), under low load condition, it can be seen that SSI strategy S_{28} has the highest cyclic variation in p_{max}, followed by SSI strategy S_{35}, which has a slight decrease in cyclic variation. The coefficient of variation in p_{max} (COV_{pmax}) for both exceeds 10%, which is not within the normal and reasonable range. While using the DSI strategy, the cyclic variation in p_{max} is significantly reduced. For example, when using DSI strategy $S_{28\&28}$, its COV_{pmax} is reduced to 7.5%, and when using DSI strategy $S_{35\&35}$, its COV_{pmax} is reduced to less than 5%. It demonstrates the remarkable effect of the DSI strategy to improve engine combustion stability.

Under full load condition, the COV_{pmax} of DSI strategy is lower than that of SSI strategy at the same spark advance, as shown in figures 5(b), 5(c) and 5(d). For example, compared with SSI strategy S_{35}, the COV_{pmax} of DSI strategy $S_{35\&35}$ is significantly lower. Although the COV_{pmax} of DSI strategy $S_{28\&28}$ is slightly higher than that of DSI strategy $S_{35\&35}$, and is basically at the same level as SSI strategy S_{35}, it is still significantly lower than that of SSI strategy S_{28}. So it shows that if the spark advance of DSI strategy $S_{28\&28}$ is appropriately increased, the combustion stability can be further improved.

Figure 6 shows p_{mi} for the individual-cycles of the continuously sampled 120 test cycles under different speed and load conditions. In figure 6(a), under low load condition, when SSI strategy S_{28} is adopted, the cyclic variation in p_{mi} is the highest, and its coefficient of variation in p_{mi} (COV_{pmi}) reaches 7.2%. However, after adopting DSI strategy $S_{28\&28}$, its cyclic variation in p_{mi} is significantly reduced, and its COV_{pmi} drops to 2.2%. Similarly, when SSI strategy S_{35} was changed to DSI strategy $S_{35\&35}$, its cyclic variation in p_{mi} was also significantly reduced, and

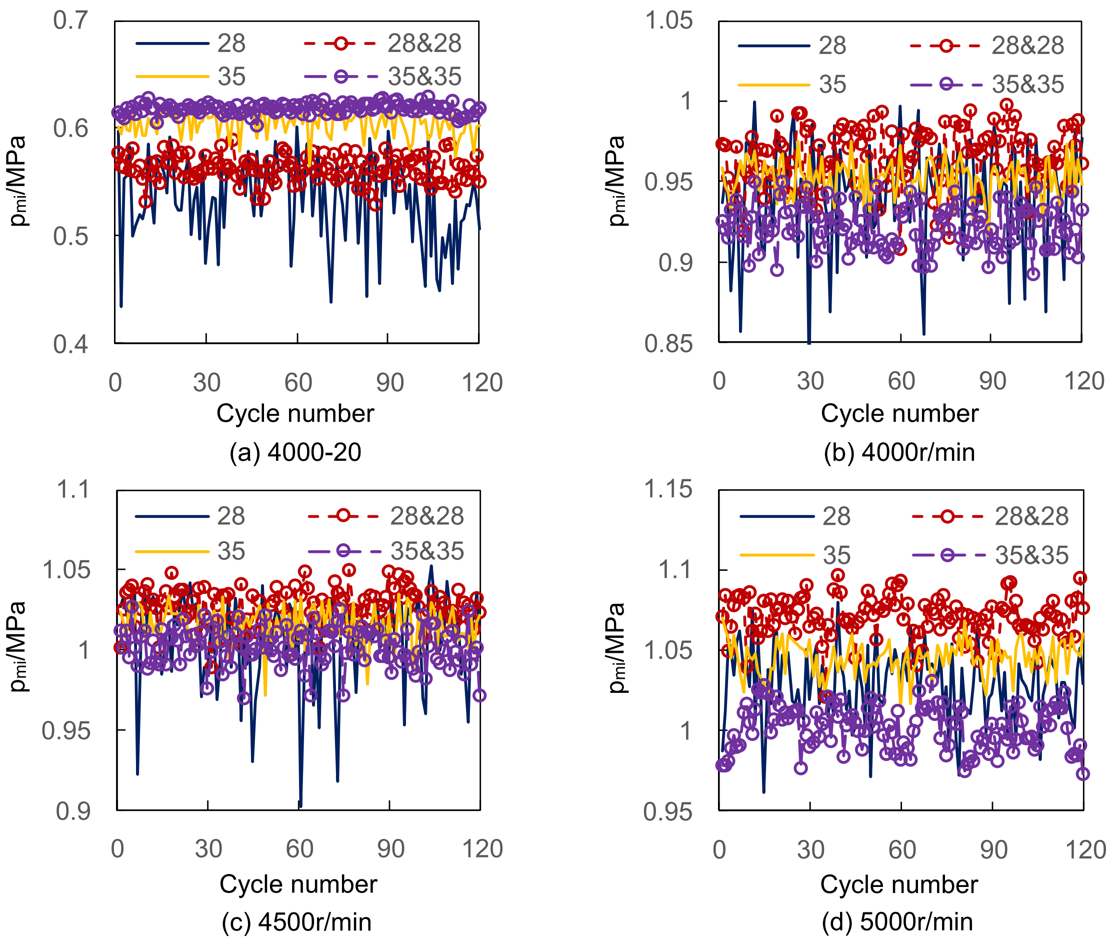

Figure 6. p_{mi} for the continuously sampled 120 cycles under different ignition strategy condition.

its COV_{pmi} dropped from 1.9% to 0.8%. It can be seen that under low load condition, DSI strategy can significantly reduce the cyclic variation of p_{mi}.

Similar to low load condition, under full load condition, the COV_{pmi} of DSI strategy $S_{28\&28}$ is significantly lower than that of SSI strategy S_{28}. But overall, the COV_{pmi} of both is relatively low, not exceeding 3% in most cases. However, when the spark advance is large, whether it is DSI strategy $S_{35\&35}$ or SSI strategy S_{35}, the COV_{pmi} is about 1.2%, and the difference in cyclic variation between the two ignition strategies is not obvious. It can be concluded that under full load condition, due to the COV_{pmi} is already at a relatively low level, the influence of the number of spark plugs on the cyclic variation of p_{mi} will become insignificant when the spark advance is large.

Figure 7 illustrates the relationship between p_{max} and combustion duration (interval between θ_i and E90, θ_i indicates the crank angle of ignition timing) under different ignition strategy condition. It shows that the correlation coefficient between p_{max} and combustion duration is basically around 0.95, which indicates that the p_{max} has a strong correlation with the combustion duration. Therefore, it is evident that the cyclic variation of combustion duration is the main factor affecting the cyclic variation in p_{max}.

Figure 8 illustrates the relationship between p_{mi} and combustion duration (interval between θ_i and E90) under different ignition strategy condition. It can be seen that there is also a strong correlation between p_{mi} and combustion duration, but its correlation coefficient is lower than the correlation coefficient between p_{max} and combustion duration. In general, the cyclic variation of combustion duration is also an important factor affecting the cyclic variation in p_{mi}.

In order to analyze the cyclic variation of combustion duration, the combustion duration (interval between θ_i and E90) is separated into three burning stages, namely flame development period (interval between θ_i and E10), rapid-burning early period (interval between E10 and E50), and rapid-burning later period (interval between E50 and E90). Then, the coefficient of cyclic variation in each burning stage is calculated, as shown in Tables 3 to Table 6.

It can be seen that when using the SSI strategy, cyclic variation of the rapid-burning early period and the rapid-burning later period are both very high, which leads to

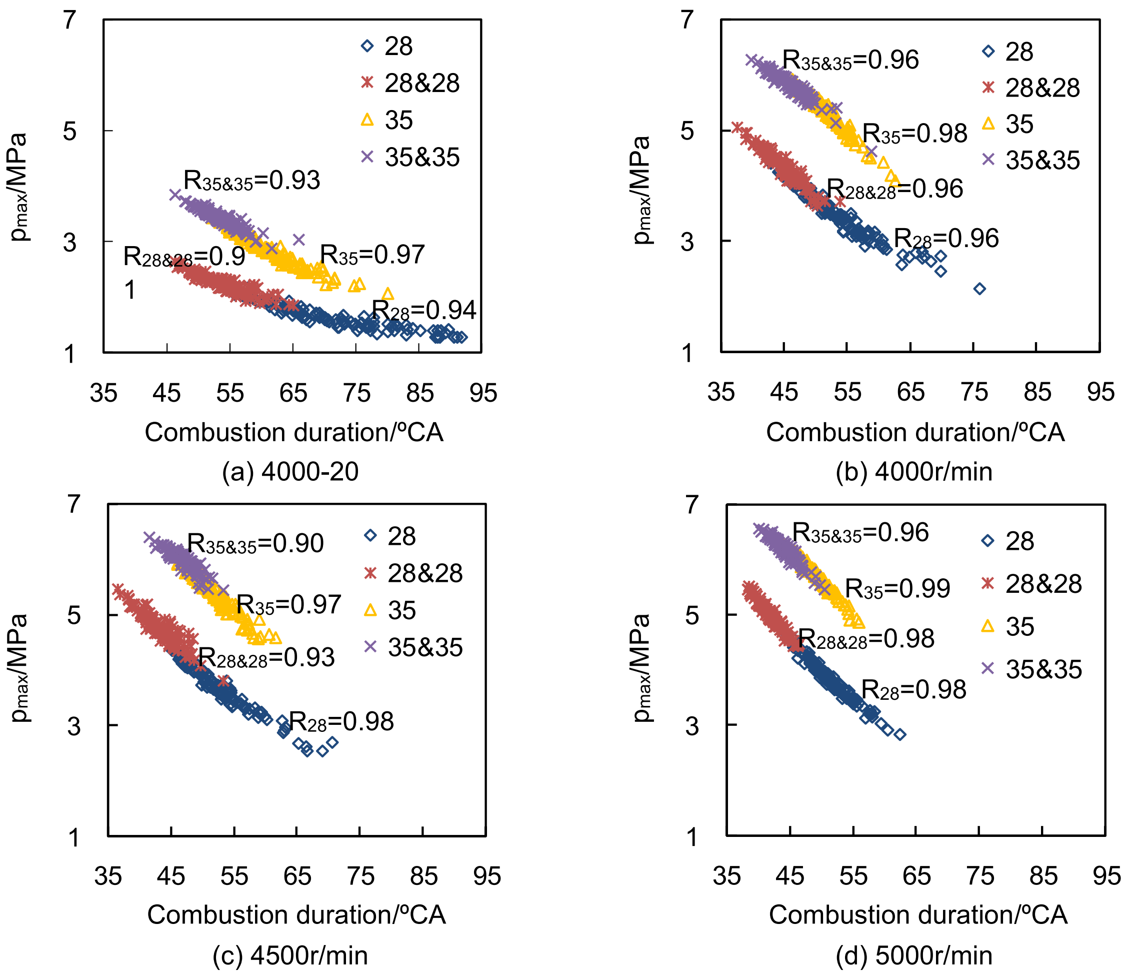

Figure 7. Correlation between p_{max} and combustion duration under different ignition strategy condition.

severe cyclic variation in combustion duration. As shown in Table 3, under low load condition, when using the SSI strategy S_{28}, the coefficient of variation in the early period of rapid-burning reaches up to 18.27% and the coefficient of variation in the later period of rapid-burning reaches up to 22.39%. As a result, the coefficient of variation of the combustion duration increases obviously, reaches up to 13.65%. In Table 4, under full load condition, when using the SSI strategy S_{28}, both the coefficient of variation of the rapid-burning early period and the rapid-burning later period are all more than 15%. It results in a higher cyclic variation in combustion duration, whose cyclic variation rate is more than 10%. While using the DSI strategy $S_{28\&28}$, cyclic variation in combustion duration is significantly reduced. As shown in Table 5, when the SSI strategy S_{28} is changed to DSI strategy $S_{28\&28}$, the cyclic variation of the rapid-burning early period and the rapid-burning later period are both significantly reduced, especially for the rapid-burning early period. For this reason, the cyclic variation rate of combustion duration is significantly reduced. In addition, under low load condition, when using the DSI strategy, the phenomenon of reducing the coefficient of variation of the rapid-burning early period is more obvious.

The decrease of the cyclic variation rate of the early period of rapid-burning is mainly due to the fact that dual ignition is beneficial to the formation and development of the early fire cores and accelerates the initial burning rate. Obviously, it can be seen that the flame development period is shortened by 2-5°CA when the SSI strategy is changed to DSI strategy. Meanwhile, due to multi-point ignition, the front area of the flame increases, and a stronger vortex is formed rapidly, which promotes the early burning rate. The faster burning rate is beneficial to the reduction of the cyclic variation rate.

3.3 *Effect of DSI on knocking*

Figure 9 shows the data of knock factor (KF) for the individual-cycles of the continuously sampled 120 test cycles under full load condition of 4500 r/min, 5000 r/min,

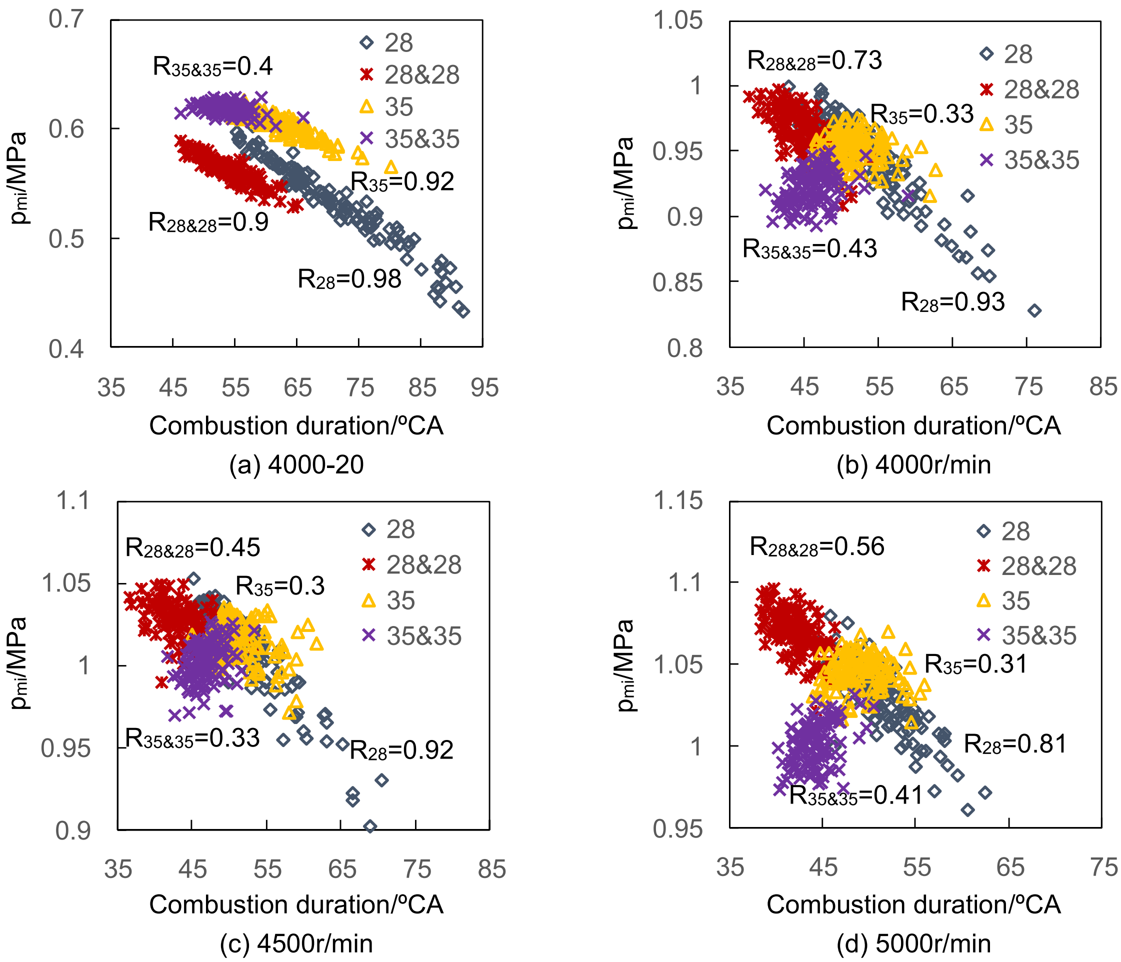

Figure 8. Correlation between p_{mi} and combustion duration under different ignition strategy condition.

Table 3. Cyclic variation of each burning stage under partial load condition of 4000 r/min.

Burning stage	28		28&28		35		35&35	
	Mean °CA	COV %	Mean °CA	COV %	Mean °CA	COV %	Mean °CA	COV %
Flame development period	27.91	5.93	25.14	5.17	32.18	5.60	29.28	4.63
Rapid-burning early period	19.53	18.27	12.20	9.35	13.63	13.83	9.58	7.92
Rapid-burning later period	23.16	22.39	16.74	14.42	16.18	14.35	14.93	11.98
combustion duration	70.61	13.65	54.08	7.20	62.00	8.33	53.80	5.42

Table 4. Cyclic variation of each burning stage under full load condition of 4000 r/min.

Burning stage	28		28&28		35		35&35	
	Mean °CA	COV %	Mean °CA	COV %	Mean °CA	COV %	Mean °CA	COV %
Flame development period	24.38	7.58	20.61	7.75	27.11	7.02	23.34	6.59
Rapid-burning early period	14.09	15.25	9.68	9.32	10.70	12.44	8.45	9.49
Rapid-burning later period	15.67	17.02	14.36	9.09	13.90	7.96	14.31	10.62
combustion duration	54.14	10.81	44.66	6.52	51.72	6.01	46.10	6.05

Table 5. Cyclic variation of each burning stage under full load condition of 4500 r/min.

	28		28&28		35		35&35	
Burning stage	Mean °CA	COV %	Mean °CA	COV %	Mean °CA	COV %	Mean °CA	COV %
Flame development period	24.14	7.32	19.91	7.16	27.87	6.66	24.04	5.79
Rapid-burning early period	13.72	14.51	9.25	9.47	10.51	12.02	8.39	7.63
Rapid-burning later period	14.79	14.78	14.23	11.46	13.26	9.86	14.39	9.42
combustion duration	52.65	9.76	43.39	6.71	51.64	6.29	46.82	4.37

Table 6. Cyclic variation of each burning stage under full load condition of 5000 r/min.

	28		28&28		35		35&35	
Burning stage	Mean °CA	COV %	Mean °CA	COV %	Mean °CA	COV %	Mean °CA	COV %
Flame development period	24.87	3.51	21.47	3.94	28.50	5.26	25.41	4.75
Rapid-burning early period	14.37	11.44	9.62	8.26	9.83	9.27	7.93	7.49
Rapid-burning later period	12.18	13.12	10.98	10.20	10.85	8.87	10.87	8.89
combustion duration	51.42	6.82	42.07	4.63	49.18	5.16	44.21	4.32

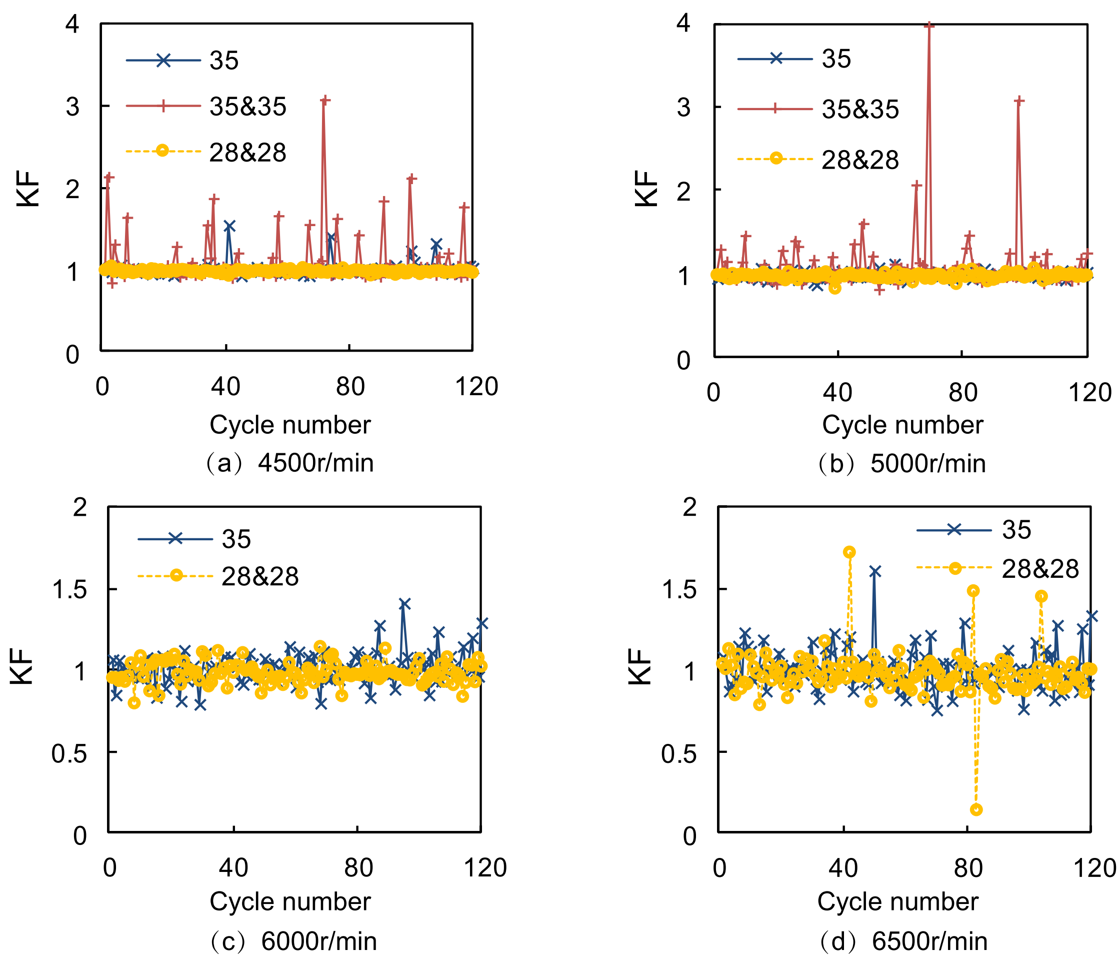

Figure 9. KF for the continuously sampled 120 cycles under different ignition strategy condition.

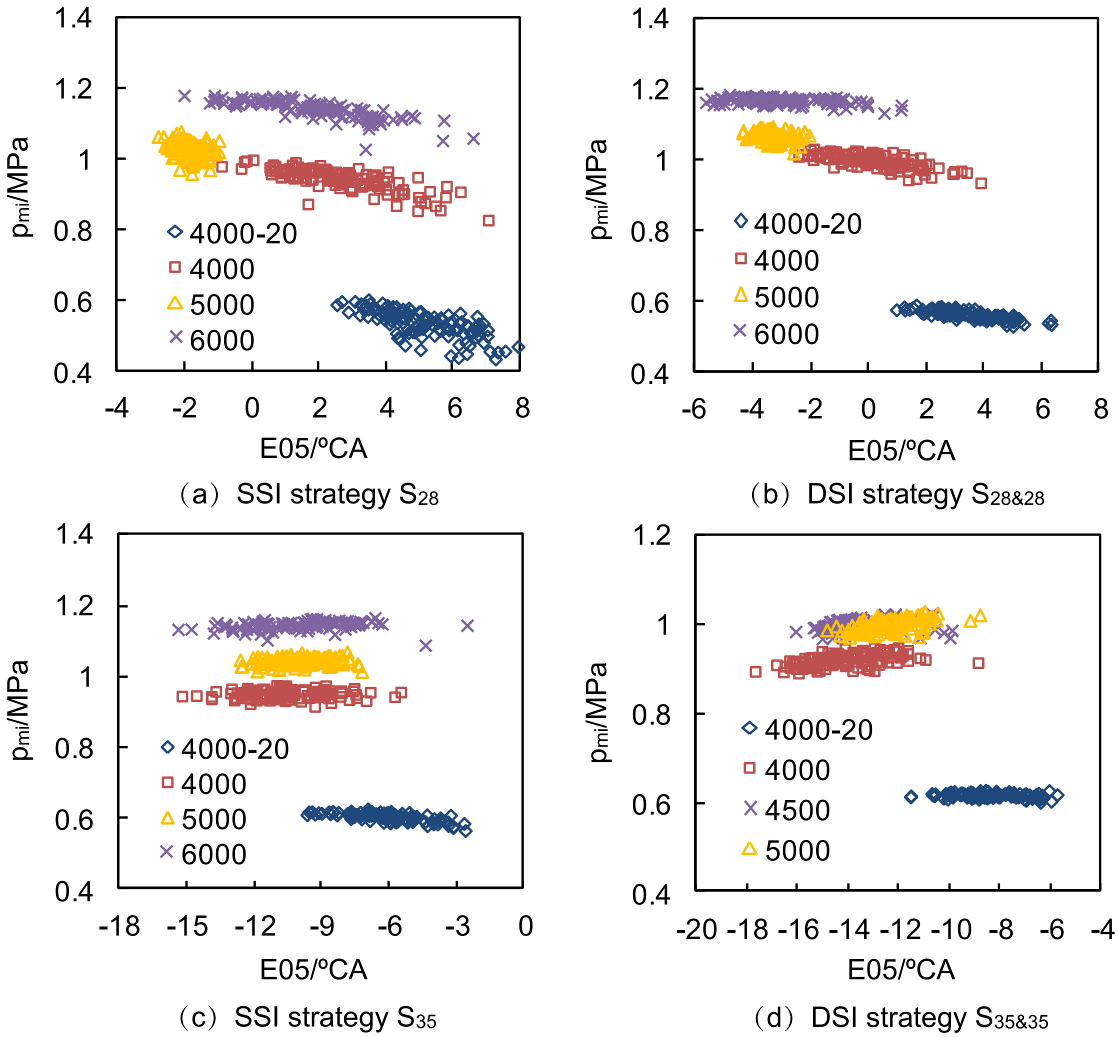

Figure 10. Correlation between p_{mi} and E05 under different ignition strategy condition.

6000 r/min and 6500 r/min. The knock factor refers to the ratio of the energy integral value of the knocking signal to the energy integral value of the background noise. The larger the knock factor value, the higher the knocking tendency. In figure 9, it can be seen that the original 158FMI SSI engine (which using the SSI strategy S_{35}) has a certain degree of knocking tendency, but its KF value does not exceed the empirical value range (1.8-2.0) [17]. Thus, in this paper, the knock characteristics of the original 158FMI SSI engine at various speeds are regarded as the reference scale of the knock limit of the DSI strategy at the corresponding speeds.

In figures 9(a) and 9(b), under full load condition of 4500 r/min and 5000 r/min, when the DSI strategy $S_{35\&35}$ is used on the 158FMI engine, the knocking tendency increases significantly, and its KF value greatly exceeds the knocking threshold, and the maximum KF value is as high as 4. It shows that knocking tendency of the DSI strategy is more obvious than the SSI strategy at the same spark advance. However, for the DSI strategy $S_{28\&28}$, since the spark advance is relatively small, its KF value is significantly lower than that of the original 158FMI SSI engine in the range of 4000 r/min to 6000 r/min, as shown in figures 9(a), (b) and (c). The decrease in the tendency of knocking makes it possible for the dual-spark plug gasoline engine to adopt a higher compression ratio to improve its thermal efficiency.

So it can be seen that with the DSI strategy, it is necessary to retard the ignition timing to suppress knocking. But at 6500 r/min, as shown in figure 9(d), knocking tendency of the DSI strategy $S_{28\&28}$ is close to the level of the original 158FMI SSI engine. It can be considered that the spark advance of DSI strategy $S_{28\&28}$ at 6500 r/min (whose value is 23.7°CA BTDC at 6500 r/min) may be close to the edge of knocking. Thus, for the DSI strategy $S_{28\&28}$, in order to avoid knocking, 23.7°CA BTDC should be used as the reference value at 6500 r/min, and the minimum spark advance for best torque (MBT) should be set near it.

3.4 *Effect of DSI on indicated mean effective pressure*

The average value of p_{mi} for the continuously sampled 120 test cycles shows that under full load condition, when using DSI strategy $S_{28\&28}$, data of p_{mi} is the largest, which has a 2%-3% improvement compared with the original 158FMI SSI engine. While using DSI strategy $S_{35\&35}$, data of p_{mi} is lower than the original 158FMI SSI engine. Therefore, it can be considered that DSI strategy is quite sensitive to the influence of the ignition timing and the potential of the DSI strategy to improve engine performance largely depends on the optimization of the spark advance.

Figure 10 illustrates the relationship between p_{mi} and E05 (Which shows the starting time of combustion) under different ignition strategy condition. In figure 10(a), it shows that E05 and p_{mi} are almost linear correlation, individual-cycles with earlier starting time of combustion can obtain higher value of p_{mi}, which indicates that the spark advance of the SSI strategy S_{28} is relatively small. In figure 10(b), there is a similar situation. In figure 10(c), under full load condition, as the advancing of E05, data of

Table 7. Spark advances of the nine different DSI strategies.

Speed r/min	A °CA	B °CA	C °CA	D °CA	E °CA	F °CA	G °CA	H °CA	I °CA
4000	18.5/18.5	19/19	18.3/18.3	20.4/20.4	19.9/19.9	21.5/21.5	20.4/20.4	19.6/19.6	20.9/20.9
4500	19.7/19.7	20/20	19.3/19.3	21.4/21.4	21.5/21.5	23.7/23.7	21.5/21.5	20.6/20.6	21.7/21.7
5000	20.9/20.9	21/21	20.5/20.5	22.5/22.5	23.1/23.1	25.8/25.8	22.6/22.6	21.5/21.5	22.5/22.5
5500	22.1/22.1	22/22	21.5/21.5	23.6/23.6	24.8/24.8	28.0/28.0	23.7/23.7	22.4/22.4	23.3/23.3
6000	23.3/23.3	23/23	22.5/22.5	24.6/24.6	26.4/26.4	30.2/30.2	24.8/24.8	23.4/23.4	24.1/24.1
6500	24.5/24.5	24/24	23.7/23.7	25.7/25.7	28.0/28.0	32.3/32.3	25.8/25.8	24.3/24.3	24.9/24.9

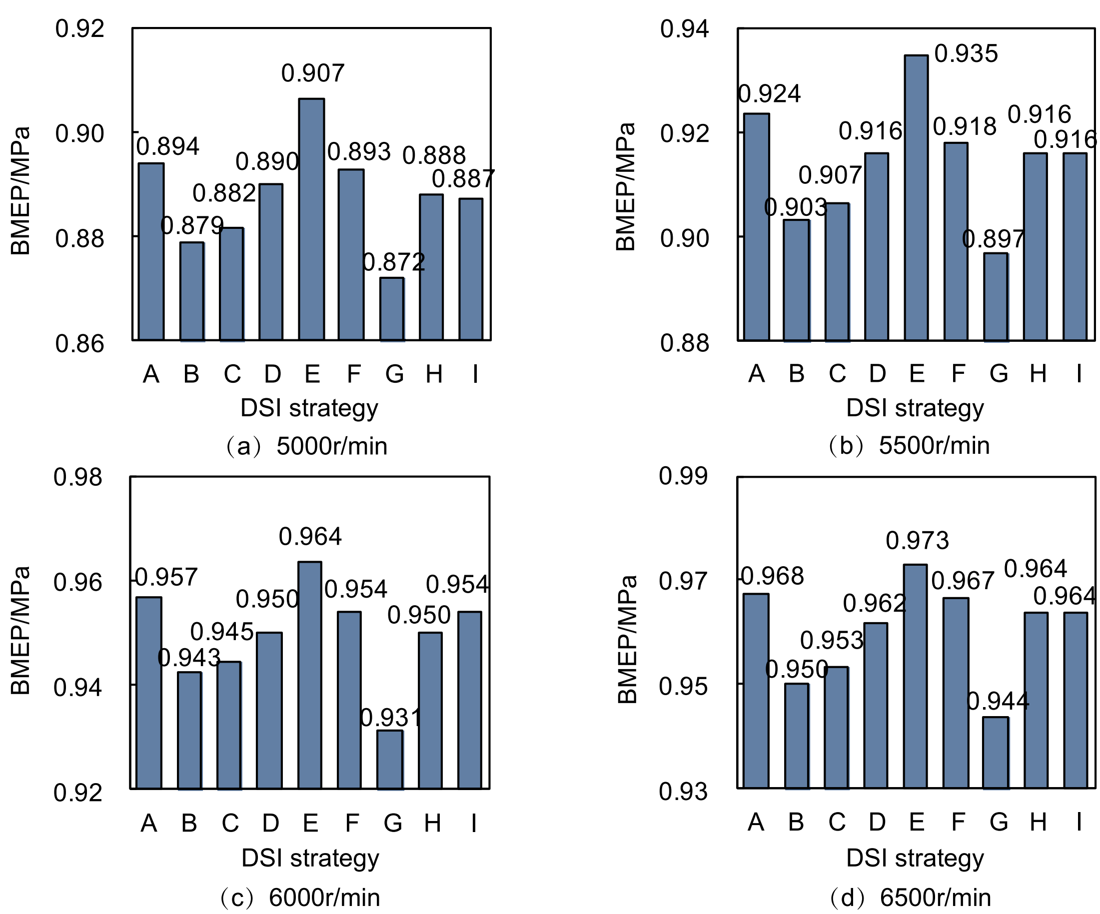

Figure 11. Comparison of BMEP under different DSI strategy condition.

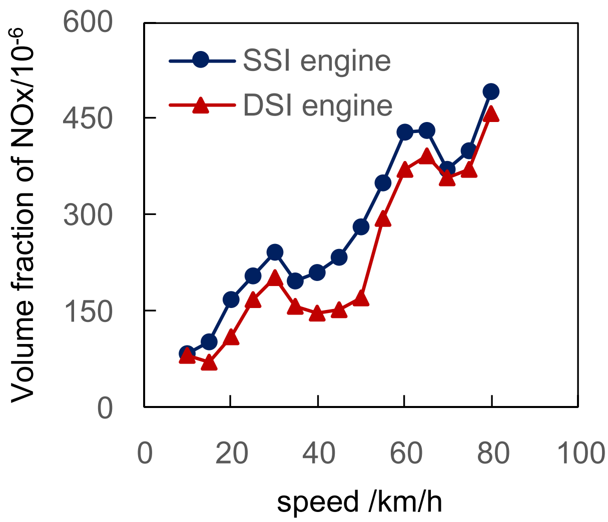

Figure 12. NOx emission of the 158FMI engine motorcycle with SSI and DSI strategy at different constant speed.

p_{mi} does not increase and is almost on a horizontal line. In figure 10(d), under full load condition, data of p_{mi} for the individual-cycles with earlier starting time of combustion has a tendency to decline. So it can be considered that the spark advance of SSI strategy S_{35} is relatively moderate and the spark advance of DSI strategy $S_{35\&35}$ is too large and should be appropriately reduced. Obviously, the spark advance of SSI strategy S_{28} and DSI strategy $S_{28\&28}$ is relatively small. For DSI strategy $S_{28\&28}$, if the spark advance is appropriately advanced, p_{mi} has a tendency to further improve, especially at full load condition of 4000 r/min and 5000 r/min. In addition, for the DSI strategy $S_{28\&28}$, as the ignition timing advances, its combustion stability will be further improved.

Therefore, in order to further improve the performance of 158FMI DSI engine, nine different DSI strategies such as A, B, C, D, E, F, G, H, and I are designed for testing. The spark advances of these DSI strategies are shown in Table 7. The results show that the break mean effective pressure (BMEP) of each DSI strategy is improved except for the B and G ignition strategies, as shown in figure 11. By appropriately increasing the spark advance of the DSI strategy $S_{28\&28}$, the BMEP is further improved, which is about 5%-6% higher than that of the original 158FMI SSI engine.

3.5 *Effect of DSI on NOx*

Figure 12 shows the comparison of NOx emissions of the 158FMI engine motorcycle with SSI and DSI strategy on the chassis dynamometer under different constant speed condition. It can be seen that under the same constant speed condition, the NOx emission of the DSI strategy is significantly lower than that of the SSI strategy, especially at low and medium constant speed. For example, at 50 km/h constant speed, after adopting DSI strategy, the volume fraction of NOx dropped from 281 ppm to 170 ppm, a decrease of 39.5%. DSI strategy is more effective in reducing NOx emission. This is mainly due to the fact that under DSI strategy condition, the ignition timing delay will reduce the maximum combustion pressure and temperature in the cylinder, which will inhibit the generation of NOx and reduce NOx emission.

In summary, the DSI strategy can effectively promote the in-cylinder combustion process, reduce combustion cycle fluctuations, and improve combustion stability. Through the optimization of spark advance, DSI strategy can not only improve the power of the engine, but also significantly reduce the knocking tendency. Compared with the SSI strategy, the ignition timing is delayed in the dual spark plug mode, and the temperature and pressure of the mixture in the cylinder are higher at the ignition timing, which will facilitate ignition and rapid combustion, and improve the heat utilization rate. Meanwhile, delaying the ignition timing is also conducive to reducing NOx emissions. In addition, the mixture in the combustion chamber is not uniform in space and time, so there is a problem with the probability of ignition in the cylinder. The use of two spark plugs for ignition can double the probability of ignition. Therefore, it can be foreseen that under low temperature starting or lean burn condition, the utility of dual spark plug ignition will be very beneficial.

4. Conclusion

(1) When using DSI strategy, since two points are ignited at the same time, a stronger vortex will be formed, which will promote the burning rate. Meanwhile, the flame propagation distance is shortened by 1/2, and the burning time is also shortened, which greatly reduces the tendency of knocking. Therefore, a higher compression ratio can be used for the DSI engine to improve its thermal efficiency.
(2) After adopting DSI strategy, the spark advance was delayed due to the accelerated burning rate. Therefore, at the moment of ignition, the temperature and pressure of the mixture in the cylinder are higher, which is beneficial to ignition and rapid combustion, and improves the heat utilization rate. However, the potential of DSI strategy to improve engine performance largely depends on the optimization of spark advance.
(3) The cyclic variation of combustion duration has obvious correlation with the cyclic variation of p_{max} and p_{mi}. When using DSI strategy, both the cyclic variation of the rapid-burning early period and the rapid-burning later period are reduced, especially for the rapid-burning early period. As a result, the cyclic variation rate of combustion duration is reduced. Under low load condition, this phenomenon is more obvious.

(4) Since the burning rate in the early period of rapid-burning (interval between E10 and E50) is greatly accelerated, the knocking tendency of DSI strategy is more obvious than that of SSI strategy at the same spark advance. So for the DSI strategy, it is necessary to delay ignition timing to suppress knocking.
(5) The mixture in the combustion chamber is not uniform in space and time, so there is a problem with the probability of ignition in the cylinder. The use of two spark plugs for ignition can double the probability of ignition. Therefore, under low temperature starting or lean burn condition, the utility of dual spark plug ignition will be very beneficial.

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List of Symbols

DSI	double-spark plug ignition
COV	coefficient of cyclic variation
BMEP	break mean effective pressure
SI	spark ignition
EGR	exhaust gas recirculation
SSI	single-spark plug ignition
BTDC	before top dead center
p_{max}	maximum combustion pressure
p_{mi}	indicated mean effective pressure
E05	crank angle corresponding with the burned mass fraction of 5%
E10	crank angle corresponding with the burned mass fraction of 10%
E50	crank angle corresponding with the burned mass fraction of 50%
E90	crank angle corresponding with the burned mass fraction of 90%
BSFC	brake-specific fuel consumption
COV_{pmax}	coefficient of variation in p_{max}
COV_{pmi}	coefficient of variation in p_{mi}
θ_i	the crank angle of ignition timing
KF	knock factor
MBT	the minimum spark advance for best torque

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