Experimental Investigation about the Effect of Double-Spark Plug Ignition on Combustion Characteristics for Motorcycle Gasoline Engines with a Mild Lean Mixture

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ABSTRACT: To investigate the effect of double-spark plug ignition (DSI) on the mild lean combustion characteristics of motorcycle gasoline engines, three combustion modes were set up on a gasoline engine for testing, namely, the single-spark plug ignition (SSI) stoichiometric combustion mode ($\lambda = 1$, $\lambda$ represents the excess air coefficient), the DSI stoichiometric combustion mode ($\lambda = 1$), and the DSI mild lean combustion mode ($\lambda = 1.1$). The results show that the double-spark plug ignition as that in the DSI mild lean combustion mode and DSI stoichiometric combustion mode is more prominent in accelerating the combustion process, reducing the cyclic variation, and improving the lean burn stability. It is verified that the overall effect of double-spark plug ignition on accelerating mildly homogeneous lean combustion is mainly reflected during the early period of rapid burning, which improves the stability of mildly homogeneous lean combustion and extends the lean burn limit. Further, the bench test shows that at a moderate load, the DSI mild lean combustion mode can result in lower brake-specific fuel consumption (BSFC) compared to that of the DSI stoichiometric combustion mode. And the emission reduction can also be clearly observed when using a three-way catalyst containing rare-earth materials. However, at a low load, limited by combustion stability, for the DSI mild lean combustion mode, $\lambda$ should not exceed 1.05.

1. INTRODUCTION

In Asia, motorcycles play a very important role in satisfying the needs of people's daily life and transportation. Taking into consideration the motorcycle market in China alone, more than 17 million motorcycles had been sold by Chinese manufacturers during 2020. Such a large number of motorcycles have a huge impact on our lives and environment. For example, air pollution, energy consumption, greenhouse gas emissions, and so on. In 2019, the Chinese government began to implement the fourth stage national standard for the regulation of motorcycle emissions. In response to increasingly stringent fuel consumption and emission regulations, many researchers are trying to use some means to reduce the fuel consumption and emissions of motorcycles.

Lean burn is a good way to increase engine thermal efficiency and reduce emissions to some extent. Gasoline engines, which use lean burn in partial load, can reduce the pumping loss, increase the specific heat ratio of a mixture, and improve thermal efficiency. For a long time, the stratified lean burn system has attracted extensive attention and research. However, the stratified lean burn system has problems such as difficulty in controlling the stratified state of the mixture accurately, high particulate emission and HC emission, and difficulty in postprocessing NOx emissions. Until now, stratified lean combustion technology has not been widely used in existing gasoline engine products.

Homogeneous lean combustion is another technical way for gasoline engines to achieve lean burn. Homogeneous lean burn does not have a rich mixture region, and its NOx emissions are relatively low, which is beneficial to reduce the difficulty in emission post-treatment. However, in the homogeneous lean burn state, due to the low energy contained in the unit mass of the mixture, the flame propagation speed is slow, and the air–fuel ratio can only be adjusted in a small range. Excessively lean mixture conditions will produce abnormal combustion phenomena such as intense cyclic variation, partial burning.
...and misfire.\textsuperscript{9-11} In addition, for lean mixtures, the NOx conversion efficiency of the three-way catalytic converter (TWC) will drop rapidly as the excess air ratio increases. However, studies have found that using rare-earth oxygen storage materials to improve the oxygen storage capacity of the catalyst, the working window of TWC can be expanded (the boundary of the lean burn direction of the working window can reach $\lambda = 1.06-1.08$).\textsuperscript{12-13} Rare-earth oxides, such as Ce containing oxides, were widely applied in catalysis.\textsuperscript{14-17} Through the reversible reaction $\text{CeO}_2 \leftrightarrow \text{Ce}_2\text{O}_3 + x/2\text{O}_2$, under a lean oxygen ($\lambda < 1$) condition, Ce-based rare-earth oxides can provide the oxygen required for CO and HC oxidation. Under a rich oxygen ($\lambda > 1$) condition, Ce$_2$O$_3$ can store oxygen to ensure that NOx is reduced by CO and HC. Therefore, using a mildly homogeneous lean combustion mode combined with a three-way catalytic converter containing rare-earth oxygen storage materials can reduce motorcycle fuel consumption and emissions.

However, due to the low energy content per unit mass of the mixture in the mildly homogeneous lean burn state, the flame propagation speed becomes slower and the cyclic variation becomes more intense. Multipoint ignition may be a potential technology to improve this phenomenon.\textsuperscript{18-20} Long-term practice has shown that double-spark plug ignition can significantly shorten the combustion duration, reduce cyclic variation, and expand the combustion limit.\textsuperscript{21-24} Migita et al.\textsuperscript{25} used twin-spark plugs located in a diagonal position and controlled the ignition timing in sequence to achieve rapid combustion. Forte et al.\textsuperscript{26} found that at a part load condition, a sensible reduction of cycle-by-cycle variability of indicated mean effective pressure was achieved by twin-spark, and at a full load condition, the twin-spark showed an increase of power. Maji et al.\textsuperscript{27} studied that in contrast to single-spark on a single-cylinder SI engine, the operation of dual-spark plugs increases the power output by 3-5%. Quader\textsuperscript{28} found that fast burn was achieved with the DSI strategy, and lean limits of stable operation were extended to leaner mixtures with dual-spark plugs. Kuroda et al.\textsuperscript{29} experimentally optimized the combustion chamber shape and spark plug locations to equalize the flame propagation from two spark plugs. The results show that fast burn overcomes the slow burn limitation of conventional engines and greatly extends the stable combustion range under heavy EGR conditions, with a marked reduction in NOx emission and improved fuel economy. Hillyer and Wade\textsuperscript{30} and Scussel et al.\textsuperscript{31} carried out an experimental test program on the Ford PROCO stratified charge engine and found that a dual-ignition system produces reliable, misfire-free operation with dilute mixtures and high EGR rates. Deng et al.\textsuperscript{32} studied the influence of $\lambda$ on engine performances in a four-valve single-cylinder twin-spark engine by experiments over a wide range of operating conditions. Nevertheless, there is a scarcity in the literature for investigating the effects of double-spark plug ignition on the mildly homogeneous lean combustion process of motorcycle gasoline engines.

To make a contribution in this field, a double-spark plug ignition system is added on the 183FMQ engine in this study, which is an SI engine with a single-spark plug ignition system, to investigate the effects of double-spark plug ignition on the mildly homogeneous lean burn process. Here, three combustion modes are set up for testing, namely, the SSI stoichiometric combustion mode ($\lambda = 1$), the DSI stoichiometric combustion mode (single-spark plug, $\lambda = 1$), and the DSI mild lean combustion mode (double-spark plug, $\lambda = 1$). The results show that the double-spark plug ignition as that in the DSI mild lean combustion mode and the DSI stoichiometric combustion mode is more prominent in accelerating the combustion process, reducing the cyclic variation, and improving the lean combustion stability. The overall effect of DSI in accelerating mild lean combustion is mainly reflected during the early period of rapid burning. Using the DSI mild lean combustion mode combined with a TWC containing rare-earth catalytic materials can effectively reduce motorcycle fuel consumption and emissions.

2. EXPERIMENTAL SETUP

The DSI engine used in this work is modified from the 183FMQ engine, which is a four-stroke, air-cooled, single-cylinder, single-spark plug, port injection, motorcycle gasoline engine with the following dimensions: bore 83 mm, stroke 71.6 mm, and a geometric compression ratio of 8.7. Table 1 shows the technical specifications of the engine. Based on the cylinder head structure of the 183FMQ engine, a new mounting hole is designed in the combustion chamber to install another spark plug, as shown in Figure 1. The added spark plug (same as the original engine spark plug) is symmetrically arranged on the cylinder head with the original spark plug.

Figure 2 shows the external characteristics under different ignition strategies. Here, SSI-left represents the engine torque when only the left spark plug is used. SSI-right represents the engine torque when only the right spark plug is used. It can be seen that the engine torque with only the left spark plug is almost the same as the original engine torque. However, when the DSI strategy is adopted, the torque decreases significantly. This is because the spark advance used is the original engine spark advance. With the DSI strategy, due to the fast burning, the best spark advance should be appropriately delayed. Therefore, for dual-spark plugs, the spark advance must be recalibrated. The best spark advance for the DSI strategy under different speeds and load conditions is shown in Table 2.

To investigate the effect of DSI on mild lean burn characteristics, three combustion modes were set up on this modified motorcycle engine for testing, namely, the SSI stoichiometric combustion mode ($\lambda = 1$), the DSI stoichiometric combustion mode ($\lambda = 1$), and the DSI mild lean combustion mode ($\lambda = 1.1$). The engine was operated at 5000 rpm, with intake pressure values of 45, 60, 75, and 90 kPa. The spark advance corresponding to each test condition is shown in Table 2.

The in-cylinder combustion pressure was measured with a piezoelectric transducer (Kistler Type 6052B) and a charge amplifier (Kistler Type 5011B), and the crankshaft angle was measured with an optic encoder (Kistler Type 2613B). Signals of the pressure transducer and encoder were sent into the data acquisition system of DEWE-2010, which uses a well-

Table 1. Engine Specifications

| type                  | four-stroke, single-cylinder, air-cooled, single-spark plug, port injection motorcycle gasoline engine |
|-----------------------|------------------------------------------------------------------------------------------------------|
| bore × stroke         | $83 \times 71.6$ mm$^3$                                                                             |
| comp. ratio           | 8.7                                                                                                   |
| displ.               | 387 cm$^3$                                                                                             |
| rated power           | 17 kW@6500 rpm                                                                                        |
| rated torque          | 26 N-m@5000 rpm                                                                                       |

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the intake pressure is 45 kPa, the order of the combustion modes follows: the DSI stoichiometric combustion mode > the DSI mild lean combustion mode > the SSI stoichiometric combustion mode. Except for the case when the intake pressure is 45 kPa, the order of the combustion modes is the same. When double-spark plug ignition is used, the DSI mild lean combustion mode (> the SSI stoichiometric combustion mode) when using the DSI strategy, the heat release rate is significantly increased, and the crank angle of the highest heat release rate is closer to the DSI stoichiometric combustion mode (θi = 1). It shows that double-spark plug ignition has a significant effect on accelerating the heat release rate of mildly homogeneous lean combustion.

Taking θi, CA10, CA50, and CA90 as the demarcation points (θi indicates the crank angle of ignition timing; CA10, CA50, and CA90 indicate the corresponding crank angle when the cumulative heat release accounts for 10%, 50%, and 90% of the total heat release, respectively), the combustion duration (crank angle interval between θi and CA90) is divided into three burning stages, namely, the flame development period (crank angle interval between θi and CA10), the rapid-burning early period (crank angle interval between CA10 and CA50), and the rapid-burning later period (crank angle interval between CA50 and CA90). Combustion parameters of these burning stages were calculated by averaging the continuously sampled 120 test cycles, as shown in Tables 4–7.

It shows that when the 183FMQ engine uses the DSI strategy, its combustion duration is significantly shorter, especially in the early stage of rapid burning (CA10 to CA50). At a low load, the phenomenon of shortening the rapid-burning early period in mild homogeneous lean combustion with double-spark plug ignition is more obvious. In the stoichiometric state, when using the DSI strategy, the combustion duration is shortened by about 6–10 °CA compared to that when using the SSI strategy. The flame development period is shortened by about 2–5 °CA, and the rapid-burning early period is shortened by about 3–8 °CA. However, the changes in the rapid-burning later period are relatively insignificant. Due to the slower burning rate of the

established thermodynamic methodology for cylinder pressure data analysis and combustion process characterization. Combustion parameters as well as their statistical characteristics can be calculated in real time with the DEWESOFT combustion analysis package.32,33 During the test, signal sampling resolution is set up to 0.1 °CA. Each test action continuously samples 120 cycles, and the arithmetic average of the 120 test cycles is used to calculate the combustion characteristic parameters for the test action.

3. COMBUSTION DIAGNOSIS

3.1. Influence of DSI on Lean Combustion Pressure. Figure 3 shows the comparison of the peak combustion pressure (pmax), maximum combustion pressure rise rate (dp/dθmax), and the crank angle of pmax (Apmax) for the three combustion modes at an engine speed of 5000 rpm with intake pressure values of 45, 60, 75, and 90 kPa. The SSI stoichiometric combustion mode, DSI stoichiometric combustion mode, and DSI mild lean combustion mode are, respectively, marked as “λ = 1 (SS)”, “λ = 1 (TS)”, and “λ = 1.1 (TS)”.

It can be seen that the order of the combustion modes corresponding to pmax and dp/dθmax from high to low is as follows: the DSI stoichiometric combustion mode > the DSI mild lean combustion mode > the SSI stoichiometric combustion mode. Except for the case when the intake pressure is 45 kPa, the order of the combustion modes corresponding to Apmax from small to large is the same. When the intake pressure is 45 kPa, the Apmax corresponding to the SSI stoichiometric combustion mode is the smallest. In the stoichiometric state (λ = 1), when double-spark plug ignition is used, pmax and dp/dθmax are significantly increased, and meanwhile, the crank angle of pmax is closer to the top dead center (TDC) at medium and high loads. The increase in the maximum combustion pressure and the advancement of the crank angle of pmax enable the engine to obtain a larger expansion ratio, which improves the thermal efficiency of the engine. At a low load, due to the longer combustion duration of the SSI stoichiometric combustion mode, its maximum heat release rate is reduced, rendering its Apmax relatively small. It is interesting to note that the pmax and dp/dθmax of the DSI mild lean combustion mode are lower than those of the DSI stoichiometric combustion mode but still higher than those of the SSI stoichiometric combustion mode.

3.2. Influence of DSI on the Heat Release Rate. Figure 4 shows the curves of the heat release rate for the three combustion modes at an engine speed of 5000 rpm with intake pressure values of 45, 60, 75, and 90 kPa, which were calculated by averaging the continuously sampled 120 test cycles. It shows that in the stoichiometric state (λ = 1) when using the DSI strategy, the heat release rate is significantly increased, and the crank angle of the highest heat release rate is advanced compared with the SSI strategy.

The maximum transient heat release rate of the DSI mild lean combustion mode (λ = 1.1) is lower than the DSI stoichiometric combustion mode (λ = 1), but it is still higher than the SSI stoichiometric combustion mode (λ = 1) and the curve of its integrated heat release rate is closer to the DSI stoichiometric combustion mode (λ = 1). It shows that double-spark plug ignition has a significant effect on accelerating the heat release rate of mildly homogeneous lean combustion.

Taking θi, CA10, CA50, and CA90 as the demarcation points (θi indicates the crank angle of ignition timing; CA10, CA50, and CA90 indicate the corresponding crank angle when the cumulative heat release accounts for 10%, 50%, and 90% of the total heat release, respectively), the combustion duration (crank angle interval between θi and CA90) is divided into three burning stages, namely, the flame development period (crank angle interval between θi and CA10), the rapid-burning early period (crank angle interval between CA10 and CA50), and the rapid-burning later period (crank angle interval between CA50 and CA90). Combustion parameters of these burning stages were calculated by averaging the continuously sampled 120 test cycles, as shown in Tables 4–7.

It shows that when the 183FMQ engine uses the DSI strategy, its combustion duration is significantly shorter, especially in the early stage of rapid burning (CA10 to CA50). At a low load, the phenomenon of shortening the rapid-burning early period in mild homogeneous lean combustion with double-spark plug ignition is more obvious. In the stoichiometric state, when using the DSI strategy, the combustion duration is shortened by about 6–10 °CA compared to that when using the SSI strategy. The flame development period is shortened by about 2–5 °CA, and the rapid-burning early period is shortened by about 3–8 °CA. However, the changes in the rapid-burning later period are relatively insignificant. Due to the slower burning rate of the

Figure 1. Combustion chamber of the double-spark SI engine: (a) sketch of the location of the added spark plug and (b) combustion chamber.

Figure 2. Comparison of engine torque with three different ignition schemes.

Figure 3. Influence of DSI on Lean Combustion Pressure.
lean mixture, the combustion duration of the DSI mild lean combustion mode is longer than that of the DSI stoichiometric combustion mode, but it is still shorter than that of the SSI stoichiometric combustion mode. Compared with the SSI stoichiometric combustion mode, it is shortened by about 2−7 °CA. Under a low load condition, the flame development period is shortened by 2.7 °CA, and the rapid-burning early period is shortened by 8.1 °CA. Therefore, it can be concluded that the overall effect of double-spark plug ignition in accelerating mildly homogeneous lean combustion is mainly reflected during the early period of rapid burning.

3.3. Influence of DSI on Cyclic Variations. Figure 5 shows the coefficients of the cyclic variation in $p_{\text{max}}$ (COV$_{p_{\text{max}}}$) and $p_{\text{mi}}$ (COV$_{p_{\text{mi}}}$) for the three combustion modes at an engine speed of 5000 rpm with intake pressure values of 45, 60, 75, and 90 kPa. For the SSI stoichiometric combustion mode, COV$_{p_{\text{max}}}$ is 18.63% for 45 kPa, 11.94% for 60 kPa, 10.26% for 75 kPa, and 9.89% for 90 kPa. After using the DSI strategy, the coefficients of cyclic variation are significantly reduced. For example, for the DSI stoichiometric combustion mode, COV$_{p_{\text{max}}}$ is 6.14% for 60 kPa, 5.22% for 75 kPa, and 6.29% for 90 kPa. Except for the case when the intake pressure is 45 kPa, the coefficients of cyclic variation in $p_{\text{max}}$ are reduced to less than 7%. It can be seen that the COV$_{p_{\text{max}}}$ of the DSI mild lean combustion mode is higher than the DSI stoichiometric combustion mode, but it is still lower than the SSI stoichiometric combustion mode.

In Figure 5b, it can be seen that the coefficients of cyclic variation in $p_{\text{mi}}$ are the lowest for the DSI stoichiometric combustion mode, slightly higher for the DSI mild lean combustion mode, and the highest for the SSI stoichiometric combustion mode. The COV$_{p_{\text{mi}}}$ of the DSI mild lean combustion mode is significantly better than that for the SSI stoichiometric combustion mode, especially for the low load condition of 45 kPa, under which condition the coefficient of cyclic variation in $p_{\text{mi}}$ is greatly reduced. It is evident that the double-spark plug ignition plays an important role in promoting and improving the stability of mildly homogeneous lean combustion.

3.4. Influence of DSI on $p_{\text{mi}}$. Table 8 shows the values of $p_{\text{mi}}$ for the three combustion modes at an engine speed of 5000 rpm with intake pressure values of 45, 60, 75, and 90 kPa, which were calculated by averaging the continuously sampled 120 test cycles. Due to the increase in the heat release rate and the shortening of the combustion duration, the values of $p_{\text{mi}}$ for the DSI stoichiometric combustion mode are the largest, which are about 2−4% larger than the SSI stoichiometric combustion mode at medium and high loads.

For the DSI mild lean combustion mode, due to the lean mixture, the $p_{\text{mi}}$ is lower than the SSI stoichiometric combustion mode under medium and high loads. However, at a low load, the $p_{\text{mi}}$ of the DSI mild lean combustion mode is higher than that of the SSI stoichiometric combustion mode. The $p_{\text{mi}}$ of the SSI stoichiometric combustion mode decreases to 0.204 MPa. This is because, at a low load, the SSI stoichiometric combustion mode has a lower heat release rate, longer combustion duration, higher cyclic variation, and very poor combustion stability. It verifies the remarkable effect of double-spark plug ignition in improving the stability of lean combustion.
4. CALIBRATION AND EMISSION

4.1. Calibration of the Lean Burn Zone. At idle speed, the use of a lean mixture will affect combustion stability.

| intake pressure/kPa | $\lambda = 1$ (SS)/°CA | $\lambda = 1$ (TS)/°CA | $\lambda = 1.1$ (TS)/°CA |
|---------------------|-------------------------|-------------------------|-------------------------|
| 45                  | 67                      | 55                      | 60                      |
| 60                  | 47                      | 42                      | 47                      |
| 75                  | 39                      | 34                      | 38                      |
| 90                  | 33                      | 28                      | 37                      |

Table 3. Best Spark Advance at 5000 rpm

Figure 3. $p_{\text{max}}$, $\frac{dp}{d\theta_{\text{max}}}$, and $A_{\text{p_{max}}}$ for the three modes with different intake pressure values: (a) $p_{\text{max}}$, (b) $\frac{dp}{d\theta_{\text{max}}}$, and (c) $A_{\text{p_{max}}}$.

4.2. Heat release rate for the three modes with different intake pressure values: (a) 45 kPa, (b) 60 kPa, (c) 75 kPa, and (d) 90 kPa.

Table 4. Parameters for the Three Stages with an Intake Pressure of 45 kPa

| burning stage | $\lambda = 1$ (SS)/°CA | $\lambda = 1$ (TS)/°CA | $\lambda = 1.1$ (TS)/°CA |
|---------------|-------------------------|-------------------------|-------------------------|
| $\theta_{i}$ to CA90 | 128.7                  | 115.5                   | 121.6                   |
| $\theta_{i}$ to CA10 | 64.4                    | 60.9                    | 61.7                    |
| CA10 to CA50 | 25.0                    | 15.2                    | 16.9                    |
| CA50 to CA90 | 39.3                    | 39.4                    | 43.0                    |

Table 5. Parameters for the Three Stages with an Intake Pressure of 60 kPa

| burning stage | $\lambda = 1$ (SS)/°CA | $\lambda = 1$ (TS)/°CA | $\lambda = 1.1$ (TS)/°CA |
|---------------|-------------------------|-------------------------|-------------------------|
| $\theta_{i}$ to CA90 | 77.8                    | 68.8                    | 75.7                    |
| $\theta_{i}$ to CA10 | 43.1                    | 38.8                    | 41.8                    |
| CA10 to CA50 | 13.0                    | 9.0                     | 10.1                    |
| CA50 to CA90 | 21.7                    | 21.1                    | 23.8                    |

Table 6. Parameters for the Three Stages with an Intake Pressure of 75 kPa

| burning stage | $\lambda = 1$ (SS)/°CA | $\lambda = 1$ (TS)/°CA | $\lambda = 1.1$ (TS)/°CA |
|---------------|-------------------------|-------------------------|-------------------------|
| $\theta_{i}$ to CA90 | 64.2                    | 58.3                    | 60.3                    |
| $\theta_{i}$ to CA10 | 34.9                    | 32.6                    | 34.4                    |
| CA10 to CA50 | 11.3                    | 8.4                     | 9.0                     |
| CA50 to CA90 | 18.0                    | 17.3                    | 17.0                    |
However, at a high load, the use of a lean mixture will result in insufficient power. Therefore, it is necessary to calibrate the lean burn zone. Here, to optimize the excess-air factor (λ) corresponding to the lean combustion zone when using the DSI mild lean combustion mode, four kinds of mixture with λ = 1, 1.05, 1.1, and 1.2 are set for calibration. Figure 6 shows the changes of the output torque and BSFC with the intake pressure at the engine speeds of 3800 and 5000 rpm under the DSI mild lean combustion mode with λ = 1, 1.05, 1.1, and 1.2.

As seen in Figure 6, as λ increases, the output torque decreases in turn. When λ = 1.05 and 1.1, the output torque is reduced compared to that of λ = 1, but the torque differences are not large. However, when λ reaches 1.2, the output torque decreases drastically. It shows that the excess-air factor of 1.2 may be close to the lean burn limit. In addition, under different lean burn conditions, the differences in output torque at low and high loads are relatively large, while at a medium load, the differences are relatively small. Therefore, it can be concluded that the DSI mild lean combustion mode is very suitable for the 187FMQ engine under a medium load condition.

At medium and high loads, the BSFC of the three lean combustion modes (whose λ = 1.05, 1.1, and 1.2) is lower, reduced by about 2–6% compared to the stoichiometric combustion mode (λ = 1) but higher at low loads. For example, if the intake pressure is lower than 55 kPa, the BSFC increases significantly when λ = 1.1 and 1.2. This is because, with the increase of λ under low load conditions, the cyclic variation increases and the combustion instability becomes more prominent. This leads to a significant increase in fuel consumption.

At low loads, the residual exhaust gas coefficient will increase significantly. If a lean mixture is used, combustion stability problem will become more severe. It shows that even if the DSI strategy is used, it is quite difficult to maintain the combustion stability at a normal level under high λ conditions. Therefore, when using the DSI mild lean combustion mode under low load conditions, to ensure combustion stability, λ should not exceed 1.05. The λ value corresponding to the lean burn zone for the 187FMQ engine with the DSI mild lean combustion mode was obtained through the calibration test, as shown in Table 9.

4.2. Catalyst Activity Evaluation. Under a mildly rich oxygen condition, the original catalyst of the 183FMQ engine has low NOx conversion efficiency. For this reason, a three-way catalyst with rare-earth catalytic materials is used to reduce NOx emissions, which uses rare-earth oxygen storage materials to increase the oxygen storage capacity of the catalyst and expand the three-way window, thereby increasing the NOx conversion efficiency. The experimental device shown in Figure 7 was used to evaluate the activity of the catalyst. It uses standard gas to prepare exhaust gas to evaluate the catalytic converter activity. The standard gases used include CO, CO2, C3H6, C3H8, NO, O2, and N2. These standard gases are mixed in a certain proportion to realize the simulation of different concentrations of exhaust gas.

The oxygen balance coefficient β (the ratio of the volume concentration of oxygen contained in the simulated exhaust gas to the oxygen concentration required for complete oxidation of the carbon-containing gas in the exhaust gas) is used to characterize whether the exhaust gas is an oxidizing atmosphere or a reducing atmosphere. If β > 1, it is an oxidizing atmosphere, and if β < 1, it is a reducing atmosphere. The calculation method of β is as follows

$$β = \frac{2 \times C_{O_2}}{C_{CO} + 10 \times C_{C_3H_8} + 9 \times C_{C_3H_6} - C_{NO}}$$

where $C_{O_2}$, $C_{CO}$, $C_{C_3H_8}$, $C_{C_3H_6}$, and $C_{NO}$ are the volume fractions of $O_2$, CO, $C_3H_8$, $C_3H_6$, and NO in the simulated exhaust gas, respectively.

During the test, the gas flow is controlled according to the airspeed of $(40000 \pm 1500) $ h^{-1}$, and the heating temperature of the test bench is set to 500°C. The β was gradually changed and the concentration of each component before and after the catalyst was measured. The test results are shown in Figure 8. It shows the air–fuel ratio characteristics of the original catalyst of the 183FMQ engine and the new type of catalyst containing rare-earth materials. Due to the use of cerium oxide rare-earth materials and the use of metal Mn as the doping element of the cerium–zirconium solid solution, the three-way

| Table 7. Parameters for the Three Stages with an Intake Pressure of 90 kPa |
|----------------|-----------------|-----------------|-----------------|
| burning stage | $λ = 1$ (SS)/CA | $λ = 1$ (TS)/CA | $λ = 1.1$ (TS)/CA |
| $θi$ to CA90  | 60.7            | 54.5            | 56.0            |
| $θi$ to CA10  | 32.8            | 30.4            | 31.8            |
| CA10 to CA50  | 10.7            | 7.8             | 8.5             |
| CA50 to CA90  | 17.1            | 16.2            | 15.7            |

![Figure 5](https://doi.org/10.1021/acsomega.1c06130) | ![Figure 6](https://doi.org/10.1021/acsomega.1c06130) | ![Figure 7](https://doi.org/10.1021/acsomega.1c06130) | ![Figure 8](https://doi.org/10.1021/acsomega.1c06130)
window of the new type rare-earth catalyst increases to $\lambda = 1.06$ in the lean direction, which is highly conducive to reduce NOx emissions during mild lean burn.

### 4.3. Emission Measurement

Figure 9 shows the variation of CO, HC, and NOx emissions with the intake pressure after the three-way catalytic converter under the DSI condition at an engine speed of 4000 rpm with $\lambda$ of 1.05 and 1.1. In the figure, it shows that as the load increases, CO and HC emissions show a downward trend and NOx emission shows an upward trend, which is mainly due to the increase in the combustion temperature in the cylinder as the load increases.

#### Table 8. $p_m$ for the Three Combustion Modes with Different Intake Pressure Values

| Intake pressure/kPa | $\lambda = 1$ (SS)/MPa | $\lambda = 1$ (TS)/MPa | $\lambda = 1.1$ (TS)/MPa |
|---------------------|------------------------|------------------------|------------------------|
| 45                  | 0.204                  | 0.256                  | 0.227                  |
| 60                  | 0.561                  | 0.581                  | 0.534                  |
| 75                  | 0.818                  | 0.834                  | 0.78                   |
| 90                  | 0.925                  | 0.946                  | 0.888                  |

#### Figure 6. Torque and BSFC for the DSI mild lean combustion mode with different $\lambda$ values: (a) torque at a speed of 3800 rpm, (b) BSFC at a speed of 3800 rpm, (c) torque at a speed of 5000 rpm, and (d) BSFC at a speed of 5000 rpm.

#### Table 9. Values of $\lambda$ Corresponding to the Lean Burn Zone

| Intake pressure/kPa | 3000 rpm | 3500 rpm | 4000 rpm | 4500 rpm | 5000 rpm | 5500 rpm |
|---------------------|----------|----------|----------|----------|----------|----------|
| 50                  | 1.05     | 1.05     | 1.05     | 1.05     | 1.05     | 1.05     |
| 55                  | 1.05     | 1.1      | 1.1      | 1.1      | 1.1      | 1.05     |
| 60                  | 1.05     | 1.1      | 1.1      | 1.1      | 1.1      | 1.05     |
| 65                  | 1.05     | 1.1      | 1.1      | 1.1      | 1.1      | 1.05     |
| 70                  | 1.05     | 1.05     | 1.05     | 1.05     | 1.05     | 1.05     |
However, it is worth noting that as $\lambda$ increases, NOx not only increases but also shows a downward trend, especially under a low load. At the same time, CO and HC also show a downward trend; especially for CO, the decline is obvious, and HC is also significantly reduced at low loads. This indicates that the use of a three-way catalyst with rare-earth oxygen storage materials can help reduce emissions in the mildly lean burn mode. When the intake pressure exceeds 60 kPa, the differences in HC and NOx emissions with $\lambda = 1.05$ and 1.1 are very small.

Figure 10 shows the variation of CO, HC, and NOx emissions with the engine speed after the three-way catalytic converter under the DSI condition at an intake pressure of 60 kPa with $\lambda$ of 1, 1.05, and 1.1. As the $\lambda$ increases, the emissions of CO, HC, and NOx all decrease. It shows that the use of the DSI mild lean burn mode can help reduce emissions to a certain extent. As the speed increases, CO and NOx emissions show a downward trend. However, for HC emission, as the speed increases, it shows an increasing trend, reaching the maximum value at about 6000 rpm, which is mainly due to insufficient combustion.

In general, for the mild homogeneous lean combustion mode, the use of double-spark plug ignition can help reduce emissions to a certain extent. Taking into account the characteristics of the three-way catalytic converter containing rare-earth oxygen storage materials, the rare-earth oxygen storage materials can increase the oxygen storage capacity of the catalyst and expand the working window of TWC. If combined with a three-way catalytic converter containing rare-earth materials, it can effectively reduce the emissions of motorcycles with the mild lean combustion mode.

5. CONCLUSIONS

(1) With the DSI strategy, the maximum heat release rate of the DSI mild lean combustion mode is higher than that of the SSI stoichiometric combustion mode, and the combustion duration is shortened by about 2~7 °CA. At a low load, the flame development period is shortened by 2.7 °CA, and the rapid-burning early period is shortened by 8.1 °CA. It shows that the overall effect of double-spark plug ignition in accelerating mildly homogeneous lean combustion is mainly reflected during the early period of rapid burning.

(2) COV$_{p_{\text{max}}}$ and COV$_{p_{\text{mi}}}$ of the DSI mild lean combustion mode are lower than the SSI stoichiometric combustion mode; especially at a low load, the coefficient of cyclic variation in $p_{\text{mi}}$ is greatly reduced, which renders the $p_{\text{mi}}$ of the DSI mild lean combustion mode higher than the SSI stoichiometric combustion mode. It proves that the double-spark plug ignition has obvious effects on improving the stability of mildly homogeneous lean burn and extending the lean burn limit.

(3) With double-spark plug ignition, the torque of the 183FMQ engine with $\lambda = 1.05$ and $\lambda = 1.1$ is lower than
that with $\lambda = 1$, but the difference is not large, especially at a medium load; the difference is not obvious. However, at low and high loads, the difference between the different lean burn states is greater. In addition, the BSFC in the three homogeneous lean burn states ($\lambda = 1.05$, $1.1$, and $1.2$) at medium and high loads is lower than that in the stoichiometric state ($\lambda = 1$) but higher at a low load. This is because, with the increase of $\lambda$ at a low load, the cyclic variation becomes more severe.

(4) Affected by combustion stability, the $\lambda$ of the DSI mild lean combustion mode should not exceed 1.1 and should not exceed 1.05 at a low load. Compared with the SSI stoichiometric combustion mode, the DSI mild lean combustion mode can improve the fuel economy by 3–6% and reduce emissions to a certain extent. It is foreseeable that using the SSI mild lean combustion mode combined with a TWC containing rare-earth oxygen storage materials can effectively reduce motorcycle fuel consumption and emissions.

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H.S.: methodology, investigation, validation, and writing original draft; L.Z.: conceptualization, funding acquisition, supervision, and writing—reviewing and editing; J.D.: investigation, software, and formal analysis; X.C.: investigation and data curation; and B.C.: resources.

### Notes

The authors declare no competing financial interest.

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