Quantitative Analysis of the Influence Saliency of VVA and EGR on the Fuel Economy and Mixture Combustion Characteristics of a Turbocharged Spark Ignition Engine

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ABSTRACT: To meet the stringent emission regulations and fuel economy demands of the spark ignition (SI) engine, more and more new technologies such as turbocharging, variable valve actuation (VVA), and exhaust gas recirculation (EGR) are being developed. For the turbocharged SI engine, the high boost pressure can lead to higher laminar combustion velocity with higher maximum burned gas temperature, which induces more emissions; it also carries a risk of serious knocking, which can not only deteriorate the brake-specific fuel consumption (BSFC) but also destroy the engine. As is well known, the dilution mixture gas methods, which include VVA and EGR, are effective techniques to advance the combustion phase and suppress knocking in the SI turbocharged engines. The effects of VVA and EGR rates on the BSFC and combustion characteristics of an SI engine were analyzed through 100 groups of engine experiments, and the quantitative analysis of the influence saliency of VVA and EGR rates has been introduced. Then, the optimal level of each factor was obtained by a comprehensive balance method. The results indicated that the EGR rate has the most significant influence on the BSFC and CA50. At the same time, the BSFC was only 211.7 g/kWh, which has been improved significantly, and CA50 was 12.55° CA ATDC, which effectively enhances the knock resistance when applying the optimization parameters.

1. INTRODUCTION

To meet the stringent emission regulations and fuel economy demands,1 more and more new technologies such as homogeneous charge compression ignition (HCCI),2,3 variable valve actuation (VVA),4 exhaust gas recirculation (EGR),5−9 alternative fuels,10−15 turbocharging,16,17 engine downsizing,18 and so on have been widely applied in the internal combustion engine in recent decades. For the sake of improving the power density of the engine, turbocharging, which can achieve a high intake pressure via exhaust gas, has been widely used in the recent years.19 However, as the boost pressure increases, the end-gas temperature leads to a higher laminar combustion velocity with a higher maximum burned gas temperature, and more emissions, especially NOx, are induced. In addition, the high boost pressure may lead to serious knocking, which can damage the engine. Therefore, the urgency to save energy and reduce emissions is still the main concern for the use of turbocharged engines. As is well known, VVA and EGR have been proved to be effective techniques for improving the efficiency and reducing the probability of knocking in turbocharged engines.20−23

The valve parameters of the intake and exhaust valves have a significant influence on the combustion conditions and affect the air exchange and emission production, thereby improving fuel consumption and emissions.24 For example, at high engine speeds, the durations of engine intake and exhaust are decreased, and they cannot meet the gas exchange of the engine cylinder. Therefore, the VVA system, with which the valve parameters can be modified dynamically, is very necessary and is being continuously developed and widely used. An early-intake valve closing (EIVC) or a late-intake valve closing (LIVC) of the valve motions introduced into the engine could cause the engine to take less fresh charge into the cylinder and reduce the pumping loss, which can improve the BSFC at partial load; however, the HC emissions would deteriorate.25 The VVA system can not only affect the gas exchange but also realize the internal EGR, which is effective in decreasing the burned gas temperature, thereby reducing the NOx production. The first VVA system that maintained the

Received: July 25, 2021
Accepted: October 27, 2021
Published: November 11, 2021
valve lift and duration constant with variable valve timing was introduced by Alfa Romeo (1980).26 Subsequently, valve trains have become more and more diverse in their designs. Thereafter, the continuous-variable valve actuation, which can change the valve opening timing, valve lift, and valve closing timing, was further developed. The most representative continuous-variable valve actuation was the hydraulic-variable valve actuation (HVVA), through which the valve opening timing, valve closing timing, and valve lift can be adjusted independently. Li et al. replaced the cam-based valve train with the HVVA system of a single-cylinder gasoline engine and proposed HVVA strategies with internal EGR for unthrottled engine load control. The results indicated that the BSFC average improved by 13.1% from the simulations over the entire engine speed range, the maximum reduction upon which could reach up to 15.8% at 3600 rpm on the test engine.27 Honda developed a mechanism of three-stage variable valve actuation, known as variable valve timing and lift electronic control system (VTEC), which makes proper use of the valve rocker arms driven by the cams of the different characteristics by the connection or separation of the internal organs’ pistons by oil pressure control. The VTEC helps in improving the volumetric efficiency in the process of intake, resulting in lower fuel consumption.28

Considering the reasons for using VVA to improve the combustion in the cylinder, the gas flow and residual gas in the cylinder are two parameters that can be altered by using VVA, thereby changing the initial unburned gas temperature and combustion temperature in the cylinder. This works as an internal EGR method to improve the fuel combustion efficiency and reduce the emission of the engine. Besides, the external EGR method was also an effective technique to improve the fuel combustion efficiency and reduce the emission of the engine, which introduced the exhaust gas to the intake pipe by the external EGR system, and usually combined with the EGR cooler to decrease the temperature of exhaust gas. With a cooled EGR system, the combustion was proved to be more retarded, and the burn durations were longer.6 Both the internal EGR and external EGR can effectively reduce the pump loss and NOx emission, and increase the engine efficiency of the turbocharged engines, and so they have been widely used in gasoline engines. Shen et al.20 investigated the effect of the EGR on the fuel economy and emission of the miller cycle turbocharged engine. The results reveal that EGR can not only reduce the spontaneous combustion of the exhaust gas and optimize the combustion phase but also greatly decrease the pumping losses; therefore, it can further enhance the effect of the Miller cycle on improving the BSFC and emission. In addition, EGR is also effective in combination with natural-gas SI engines and hydrogen-fueled SI engine. Talei et al.21 studied the effect of cold EGR on the combustion performance and emission of a natural-gas lean-burn engine with a pre-chamber combustion system by experimental and numerical analyses. The results indicated that by the use of pre-chamber and cold EGR simultaneously and increasing the cold EGR gradually, the release of CO2 reduced by 5%, the release of NOx decreased by 50%, and the UHC emissions decreased in a specific range of cold EGR. With EGR, the experimental study showed that the combustion characteristics were affected by natural gas—hydrogen blends. The combustion duration and flame development duration increase with increased EGR rate; however, these decreased with the increased H2 in the blends.29,30 Zhao et al.23 added hydrogen to an isobutanol—gasoline during the EGR and investigated the effects of hydrogen combined with EGR on the engine thermal efficiency and emission. The results showed that the combustion progress of the butanol—gasoline mixture slowed down with EGR, and that combining hydrogen with EGR can effectively improve the combustion stability because of reducing the burn-period extension. Splitter et al.31,32 experimentally investigated the performance of high-octane biofuels (87AKI E0 gasoline, 24% vol/vol isobutanol—gasoline IB24, 30% vol/vol ethanol—gasoline E30) and EGR in an SI engine that was equipped with a hydraulic valve actuation. The results demonstrate that for all fuels, EGR is a key enabler for increasing the engine efficiency, but is less useful for knock mitigation with E30 than for 87AKI gasoline or IB24, and that E30 with 15% EGR offers the highest stoichiometric torque capability at a high compression ratio.

The previous studies showed that both the internal and external EGR can effectively reduce the pump loss and NOx emission, and increase the thermal efficiency of the turbocharged engines. The external EGR reused and introduced the exhaust gas to the intake pipe by the external EGR system, and the internal EGR changed the mass fraction of the residual exhaust gas inside the cylinder through the VVA system. Most papers have studied the effect of the VVA and EGR rate on the fuel economy and emission of the engine; however, the quantitative analysis of the influence saliency of the VVA and EGR rates has not been introduced yet. In this research, the effects of various IVO rates, exhaust valve closing timing (EVC), and EGR strategies on the combustion characteristics and BSFC of a turbocharged engine equipped with the VVA system (with valve lift and duration kept constant, and valve opening and closing timing adjusted) were investigated on an experimental engine. The influence saliency of the IVO, EVC, and EGR rates on BSFC and CA50 was obtained by the range and variance analysis, and then, the comprehensive balance method was adopted to obtain the optimal level of each factor that can achieve a better fuel consumption and suppress the knocking of the turbocharged gasoline engine.

2. EXPERIMENTAL SETUP

Engine experiments were carried out by a 4-cylinder SI turbocharged gasoline engine, and the engine specifications are summarized in Table 1. The compression ratio of the engine is 9.6, and the stroke and bore of the engine are 84.1 and 82.1 mm, respectively. Besides, both the intake and exhaust valve trains were equipped with the VVA system, which can adjust the valve opening and closing timing, but the valve lift and duration were kept constant. The valve parameter of the VVA system is shown in Figure 1. It can be observed that the intake and exhaust valve durations were maintained at 220 and 218
°CA, respectively. IVO can be adjusted from $-59$ °CA ATDC to $-4$ °CA ATDC corresponding to the intake valve closing (IVC) timing being adjusted from $-19$ °CA ABDC to $36$ °CA ABDC. At the same time, the exhaust valve opening timing (EVO) can be adjusted from $-50$ °CA ABDC to BDC corresponding to the exhaust valve closing (EVC) timing being adjusted from $-12$ °CA ATDC to $38$ °CA ATDC. The valve overlap regions varied on changing the EVC and IVO. The exhaust gas in the exhaust manifold may come back to the cylinder when the exhaust pressure is higher than the cylinder pressure during the overlap period. Meanwhile, the same valve overlap could be obtained by various combinations of EVC and IVO.

In this research, in order to clarify the influence saliency of EGR, IVO, and EVC on the fuel economy and mixture combustion characteristics of the target engine, a total of 100 groups of experiments at 2100 rpm and 110 N m were carried out and the experimental scheme is shown in Table 2. All experimental conditions were tested in the knock-limited regime by advancing the ignition timing until knock occurred. The initial intake air pressure and the intake air temperature were set to 1.01 bar and 298.15 K during the test. The experimental test bench is shown in Figure 2. An eddy current dynamometer (CW260) with a maximum speed of 7500 rpm that could meet the full load of the target engine was used. NI-cRIO 9036 was used as the ECU to control the fuel injection, spark ignition, throttle valve angle, and the VVA system. In addition, a combustion analyzer (KIBOX 2893 AK121) was applied to obtain the combustion parameters. The air−fuel ratio could be controlled and tested by an exhaust gas analyzer (HORIBA-MEXA7100DEGR) and an air−fuel ratio measuring instrument (ETAS-ES630). The equivalence ratio combustion was used in this experimental test. The EGR circuit of the experiment engine is shown in Figure 3. It can be shown that the experimental engine with a low-pressure EGR includes an EGR valve, EGR pipe, and EGR cooler. The EGR valve was used to adjust the mass of the exhaust gas flowing into the cylinder, and the EGR rate was used to represent the percentage of exhaust gas in the combined gas in the cylinder, which is shown in eq 1. The exhaust gas coming out of the turbine and EGR valve was cooled by the EGR cooler and then introduced into the cylinder.

\[
\text{EGR rate} = \frac{\text{CO}_2(\text{exhaust})}{\text{CO}_2(\text{exhaust}) + \text{fresh air}} \quad (1)
\]

3. RESULTS AND DISCUSSION

The experimental scheme is shown in Table 2. It can be observed that IVO has 5 levels, which are $-59$ °CA ATDC, $-49$ °CA ATDC, $-39$ °CA ATDC, $-29$ °CA ATDC, and $-19$ °CA ATDC; EVC has 4 levels, which are $14$ °CA ATDC, $4$ °CA ATDC, $-6$ °CA ATDC, and $-16$ °CA ATDC; and EGR rate has 5 levels, which are 0, 10, 15, 20, and 25%. When the EGR rate is 0%, it means that the engine is without external EGR. To analyze the influence saliency of the IVO, EVC, EGR rate, and their interactions on BSFC and CA50, a total of 100 groups of engine experiments were carried out and the BSFC and combustion characteristics were measured.

Meanwhile, improving the fuel economy of the engine is the primary objective. As is known to all, the advancement of
CA50 helps to improve the BSFC; however, the risk of knocking will be increased while the CA50 is too close to TDC, which means that the ignition is too early. Therefore, for the overall performance improvement of the engine, the indicators of BSFC and CA50 were considered simultaneously in this research. Under the premise of suppressing knocking, a smaller CA50 helps to improve the BSFC and the mixture combustion characteristics.

In this research, all experimental conditions were tested at the maximum ignition advance angle until combustion knock was encountered.

3.1. Range Analysis. The indicator average value $\bar{K}_i$ is used to evaluate the influence of the level of a specific factor on BSFC and CA50, and it is defined as follows:

$$
\bar{K}_i = \frac{1}{N_i} \sum_{j=1}^{N_i} Y_j
$$

where $i$ denotes the level; $N_i$ is the number of the corresponding factor at level $i$; and $Y_j$ is the result of BSFC or CA50.

Figure 4 illustrates the indicator average values of BSFC and CA50 over 100 groups of the engine experimental results at 2100 rpm and 110 N m. The valve overlap regions varied on changing the IVO and EVC. During the overlap period, the intake manifold pipe, cylinder, and exhaust manifold pipe are simultaneously connected, and the exhaust gas may come back to the cylinder if the exhaust pressure is higher than the cylinder pressure, which is called internal EGR. A larger valve overlap leads to a bigger residual gas fraction during the experimental conditions. In this research, the ignition timing was always kept at the knock limit.

Figure 4a shows the indicator average value of BSFC and CA50 under different IVO. It can be observed that with the delay of the IVO, both the BSFC and CA50 first increase and then decrease. This is mainly because an earlier IVO leads to a large valve overlap, which results in a higher residual gas fraction, which can reduce the pump loss and improve the BSFC. Besides, a higher residual gas fraction implies that the ignition timing can be more advanced and the knock limit is extended by the internal EGR. When the IVO is $-29 \, ^\circ\text{CA ATDC}$, BSFC reaches its maximum value (219.8 g/kWh), while CA50 reaches the maximum value ($16.1 \, ^\circ\text{CA ATDC}$) when IVO becomes $-39 \, ^\circ\text{CA ATDC}$. Besides, when IVO was delayed from $-59 \, ^\circ\text{CA ATDC}$ to $-29 \, ^\circ\text{CA ATDC}$, the indicator average of BSFC increased from 218.4 to 219.8 g/kWh, by 0.6%. Meanwhile, when IVO was delayed from $-59 \, ^\circ\text{CA ATDC}$ to $-39 \, ^\circ\text{CA ATDC}$, the indicator average of CA50 was delayed from 14.9 $^\circ\text{CA ATDC}$ to 16.1 $^\circ\text{CA ATDC}$, by 1.2 $^\circ\text{CA}$.

On the other hand, a later EVC results in a larger valve overlap. It can be observed from Figure 4b that both BSFC and CA50 decrease with the delay of the EVC when it is before $4 \, ^\circ\text{CA ATDC}$, and then they all increase. The indicator averages of BSFC and CA50 reached their minimum values (218.3 g/kWh, 15.0 $^\circ\text{CA ATDC}$) when the EVC was 4 $^\circ\text{CA ATDC}$. Besides, when EVC was delayed from $-16 \, ^\circ\text{CA ATDC}$ to $-29 \, ^\circ\text{CA ATDC}$, the indicator average of BSFC was reduced from 219.0 to 218.3 g/kWh, by 0.3%, and the indicator average of CA50 was advanced from 15.9 $^\circ\text{CA ATDC}$ to 15.1 $^\circ\text{CA ATDC}$, advanced by 0.9 $^\circ\text{CA}$.

It is clear that both the internal EGR and the external EGR can introduce the burned gas into the cylinder as a dilution strategy. Figure 4c demonstrates the indicator average of the BSFC and CA50 at different EGR rates. The indicator averages of BSFC and CA50 decrease with increase of the EGR rate when it is smaller than 20%; however, when the EGR rate is greater than 20%, both BSFC and CA50 begin to increase. It is mainly because with EGR, the throttle loss in the part load range could be reduced by a wider-opening throttle angle.
Besides, the CO₂ in the exhaust gas is introduced into the cylinder to mix fresh air, which reduces the combustion temperature, improves the knock resistance, and advances the ignition timing, thereby improving the BSFC. The indicator averages of BSFC and CA₅₀ reached their minimum values (215.8 g/kWh, 11.8 °CA ATDC) when the EGR rate was 20%. When the EGR rate was 20%, the indicator average of BSFC was improved by 5.1% and the indicator average of CA₅₀ was advanced by 6.9 °CA compared to that without external EGR.

The difference of the maximum and minimum indicator averages for the corresponding factor is defined as

$$\text{range} = \max(\bar{X}_1, \bar{X}_2, \bar{X}_3, ...) - \min(\bar{X}_1, \bar{X}_2, \bar{X}_3, ...)$$  \hspace{1cm} (3)

The range indicates the influence weight of different factors. The larger the range value, the more significant the influence of the factors on the indicator. As shown in Figure 5, the EGR rate has the most significant influence on BSFC and CA₅₀, IVO has the slightest influence on BSFC, and EVC has the slightest influence on CA₅₀.

\[\text{Figure 5. Range of BSFC and CA₅₀.}\]

3.2. Variance Analysis. Range analysis cannot provide a quantitative analysis for estimating whether the influence of the variables is noticeable, and it ignored the error existing in the experiment. To solve this problem, variance analysis was implemented to study the influence of various factors in this paper. Because the interaction among the EGR rate, IVO, and EVC has little effect on BSFC and CA₅₀, this article ignores the secondary interaction among the three, and only considers the first-level interaction between the three. The sum of squared deviations and the degree of freedom of the secondary interaction among the three was incorporated into the errors.

The degree of freedom (DOF) of the factor was calculated as follows:

$$\text{DOF}_A = a - 1$$  \hspace{1cm} (4)

$$\text{DOF}_{AB} = (a - 1) \times (b - 1)$$  \hspace{1cm} (5)

where \(a\) is the number of levels of factor A and \(b\) is the number of levels of factor B. \(\text{DOF}_A\) is the DOF of factor A and \(\text{DOF}_{AB}\) is the DOF of the interaction between factors A and B.

Due to both the IVO and EGR rates having 5 levels, their DOF is 4, and because the EVC has 4 levels, its DOF is 3.

The variance analysis equation is as follows:

$$F_j = \frac{\text{SS}_j / \text{DOF}_j}{\text{SS}_e / \text{DOF}_e}$$  \hspace{1cm} (6)

where \(F_j\) is the \(F\) value of \(j\) factor, \(\text{SS}_j\) is the sum of squared deviations caused by factor \(j\), \(\text{DOF}_j\) is the degree of freedom of factor \(j\), \(\text{SS}_e\) is the sum of squares of errors, and \(\text{DOF}_e\) is the degree of freedom of errors.

The influence of factors (EVC, IVO, and EGR) on the indicators (BSFC and CA₅₀) can be evaluated through the F-test: if \(F_A < F_{0.05(j \times k)}\), A has little influence on the indicator; if \(F_{0.05(j \times k)} < F_A < F_{0.01(j \times k)}\), A has a certain influence on the indicator, and its saliency is \(*\); if \(F_{0.01(j \times k)} < F_A\), A has a significant influence on the indicator, and its saliency is \(**\).

The variance analysis table of the BSFC is shown in Table 3. By comparing the \(F_j\) value with the corresponding standard \(F\) distribution table, the influence saliency of different factors was obtained. It can be observed that the \(F_I\) of EGR reaches 174.95, which is much greater than \(F_{0.01(4,48)}\); therefore, EGR has the most significant influence on BSFC; at the same time, the interaction between IVO and EGR also has a great influence on BSFC, and their saliency is \(**\). Besides, the \(F\) of EVC is 3.59, which is greater than \(F_{0.05(3,48)}\) and less than \(F_{0.01(3,48)}\); therefore, the influence saliency of EVC is \(*\), and it also has a certain influence on BSFC. However, the \(F\) values of IVO, IVO × EVC, and EVC × EGR are less than \(F_{0.05(4,48)}\), \(F_{0.05(12,48)}\), and \(F_{0.05(16,48)}\), respectively. Thus, all of them have little effect on the BSFC.

Besides, the variance analysis table of CA₅₀ is shown in Table 4. It can be observed that the \(F_I\) of EGR reaches 144.75, which is much greater than \(F_{0.01(4,48)}\); therefore, the influence saliency of EGR is \(**\) and it has the most significant influence on CA₅₀. At the same time, the \(F\) values of IVO, IVO × EGR, and EVC × EGR are all greater than \(F_{0.01(4,48)}\), \(F_{0.01(16,48)}\), and \(F_{0.05(12,48)}\), respectively. So, the influence saliency values of IVO, IVO × EGR, and EVC × EGR are \(**\) and all of them have a significant influence on CA₅₀. Besides, the \(F_I\) of EVC is 3.86, which is greater than \(F_{0.05(3,48)}\) and less than \(F_{0.01(3,48)}\); therefore, the influence saliency of EVC is \(*\), and it also has a certain influence on CA₅₀. However, the \(F_I\) of IVO × EGR is less than \(F_{0.05(12,48)}\); therefore, it has little effect on the CA₅₀.

3.3. Optimization Scheme of IVO, EVC, and EGR. Based on the results of the variance analysis, EGR has a significant influence on BSFC and CA₅₀, and IVO has a significant influence on CA₅₀ but has little influence on BSFC. Although EVC has little influence on BSFC, it has a certain...
influence on CA50. Therefore, in order to improve the BSFC and improve the knock resistance simultaneously, the influence of each factor on the indicator must be considered comprehensively.

The comprehensive balance analysis should be based on the following principles. Firstly, the optimal level of the factors that have the most significant influence on the most important indicator was obtained. Then, the optimal level of the other factors was determined according to the influence saliency order in turns. When the interaction between two factors was more important than the influence of a single factor, the optimal levels of interaction factors were determined through the interaction table. When the influence saliency of different factors was of equal importance to different indicators, priority should be given to the more important indicator. In this study, CA50 represents the knock limit and improving the BSFC is the primary objective of optimization, and at the same time, improving the knock resistance.

As analyzed above, the EGR rate has the most significant influence on BSFC and CA50, so the optimal level of the EGR rate was determined firstly. When the EGR rate was 20%, the indicator average of BSFC reached its minimum value of 215.8 g/kWh and the indicator average of CA50 was 11.8 °CA ATDC, which can effectively improve the knock resistance. Therefore, the optimal EGR rate is 20%. Besides, the interaction between IVO and EGR was the second important factor for BSFC and also has a significant influence on CA50; at the same time, its influence saliency was more significant than that of IVO. Therefore, the interaction between IVO and EGR was analyzed using the interaction table, which is shown in Tables 5 and 6.

Table 5 shows the cylinder pressure and heat release rate on applying the optimization parameters. It can be shown that the CA10, CA50, and CA90 are 2.2 °CA ATDC, 12.55 °CA ATDC, and 24.1 °CA ATDC, respectively. CA10 is close to TDC compared to that of other experimental cases (even higher than 13.6 °CA ATDC) and the optimized case is beneficial to achieving high combustion efficiency. The CS50 as the combustion phase was varied using the advanced ignition timing and CA10–CA90 as the fuel burning duration, which has a significant effect on the combustion of the engine. In this paper, for the optimized case, CA50 is 12.55 °CA. Considering that the BSFC indicator is more important and CA50 changes slightly, therefore, the optimal IVO is −29 °CA ATDC. Finally, the optimal level of EVC was determined. As shown in Figure 6b, with the delay of the EVC, the BSFC decreased and then increased. When the EVC was 4 °CA ATDC, BSFC reached its minimum value of 218.3 g/kWh and CA50 was 15.0 °CA ATDC; therefore, the optimal level of EVC is 4 °CA ATDC. Finally, through the comprehensive analysis, the optimal parameters obtained for each factor are shown in Table 7.

Table 4. Variance Analysis Table of CA50

| source | sum of squared deviations, ##SS## | degree of freedom, ##DOF## | mean squares, #### | Fj | saliency |
|--------|---------------------------------|----------------------------|-------------------|-----|----------|
| IVO    | 17.41                           | 4                          | 4.35              | 4.26| **       |
| EVC    | 11.83                           | 3                          | 3.94              | 3.86| *        |
| EGR    | 590.54                          | 4                          | 147.64            | 144.75| **       |
| IVO × EVC | 23.29                          | 12                         | 1.94              | 1.90|          |
| IVO × EGR | 86.46                          | 16                         | 5.40              | 5.29| **       |
| EVC × EGR | 35.92                          | 12                         | 2.99              | 2.93| **       |

*##F_{0.01}(4,48) = 2.40##. **##F_{0.05}(16,48) = 2.40##.##F_{0.01}(12,48) = 2.16##. **##F_{0.01}(3,48) = 3.74##. ##F_{0.01}(3,48) = 4.22##. ##F_{0.01}(12,48) = 2.58##.##F_{0.01}(16,48) = 2.40##.

Table 6. Interaction Table of CA50

| IVO            | EGR (%) | EGR (%) |
|----------------|---------|---------|
| −49 °CA ATDC   | 17.06   | 14.24   |
| −39 °CA ATDC   | 18.76   | 15.64   |
| −29 °CA ATDC   | 19.94   | 16.20   |
| −19 °CA ATDC   | 19.03   | 17.25   |
| −9 °CA ATDC    | 18.90   | 17.19   |

Table 7. Optimization Scheme of the Parameters

| factors | optimal value |
|---------|---------------|
| IVO     | −29 °CA ATDC  |
| EVC     | 4 °CA ATDC    |
| EGR     | 20%           |

3.4. Discussion. In SI engines, a homogeneous air–fuel mixture was obtained in the combustion chambers before combustion. The spark plug initiated the ignition process around the end of the compression stroke. The combustion flame speed would depend on the fuel, air–fuel ratio, turbulence, residual gases, compression ratio, etc., which can have effects on the temperature of the flame front. For normal combustion (without knock and too high COV), good-quality combustion is always close to TDC with a fast burn cycle, whereas poor combustion quality consists of late and delayed burn cycles. CA10 represents the combustion starting point and CA10–CA90 represents the combustion duration. A CA10 close to TDC and a small combustion duration are beneficial to achieving high combustion efficiency.

Figure 6 shows the cylinder pressure and heat release rate on applying the optimization parameters. It can be shown that the CA10, CA50, and CA90 are 2.2 °CA ATDC, 12.55 °CA ATDC, and 24.1 °CA ATDC, respectively. CA10 is close to TDC compared to that of other experimental cases (even higher than 13.6 °CA ATDC) and the optimized case is beneficial to achieving high combustion efficiency. The CA50 as the combustion phase was varied using the advanced ignition timing and CA10–CA90 as the fuel burning duration, which has a significant effect on the combustion of the engine. In this paper, for the optimized case, CA50 is 12.55 °CA ATDC and CA10–CA90 is 21.9 °CA. CA50 is a result of suppressed knocking by EGR dilution, which made the knock limited and the spark advance significantly compared to the other cases, especially without the EGR cases. CA10–CA90 represents the fuel burning speed in the combustion chamber, and a small value of CA10–CA90 with 21.9 °CA indicates a high burning speed.

In addition, the combustion stability of the engine condition can be characterized by COV(IMEP) against crank as the main characteristic parameter of cycle variations of the combustion.
in the cylinder.33 The COV(IMEP) can be obtained by eq 7, where σ and μ are the standard deviation and the mean value to calculate it.34 Besides, the knock limit can be estimated by eq 8, in which the knock will happen if the integral value of ignition delay τ (Livengood–Wu integral) is 1. Moreover, the knock intensity (KI) is characterized by the knock limit to decide the frequency of knock occurrence, and calculated by the maximum peak-to-peak amplitude.35 When KI was higher than 0.5 bar, it was defined as the knock cycle.

\[
\text{COV(IMEP)} = \frac{\sigma(\text{IMEP})}{\mu(\text{IMEP})}
\]

\[1 = \int_{\theta_{\text{IVO}}}^{\theta_{\text{EVC}}} \frac{1}{\tau} d\theta\]

The experimental results on applying the optimization parameters are shown in Table 8. It can be observed that BSFC has significantly improved, which was only 211.7 g/kWh when applying the above optimization parameters. Meanwhile, the COV(IMEP) is 0.01 and the KI (300 cycles, 0.5 bar) only 2.1%, indicating that the combustion in the engine during the above condition remained stable, which is beneficial to improve the combustion efficiency.

4. CONCLUSIONS

Both the internal EGR which was realized by the VVA system and the external EGR which was realized by the external EGR system were effective techniques to improve fuel combustion efficiency and reduce the emission of the SI turbocharged engine. The effects of IVO, EVC and EGR rates on the BSFC and mixture gas combustion characteristics of SI engine were investigated by engine experiment and the results were analyzed by the range and variance analysis which can obtain the influence saliency of the VVA and EGR rate in this paper. The detailed conclusions are summarized as follows:

1. EGR rate has the most significant influence on BSFC and knock resistance. When the EGR rate is 20%, the indicator average of BSFC reached its minimum value of 215.8 g/kWh and it has been improved by 5.1% compared with without external EGR. Besides, the indicator average of CA50 is 11.8 °CA ATDC which is advanced by 6.9 °CA compared with without external EGR. It is can be proved that the BSFC and knock resistance have been significantly improved by EGR.

2. IVO has a significant influence on CA50, but, it has little influence on BSFC. However, the interaction between IVO and EGR also has a significant influence on BSFC and CA50. Through the interaction table of IVO and EGR, the optimal IVO is −29 °CA ATDC.

3. Although EVC has little effect on BSFC, it has a certain effect on CA50. When the EVC was delayed from −16 °CA ATDC to 4 °CA ATDC, the indicator average of BSFC was reduced from 219.0 to 218.3 g/kWh, improved by 0.3%, and the indicator average of CA50 was advanced from 15.9 °CA ATDC to 15.5 °CA ATDC, advanced by 0.9 °CA.

4. The optimization parameters of each factor were obtained by the comprehensive balance method and the BSFC of the engine was only 211.7 g/kWh which has been significantly improved and the CA50 is 12.55 °CA ATDC which effectively enhances the knock resistance during the optimization parameters.

Table 8. Experimental Results on Applying the Optimization Parameters

| parameters              | results       |
|-------------------------|---------------|
| COV(IMEP)               | 0.01          |
| BSFC                    | 211.7 g/kWh   |
| CA10                    | 2.2 °CA ATDC  |
| CA50                    | 12.55 °CA ATDC|
| CA10−CA90               | 21.9 °CA      |
| ignition delay          | 24.6 °CA      |
| THC                     | 2246.1 ppm    |
| NOx                     | 1221.39 ppm   |
| KI (300 cycles, 0.5 bar)| 2.1%          |

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Notes

The authors declare no competing financial interest.

NOTATIONS

ABDC after bottom dead center
ATDC after top dead center  
BSFC brake-specific fuel consumption  
CA crank angle  
EIVC early-intake valve closing  
EVC exhaust valve closing timing  
EVO exhaust valve opening timing  
EGR exhaust gas recirculation  
HCCI homogeneous charge compression ignition  
HVVA hydraulic-variable-valve actuation  
IVC intake valve closing timing  
IVO intake valve opening timing  
IMEP indicated mean effective pressure  
KI knock intensity  
LIVC late-intake valve closing  
TDC top dead center  
SI spark ignition  
VVA variable valve actuation  
VTEC variable valve timing and lift electronic control system

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