Study on the Effects of EGR and Spark Timing on the Combustion, Performance, and Emissions of a Stoichiometric Natural Gas Engine

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ABSTRACT: This paper involved conducting an experimental investigation on the effects of exhaust gas recirculation (EGR) and spark timing on the combustion, performance, and emission characteristics of a China-VI heavy-duty, natural gas engine fueled with high-methane content. The results showed that increasing the EGR rate extends the spark timing range and slows the combustion. This then increases ignition delay, prolongs combustion duration, and decreases heat release rate. Peak in-cylinder pressure (PCP) and indicated thermal efficiency (ITE) initially increase because of higher boost pressure with increasing EGR rate. However, as EGR rate increases further, PCP and ITE begin to decrease because of the deviation of combustion phasing. Lower in-cylinder temperature caused by higher EGR rate may cause nitrogen oxide (NOx) emissions to reduce significantly, while total hydrocarbon (THC) and carbon monoxide (CO) emissions increase, and THC emissions could increase exponentially at high EGR rates. In-cylinder pressure, temperature, and heat release rate increase with early spark timing, but the rate of increase is reduced at higher engine speeds. Early spark timing causes THC and CO emissions to increase at part-load conditions, whereas there is little change at full-load conditions. NOx emissions also increase with early spark timing because of the higher in-cylinder temperature.

1. INTRODUCTION

The use of alternative fuels in internal combustion engines (ICEs) is on the rise because of stringent emission regulations and higher cost of diesel fuel. Alternative fuels also provide solutions to an array of environmental and economic problems. Alternative fuels, including biofuels and gaseous fuels such as methanol, natural gas (NG), and hydrogen, show potential to reduce emissions and fuel consumption and therefore have been studied and widely used.1–3 Besides, alternative fuels can reduce dependence on imported oil and enhance national energy security.4,5 Among alternative gaseous fuels, NG is regarded as the most promising for ICE because of its clean combustion, competitive pricing, varied sources, and large reserves.6,7 NG can be burned in spark ignition (SI) engines as a homogeneous NG–air mixture, taking advantage of the excellent knock-resisting properties of methane without utilizing a complex fuel injection system.8–10 As China has the largest population and about 5 million NG vehicles,11 China has taken the development and utilization of natural resources has been taken in recent years as a strategic component of economic and social development. The economic and environmental advantages of NG engines have led to their increasing applications in heavy-duty vehicles in recent years.12,13 Heavy-duty NG engines are usually developed using heavy-duty diesel engines as platforms. Before the implementation of the latest emission standards on heavy-duty engines, lean-burn mode was generally applied to turbocharged NG SI engines. This reduced knock tendency and led to better thermal efficiency, compared with stoichiometric combustion mode.14

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However, to meet the stringent nitrogen oxide (NOx) emissions requirement of the China-VI emission standard for NG engines, the latest heavy-duty NG SI engines are designed to operate on a stoichiometric mixture, combined with a three-way catalyst (TWC). This mode is generally recognized as the most effective for NG engines because of its very low emissions and after-treatment costs compared with lean burn operation. However, stoichiometric combustion still presents some problems and therefore research on stoichiometric engines has gradually increased. One is the high thermal load caused by methane’s high activity energy and slow laminar flame propagation speed could result in significantly higher combustion temperature, which leads to higher heat transfer loss and knock tendency. When AFR changes from 1.06 to 1.00, the maximum in-cylinder temperature can increase about 100 K and reduce NOx emissions by about 30%. Also, more throttling is needed at low to medium loads, which leads to more pumping loss. These factors result in decreased thermal efficiency and increased thermal load, which leads to higher fuel consumption and knock tendency. NG composition and slow laminar flame propagation speed counteracts its economic advantage because of large cycle-by-cycle variations (CCV), particularly during cold starts, idle and low load conditions, and transient acceleration. Besides, the ammonia emissions generated by TWC is also an important pollutant restricted by latest emission standard. Zhang et al. investigated the ammonia emissions of a stoichiometric NG engine with exhaust gas recirculation (EGR) and TWC and found that NH3 emissions after TWC were higher than the limit of the latest emission standard, which means that an ammonia slip catalyst (ASC) device is essential.

Methods such as reducing compression ratio, retarding spark timing, and applying EGR are generally used in reducing emissions and the occurrence of knock in stoichiometric turbocharged heavy-duty NG SI engines. Just as in diesel engines, EGR and timing control are both effective method for decreasing emission and improving the performance of the engines.

Hot EGR is preferred in promoting better combustion, and a marginal quantity of cooled EGR is sufficient for suppressing the NOx penalty. Several researchers have studied the effects of EGR and spark timing strategies on NG engines with certain fuel characteristics and control methods. EGR has an adverse effect on combustion, and with its introduction, the position of peak in-cylinder pressure (PCP) stays away from the top dead center (TDC), decreasing heat-work conversion efficiency. However, the probability of knock is suppressed, and acceptable range of spark timing is widened. Huang et al. investigated the CCV of an SI HNG engine. The results showed that CCV of PCP, maximum rate of pressure rise, and indicated mean effective pressure (IMEP) all increased with increasing EGR rate. Li et al. reported that at lower engine speeds, EGR decreases the maximum combustion temperature, hence reducing NOx emissions. At higher speeds, EGR has strong influences on the engine performance. Hu et al. investigated the effect of EGR on an SI engine equipped with EGR and reported that the coefficient of variation (COV) of IMEP increased with increasing of EGR rate. Handford and Checkel reported that supercharging and high EGR rates can extend the load range of NG engines. Abdelaal and Hegab conducted an experimental study on an NG-diesel dual-fuel engine and concluded that EGR could reduce PCP, hence prolonging engine life. EGR can significantly reduce NOx emissions, but it increases carbon monoxide (CO), hydrocarbon (HC), and particulate matter emissions. Bhargava conducted an experimental study on a 3.7 L lean-burn NG engine and discovered that EGR reduces NOx emission and brake thermal efficiency (BTE) but increases HC emissions. A similar conclusion was reported in McTaggart-Cowan’s research. Einewall et al. and Ibrahim and Barli investigated the effect of EGR on emissions of NG engine. The results showed that EGR could reduce NOx and HC emissions and appropriate EGR rate could reduce NOx emissions by about 50%.

Spark timing also shows great impact on the combustion and emissions on an NG engine. Huang et al. conducted an experimental study on a direct-injection engine, fueled by NG with hydrogen addition. The results show that with earlier spark timing, NOx emissions increased, and CO concentration decreased, with little variation under various spark timings. Park et al. studied the performance and emission characteristics on an 11 L heavy-duty lean-burn engine and reported that retarded spark timing is more effective for the reduction of emissions than that of spark timing. Chen’s research on a dual-fuel engine showed that retarded spark timing can shorten ignition delay and prolong the duration of combustion (DOC). In addition, reduced spark advance angle has little influence on the formation of CO emissions but can significantly decrease the formation of total hydrocarbon (THC) emission. Li’s research showed that with the optimal spark timing, NOx emissions and brake-specific fuel consumption (BSFC) can be reduced. Moreover, some research has focused on the emissions of regulated and unregulated pollutants from heavy-duty stoichiometric NG engines.

The research studies that have been presented thus far were conducted on engines fueled with relatively low-methane (about 93–95%) NG. Some studies are now presented that were conducted on high-methane (>99%) NG. Using a lean-burn 9.7 L SI NG engine fueled with 99% methane content, Wang et al. investigated the effect of CR, EGR, and spark timing on combustion and NOx emissions. Chen et al. reported that NG engines with 99% methane content yield higher BTE and lower pressure increase rates than that of NG engines with 93% methane content. Zhou et al. studied the energy-balance testing for a liquefied methane gas engine fueled with 99% methane content under mapping characteristic conditions. However, few studies have combined stoichiometric operation with EGR and spark timing to investigate the combustion, performance, and emission characteristics of heavy-duty stoichiometric NG SI engines fueled by high-methane content.

Therefore, this paper presents an experimental study that was conducted on a turbocharged heavy-duty China-VI stoichiometric NG SI engine equipped with a high-pressure-loop cooled EGR system. The study aims to comprehensively investigate the effects of EGR rate and spark timing on the combustion, performance, and emission characteristics of the system.

2. EXPERIMENTAL SETUP AND SIMULATION

2.1. Test Platform and Experimental Apparatus. A six-cylinder, 12.42 L turbocharged NG SI engine with a compression ratio of 11.46:1 was used for this experimental study. The specifications of the tested engine are shown in Table 1. A continuous-flow valve was employed for precise fuel supply control. The excess air ratio (λ) was controlled at
stoichiometry by a closed-loop control system with a broadband oxygen sensor.

The schematic of the experimental device is illustrated in Figure 1. A high-pressure loop external EGR system was implemented, which consisted of an EGR cooler, a one-way valve, and a cold-side EGR valve.

The EGR rate is defined by eq 1

$$\text{EGR rate} = \frac{\text{CO}_2\text{-inlet}}{\text{CO}_2\text{-outlet}} \times 100\%$$

where CO$_2$-inlet and CO$_2$-outlet are the volumetric concentration of carbon dioxide (CO$_2$) in the intake and exhaust system, respectively.

The composition of NG has a significant impact on engine combustion. The NG used in the test had high-methane content, and the main properties of the fuel at 20 °C and 1 standard atmosphere (atm) are shown in Table 2.

To get the combustion state of the engine, a Kistler combustion analysis system (Kistler Group, Switzerland) was used. A Kistler crank angle adapter was used to detect the crank angle position of all engine cycles and measure engine speeds. The in-cylinder pressure of the second cylinder was measured by Kistler 6052CU20 pressure transducers and Kistler charge amplifier Type 5064C. All data were recorded by a Kistler Ki-box, which is the data acquisition system related with the engine by a crank angle every 0.1 crank angle degree (°CA). The average cylinder pressure of 200 consecutive cycles was acquired to eliminate the impact of cyclic variation and the combustion analyzer could calculate the rate of heat release (ROHR) and in-cylinder temperature combined with the signal obtained from the crank angle adapter.

Besides, a SEMTECH-D emissions test system (Sensors, Inc., USA) was used to detect THC, NOx, and CO concentrations in the exhaust gas. Before the test, the precision of the instruments was re-calibrated according to the calibration manual. The parameters of instruments used in the test are listed in Table 3.

2.2. Experimental Procedures. This study investigated the effect of different EGR rates and spark timing on the combustion, performance, and emissions of the engine.

Figure 1. Schematic diagram of the experimental setup and engine test bench.
Electronic throttle, spark timing, excess air ratio, and EGR rate were controlled using electronic control unit (ECU) software. Before each test, the backpressure of the engine was adjusted to 13.5 bar with 100% load at 1800 rpm. During the test, the engine was fully warmed, and the outlet cooling temperature of the intercooler was controlled by a proportional integral derivative controller. The control target was set to 90 °C. An inlet air conditioning system was used to maintain the temperature, humidity, and pressure of the inlet air at 20 ± 2 °C, 45 ± 3%, and 101 ± 1 kPa, respectively.

The engine test was conducted on an electric dynamometer with 50 and 100% load, operating at 1300 rpm (maximum torque speed) and 1800 rpm (maximum power speed). During the test, the engine was allowed to maintain a steady-state for 2 min before emissions were sampled, and data were collected.

High thermal load causes the cylinder head to crack; therefore, the EGR valve was first set wide open and then EGR rate was incrementally reduced in steps of 2.5%. Only five operating points were taken from the maximum EGR rate for analysis. The throttle opening of the bench remained at constant value, while spark timing was adjusted by ECU software based on the control map, considering engine load, speed, and knock tendency. During the test, the maximum EGR rate of 25% could be achieved with 100% load at 1800 rpm; 22.5% could be achieved with 50% load at 1800 rpm, and 20% could be achieved with 50 and 100% load at 1300 rpm.

To explore the effect of spark timing on combustion and emissions, spark timing sweeps were conducted while bench throttle opening and EGR rates were kept at a constant value. This allowed the maximum brake torque (MBT) points, or the knock limit, to be quantitatively identified at each operating condition.

2.3. One-Dimensional Simulation and Thermal Efficiency Analysis. Thermal efficiency is affected by many factors, including combustion efficiency, degree of constant volume heat release, heat transfer loss, and mechanical efficiency. The effect of these factors cannot be clearly analyzed using bench experiments. However, they can be resolved with thermodynamic analysis using a one-dimensional (1-D) simulation model.

Numerical simulation was carried out using a GT-Power engine simulation model to investigate combustion progress of the heavy-duty SI NG engine. The initial inlet and outlet boundary conditions of such as the temperature, pressure, intake charge mass flow rate, and composition contents were directly measured from the experiments. The combustion efficiency and heat release rate were also calculated from the experimental data and in-cylinder heat transfer was considered using the Woschni GT model. Before the thermal efficiency analysis, the simulation model was carefully calibrated using the experimental data. For each operating condition, the peak in-cylinder pressure and its position, net and gross IMEPs (IMEP, and IMEPg) were well calibrated, and the deviations between the calculated and measured are less than 2% for fuel consumptions and the intake manifold pressure.

After proper calibration of the 1-D simulation model, thermal efficiency analysis considering the influencing factors mentioned above was conducted. The thermodynamics theory referred to in Yan’s research is summarized as follows. The IMEPg can be calculated using the simulation model setup, assuming all the fuel present in the cylinder is completely burned, combustion occurs at TDC, DOC—defined as the crank angle between 10 and 90° heat release position—is less than 0.5CA, and there is no heat transfer or gas exchange loss. IMEPg, IMEPg1, and IMEPg4 can be calculated using the GT-Power engine simulation model through adding the effects of incomplete combustion, combustion phasing deviation, and heat transfer step-by-step. The maximum theoretical thermal efficiency ($\eta_{\text{theo}}$), combustion efficiency loss ($\eta_{\text{comb}}$), combustion phasing deviation loss ($\eta_{\text{dev}}$), heat transfer loss ($\eta_{\text{heat}}$), and gas exchange loss ($\eta_{\text{gasech}}$) can be calculated using eqs 2–7

\[
\eta_{\text{theo}} = \frac{\text{IMEP}_{\text{g}}}{\text{IMEP}_{\text{fuel}}}
\]

\[
\eta_{\text{comb}} = \left( \frac{\text{IMEP}_{\text{g1}} - \text{IMEP}_{\text{g2}}}{\text{IMEP}_{\text{fuel}}} \right)
\]

\[
\eta_{\text{dev}} = \left( \frac{\text{IMEP}_{\text{g3}} - \text{IMEP}_{\text{g4}}}{\text{IMEP}_{\text{fuel}}} \right)
\]

\[
\eta_{\text{heat}} = \left( \frac{\text{IMEP}_{\text{g4}} - \text{IMEP}_{\text{n}}}{\text{IMEP}_{\text{fuel}}} \right)
\]

\[
\eta_{\text{gasech}} = \left( \frac{\text{IMEP}_{\text{fuel}} \cdot \text{LHV}_{\text{fuel}}}{V_D} \right)
\]

where $M_{\text{fuel}}$ is each cylinder’s fuel consumption per cycle, $\text{LHV}_{\text{fuel}}$ is the lower heating value of the fuel, and $\text{IMEP}_{\text{fuel}}$ is the corresponding total energy put into the engine and normalized by the displacement volume $V_D$.

The decreased thermal efficiencies caused by the factors mentioned above on $\eta_{\text{theo}}$ are calculated by eqs 8–11

\[
\eta_{\text{comb}} = \eta_{\text{theo}} - \eta_{\text{comb}}
\]

\[
\eta_{\text{dev}} = \eta_{\text{comb}} - \eta_{\text{dev}}
\]

\[
\eta_{\text{heat}} = \eta_{\text{dev}} - \eta_{\text{heat}}
\]

\[
\eta_{\text{gasech}} = \eta_{\text{heat}} - \eta_{\text{gasech}}
\]

3. RESULTS AND DISCUSSION

In this section, the effect of varying the percentage of EGR rate and spark timing on combustion, performance, and emission are evaluated at four operating conditions. Table 4 depicts the original control values and the performance parameters of the tested NG engine.

| Table 4. Original Property Values of the Tested Engine |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| item            | 1300 rpm 100% load | 1300 rpm 50% load | 1800 rpm 100% load | 1800 rpm 50% load |
| spark timing (°CA BTDC) | 20.0 | 27.6 | 28.0 | 36.0 |
| EGR rate (%)     | 15.5 | 17.5 | 19.5 | 19.5 |
| BSFC (g/kWh)     | 202.5 | 219.6 | 215.1 | 236.0 |

3.1. Effect of EGR on Combustion Characteristics. According to the experimental procedure presented in Section 3, the effect of EGR on the combustion process is analyzed at 1300 and 1800 rpm. Figure 2 shows the effect of EGR on in-cylinder pressure and ROHR on the stoichiometric heavy-duty NS engine, operating with 100% load at different engine speeds. It was observed that the trends of PCP with increasing EGR rate are basically the same at 1300 and 1800 rpm. With the increase in the EGR rate, PCP initially begins to increase before eventually beginning to decrease. The rate of change of PCP increases with increasing EGR rate. PCP remains the same when the
EGR rate is relatively low; for example, there is no significant change to the in-cylinder pressure curve when the EGR rate grows from 10 to 12.5% with 100% load at 1300 rpm. However, a decline of 12.9 bar is observed when the EGR rate increases from 17.5 to 20%. As EGR rate increases, the proportion of high specific heat capacity component such as carbon dioxide and water vapor increase and cause slower combustion. Therefore, EGR dilution is capable of reducing in-cylinder stresses.\(^6\) Besides, in the process of increasing EGR rate, the boost pressure is increased to maintain the equivalent ratio of the combustion process, which leads to higher PCP.\(^4\)\(^8\) Therefore, PCP increases initially with increasing EGR rates because of the higher compression pressure before combustion in a certain range of EGR rates, and when EGR rate is relatively high, PCP starts to decrease because of the slower heat release process and the delay of combustion phase. In the lower part of Figure 2, it is also observed that with an increasing EGR rate, the maximum ROHR decreases, and its position is delayed due to an increase of EGR rate. The decrease and delay of ROHR is marginal when the EGR rate is relatively low. However, it becomes significant when the EGR rate rises above 20% with 100% engine load at 1800 rpm.

Figure 3 illustrates the effect of EGR rates on the in-cylinder temperature and cumulative heat release of the heavy-duty NG engine with 100% load and at two different speeds. As shown in Figure 3, the peak and average in-cylinder temperature decrease with an increasing EGR rate. As mentioned above, more residual gas sent into the cylinder absorbs more combustion heat, which slows down combustion and leads to a lower in-cylinder combustion temperature.\(^1\)\(^6\) A decrease in ROHR can also be a factor, which can be seen from the lower curves in Figure 2. When the EGR rate is relatively low, the effect of introducing more residual gas is marginal. Referring to Figure 3, it is observed that with an increase in EGR rate, the positions of 100% cumulative heat release and combustion start are gradually retarded, while the magnitude increases. At higher EGR rates, the effect on combustion can be more obviously observed in Figure 3b.

Figure 4 shows the effect of EGR on CCV of PCP of the heavy-duty NG engine under four different operating conditions. As shown in Figure 4, although PCP of the engine initially begins to increase before eventually beginning to decrease with the increase of EGR rate, the CCV of PCP increases with an increasing EGR rate. For example, COV\(_{PCP}\) increases from 6.38 to 8.14%, when EGR rates increase from 10 to 20% with 100% load at 1300 rpm. The lower heat release rate during combustion progress and unstable combustion resulting from too much dilution mixture could be the main reasons.

Figures 5 and 6, respectively, illustrate the effect of EGR on spark timing and the position of 50% accumulative heat release (CA50) of the heavy-duty NG engine under four different operating conditions. As shown in Figure 5, increase in engine speeds and EGR rates lead to earlier spark timing.
the spark timing from different operating conditions, it is concluded that spark timing advances almost linearly with the increase of EGR rate but slows rapidly as the EGR rate approaches maximum value. As illustrated in Figure 6, CA50 retarded along with the EGR rate becomes higher. The aforementioned trend is not exactly the case with 100% load at 1300 rpm, which is the result of the much-retarded spark timing at low EGR rates due to knock limit.

Figures 7 and 8, respectively, depict the effect of EGR on ignition delay (crank angle between spark timing and 10% heat release position) and the DOC on the heavy-duty NG engine operating under four different conditions. Figure 7 shows that with the increase of EGR rate, the ignition delay increases almost linearly. Comparing the curves for different operating conditions, it is observed that ignition delay is prolonged at higher engine speeds or lower load conditions. As is known, the flame development duration is contingent upon the flow movement near the spark plug, the ignition energy, and the temperature and pressure at the time of ignition. According to Wang’s research, the ignition delay increases with the decrease of in-cylinder temperature. When the engine operates at high engine speeds or medium engine load, the spark timings are greatly advanced, leading to lower in-cylinder pressure and temperature at the ignition period, which slows down the flame propagation at initial stages and enhances the ignition delay. Figure 8 shows that increase of EGR rate leads to a slight increase in DOC at moderate EGR rate and considerably increases at high EGR rate (>20%). With more dilution gas introduced into the cylinder, spark kernel development and formation are suppressed, which increases ignition delay and DOC. When the EGR rate increases from 20 to 25% with 100% load at 1800 rpm, DOC increases by about 10 °CA, indicating a sharply deteriorated combustion. Comparing the DOC from different operating conditions, it can be found that DOC increases with the increasing engine speeds or decreasing engine load. With increase of engine load, the in-cylinder temperature increases and the heat loss decreases. The temperature at the end of compression rises and thus DOC decreases. With increase of engine speed, engine torque, circulating air intake, and intake pressure decrease, resulting in decrease in in-cylinder temperature and
pressure when the engine ignites. For example, when EGR rate is 20% and engine load is 100%, the in-cylinder temperature at 1300 and 1800 rpm are respectively 652 and 626 K and pressures are respectively 40.5, 30.8 bar. The drop in in-cylinder temperature and pressure at ignition timing leads to an increase in the combustion duration. Besides, the effect of EGR on in-cylinder temperature is more obvious when engine load and speed are higher, and thus the increase of DOC is more remarkable in Figure 8.

The result of thermodynamic analysis of the heavy-duty NG engine is illustrated in Figure 9. The thermal efficiencies and corresponding efficiency losses are illustrated in the lower and upper figures, respectively. Figure 9a shows that at 50% load condition, combustion, and phasing loss gradually increase with increase of EGR rate. The former increases are mainly due to DOC increase, and the latter is related to the retard of CA50. With more dilution gas introduced into the cylinder, the gas exchange loss slightly decreases, and Eff_gasexch, namely, the net indicated thermal efficiency (ITE) gradually increases. From the upper part of the figure, it can be found that the main parts of efficiency losses are heat transfer and combustion phase losses. Referring to Figure 9b, at high load conditions, the significant retard of CA50 leads to a higher phasing loss when EGR rate is greater than 20%. Gas exchange loss initially decreases with increasing EGR rate; it then begins increasing as EGR rate increases further. Net ITE decreases sharply when the EGR rate exceeds 20%.

3.2. Effect of EGR on Performance and Emission Characteristics. Figures 10 and 11 respectively state the effect of EGR on brake torque and BSFC of the heavy-duty NG engine operating under four different conditions. Referring to Figure 10, with the increase of the EGR rate, the brake torque of the engine gradually increases, before eventually beginning to decrease, the change is slight at 50% load condition, but quite obvious at 100% load condition, which is related to the large changes in combustion. As the manifold air pressure increase and spark timing advance with increase of EGR rates, engine torque initially increases in a certain range of EGR rate. When the percentage of EGR dilution is high, deviation of combustion phasing and prolonged DOC leads to lower engine torque. Referring to Figure 11, BSFC of the engine decreases before sharply increasing with rising EGR rate. The dilution of inlet mixture reduced in-cylinder thermal and mechanical stresses which prevented surface ignition occurrence and decreased cylinder heat transfer, which allows more advanced spark timing and resulted in a decrease in engine fuel consumption. However, when the EGR rate is large, CA50 moves away from TDC and DOC increases linearly, which increases phasing loss and combustion loss, the thermal efficiency decreases and thus engine fuel consumption is higher. The extremum—which means the highest power performance and best economy the engine can achieve at this operation condition—can be reached at a moderate EGR rate, such as 17.5 with 100% load at 1800 rpm.

Figure 12 illustrates the effects of EGR on THC, CO, and NOx emissions of the heavy-duty NG engine operating under four different conditions. Figure 12a,b shows the effect of EGR...
on THC and CO emissions. It is seen that THC and CO emissions increase with increasing EGR rates, and the rate of increase accelerates at high EGR rates. The reason for this is the increase in the EGR rate suppresses the in-cylinder combustion process, resulting in longer ignition delay and DOC, which generates more CO and THC emissions. THC emissions from wall and bulk quenching is increased due to decreasing in-cylinder wall temperature and slow flame propagation speed, coupled with increasing EGR rates. As shown in Figure 12c, NOx emissions continuously decrease with increasing EGR rate. Per Zeldovich, NOx formation depends on in-cylinder temperature, total air-excess ratio, and reaction time. With increasing dilution gas, in-cylinder temperature decreases, as is shown in Figure 3, suppressing NOx generation. NOx emissions are higher because of longer DOC when the engine speed increases from 1300 to 1800 rpm. As the conversion efficiency of NOx, THC, and CO using TWC are extremely high, normally more than 90%, small changes in raw emissions have no significant impact on the emissions after TWC. When EGR is within 20%, the change in
EGR rate has no obvious influence on emissions. When balancing the emission and efficiency, priority can be given to better engine performance. When the EGR rate is increased to more than 20%, although NOx emissions are greatly reduced, the exponential growth of THC emissions and drastic deterioration of engine performance are unacceptable and should be avoided.

### 3.3. Effect of Spark Timing on Combustion Characteristic

The effects of spark timing on combustion, performance, and emissions were analyzed with engine speeds at 1300 and 1800 rpm. The EGR rate remains constant with change in spark timing. Figure 13 illustrates the effect of spark timing on in-cylinder pressure and ROHR of the stoichiometric heavy-duty NG engine, operating with 100% load at two different speeds. It was concluded from Figure 13a that the PCP increases with earlier spark timing. Additionally, the corresponding crank angle occurs earlier with the spark timing advance. Maximum ROHR and its position also advance with earlier spark timing. A reason for this could be that appropriate spark timing leads to higher fuel consumption at TDC. This causes the release of additional heat in the combustion chamber, resulting in a more isochoric combustion. Comparing Figure 13a,b, it can be observed that the trend and location of PCP and maximum ROHR are similar. However, the value, increasing pressure, and ROHR with earlier spark timing may be smaller because of higher engine speeds. Figure 14 illustrates the effect of spark timing on the in-cylinder temperature and cumulative heat release of the heavy-duty NG engine with 100% load and two different speeds. As shown in Figure 14a, in-cylinder temperature decreases with retard of spark timing and the cumulative heat release rate grows slower, which is mainly due to the decrease in ROHR, as seen in Figure 13a. As shown in Figure 14b, the trends of in-cylinder temperature and cumulative heat release are similar to those in Figure 14a, although at higher speeds, in-cylinder temperature decreases, crankshaft angles at 90% cumulative heat release and combustion start both reduced.

Figures 15 and 16 illustrate the effects of spark timing on ignition delay and DOC at four selected operating conditions. As shown in Figure 15, the maximum spark advance angle varies with engine speed and load. At the maximum torque condition of the engine—100% load at 1300 rpm—high thermal load and knock tendency reduce maximum spark timing, which is about 21 °CA BTDC. By decreasing BMEP through reducing load or increasing speed, the range of spark timing is extended to about 40 °CA BTDC with 50% load at 1800 rpm. It can be observed from Figure 15 that with earlier spark timing, ignition delay increases in all operating conditions. This is due to the lower in-cylinder temperature and pressure at ignition time, as a result of advanced spark timing and more time to form a fire core. As shown in Figure 16 with reduction of spark timing, DOC is initially reduced, before eventually increasing, creating a valley on the curves for 50% load condition. At full-load condition, the strong knock
tendency restricts the advance of spark timing, thus DOC is unable to decrease further. Figures 17 and 18, respectively, show the effects of spark timing on ITE and exhaust gas temperature. ITE increases with increasing spark timing. ITE increases rapidly at full-load condition, while at 50% load, it increases at a slower rate. In Figure 18, it can be seen that earlier spark timing reduces the exhaust temperature. This is due to the advance of CA50 and increase of PCP, which increases the thermal efficiency and reduces the after burn of unburned HC.48

3.4. Effect of Spark Timing on Performance and Emission Characteristics. Figures 19 and 20, respectively, illustrate the effects of spark timing on brake torque and BSFC. As shown in Figure 19, in the curve of 50% load, brake torque initially increases with increasing spark timing before beginning to decrease. However, at full-load condition, torque increases, and it may not reach its maximum value because of the increasing probability of knock. As shown in Figure 20, with earlier spark timing, BSFC initially decreases before beginning to increase. It was discovered that better engine torque and fuel consumption can be achieved with moderate spark timing.

Figure 21 illustrates the effects of spark timing on THC, CO, and NOx emissions. It is shown in Figure 21a that spark timing has a marginal effect on THC emissions at full-load condition. However, THC emissions decrease with the retard of spark timing at 50% load condition. The retard of spark timing aids post-combustion, therefore increasing exhaust temperature and the after burn of unburned HC. At a moderate load condition, the in-cylinder temperature is lower, and the reduction of spark timing may increase the generation of THC and cause wall quenching. Referring to Figure 21b, CO emissions increase with increasing spark timing at 50% load condition; however, it makes no significant change at full-load condition. CO emission is mainly related to in-cylinder temperature. Combustion temperature is lower at moderate load conditions and increases with advancing spark timing. When combustion temperature rises sufficiently for CO generation at full-load condition, it begins to have less effect on CO emissions.52 Referring to Figure 21c, NOx emissions sharply increase with advance of spark timing, mainly due to increasing in-cylinder temperature. For example, considering the curve for 50% load at 1800 rpm in Figure 21c, when spark timing changes from 32 °CA BTDC to 40 °CA BTDC, the NOx emissions increase from 2.9 to 4.5 g/kW h. This represents an increase of about 52%. Advancing the spark timing can improve engine output and reduce fuel consumption but also cause significant increase in NOx emissions. Even if TWC has high conversion efficiency, the increase of raw NOx emissions is quite obvious. When adjusting the spark timing, some trade-offs should be made for NOx and engine performance based on the emission standard.

4. CONCLUSIONS
This paper studied the combustion, performance, and emissions of a China-VI turbocharged stoichiometric heavy-duty NG engine at different EGR rates and spark timing. The engine was equipped with a high-pressure-loop EGR system and fueled with high-methane content. The main conclusions from the study are summarized as follows:
Employing a higher EGR rate can advance the spark timing and slow down the combustion, which brings higher ignition delay, retard of CA50, longer DOC, and lower in-cylinder temperature. These changes lead to higher combustion phase loss and heat transfer loss. With increasing EGR rate, PCP and ITE initially increase before eventually decreasing due to increasing boost pressure and deviation of combustion phasing. At each operation condition, optimal torque and fuel consumption can be achieved at moderate EGR rates, such as 17.5% with 100% load at 1800 rpm. An increasing EGR rate reduces NOx emissions; meanwhile, THC and CO emissions increase. When the EGR rate rises above 20%, combustion deteriorates sharply, and THC emissions could increase exponentially.

With earlier spark timing, the lower pressure and temperature at ignition timing brings higher ignition delay. DOC is initially reduced before eventually increasing at 50% load conditions, but monotonously decreases at full-load condition due to the restriction of knock tendency. Higher in-cylinder temperature and faster heat release can be achieved with earlier spark timing and leads to higher thermal efficiency as well as lower exhaust temperature.

As the spark timing advances, fuel consumption decreases before it eventually increases. However, BSFC cannot reach optimal value at high load conditions because of the limitation of knock and the best fuel consumption can be achieved when the spark timing reach the edge of knock. THC and CO emission increase with the advance of spark timing at moderate load, but change only slightly at full-load condition. With the increase of in-cylinder temperature with earlier spark timing, NOx emissions sharply increase.

(1) Employing a higher EGR rate can advance the spark timing and slow down the combustion, which brings higher ignition delay, retard of CA50, longer DOC, and lower in-cylinder temperature. These changes lead to higher combustion phase loss and heat transfer loss. With increasing EGR rate, PCP and ITE initially increase before eventually decreasing due to increasing boost pressure and deviation of combustion phasing.

(2) At each operation condition, optimal torque and fuel consumption can be achieved at moderate EGR rates, such as 17.5% with 100% load at 1800 rpm. An increasing EGR rate reduces NOx emissions; meanwhile, THC and CO emissions increase. When the EGR rate rises above 20%, combustion deteriorates sharply, and THC emissions could increase exponentially.

(3) With earlier spark timing, the lower pressure and temperature at ignition timing brings higher ignition delay. DOC is initially reduced before eventually increasing at 50% load conditions, but monotonously decreases at full-load condition due to the restriction of knock tendency. Higher in-cylinder temperature and faster heat release can be achieved with earlier spark timing and leads to higher thermal efficiency as well as lower exhaust temperature.

(4) As the spark timing advances, fuel consumption decreases before it eventually increases. However, BSFC cannot reach optimal value at high load conditions because of the limitation of knock and the best fuel consumption can be achieved when the spark timing reach the edge of knock. THC and CO emission increase with the advance of spark timing at moderate load, but change only slightly at full-load condition. With the increase of in-cylinder temperature with earlier spark timing, NOx emissions sharply increase.

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Notes
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**ABBREVIATIONS**

EGR, exhaust gas recirculation; NG, natural gas; SI, spark ignition; PCP, peak in-cylinder pressure; ITE, indicated thermal efficiency; BSFC, brake-specific fuel consumption; NOx, nitrogen oxides; THC, total hydrocarbon; CO, carbon monoxide; CO2, carbon dioxide; ICE, internal combustion engine; TWC, three-way catalyst; ASC, ammonia slip catalyst; CCV, cycle-by-cycle variations; CA, crank angle degree; TDC, top dead center; BTDC, before TDC; ATDC, after TDC; IMEP, indicated mean effective pressure; COV, coefficient of variation; ECU, electronic control unit; λ, excess air ratio; DOF, duration of combustion; ROHR, rate of heat release; CAS0, combustion phasing defined by the crank angle of 50% accumulative heat release; MBT, maximum brake torque

**REFERENCES**

(1) Fagundez, J. L. S.; Golke, D.; Martins, M. E. S.; Salau, N. P. G. An investigation on performance and combustion characteristics of pure n-butanol and a blend of n-butanol/ethanol as fuels in a spark ignition engine. *Energy* 2019, 176, 521–530.

(2) Li, M.; Zhang, Q.; Li, G.; Li, P. Effects of Hydrogen addition on the performance of a pilot-ignition direct-injection natural gas engine: A numerical study. *Energy Fuels* 2017, 31, 1407–1423.

(3) Zhang, Y.; Lou, D.; Hu, Z.; Tan, P. Particle number, size distribution, carbons, polycyclic aromatic hydrocarbons and inorganic ions of exhaust particles from a diesel bus fueled with biodiesel blends. *J. Clean. Prod.* 2019, 225, 627–636.

(4) Liu, J.; Ma, B.; Zhao, H. Combustion parameters optimization of a diesel/natural gas dual fuel engine using genetic algorithm. *Fuel* 2020, 260, 116365.

(5) Wang, Z.; Du, G.; Li, Z.; Wang, X.; Wang, D. Study on the combustion characteristics of a high compression ratio HCCI engine fueled with natural gas. *Fuel* 2019, 255, 115701.

(6) Ibrahim, A.; Bari, S. An experimental investigation on the use of EGR in a supercharged natural gas SI engine. *Fuel* 2010, 89, 1721–1730.

(7) Hajibabaei, M.; Karavalakis, G.; Johnson, K. C.; Lee, L.; Durbin, T. D. Impact of natural gas fuel composition on criteria, toxic, and particle emissions from Transit buses equipped with lean burn and stoichiometric engines. *Energy* 2013, 62, 425–434.

(8) Li, H.; Gatts, T.; Liu, S.; Wayne, S.; Clark, N.; Mather, D. An experimental investigation on the combustion process of a simulated turbocharged spark ignition natural gas engine operated on stoichiometric mixture. *J. Eng. Gas Turbines Power* 2018, 140, 091504.

(9) Duan, X.; Liu, Y.; Liu, J.; Lai, M.-C.; Jansons, M.; Guo, G.; Zhang, S.; Tang, Q. Experimental and numerical investigation of the effects of low-pressure, high-pressure and internal EGR configurations on the performance, combustion and emission characteristics in a hydrogen-enriched heavy-duty lean-burn natural gas SI engine. *Energy Convers. Manage.* 2019, 195, 1319–1333.

(10) Zhang, S.; Duan, X.; Liu, Y.; Guo, G.; Zeng, H.; Liu, J.; Lai, M.-C.; Talekar, A.; Yuan, Z. Experimental and numerical study the effect of combustion chamber shapes on combustion and emissions characteristics in a heavy-duty lean burn SI natural gas engine coupled with detail combustion mechanism. *Fuel* 2019, 258, 116130.

(11) Chen, H.; He, J.; Zhong, X. Engine combustion and emission fuelled with natural gas: A review. *J. Energy Inst.* 2019, 92, 1123–1136.

(12) Fadiran, G.; Adebusuyi, A. T.; Fadiran, D. Natural gas consumption and economic growth: Evidence from selected natural gas vehicle markets in Europe. *Energy* 2019, 169, 467–477.

(13) Karavalakis, G.; Hajibabaei, M.; Durbin, T. D.; Johnson, K. C.; Zheng, Z.; Miller, W. J. The effect of natural gas composition on the regulated emissions, gaseous toxic pollutants, and ultrafine particle number emissions from a refuse hauler vehicle. *Energy* 2013, 50, 280–291.

(14) Einewall, P.; Tunestål, P.; Johansson, B. Lean Burn Natural Gas Operation vs Stoichiometric Operation with EGR and a Three Way Catalyst; SAE Technical Paper, 2005.

(15) Liu, J.; Dumitrescu, C. E. Numerical investigation of methane number and Wobbe index effects in lean-burn natural gas spark-ignition combustion. *Energy Fuels* 2019, 33, 4564–4574.

(16) Li, Y.; Wang, P.; Wang, S.; Liu, J.; Xie, Y.; Li, W. Quantitative investigation of the effects of CR, EGR and spark timing strategies on performance, combustion and NOx emissions characteristics of a heavy-duty natural gas engine fueled with 99% methane content. *Fuel* 2019, 255, 115803.

(17) Zheng, J.; Wang, J.; Zhao, Z.; Wang, D.; Huang, Z. Effect of equivalence ratio on combustion and emissions of a dual-fuel natural gas engine ignited with diesel. *Appl. Therm. Eng.* 2019, 146, 738–751.

(18) Ruter, M. D.; Olsen, D. B.; Scotto, M. V.; Perna, M. A. NOx reduction from a large bore natural gas engine via reformed natural gas prechamber fueling optimization. *Fuel* 2012, 91, 298–306.

(19) Zhang, Q.; Xu, Z.; Li, M.; Shao, S. Combustion and emissions of a Euro VI heavy-duty natural gas engine using EGR and TWC. *J. Nat. Gas Sci. Eng.* 2016, 28, 660–671.

(20) Yan, B.; Tong, L.; Wang, H.; Zheng, Z.; Qin, Y.; Yao, M. Experimental and numerical investigation of the effects of combustion chamber reentrant level on combustion characteristics and thermal efficiency of stoichiometric operation natural gas engine with EGR. *Appl. Therm. Eng.* 2017, 123, 1473–1483.

(21) Liu, B.; Huang, Z.; Zeng, K.; Chen, H.; Wang, X.; Miao, H.; Jiang, D. Experimental study on emissions of a spark-ignition engine fueled with natural gas—Hydrogen blends. *Energy Fuels* 2008, 22, 273–277.

(22) Huang, B.; Hu, E.; Huang, Z.; Zheng, J.; Liu, B.; Jiang, D. Cycle-by-cycle variations in a spark ignition engine fueled with natural gas—Hydrogen blends combined with EGR. *Int. J. Hydrogen Energy* 2009, 34, 8405–8414.

(23) Zhang, Q.; Li, M.; Shao, S.; Li, G. Ammonia emissions of a natural gas engine at the stoichiometric operation with TWC. *Appl. Therm. Eng.* 2018, 130, 1363–1372.

(24) Bade shrestha, S. O.; Rodrigues, R. Effects of diluents on knock rating of gaseous fuels. *Proc. Inst. Mech. Eng., Part A* 2008, 222, 587–597.

(25) Tian, J.; Cui, Z.; Ren, Z.; Tian, H.; Long, W. Experimental study on jet ignition and combustion processes of natural gas. *Fuel* 2020, 262, 116467.

(26) Geng, L.; Xiao, Y.; Li, S.; Chen, H.; Chen, X. Effects of injection timing and rail pressure on particulate size-number distribution of a common rail DI engine fueled with fischer-tropsch diesel synthesized from coal. *J. Energy Inst.* 2020, DOI: 10.1016/j. joei.2020.08.008.

(27) Geng, L.; Li, S.; Xiao, Y.; Xie, Y.; Chen, H.; Chen, X. Effects of injection timing and rail pressure on combustion characteristics and cyclic variations of a common rail DI engine fuelled with FT diesel synthesized from coal. *J. Energy Inst.* 2020, DOI: 10.1016/j.joei.2020.05.009.

(28) Thangaraj, J.; Kannan, C. Effect of exhaust gas recirculation on advanced diesel combustion and alternate fuels-A review. *Appl. Energy* 2016, 180, 169–184.

(29) Johnson, T.; Joshi, A. Review of vehicle engine efficiency and emissions. *SAE Int. J. Engines* 2018, 11, 1307–1330.

(30) Park, C.; Kim, C.; Lee, S.; Lim, G.; Lee, S.; Choi, Y. Effect of control strategy on performance and emissions of natural gas engine for cogeneration system. *Energy* 2015, 82, 353–360.

(31) Reddy, H.; Abraham, J. Ignition kernel development studies relevant to lean-burn natural-gas engines. *Fuel* 2010, 89, 3262–3271.

(32) Zhang, Q.; Li, M.; Li, G.; Shao, S.; Li, P. Transient emission characteristics of a heavy-duty natural gas engine at stoichiometric operation with EGR and TWC. *Energy* 2017, 132, 225–237.

(33) Hu, E.; Huang, Z.; Liu, B.; Zheng, J.; Gu, X. Experimental study on combustion characteristics of a spark-ignition engine fueled with natural gas—Hydrogen blends combining with EGR. *Int. J. Hydrogen Energy* 2009, 34, 1035–1044.
(34) Handford, D. I.; Checkel, M. D. Extending the Load Range of a Natural Gas HCCI Engine Using Direct Injected Pilot Charge and External EGR; SAE Technical Paper, 2009.
(35) Abdelaal, M. M.; Hegab, A. H. Combustion and emission characteristics of a natural gas-fueled diesel engine with EGR. Energy Convers. Manage. 2012, 64, 301−312.
(36) Bhargava, S.; Clark, N. N.; Hildebrand, M. W. Exhaust Gas Recirculation in a Lean-Burn Natural Gas Engine; SAE Technical Paper, 1998.
(37) Mctaggart-Cowan, G. P.; Bushe, W. K.; Rogak, S. N.; Hill, P. G.; Munshi, S. R. The effects of varying EGR test conditions on a direct injection of natural gas heavy-duty engine with high EGR levels. SAE Trans. 2004, 1500−1509.
(38) Mctaggart-cowan, G. P.; Rogak, S. N.; Munshi, S. R.; Hill, P. G.; Bushe, W. K. The influence of fuel composition on a heavy-duty, natural-gas direct-injection engine. Fuel 2010, 89, 752−759.
(39) Huang, Z.; Wang, J.; Liu, B.; Zeng, K.; Yu, J.; Jiang, D. Combustion characteristics of a direct-injection engine fueled with natural gas−Hydrogen blends under different ignition timings. Fuel 2007, 86, 381−387.
(40) Park, C.; Kim, C.; Choi, Y.; Won, S.; Moriyoshi, Y. The influences of Hydrogen on the performance and emission characteristics of a heavy duty natural gas engine. Int. J. Hydrogen Energy 2011, 36, 3739−3745.
(41) Chen, Z.; Wang, L.; Zhang, Q.; Zhang, X.; Yang, B.; Zeng, K. Effects of spark timing and methanol addition on combustion characteristics and emissions of dual-fuel engine fuelled with natural gas and methanol under lean-burn condition. Energy Convers. Manage. 2019, 181, 519−527.
(42) Yoon, S.; Collins, J.; Thiruvengadam, A.; Gautam, M.; Herner, J.; Ayala, A. Criteria pollutant and greenhouse gas emissions from CNG Transit buses equipped with three-way catalysts compared to lean-burn engines and oxidation catalyst technologies. J. Air Waste Manage. Assoc. 2013, 63, 926−933.
(43) Szwaja, S.; Ansari, E.; Rao, S.; Szwaja, M.; Grab-rogalinski, K.; Naber, J. D.; Pyrc, M. Influence of exhaust residuals on combustion phases, exhaust toxic emission and fuel consumption from a natural gas fueled spark-ignition engine. Energy Convers. Manage. 2018, 165, 440−446.
(44) Wang, S.; Li, Y.; Fu, J.; Liu, J.; Dong, H.; Tong, J. Quantitative investigation of the effects of EGR strategies on performance, cycle-to-cycle variations and emissions characteristics of a higher compression ratio and heavy-duty NGSI engine fueled with 99% methane content. Fuel 2020, 263, 116736.
(45) Chen, Z.; Zhang, F.; Xu, B.; Zhang, Q.; Liu, J. Influence of methane content on a LNG heavy-duty engine with high compression ratio. Energy 2017, 128, 329−336.
(46) Zhou, F.; Fu, J.; Li, D.; Liu, J.; Lee, C.-f.; Fu, J. Experimental study on combustion, emissions and thermal balance of high compression ratio engine fueled with liquefied methane gas. Appl. Therm. Eng. 2019, 161, 114125.
(47) Su, J.; Xu, M.; Li, T.; Gao, Y.; Wang, J. Combined effects of cooled EGR and a higher geometric compression ratio on thermal efficiency improvement of a downsized boosted spark-ignition direct-injection engine. Energy Convers. Manage. 2014, 78, 65−73.
(48) Li, M. Investigation on the Combustion and Emission Characteristics of High-Pressure Direct Injection Natural Gas Engine; Shandong University: Jinan, 2017.
(49) Hu, E.; Huang, Z.; Liu, B.; Zheng, J.; Gu, X.; Huang, B. Experimental investigation on performance and emissions of a spark-ignition engine fuelled with natural gas−Hydrogen blends combined with EGR. Int. J. Hydrogen Energy 2009, 34, 528−539.
(50) Heywood, J. B. Combustion Engine Fundamentals, 1st ed; Massachusetts Institute of Technology: Estados Unidos, 1988.
(51) Fan, L. Development of a Multi-Point Sequential Injection System and Experimental Research on a Compressed Natural Gas Engine; Tianjin University: Tianjin, 2007.
(52) Xu, Z. Study on Characteristics and Control Strategy of Emission in a Natural Gas Engine; Shandong University: Jinan, 2017.