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Article

Study on the Effects of Ignition Timing and Excess Air Ratio on Lean-Burn Performance of Small-Bore Natural Gas Engines

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Abstract: This study investigates the effects of ignition timing and excess air ratio on combustion and emission performance under lean-burn conditions using a small-bore intake manifold injection natural gas engine test bench. Results indicate that as the excess air ratio increases, ignition delay period and the combustion center shift backward; combustion duration first shortens, then lengthens; NO_x emissions initially rise, then decrease, while THC and CO emissions first decrease, then increase; COV_{IMEP} increases, and effective thermal efficiency first rises, then falls. As ignition timing advances, the ignition delay period shortens and the combustion center advances; the combustion duration first shortens, then lengthens; NOx emissions significantly increase, CO emissions slightly decrease, then increase, and THC emissions vary under different excess air ratios; COV_{IMEP} decreased initially, then increased, while effective thermal efficiency rose initially, then decreased. Compared to stoichiometric combustion, lean-burn technology combined with ignition advance improved engine thermal efficiency, reaching a maximum of 40.47% at an excess air ratio of 1.4.

Keywords: ignition timing; excess air ratio; natural gas engine; dilution performance

1. Overview

Against the backdrop of global climate change mitigation efforts, China's "dual carbon" goals have established clear requirements for transforming its energy structure and developing low-carbon powertrain systems. As a major source of carbon emissions, the transportation sector urgently requires the development of low-carbon fuels and efficient clean combustion technologies to achieve deep emission reductions [1]. Natural gas, with its abundant reserves, relatively low cost, and lower carbon emissions during combustion, is widely regarded as a practical low-carbon transition fuel [2]. Compared to gasoline, natural gas possesses a higher hydrogen-to-carbon ratio and octane rating, which not only helps reduce CO_2 emissions but also facilitates increased engine compression ratios, thereby improving thermal efficiency [3]. Addressing these challenges, lean-burn technology has gained increasing attention as a key pathway to enhance thermal efficiency and reduce emissions in natural gas engines. Therefore, systematically investigating combustion organization and control mechanisms in natural gas engines under lean-burn conditions holds significant engineering value for advancing clean automotive energy and supporting carbon neutrality goals in transportation.

Currently, extensive research on lean-burn/ignition timing for large-bore natural gas engines has been conducted worldwide, yielding outstanding results. Pang et al. investigated the effects of excess air ratio on the power performance and emission characteristics of a turbocharged lean-burn compressed natural gas engine with a cylinder bore of 112 mm. Test results indicate that the excess air ratio has a negligible impact on engine torque output. However, as the excess air ratio increases, CH_4 emissions rise while nitrogen oxide emissions decrease significantly [4]. Wei et al. investigated the effect of excess air ratio on the performance of a marine lean-burn spark-ignited natural gas engine with a bore diameter of 123 mm based on the GT-Power configuration. Test results indicate that as the excess air ratio increases, combustion duration extends, CA50 shifts away from TDC, peak cylinder pressure and NOx emissions decrease, while the brake specific fuel consumption (BSFC) slightly

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increases [5]. Lu et al. conducted experimental studies on the combustion and emission performance of a turbocharged lean-burn CNG engine with a cylinder bore diameter of 112 mm at different ignition timings. The test results indicate that ignition timing has a negligible effect on engine torque output and CH_4 emissions, while nitrogen oxide emissions decrease significantly as ignition timing is retarded [6]. Shi et al. investigated ignition timing effects on combustion and emissions in natural gas engines. Findings indicated that advancing ignition timing shifted the combustion center forward, shortened combustion duration, and increased peak values for maximum pressure rise rate, cylinder pressure, and heat release rate [7].

The above studies reveal the significant influence of lean-burn conditions and ignition timing on combustion and emission performance in large-bore natural gas engines. Lean-burn technology substantially reduces combustion temperature by increasing in-cylinder dilution, thereby suppressing NOx formation and knock tendency while further improving indicated thermal efficiency. However, excessive dilution also leads to reduced combustion rates and phase lag, causing increased cycle fluctuations and power loss [8]. Previous studies indicate that synergistically optimizing the excess air ratio and ignition timing can effectively improve the fuel economy and emission characteristics of gas engines while maintaining stable combustion. Despite extensive research on natural gas internal combustion engines globally, systematic analysis of the coupled effects of ignition timing and excess air ratio in small-bore, turbocharged PFI natural gas engines remains limited. This study focuses on a small-bore spark-ignited natural gas engine to investigate the influence patterns of different excess air ratios and ignition timing on combustion processes, energy consumption characteristics, and key pollutant emissions such as NOx. The objective is to achieve an optimal balance between fuel economy and emission performance through the coordinated optimization of dilution levels and ignition strategies, providing experimental evidence and theoretical references for the development of efficient and clean combustion technologies for small-bore natural gas engines.

2. Experimental Setup

2.1. Experimental Setup

This study employs a four-cylinder, four-stroke, 2.0 L spark-ignited engine featuring intake manifold injection and turbocharging. Its primary technical parameters are listed in Table 1. Key instruments and equipment used during testing are detailed in Table 2.

Table 1. Key technical parameters of a spark-ignited natural gas engine.

Type	L4
Bore	82.5 mm
Stroke	93 mm
Connecting rod length	144.5 mm
Displacement	2.0 L
Compression Ratio	13

Table 2. Main instrumentation and equipment for testing.

Instrument Name	Manufacturer	Instrument Model
Electric Dynamometer	HORIBA	Li-250
Emissions Analyzer	HORIBA	MEXA-7100
Combustion Analyzer	AVL	INDIMICRO 602
Micro-Carbon Smoke Meter	AVL	483
Particle Counter	AVL	489
Gasoline Fuel Consumption Meter	AVL	AVL735
Alcohol Fuel Consumption Tester	Shanghai Tongyuan	CMFG025
Air Leakage Tester	Shanghai Tongyuan	TOCEILMAS02
Temperature Control System	CAMA	BTWTC40
Air Flow Meter	Shanghai Tongyuan	TOCEIL2N150
Lambda Meter	ETAS	ES600
Inlet Air Conditioning	Nanjing Ruihao Xiang	TH1600
Environmental Air Conditioning	Nanjing Ruihao Xiang	KZE2521DH

2.2. Experimental Procedure

During testing, the aftercooled intake air temperature was maintained at 28 ± 2 °C, and the engine coolant temperature was maintained at 95 ± 2 °C. For each operating condition, 200 consecutive cycles were recorded, and the cylinder pressure data used herein represents the average of these 200 cycles. In this experiment, with the engine speed stabilized at 2500 rpm, BEMP maintained at 9 bar, as the excess air ratio was varied, the throttle opening was adjusted accordingly to maintain the desired load condition, injection timing fixed at 270° CA BATC, intake VVT set at 20° CA BTDC, and exhaust VVT set at −5° BTDC, Experimental Protocol Reference Table 3.

Table 3. Experimental plan.

Excess Air Ratio	Ignition Timing (°CA ATDC)
1	−12, −15, −18, −21, −24
1.1	−12, −15, −18, −21, −24
1.2	−12, −15, −18, −21, −24
1.3	−12, −15, −18, −21, −24
1.4	−12, −15, −18, −21, −24
1.5	−12, −15, −18, −21, −24

2.3. Parameter Definitions

Ignition delay period, combustion center, and combustion duration are three characteristic parameters describing the heat release pattern of combustion. In this paper, CA50 is defined as the crankshaft angle at which the cumulative heat release of the cycle fuel reaches 50% of the total heat release starting from compression top dead center; CA10 and CA90 are defined similarly. Combustion duration is defined as the crankshaft angle interval from 10% cumulative heat release to 90% cumulative heat release. Ignition delay period is defined as the crankshaft angle interval from spark ignition to the release of 10% cumulative heat release. Cycle variation refers to the fluctuation level of combustion process parameters during consecutive engine operating cycles, quantified as the percentage of the standard deviation of mean effective pressure (IMEP) relative to its mean value.

ATDC—After Top Dead Center

BTDC—Before Top Dead Center

When fuel burns in the cylinder, not all chemical energy is converted into mechanical energy. Other losses include incomplete combustion, heat transfer, and exhaust loss. The energy composition during combustion is as follows:

$$Q = Q_i + Q_{ex} + Q_\mathrm{h} + W_i \tag{1}$$

where: Q is the total chemical energy delivered to the cylinder for combustion, Q_i is the loss due to incomplete combustion, Q_{ex} is the heat loss carried away by the exhaust gases, Q_h is the heat transfer loss, and W_i is the net indicated power.

Formula for calculating incomplete combustion losses:

$$Q_i = \frac{M_{CO} \times LHV_{CO} + M_{THC} \times LHV_{FUEL}}{3600} \tag{2}$$

where M_{THC} and $M_{(CO)}$ are the direct flow emissions of total hydrocarbons and carbon monoxide (g/h), respectively; LHV_{CO} is the lower heating value of carbon monoxide (MJ/kg); LHV_{THC} is the lower heating value of the fuel (MJ/kg).

Exhaust gas loss calculation formula:

$$Q_{ex} = Q_{exh} - Q_{inh} \tag{3}$$

where Q_{exh} is the enthalpy of exhaust flow, and Q_{inh} is the enthalpy of intake flow.

$$Q_{exh} = \frac{M_{exh} \times Cp_{exh} \times (T_{exh} - 20)}{3.6 \times 10^6} \tag{4}$$

where: M_{exh} is the wet-basis mass flow rate of exhaust gas (kg/h), Cp_{exh} is the specific heat capacity of exhaust gas at constant pressure (J/(kg·K)), and T_{exh} is the exhaust manifold temperature (°C).

$$Q_{inh} = \frac{M_{inh} \times Cp_{inh} \times (T_{inh} - 20)}{3.6 \times 10^6} \tag{5}$$

where: M_{inh} is the wet-basis mass flow rate of the inlet gas (kg/h); Cp_{inh} is the specific heat capacity of the inlet gas at constant pressure (J/(kg·K)); T_{inh} is the inlet manifold temperature (°C).

The CA50, ignition delay period, combustion duration, COV_{IMEP}, and emissions presented in this study were derived from the average values of 200 individual combustion cycles. The combustion losses were calculated based on these average values, ensuring a representative and statistically robust assessment of engine performance. This methodology was employed to minimize the impact of cycle-to-cycle variation, providing more reliable insights into the combustion characteristics and emissions behavior under the tested conditions.

By comparison with similar experiments, all measured parameters fall within reasonable ranges.

3. Experimental Results and Analysis

3.1. Effects of Excess Air Ratio and Ignition Timing on In-Cylinder Combustion in Natural Gas Engines

As shown in Figure 1, when the ignition timing is −21°CA ATDC, increasing the excess air ratio from 1.0 to 1.5, the overall ignition delay period of the natural gas engine increased. However, when the excess air ratio varied between 1.0 and 1.3, the ignition delay period showed minimal change, remaining at approximately 16°CA. When the excess air coefficient was further increased from 1.3 to 1.5, the ignition delay period was significantly prolonged, extending by approximately 60% compared to the excess air coefficient of 1.3. As the excess air ratio increases, the concentration of natural gas is "diluted" (Reflected in the cylinder pressure curve), and the in-cylinder temperature and pressure during the early stage of combustion gradually decrease. This occurs because earlier ignition shifts the combustion process further away from top dead center, resulting in a lower effective compression temperature and pressure at the onset of heat release. This hinders the formation of the fire kernel and the initial flame propagation, resulting in a longer ignition delay period as the excess air ratio increases. However, at low excess air ratios, the impact of increased work done on temperature rise is minimal. Simultaneously, the increased work done elevates cylinder pressure, potentially enhancing the effective collision frequency between fuel molecules and oxygen molecules [9]. Consequently, at small excess air ratios, the ignition delay period shows little change with increasing excess air ratio. At the same excess air ratio, the overall ignition delay period shortens as ignition timing advances. At an excess air ratio of 1.3, when ignition timing advances from −12°CA ATDC to −24°CA ATDC, the ignition delay period shortens by approximately 10% relative to ignition timing at −12°CA ATDC. As ignition timing advances, cylinder temperature and pressure gradually decrease during ignition. To compensate for the torque loss caused by the lower temperature and pressure of the mixture, the amount of fresh air entering the cylinder per cycle increases. This significantly optimizes the cylinder environment, with its positive effects dominating during the initial development of the flame nucleus. Consequently, the ignition delay period shortens.

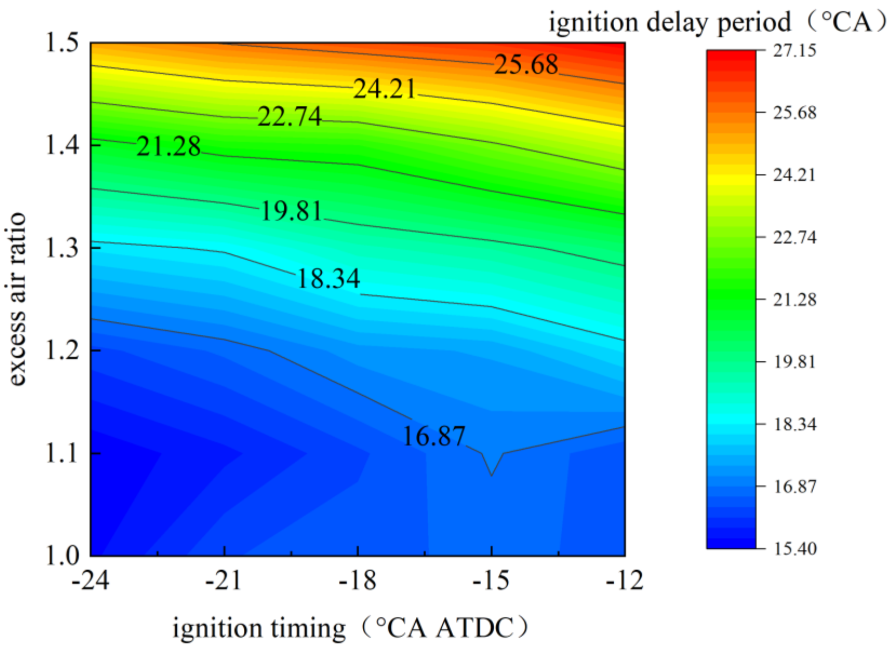

Figure 1. Effects of excess air ratio and ignition timing on the ignition delay period.

As shown in Figure 2, the CA50 of the natural gas engine lags as the excess air ratio increases. At an ignition timing of −15°CA ATDC: As the excess air ratio increases from 1.0 to 1.5, CA50 delays by 16.70°CA. With the rising excess air ratio, the natural gas concentration is reflected in the cylinder pressure curve. Consequently, the temperature rise during combustion slows, flame propagation speed decreases, and combustion rate declines, causing CA50 to shift backward. CA50 advances as ignition timing advances. When the excess air coefficient is 1.0, advancing the ignition timing from −12°CA ATDC to −24°ATDC shifts CA50 forward by approximately 15°CA. Early ignition initiates combustion earlier in the compression stroke, leveraging the high-temperature, high-pressure environment within the cylinder to accelerate the combustion process, thereby moving CA50 forward.

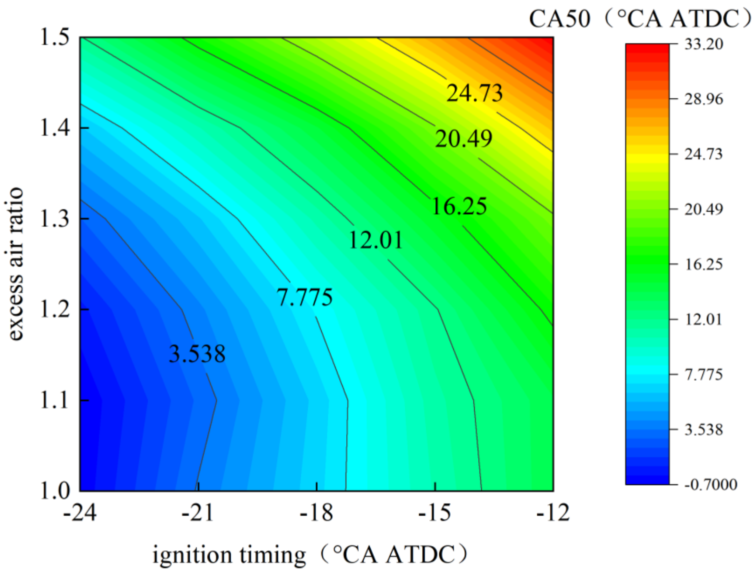

Figure 2. Effect of excess air ratio and ignition timing on combustion center of gravity.

Figure 3 illustrates the trend of combustion duration in a natural gas engine under varying ignition timing and excess air ratios. It shows that as the excess air ratio increases, combustion duration first shortens, then lengthens. At ignition timing of −18°ATDC, when the excess air coefficient increases from 1.0 to 1.5, the combustion duration first shortens by 13.5% and then lengthens by 37.2% compared to when the excess air coefficient is 1.0. As the excess air ratio increases, the concentration of natural gas is "diluted" (Reflected in the cylinder pressure curve shown in Figure 4), causing the temperature rise during combustion to slow down. Simultaneously, the increased excess air leads to higher cylinder pressure, which may enhance the effective collision frequency between fuel molecules and oxygen molecules. Consequently, under the coupled effect, the combustion duration first shortens and then lengthens as the excess air ratio increases. The combustion duration first shortens and then lengthens as ignition timing advances. When the excess air ratio is 1.3, the reference point is set at −12°CA ATDC. As ignition timing advances from −18°CA ATDC to −24°CA ATDC, the combustion duration increases by 10.1%. This occurs because excessively early ignition timing results in relatively low cylinder temperatures and pressures, which hinder rapid flame propagation, thereby prolonging combustion duration. Conversely, as ignition timing is retarded from −18°CA ATDC to −12°CA ATDC, the combustion duration increases by 12.8%. This occurs because with overly retarded ignition timing, the combustion of the mixture extends longer into the piston's downward stroke. The piston's downward movement during the expansion stroke increases the distance the flame must travel, degrading the isochoric combustion properties and consequently prolonging the combustion duration.

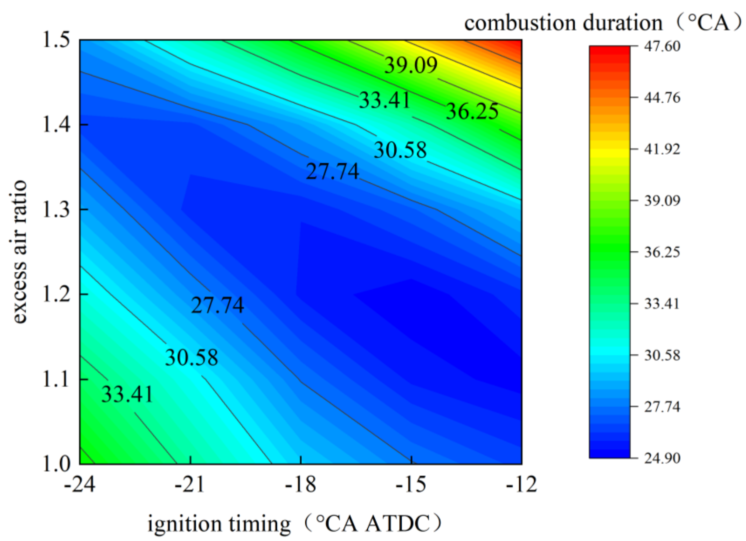

Figure 3. Effect of excess air ratio and ignition timing on combustion duration.

With ignition timing held constant, experiments indicate the maximum thermal efficiency occurs at an excess air ratio of 1.4 and an ignition timing of −21°CA ATDC. Therefore, ignition timing is set to −21°CA ATDC, and experiments are conducted by varying the excess air ratio. Figure 4 shows the trend of average cylinder pressure in a natural gas engine under different excess air ratios. It can be observed that, with ignition timing fixed, as the excess air ratio increases from 1.0 to 1.5, the peak cylinder pressure first rises by 3.3% and then decreases by 31% compared to when the excess air ratio is 1.0. The phase of the peak cylinder pressure is retarded from 8°CA ATDC to 13.0°CA ATDC. At low excess air ratios, the combustion center and ignition delay period remain relatively stable. Simultaneously, increased working mass leads to higher cylinder pressure and greater oxygen content, causing the maximum combustion pressure to rise. As the excess air coefficient continues to increase, the combined effects of temperature decrease, delayed combustion center, and prolonged ignition delay period exert a greater influence on reducing the combustion rate, thereby causing the maximum combustion pressure to decrease.

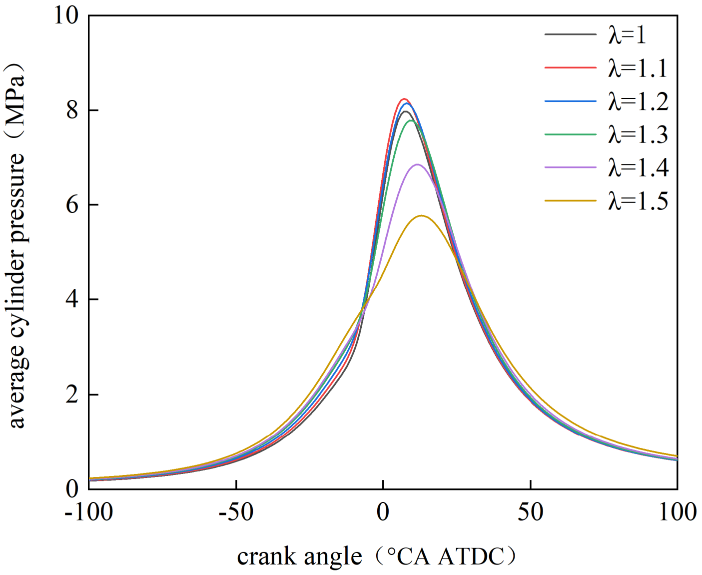

Figure 4. Average intra-cylinder pressure variation curves at different excess air ratios.

Maintaining stoichiometric combustion, experiments were conducted by altering ignition timing. Figure 5 shows the trend of average cylinder pressure in the natural gas engine under different ignition timings. As ignition timing advances from −12°CA ATDC to −24°CA ATDC, peak cylinder pressure increases by 12.9% relative to ignition timing at −12°CA ATDC, and the peak cylinder pressure phase advances from 16°CA ATDC to 5°CA ATDC.

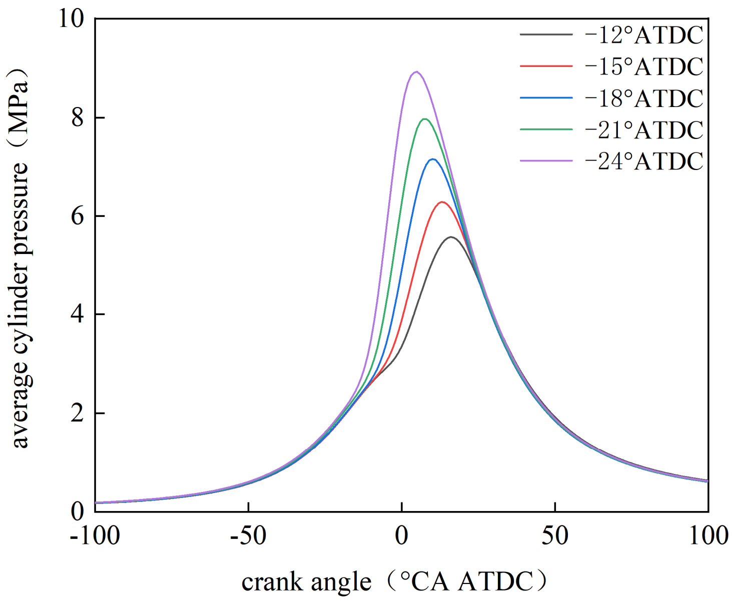

Figure 5. Average intracylinder pressure variation curves at different ignition timings.

3.2. Effects of Excess Air Ratio and Ignition Timing on Natural Gas Emissions

As shown in Figure 6, THC emissions from the natural gas engine exhibit a trend of initially decreasing and then increasing with rising excess air ratio. At an ignition timing of −18°CA ATDC, when the excess air ratio increased from 1.0 to 1.5, THC emissions first decreased by 10.7% relative to an excess air ratio of 1.0, then sharply rose by 118%. The reason is that at low excess air ratios, increasing the excess air ratio has a smaller effect on temperature rise due to the increased working charge. The increased working charge in the cylinder may reduce the probability of forming local oxygen-deficient regions, thus lowering THC emissions. As the excess air ratio continues to increase, the sustained rise in working fluid volume slows cylinder temperature growth, delays ignition, and prolongs the combustion duration. This unfavorable combustion environment exacerbates flame quenching and expands unburned regions, causing THC emissions to rise again. At low excess air ratios, THC emissions monotonically increase with earlier ignition timing. For example, at an excess air ratio of 1.0, advancing ignition timing from −12° to −24°CA ATDC increases THC emissions by approximately 75%. This occurs because the earlier combustion process increases the cylinder pressure and higher combustion temperatures within the cylinder. This creates significant temperature gradients on the cylinder walls and other surfaces. Such gradients may increase heat loss, thereby raising the likelihood of quenching effects occurring [10]. Under lean-burn conditions, THC emissions exhibit an inverse trend with advancing ignition timing. For instance, at an excess air ratio of 1.5, as ignition timing advances from −12°ATDC to −24°CA ATDC, THC emissions decreased by 38.8% compared to an ignition timing of −12°ATDC. This reduction stems from delayed initial combustion phases, where the mixture may not have sufficient time to burn completely, leading to incomplete combustion. Advancing the ignition timing effectively optimizes the combustion center, shortens the combustion duration, and increases the cylinder temperature. This simultaneously suppresses THC formation and promotes its subsequent oxidation.

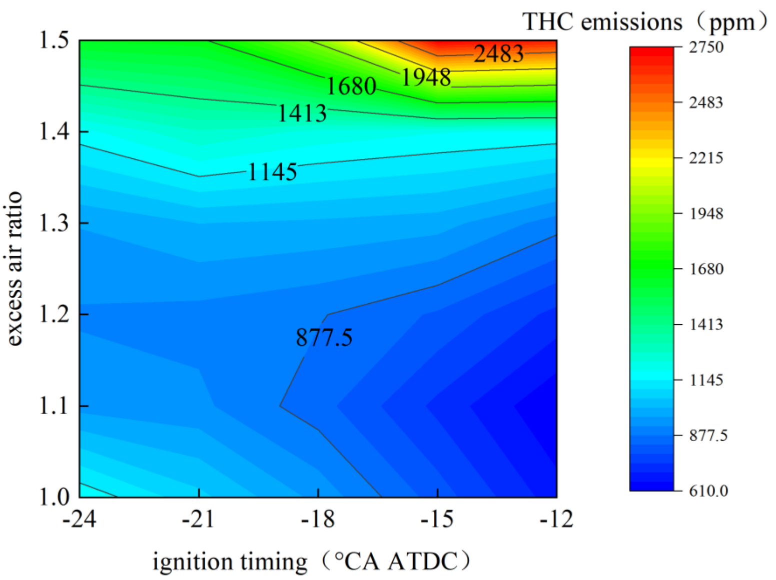

Figure 6. Effect of excess air ratio and ignition timing on THC emissions.

As shown in Figure 7, natural gas engine NOx emissions exhibit a trend of first increasing and then decreasing with rising excess air ratio. At an ignition timing of −18°CA ATDC, when the excess air ratio increases from 1.0 to 1.5, NO_x emissions first rise by 53.6% compared to an excess air ratio of 1.0, then sharply decrease by approximately 149%. The reason is that at low excess air ratios, oxygen content is the primary factor influencing NO_x emissions. As the excess air ratio increases, NO_x emissions peak at an excess air ratio of 1.1. At this point, the combustion temperature is not the highest, but the combustion rate is sufficiently fast, the temperature is sufficiently high, and the oxygen content is adequate. As the excess air ratio continues to increase, oxygen content rises further. However, the cooling effect of air on the flame intensifies, causing the combustion temperature to decrease and consequently reducing NO_x emissions [11]. Therefore, lean-burn operation is an effective method for lowering NO_x emissions in natural gas engines. Significantly advancing ignition timing markedly increases NO_x emissions. As ignition timing advances significantly increase NOx emissions, at an excess air ratio of 1.1, advancing ignition timing from −12°CA ATDC to −24°CA ATDC resulted in a 121.9% increase in NOx emissions compared to −12°CA ATDC. With advancing ignition timing, peak combustion pressure and temperature within the cylinder rise, leading to increased NOx emissions.

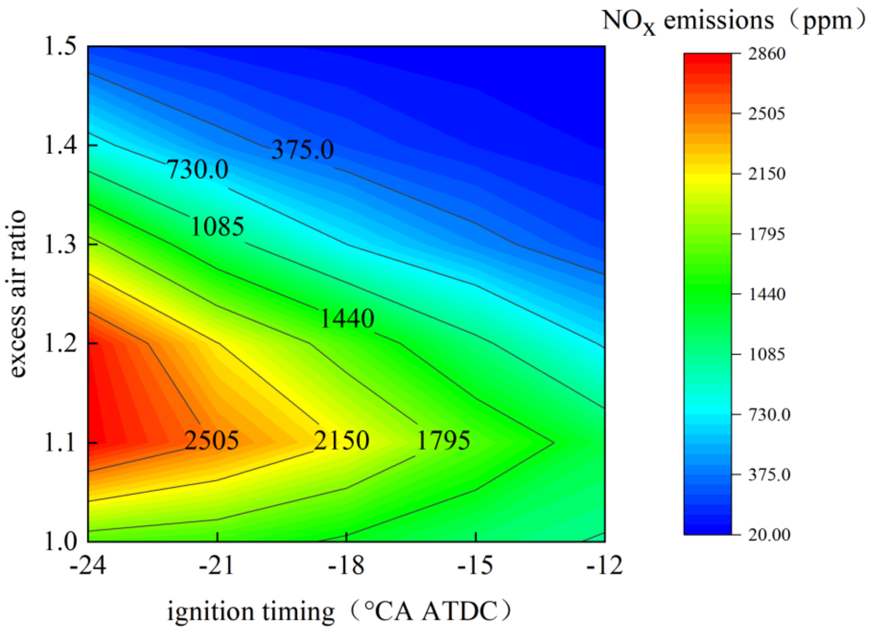

Figure 7. Effect of excess air ratio and ignition timing on NO_x emissions.

CO is an intermediate product of the incomplete oxidation of hydrocarbon fuels, indicating localized oxygen deficiency. Figure 8 shows the CO emissions curve of a natural gas engine as a function of excess air ratio. The graph reveals that CO emissions are primarily influenced by the excess air ratio. At an ignition timing of −21°CA ATDC, increasing the excess air ratio from 1.0 to 1.1 resulted in a significant reduction of 83.8% in CO emissions. At an excess air ratio of 1.0, the relatively low oxygen concentration causes incomplete fuel combustion, resulting in higher CO production. As the excess air ratio increases, the oxygen concentration in the mixture rises, enabling sufficient oxidation of carbon monoxide, thus rapidly reducing CO formation. Richard S. Brokaw's seminal kinetic analysis of the fundamental CO + O_2 reaction provides the mechanistic pathway and rate expression for the oxidation of CO to CO_2, elucidating how CO behaves as a function of O_2 [12]. Beyond an excess air ratio of 1.1, CO emissions gradually increase as oxygen levels remain sufficient, with temperature control becoming dominant. Temperature slowly decreases as the excess air coefficient rises, potentially slowing the oxidation rate of CO to CO_2. CO emissions show little variation with changes in ignition timing advance.

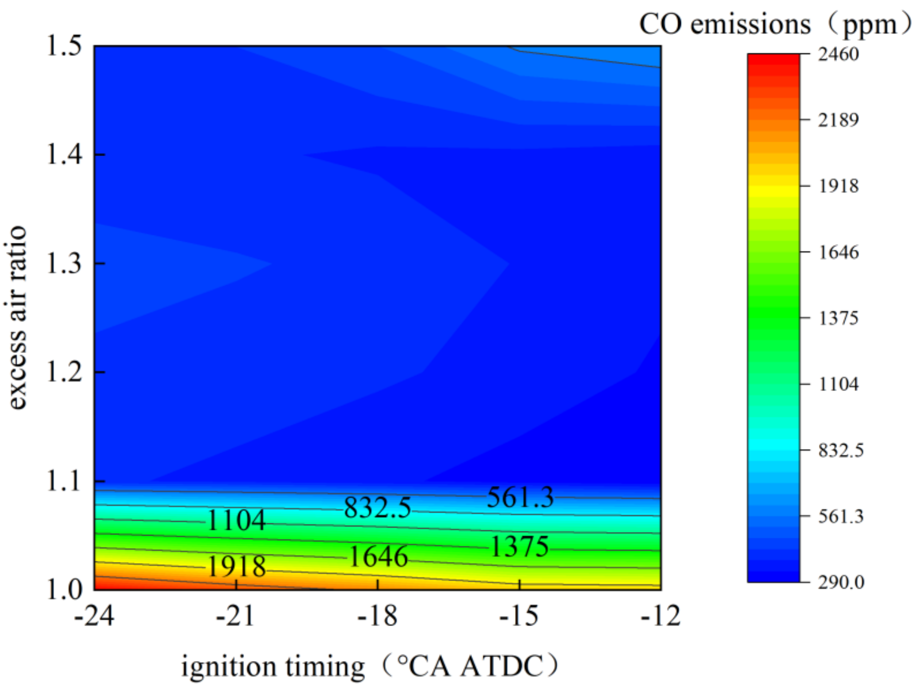

Figure 8. Effect of excess air ratio and ignition timing on CO emissions.

3.3. Effects of Excess Air Ratio and Ignition Timing on the Fuel Economy of Natural Gas Engines

Incomplete combustion losses refer to energy losses caused by insufficient oxidation of fuel to release chemical energy. Their magnitude is determined by the mass concentrations of unburned hydrocarbons and carbon monoxide in the exhaust. Figure 9 shows the trend of incomplete combustion losses in a natural gas engine under different ignition timings and excess air ratios. As the excess air ratio increases, the incomplete combustion loss first decreases and then increases. When the ignition timing is −12°CA ATDC, increasing the excess air ratio from 1.0 to 1.5 causes the incomplete combustion loss to first decrease by approximately 34.7% relative to an excess air ratio of 1.0, followed by a sharp increase of 364%. This behavior can be directly linked to changes in the in-cylinder pressure evolution and combustion development. At moderately lean conditions, improved air–fuel mixing and more favorable flame propagation led to a higher effective heat release, reflected by a higher and more concentrated pressure rise, thereby reducing unburned fuel losses. However, under excessively lean conditions, the reduced flame speed and increased tendency toward partial flame quenching weaken the pressure rise and extend the combustion duration, resulting in incomplete oxidation of the fuel and a corresponding increase in THC emissions. Since CO emissions decrease initially and then remain relatively stable with increasing excess air ratio, the observed variation in incomplete combustion loss is primarily governed by the behavior of THC. Since ignition timing has little effect on CO emissions, its influence on unburned fuel loss follows the same pattern as THC emissions: at low excess air ratios, unburned fuel loss increases monotonically with earlier ignition timing, while under lean-burn conditions, it shows the opposite trend with earlier ignition timing (This behavior can be directly related to the pressure change inside the cylinder as shown in Figure 5). The minimum unburned fuel loss of 1.11 kJ/s occurs at an excess air ratio of 1.1 and an ignition timing of −12°CA ATDC.

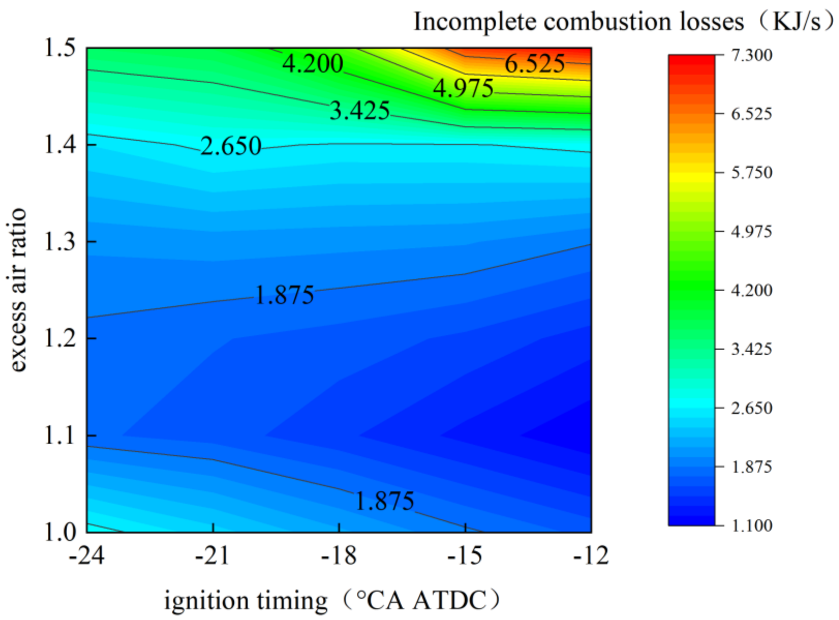

Figure 9. Effect of excess air ratio and ignition timing on incomplete combustion losses.

Exhaust losses characterize the thermodynamically available energy carried in the exhaust, determined by exhaust mass flow rate, exhaust temperature, and exhaust specific heat capacity. Figure 10 illustrates the trend of exhaust losses in a natural gas engine under varying ignition timing and excess air ratios. It can be seen that when the combustion phase is moderate, increasing the excess air ratio causes exhaust losses to decrease initially and then increase. At an ignition timing of −18°CA ATDC, increasing the excess air ratio from 1.0 to 1.5 resulted in exhaust losses decreasing by approximately 2.1% compared to an excess air ratio of 1.0, followed by a subsequent increase of about 12.8%. At lower excess air ratios, the reduction in exhaust temperature has a greater impact, but the increase in exhaust mass flow is minimal. At higher excess air ratios, although exhaust temperature decreases, the total exhaust mass increases significantly, leading to an overall rise in exhaust energy loss. At lower excess air ratios, the reduction in exhaust temperature has a greater impact, but the increase in exhaust mass flow is minimal. At higher excess air ratios, although exhaust temperature decreases, the total exhaust mass increases significantly, leading to a rise in total exhaust energy loss. Under conditions of a delayed combustion phase, exhaust losses increase significantly with increasing excess air ratio. As the excess air ratio increases, the combustion duration extends, and CA50 is delayed, exacerbating combustion phase lag. Combustion lag means more fuel burns during the expansion stroke, preventing efficient energy conversion into work. Instead, this energy is expelled as high-temperature exhaust gases, thereby increasing exhaust losses. At low excess air ratios, ignition timing has minimal impact on exhaust losses, which fluctuate around a fixed value. For example, at λ = 1, exhaust losses fluctuate around 21.31 kJ/s. When the excess air ratio is small, the combustion process itself is already highly efficient, leaving little room for adjustment in ignition timing, thus having a negligible effect on exhaust losses. Under lean-burn conditions, exhaust gas losses decrease as ignition timing advances. At an excess air ratio of 1.4, advancing ignition timing from −12°CA ATDC to −24°CA ATDC reduces exhaust gas losses by 19.6% compared to −12°CA ATDC. Under lean conditions, slow combustion speeds and prolonged burn duration mean that delayed ignition timing can lead to incomplete combustion. Partial fuel may still burn during the exhaust stroke, further elevating exhaust temperatures. Advancing ignition timing significantly optimizes combustion phases, enhances thermal efficiency, lowers exhaust temperatures, and consequently reduces exhaust losses.

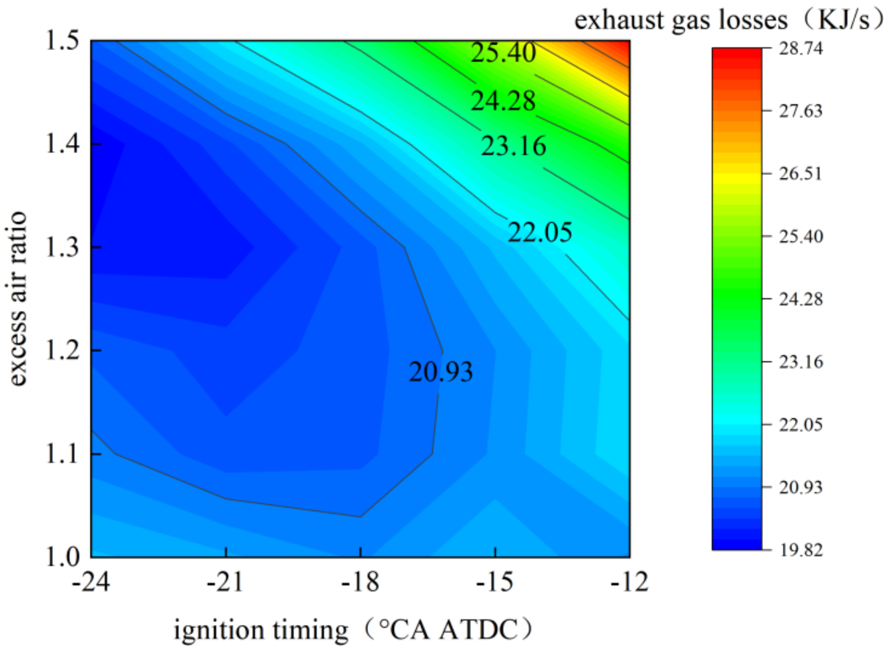

Figure 10. Effect of excess air ratio and ignition timing on exhaust gas losses.

Heat transfer losses represent heat dissipated through the cylinder wall to the cooling system, calculated by subtracting useful work, incomplete combustion losses, and exhaust losses from total fuel energy. Figure 11 illustrates the trend of heat transfer losses in a natural gas engine under varying ignition timing and excess air ratios. The general trend shows that heat transfer losses decrease as the excess air ratio increases. At an ignition timing of –24°CA ATDC, when the excess air ratio increases from 1.0 to 1.5, heat transfer losses decrease significantly compared to an excess air ratio of 1.0, with a reduction of 24.9%. This occurs because the leaner mixture lowers the peak combustion temperature. According to heat transfer principles, the temperature difference between the cylinder gases and the cooling medium decreases, reducing the heat transfer rate and consequently lowering heat transfer losses. At low excess air ratios, heat transfer losses exhibit a trend of initially decreasing, then increasing with advancing ignition timing. For example, when the excess air ratio is 1.0, advancing the ignition timing from −12°CA ATDC to −24°CA ATDC results in heat transfer losses that first decrease by 5.3% relative to the −12°CA ATDC timing, then subsequently increase by 9.1%.This phenomenon originates from the combustion center of mass initially approaching the optimal position of 8–10°CA after TDC, as determined later, resulting in reduced heat transfer losses. However, as ignition timing advances further, CA50 becomes excessively early, increasing combustion temperature and prolonging duration, causing heat transfer losses to rise again. Under lean-burn conditions, heat transfer losses exhibit a decreasing trend as ignition timing advances. When ignition timing advances from −12°CA ATDC to −24°CA ATDC, heat transfer losses decrease by 19.3% relative to the −12°CA ATDC ignition timing. Under lean-burn conditions, the overall combustion center of gravity lags. Advancing ignition timing gradually approaches the optimal phase, promoting increased combustion isochoric capacity and shorter duration, thereby reducing heat loss. Ultimately, at an excess air ratio of 1.5 and ignition timing of –24°CA, heat transfer loss reaches its minimum value of 28.09 kJ/s.

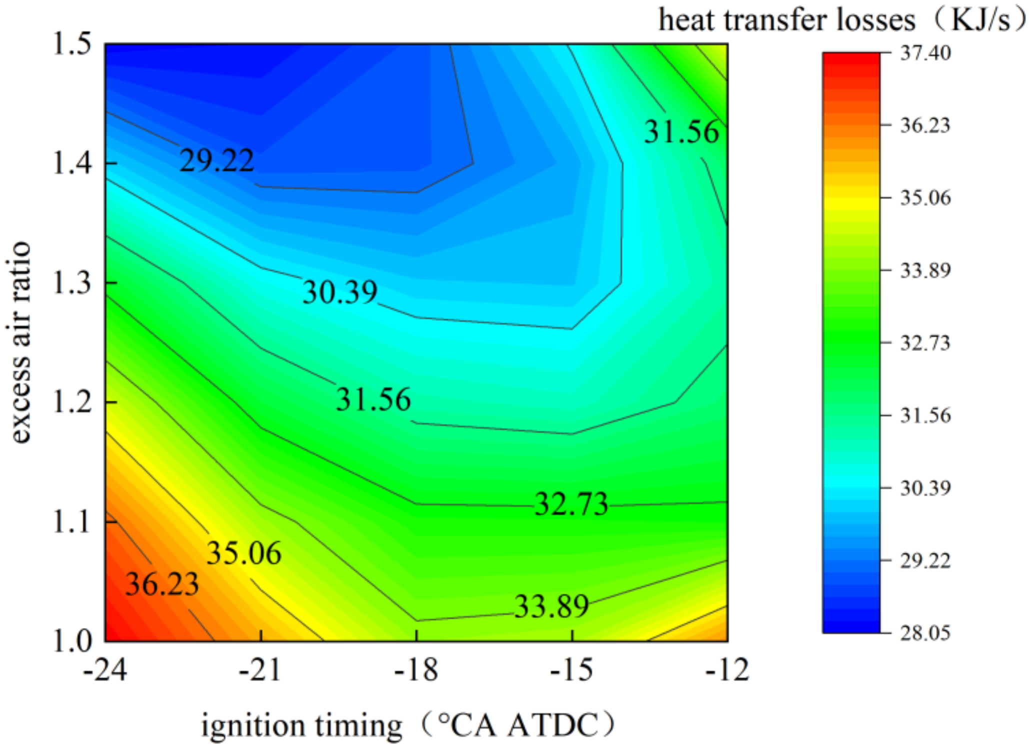

Figure 11. Effect of excess air ratio and ignition timing on heat transfer losses.

Figure 12 illustrates the trend of thermal efficiency variation in natural gas engines under different ignition timing and excess air ratios. This study reveals the synergistic effect of both parameters on thermal efficiency by regulating the excess air ratio and ignition timing. Results indicate that thermal efficiency initially increases with rising excess air ratio before decreasing. At ignition timing of −18°CA ATDC, when the excess air ratio increases from 1.0 to 1.5, thermal efficiency increased from 38.21% to 40.34% before decreasing to 38.67%. The initial abundance of oxygen promoted the oxidation of unburned hydrocarbons and CO, significantly reducing incomplete combustion losses. The combustion temperature decreased due to the leaner mixture, reducing the temperature difference between the cylinder gases and the cylinder wall. This decreased heat transfer losses, leading to an increase in thermal efficiency. In the later stages, the dominant factors became the delayed combustion phase and increased cycle variation due to excessively slow combustion rates. The resulting increase in exhaust gas losses and unburned fuel losses completely offset and exceeded the theoretical gains from lean burning, causing thermal efficiency to enter a decline phase. Thermal efficiency initially increases, then decreases with advancing ignition timing. At an excess air ratio of 1.3, advancing ignition timing raises efficiency from 39% to 40.34% before dropping to 39.39%. Optimal ignition timing occurs when the combustion phase approaches TDC, enabling more complete combustion, concentrated energy release, and peak thermal efficiency. Excessively early ignition timing may cause knocking or unstable combustion, while excessively late ignition timing leads to delayed combustion, reduced energy utilization, and decreased thermal efficiency. At $\lambda = 1.4$ and ignition timing of −21°CA ATDC, total heat loss is minimized at 52.09 kJ/s, and thermal efficiency reaches its maximum value of 40.47%.

The optimal ignition timing for thermal efficiency in natural gas engines advances with increasing excess air ratio. For instance, the optimum timing is −15°CA ATDC at an excess air ratio of 1.0, while it shifts to −24°CA ATDC at an excess air ratio of 1.5. Increasing the excess air ratio dilutes the mixture, primarily reducing the combustion rate. This prolongs the ignition delay period and combustion duration, significantly retarding the CA50 phase. Consequently, the heat release process occurs predominantly during the latter stages of the expansion stroke. The effective expansion ratio decreases, thermal-to-mechanical conversion efficiency plummets, and exhaust energy loss increases substantially. To counteract the decline in combustion rate and maintain optimal combustion timing, ignition timing must be advanced accordingly. This represents a key control strategy for optimizing thermal efficiency in lean-burn engines.

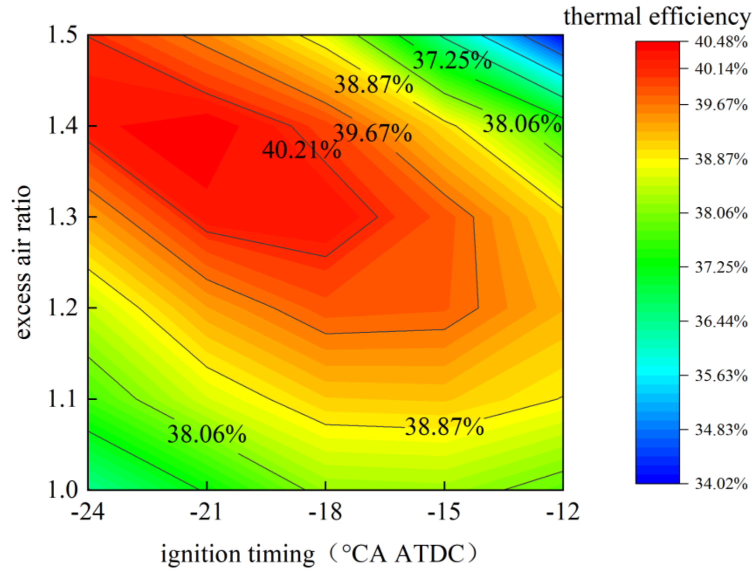

Figure 12. Effect of excess air ratio and ignition timing on thermal efficiency.

Figure 13 illustrates the variation trend of COV_{IMEP} in a natural gas engine under different ignition timings and excess air ratios. COV_{IMEP} increases with rising excess air ratios. When the excess air ratio is below 1.4, COV_{IMEP} fluctuates within a low-value range, rising gradually, indicating stable and reliable combustion. When λ (air-fuel ratio) is greater than or equal to 1.4, COV_{IMEP} increases significantly. Particularly at an air-fuel ratio of 1.5, COV_{IMEP} rises sharply, reaching an average value of 13.6%, indicating unstable combustion at high dilution ratios. COV_{IMEP} first decreases, then increases with advancing ignition timing. At an excess air ratio of 1.5, when ignition timing advances from −12°CA ATDC to −24°CA ATDC, COVIMEP decreases by 61.2% compared to the −12°CA ATDC ignition timing point, then rebounds by 46.2%. Both premature and delayed ignition timing worsen COV_{IMEP}. Premature timing results in insufficient cylinder pressure and temperature, prolonging flame development and increasing cycle fluctuations. Delayed ignition timing reduces the effective expansion ratio, intensifies afterburning, and diminishes combustion phase stability. The narrow flammability limits of lean mixtures make ignition timing deviations more likely to cause incomplete combustion or misfires, amplifying cycle variations.

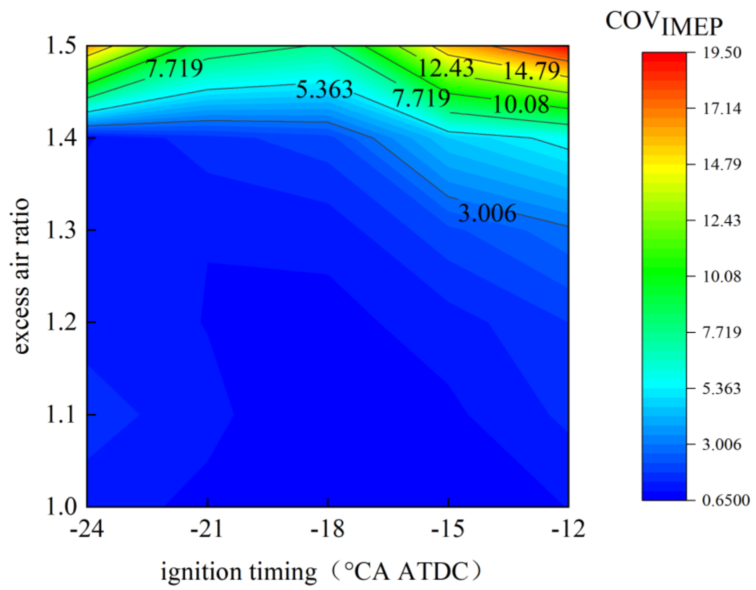

Figure 13. Effect of excess air ratio and ignition timing on COV_{IMEP}.

Figure 14 indicates that the operating condition balancing low NOx emissions and high thermal efficiency for natural gas engines occurs at an excess air ratio of 1.5 and ignition timing of −21°CA ATDC. At this point, NOx emissions are 105 ppm, and thermal efficiency is 39.55%. As shown in Figure 15, when CA50 is between

8−10°CA ATDC, the engine achieves optimal thermal efficiency within this range, demonstrating superior fuel economy. This is in line with the conclusion drawn by Caton Jerald A. For conventional engines, under the studied conditions, the optimal CA50 varies between approximately 5 and 11°aTDC [13].

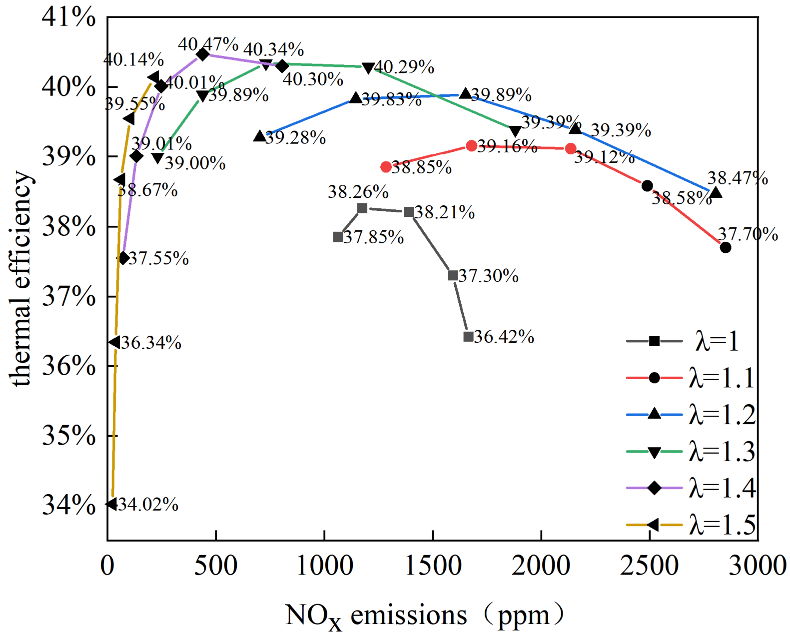

Figure 14. Relationship between NOx emissions and thermal efficiency.

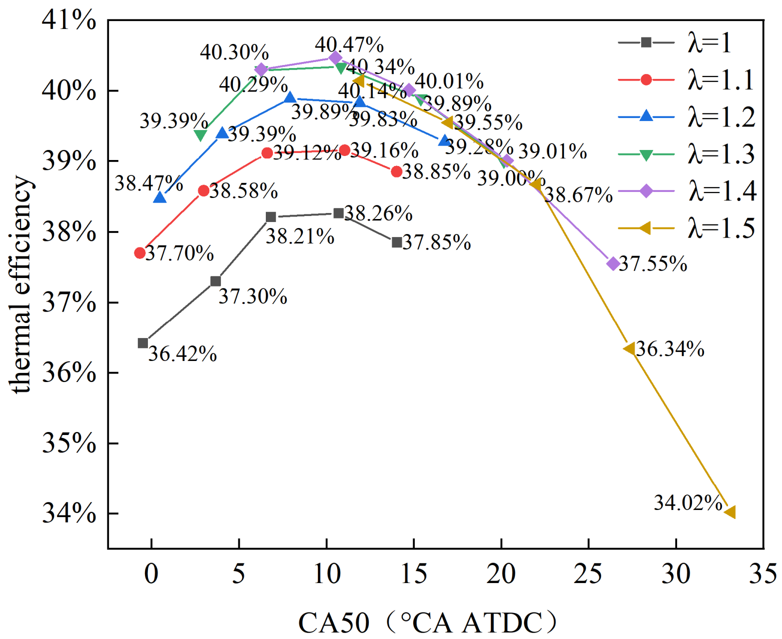

Figure 15. Relationship between CA50 and thermal efficiency.

4. Conclusions

The experimental system investigated the combustion characteristics, emission behavior, and energy distribution patterns of a small-bore turbocharged intake manifold natural gas engine operating under lean-burn conditions at different excess air ratios (λ = 1.0–1.5) and ignition timing points (−12°CA to −24°CA ATDC). Conducted at a fixed speed of 2500 r/min with BEMP stabilized at 9 bar, the experiments focused on analyzing the combined effects of combustion phase parameters, cycle variations, key pollutant emissions, and various heat losses on final thermal efficiency. This aimed to clarify the synergistic mechanism between dilution levels and ignition strategies, providing a theoretical basis and optimization directions for efficient and clean operation of small-bore natural gas engines.

(1) As the excess air ratio increases, the ignition delay period lengthens and the combustion center shifts backward. The combustion duration first shortens, then lengthens, while the peak cylinder pressure first rises, then falls, with the peak pressure phase delayed. As ignition timing advances, the ignition delay period shortens and the combustion center advances. The combustion duration first shortens, then lengthens, the peak cylinder pressure increases, and the peak pressure phase advances. When CA50 is between 8–10°CA ATDC, the engine's thermal efficiency reaches its optimal range, demonstrating superior fuel economy.

(2) As the excess air ratio increases, THC emissions first decrease, then increase; NO_x emissions first increase, then decrease; while CO emissions initially drop sharply before stabilizing. With advancing ignition timing, THC emissions monotonically increase at low excess air ratios. Under lean-burn conditions, the trend reverses with advancing ignition timing, NO_x emissions significantly increase, and CO emissions remain relatively stable. The operating condition balancing low NOx emissions and high thermal efficiency occurs at an excess air ratio of 1.5 and ignition timing of −21°CA ATDC, yielding NOx emissions of 105 ppm and thermal efficiency of 39.55%.

(3) As the excess air ratio increases, the trend of incomplete combustion losses is to decrease initially and then increase. Heat transfer losses decrease, thermal efficiency increases initially, and then decreases, while COV_{IMEP} increases. Under conditions of a moderate combustion phase, exhaust gas losses decrease initially and then increase with rising excess air ratio; under conditions of a delayed combustion phase, exhaust gas losses increase significantly. As ignition timing advances, thermal efficiency first increases, then decreases. The optimal ignition timing for thermal efficiency advances with increasing excess air ratio, while COV_{IMEP} first decreases, then increases. Under low excess air ratios, incomplete combustion losses monotonically increase with earlier ignition timing. Under lean-burn conditions, they exhibit the opposite trend with earlier ignition timing. At low excess air ratios, ignition timing has little effect on exhaust gas losses. Under lean-burn conditions, exhaust gas losses decrease with earlier ignition timing. At low excess air ratios, heat transfer losses first decrease, then increase with earlier ignition timing. Under lean-burn conditions, heat transfer losses decrease with earlier ignition timing. At an excess air ratio of 1.4 and an ignition timing of −21°CA ATDC, the total heat loss is minimized at 52.09 kJ/s, and thermal efficiency reaches its maximum value of 40.47%.

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