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A Twice-Open Control Method for a Hydraulic Variable Valve System in a Diesel Engine

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Abstract: In order to solve the cold-starting problem and improve the intake and exhaust pipe temperatures of diesel engines under cold-starting and low- and medium-speed conditions, this paper proposes a twice-open control method for a hydraulic variable valve system. First, a hydraulic variable valve system that can realize a fully variable valve lift and phase angle is applied to replace the original intake system in order to meet the air intake requirements of different conditions. Then, a twice-open control method in which the intake valve opens two times at the exhaust stroke and intake stroke is proposed to improve the intake pipe temperature and solve the cold-starting problem. This paper contains a numerical work analysis. A GT-POWER model is constructed to validate the intake valve twice-open control method. The cylinder pressure, cylinder temperature, intake pipe pressure, and intake pipe temperature are obtained and compared between the original intake valve system and the hydraulic variable valve system with the proposed intake valve twice-open control method. The results show that the twice-open control method can increase the intake pipe temperature to 260 K or even higher, which can improve the cold-starting performance and the exhaust temperature at low and medium speeds. At the same time, the performance under low- and medium-speed conditions is improved.

Keywords: diesel engine; hydraulic variable valve system (HVVS); cold start; twice-open control method; simulation analysis

Citation: Guo, D.; Tang, J.; Xie, Z.; Li, X.; Cao, X. A Twice-Open Control Method for a Hydraulic Variable Valve System in a Diesel Engine. *Processes* **2024**, *12*, 1526. https://doi.org/10.3390/pr12071526

Academic Editor: Blaž Likozar

Received: 12 June 2024
Revised: 17 July 2024
Accepted: 18 July 2024
Published: 19 July 2024

1. Introduction

In recent years, due to stringent environmental regulations, ensuring a reduction in exhaust gas emissions has become a tough challenge for automotive engineering [1,2]. Stricter NO_X and CO_2 emission targets for gasoline and diesel engines require new technologies. For diesel engines, exhaust gas after-treatment plays an important role in meeting the NO_X target values. The challenge is related to how to heat up the catalysts as fast as possible after starting the engine [3]. To solve the difficulty in the cold starting of diesel engines, different methods are applied, such as using a retarder starter, preheating the coolant, and preheating the intake pipe. Preheating technology is one of the important technologies used to improve engines' cold-starting performance. In addition, in order to improve the performance of diesel engines, electronic control, direct injection, common rails, turbocharging, intermediate cooling, variable valve technology, and other emerging technologies are widely used, providing diesel engines with a wider range of applications [4].

Variable valve technology has the advantages of reducing pump air loss, achieving internal EGR, achieving a variable effective compression ratio, achieving variable displacement, improving idle stability, increasing inflation efficiency, and reducing energy consumption. Compared with traditional valve systems, variable valve technology can continuously change the valve's opening and closing time and can change the lift of the valve according to different working conditions. Therefore, variable valve technology can improve the intake and exhaust performance and better meet the requirements of power, economy, and exhaust emissions of the engine at high and low speeds and under large and small loads [5]. To utilize the advantages of variable valve technology, lots of prototype systems have already been proposed for variable valve actuation (VVA) systems. However, only a few types with less flexibility have entered into the production stage, while the rest are still at the research level [6].

There are two main kinds of VVA systems, namely camless and cam-based valve trains. A camless system has no cam drive and thus applies electromagnetic, mechanical, and electro-hydraulic methods to realize fully variable valve technology. For instance, fully variable electromagnetic valve systems use electromagnetic force to overcome the valve spring force to open the valve. Fully variable electromagnetic valve systems can further be divided into three types: springless, single-spring, and double-spring. However, electromagnetic valve systems have a fast response when the valve is closed, causing a high valve seating speed. Springless fully variable electromagnetic valve systems have no springs to store valve energy [7], leading to high valve vibration, unstable movement, high levels of noise, and other problems. Single-spring fully variable electromagnetic valve systems [8] have a slow response speed and high energy consumption. However, the valve seating speed is also high. Double-spring electromagnet valve systems also have some problems, like uneven valve landing and a large impact when the valve closes. Compared with these other systems, fully variable systems have a high level of flexibility in valve timing and valve lift. However, a well-designed fully variable system may have problems like high cost, low reliability, high power consumption, and control complexity, which deter manufacturers from incorporating these systems in engines.

Unlike camless valve trains, cam-based VVA systems are mechanically linked to the engine crankshaft. In order to realize the variability in the valve timing and lift, hydraulic and motor actuators are applied in these VVA systems. For instance, a variable valve lift (VVL) system was proposed by Zhilong Hu et al. [9], employing a hydraulic actuator between the engine cam and the valve. The hydraulic actuator consisted of a driving plunger, a driven plunger, and a hydraulic cylinder. This VVL system was able to regulate valve lift by rotating the driving plunger. Its effectiveness and working stability were validated through experiments. In addition, a continuous variable valve lift (CVVL) system was proposed by Qingyu Li et al. [10]. In this system, an electric motor was employed to drive the gear through a worm, which actuated a rocker arm that determined valve lift. Meanwhile, the German automobile company BMW invented a mechanical full variable valve mechanism by using the Valvetronic (variable lift) mechanism and the Vanos (variable phase) mechanism [11–13]. However, due to its complex structure and limited adjustment range, this mechanism cannot be applied to high-speed engines.

For fluid simulation models, Pradeep Menon et al. proposed the use of CFD analysis to study the in-cylinder process of diesel engines to achieve the purpose of improving performance and reducing fuel consumption and emissions [14]. J P Panda et al. proposed a simulation method based on a high-fidelity Reynolds stress model to study the drag reduction mechanism of a shallow concave axisymmetric rotating body. It is observed that the drag of the body is reduced by a maximum of 31% with such a shape modification (for a depth-to-diameter ratio of 7.5% and a coverage ratio of 52.8%) [15]. Li et al. developed a transient computational fluid dynamics (CFD) model to predict the hydraulic characteristics of a fully open valve tray. Their CFD simulations reflect the chaotic tray hydrodynamics [16]. Jyoti Prakash Panda et al. proposed the effect of twisted tape length on the thermal performance of a heat exchange tube and discussed the effect of twisted tape length under different twist ratios (TRs) at $4700 < Re < 22{,}800$ [17]. Michel Takken et al. proposed a simulation method that accelerates CFD simulations by exploiting simulation methods on higher levels of abstraction [18]. Li et al. established a three-dimensional computational fluid dynamics model of a new type of fixed air distribution tray. Clear liquid height, gas hold-up, and gas and liquid velocity profiles were predicted for various combinations of weir height, gas, and liquid flow rates. The predicted clear liquid height was generally in good agreement with the measurements [19].

Aiming to assess the influence of valves on diesel engine performance, Lan et al. used a low-speed diesel fuel system test bed to analyze the pressure performance of a dual-valve control fuel system. Their results show that the excessive pressure peak is caused by the high rising rate of fuel pressure [20]. Michael G. Thurston et al. developed a new predictive function that tracks damage to diesel injectors based on the measured exhaust gas temperature of each cylinder, whereas previous work was limited to fault detection [21]. Lisa M. Weatherly et al. proposed that diesel exhaust (DE) is an air pollutant containing gaseous compounds and particulate matter. Their results show that DE exposure induced modifications to the cellularity of phenotypic subsets that may impair immune function and contribute to airway inflammation induced by DE exposure in rats [22]. Arshed Abdulhamed Mohammed adopted a noise-based test method to record the engine noise of a Dodge station wagon and analyzed the recorded data using the Hilbert Huang transform (HHT). This study succeeded in determining which of the engine's combustion chambers had a problem through acoustic tests, in addition to being able to detect malfunctions of the airflow system early [23]. Kagramanian Artur et al. researched the effect of carbon deposition on the diesel engine performance index. The technology of cleaning the fuel system, the fuel injection device and cylinder, and the piston group of an internal combustion engine with a special cleaning agent was put forward [24]. Lina Jamal et al. investigated the effects of exhaust gas recirculation (EGR) on the performance and exhaust emissions of a single-cylinder air-cooled direct injection diesel engine. This study showed that European diesel fuel positively impacts engine performance and emissions [25]. Han et al. used n-butanol as a less reactive fuel and n-heptane as a highly reactive fuel with direct intake to achieve high thermal efficiency and low soot/NOx emissions. Their results show that single direct injection causes either too early combustion phasing or excessive HC/CO emissions [26]. Hayder Q. Alwan used a Zittel Z-6901 three-compression ring engine to complete their experimental work. An indicator chart was recorded at different engine speeds $P = f(\alpha)$. For the verification of a mathematical model, a static test rig apparatus was designed in order to measure the inter-ring volume pressure within the range of compression pressure, i.e., 1 bar to 33.8 bar. The comparison between mathematical and experimental results shows good agreement [27]. G. Papalambrou et al. researched the problem of improving load acceptance and reducing the flue gas emissions of marine turbocharged diesel engines under the transient conditions of rapid load increase. Their engine model was derived using the system identification method. Transient response experiments on a full-size marine diesel engine were carried out to verify the effectiveness of the control system. Their results for various engine parameters show that the transient load is improved compared with the standard condition without jet [28].

In this paper, to address the problems of cold starting and low exhaust temperature under low- and medium-speed conditions in winter temperatures as low as −40 °C in diesel engines, the intake system is replaced with a variable valve system. A twice-open control method is applied to control the intake valve so that it opens two times during the intake stroke and the exhaust stroke. The intake valve opening during the exhaust stroke allows some of the compressed high-temperature air or the high-temperature combustion exhaust to flow back into the intake pipe, increasing the temperature of the intake air to improve the cold start performance and emission performance of diesel engines under medium- and low-speed working conditions. According to the structure characteristics and related parameters of the studied diesel engine, the GT-POWER performance simulation model is established. Based on this model, the variations in cylinder pressure, intake pipe temperature and pressure, and exhaust pipe temperature are simulated and obtained based on the model under cold-starting and low- and medium-speed conditions.

2. Working Principle of HVVS and Twice-Open Control Method

In this paper, a 1110 diesel engine working in a −40 °C environment in winter is taken into consideration. The main technical parameters of the 1110 engine are shown in Table 1.

Due to the low environmental temperature, this engine takes a long time to start in winter and the performance under low- and medium-speed conditions needs to be improved. To meet the air intake requirements under different conditions, the original intake valve system is replaced with a hydraulic variable valve system, as shown in Figure 1. The applied HVVS mainly consists of a hydraulic control system and a mechanical transmission system. The hydraulic control system is composed of a high-pressure system and a low-pressure system. The high-pressure system can open the intake value at the right time and mainly consists of a plunger chamber, a piston chamber, and pipelines between components. In contrast, the low-pressure system can supply enough hydraulic oil and recover the oil flowing from the high-pressure system after the oil drain valve is opened. The low-pressure system consists of an overflow valve, an oil tank, a low-pressure oil passage, an oil pump, etc. The mechanical transmission system mainly consists of four parts: an intake cam, a hydraulic tappet, a hydraulic piston, and a valve assembly. The main function of the mechanical transmission system is to open and shut the intake valve by converting the mechanical driving motion of the intake cam into hydraulic pressure through the hydraulic tappet.

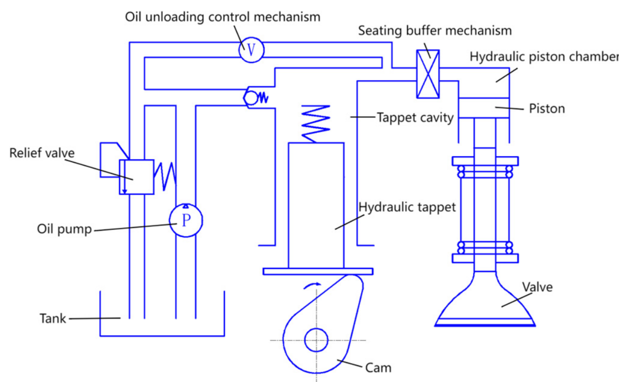


Figure 1. Schematic diagram of the hydraulic variable valve system.

The working principle can be described as follows: when the oil drain valve is closed, the hydraulic piston moves upward due to the valve cam. The pressure of the high-pressure system will rise and generate hydraulic force, and the intake valve will open when the hydraulic force overcomes the spring resistance force. When the intake valve needs to be closed, the oil drain valve will open, the pressure of the high-pressure system will reduce, and the intake valve will be closed by the spring force [6,29–31].

Table 1. Engine parameters.

Rated Engine Speed (r/min)	3800
Rated power (kW)	92
Oil consumption (g/kWh)	247
Combustion chamber	ω type
Fuel injection system	Common rail direct injection
Injection pressure (Bar)	1800
Cylinder diameter (mm)	110
Stroke (mm)	110
Connecting rod length (mm)	183

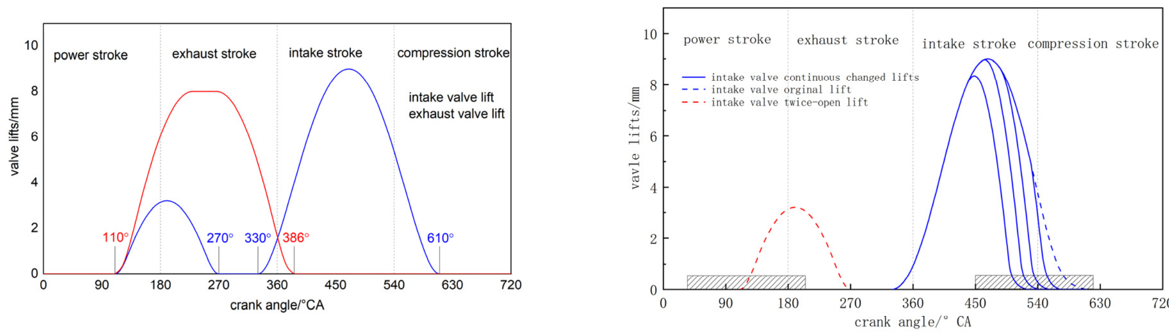
Compression ratio	13.5
Number of spray holes (-)	10
Spray hole diameter (mm)	0.22
Oil beam angle (°)	157

In order to improve the performance of the engine under cold-starting and low-speed conditions, this paper proposes a twice-open control method for the intake valve and sets a throttle in the intake pipe to realize the rapid heating of intake air. The twice-open control method can control the intake valve so that it opens two times during the intake stroke and the exhaust stroke.

The mechanism of the twice-open control method can be described as follows: when the valve opens during the intake stroke, the low-temperature air enters the intake pipe and then enters the cylinder. At the same time, the throttle in the intake pipe closes and a vacuum is formed inside the intake pipe. The temperature of the air rises during the compression stroke. Because the cylinder temperature and the air temperature are low, the fuel injector does not work at the beginning of the cycle. Then, in the exhaust stroke, the intake valve opens a second time, while the exhaust valve also opens. Most of the heated air will flow back into the intake pipe due to the vacuum in the intake pipe. In the next cycle, the air in the intake pipe will flow into the cylinder again and the temperature of the air will rise further during the second compression stroke. After multiple cycles, the intake temperature significantly increases and then the injector works and the engine can start smoothly. After the engine starts, the throttle opens and fresh air flows into the engine regularly. When the engine works under low- and medium-speed conditions, the intake valve also opens during the exhaust stroke. When the throttle opens, the intake pipe pressure is normal, and only a small amount of exhaust gas can flow back into the intake pipe to improve the temperature of the intake, as in EGR. Therefore, the performance can be improved under low- and medium-speed conditions. Under higher-speed conditions, the intake valve will not open during the exhaust stroke, and the engine works normally.

The twice-open intake valve lift and the exhaust valve lift of the original engine are shown in Figure 2a. As shown in Figure 2a, the original engine's intake valves open at 330° CA and close at 610° CA during the intake stroke, taking the top dead center of the power stroke as 0° CA. The intake valve can also open during the exhaust stroke, normally opening at 110° CA and closing at 270° CA. The original engine's exhaust valve opens at 110° CA and closes at 386° CA.

Figure 2b shows the continuously changing intake lifts induced by the oil drain valve control of the HVVS. As shown in Figure 2b, the intake valve's opening time, closing time, and lift can change according to the condition requirements. At the same time, the intake valve lift during the exhaust stroke can be changed or canceled by the HVVS. The intake valve lifts shown in Figure 2b were obtained via an experiment that validated the effects of the HVVS in valve lift control.



(**a**) (**b**)

Figure 2. Twice-open intake valve lift and the exhaust valve lift of the original engine and the HVVS: (**a**) twice-open intake valve lift and the exhaust valve lift of the original engine; (**b**) continuously changing intake valve lifts of the HVVS.

3. Simulation Model Construction

3.1. Simulation Model Construction

In order to verify the effectiveness of the twice-open control method, this paper established an engine performance simulation model based on the characteristics of the 1110 diesel engine using GT-POWER, as shown in Figure 3. This model contains the environment system, the intake system, the power system, and the exhaust system. The environment system can simulate environmental temperature. The intake system includes the environmental inlet, the intake port, the throttle, and the intake valves. The intake system can set the valve lift curve to control the opening angle and duration of the valve and simulate the opening and closing of the intake valve under different working conditions. Meanwhile, the exhaust system contains exhaust valves, exhaust ports, and the exhaust pipe. The intake system and the exhaust system can simulate the characteristics of the pipes and the intake and exhaust process. The power system contains the engine, the cylinder, and the injector. The power system includes the fuel injection nozzle, the cylinder, and the crank connecting rod mechanism, which can control the fuel injection nozzle and how much oil is injected in order to simulate different combustion conditions by means of parameter setting. The structure simulation of the cylinder and crankshaft can also be realized by setting parameters such as the cylinder diameter and crank radius, and the starting angle of the crankshaft can be controlled by means of parameter setting. This part can simulate the compression and power stroke process. The details of the parameters of these components are given in the following section.

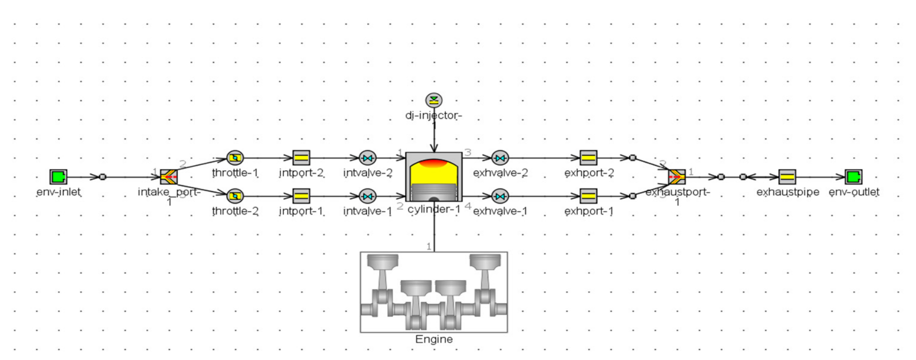


Figure 3. Engine performance simulation model.

3.2. Parameter Settings of Model Components

3.2.1. Cold Starting Parameter Settings

This paper mainly studies the effectiveness of the twice-open control strategy of the HVVS in diesel engines under cold-starting conditions.

For an ambient temperature of −40 °C, the initial wall temperature in the intake module, the cylinder module, and the exhaust module was set to −40 °C. The inlet diameter, outlet diameter, manifold length, and manifold discrete length of the intake and exhaust manifold were set according to the actual structure. For example, the basic parameters of the intake manifold were 40 mm for the diameter at the inlet end, 32 mm for the diameter at the outlet end, and 300 mm for the length. The engine parameters were set according to Table 2. The intake valve lift set under cold-starting conditions is shown in Figure 4. The maximum lift attained is 3.2 mm and 4.6 mm due to the lower air requirements. The intake valve opens at 390° CA and closes at 550° CA during the intake stroke, while it opens at 110° CA and closes at 250° CA during the exhaust stroke. Considering a throttle valve set in the intake manifold, the influence of the throttle valve's opening angle needs to be studied. In order to form a vacuum environment in the intake pipe, the throttle angle was set to 0°, meaning that the throttle is closed after the air flows into the cylinder.

Table 2. Engine cold start parameter.

Inlet of Intake Manifold (mm)	**40**
Outlet of intake manifold (mm)	32
Intake manifold length (mm)	300
Maximum lift (mm)	4.6
Throttle angle (°)	0
Ambient temperature (°C)	−40

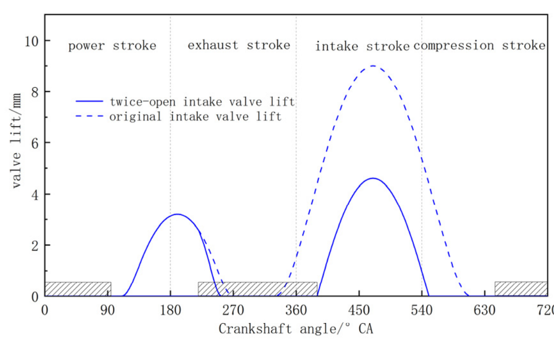


Figure 4. Intake valve lift under cold-starting conditions.

3.2.2. Low-Speed Conditions' Parameter Settings

Low-speed conditions here indicate idle operating conditions. Considering that the wall temperature of the engine increases after starting, the ambient temperature and the temperature of the intake module, cylinder module, and exhaust module were set at 20 °C. At the same time, due to combustion, the temperature inside the cylinder increases significantly. Therefore, the cylinder head temperature was set to 550 K, the piston temperature was set to 590 K, and the cylinder temperature was set to 450 K. For the injector module, the injected fluid temperature was set to 305 K and the fuel injection quantity was set to 50 mg. Figure 5 shows the intake valve lift curve under the idle operating condition. As shown in this figure, the intake valve opens twice at 110° CA and 330° CA. The maximum intake valve lift is 3.2 mm and 9 mm. Under these conditions, the fresh intake air needs to flow into the cylinder continuously; therefore, the throttle angle should be larger than 0°. In this paper, the angle was set to 90°.

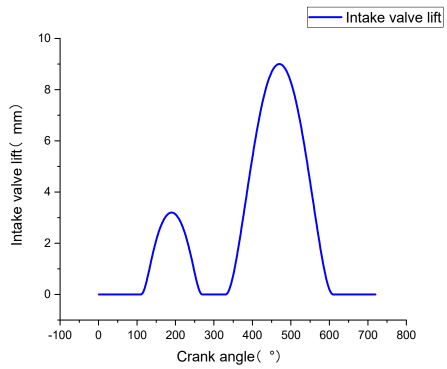


Figure 5. Intake valve lift under idle operating conditions.

3.2.3. Medium-Speed Conditions' Parameter Settings

After the engine warms up, the engine runs at medium-speed conditions and the temperature of the intake module, cylinder module, and exhaust module is set to 60 °C. The intake valve lift is the same as under low-load conditions, as shown in Figure 6. In addition, because the speed and load increase, the required fuel injection amount increases. The fuel injection amount was set to 135 mg. The wall temperature of the exhaust main pipe and exhaust manifold was set to 60 °C. Other structural parameters of the model were the same as for the cold-starting condition. Under these conditions, the throttle angle was also set to 90°.

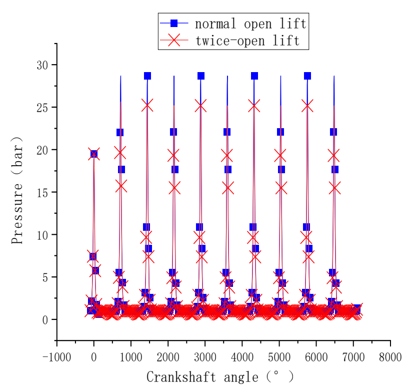


Figure 6. Plots of corresponding in-cylinder pressure for different lifts.

4. Results and Discussion of Cold-Starting Performance

In order to analyze the effectiveness of the twice-open control method, simulations were conducted under two different intake valve lift conditions, including normal open lift conditions (the valve opens only during the intake stroke, as in the original intake system, and there is no throttle) and twice-open lift conditions. The lift in the intake stroke was the same in both of these lifts. Also, because a throttle is set in the intake pipe, the position of the throttle may influence the performance of the engine. Therefore, the influence of the throttle position was studied based on the model. The cylinder pressure, cylinder temperature, intake temperature, and intake pressure were obtained based on the simulation model and the results were compared for different intake valve lifts.

4.1. Influence of the Twice-Open Method

4.1.1. Comparison of Cylinder Pressure

Because the normal open lift process does not need to open the valve during the exhaust stroke, as in the original engine, the throttle open angle is set to 90°, while in the twice-open lift condition, the open angle is set to 0°. Figure 6 shows the comparison of the results of the cylinder pressure under the two different valve lift conditions. As shown in this figure, the peak pressure of the cylinder under normal open lift conditions is greater than the peak pressure of the cylinder under twice-open lift conditions. This is because under the twice-open lift conditions, most of the gas in the cylinder flows back into the intake pipe and some flows out into the exhaust pipe, resulting in a decrease in the amount of gas entering the cylinder in the next cycle. Therefore, the pressure is lower than under normal intake conditions.

4.1.2. Cylinder Temperature

Figure 7 shows the comparison curves of the temperature inside the cylinder under different lift conditions. From this figure, it can be seen that the variation tendencies of the cylinder temperature corresponding to the normally open and twice-open conditions are basically the same. The temperature of the cylinder under the twice-open lift conditions is about 580 K, and the temperature of the cylinder under the normal open lift conditions is about 560 K. The temperature of the cylinder under the twice-open lift method is higher than that under the normal open method, indicating that the twice-open method is beneficial for increasing the temperature in the cylinder.

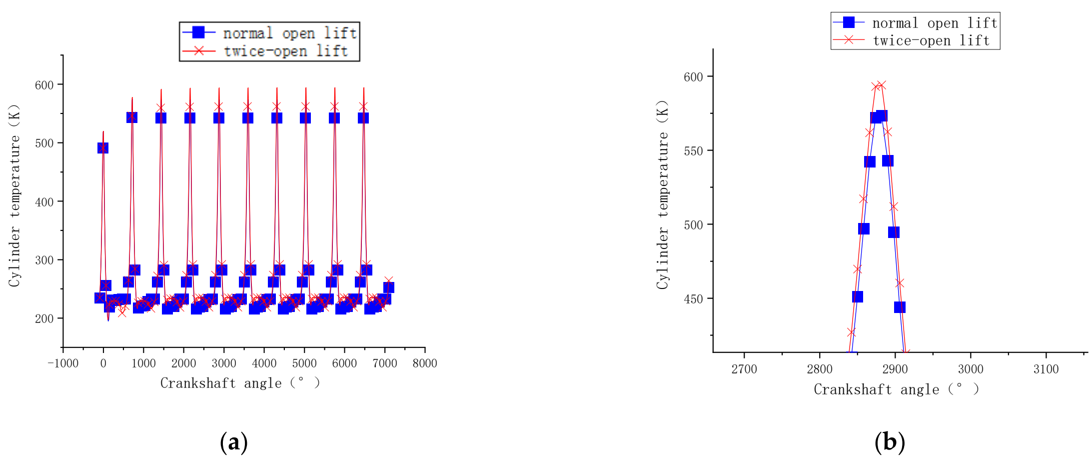


Figure 7. In-cylinder temperature diagram for different lifts: (**a**) original figure; (**b**) partial enlarged figure.

4.1.3. Intake Pipe Temperature

Figure 8 shows the temperature curves of the intake pipe corresponding to the normal open lift and twice-open lift conditions. As shown in this figure, under normal lift conditions, the temperature of the intake pipe is always equivalent to the ambient temperature. However, when the intake valve opens again during the exhaust stroke, the temperature of the intake pipe changes significantly, reaching a maximum value of nearly 265 K, which is about 32 K higher than that obtained with a normal open lift. However, there may be a drop in some positions. Overall analysis shows that the twice-open control method helps to increase the temperature of the intake pipe.

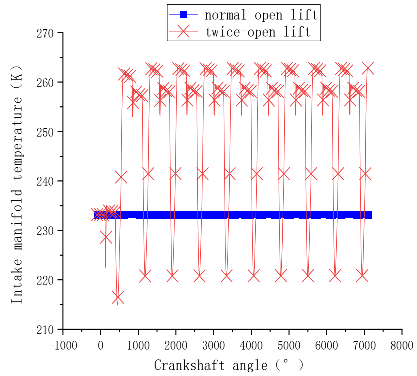


Figure 8. Temperature plot of the intake pipe for different lifts.

4.1.4. Intake Pipe Pressure

Figure 9 shows the pressure curves of the intake pipe corresponding to the normal open and twice-open conditions. It can be seen from this figure that compared to the normal open lift, the twice-open lift can create a vacuum in the intake pipe, with a pressure lower than the cylinder pressure, which is conducive to the compressed and heated gas in the cylinder returning to the intake pipe, heating up the intake pipe, and improving cold-starting performance.

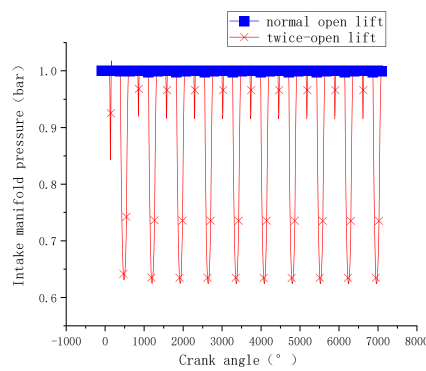


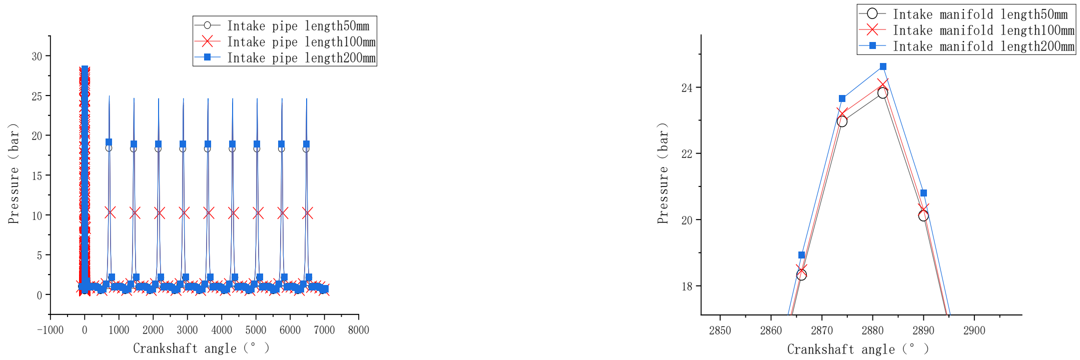
Figure 9. Plot of the inlet pipe pressure corresponding to the different schemes.

4.2. Analysis of the Impact of Throttle Position

The above analysis shows that the control strategy of closing the throttle valve and the twice-open method is beneficial for increasing the intake pipe temperature and the cylinder temperature and is conducive to improving cold-starting performance. However, the installation position of the throttle valve may have an impact on the formation of the vacuum and the amount of compressed air flowing back into the intake pipe. Therefore, this paper also analyzed the influence of the throttle valve position on cylinder pressure, cylinder temperature, and intake pipe temperature. When comparing the influence of the throttle position, it can be seen that the intake pipe length from the throttle to the cylinder is changed, which means that the intake pipe length is changed. Therefore, in this paper, the throttle position is expressed by the intake pipe length. We propose setting the intake pipe length at 50 mm, 100 mm, and 200 mm.

4.2.1. Cylinder Pressure

Figure 10 shows the cylinder pressure curves under different intake pipe lengths. As shown in this figure, when the length of the intake pipe is 200 mm, the compression pressure of the cylinder is at its maximum level, while when the length of the intake pipe is 50 mm, the compression pressure of the cylinder is at its lowest. Our analysis indicates that as the length of the intake pipe increases, the amount of air flowing back into the intake pipe increases, and the amount of air entering the cylinder in the next cycle increases, resulting in an increase in the cylinder pressure.

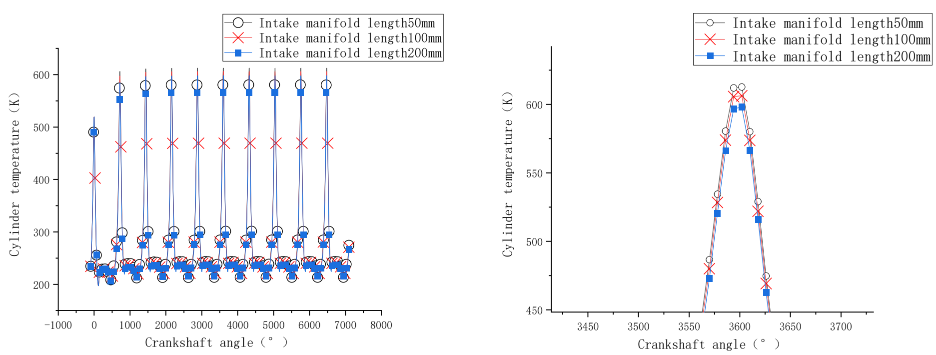


(**a**) (**b**)

Figure 10. Cylinder pressure curves for different pipe lengths: (**a**) original figure; (**b**) partial enlarged figure.

4.2.2. Cylinder Temperature

Figure 11 shows the temperature curves of the cylinder under different intake pipe lengths. As shown in this figure, the variations in the cylinder temperature under different intake pipe lengths are the same. When the intake pipe length is 50 mm, the maximum temperature rises to its highest level. However, the difference between the maximum temperature produced by the three different intake pipe lengths is small. Our comparison shows that the length of the intake pipe has no significant effect on the cylinder temperature, as shown in Figure 11.



(**a**) (**b**)

Figure 11. Cylinder temperature curves corresponding to different intake pipe lengths: (**a**) original figure; (**b**) partial enlarged figure.

4.2.3. Intake Pipe Temperature

Figure 12 shows the temperature curves of the intake pipe under different intake pipe lengths. As shown in this figure, when the intake pipe length is 100 mm, the intake pipe temperature rises the fastest and to the highest level, with a good heating effect. This is because when the length of the intake pipe is short, the space for vacuum formation is small, smaller than the cylinder volume. The intake pipe thus may not be able to accommodate the air flowing back from the cylinder, causing some gas to flow out to the exhaust pipe. Meanwhile, if the intake pipe is too long, the space for vacuum formation is too large, leading to faster heat loss, resulting in a poor heating effect.

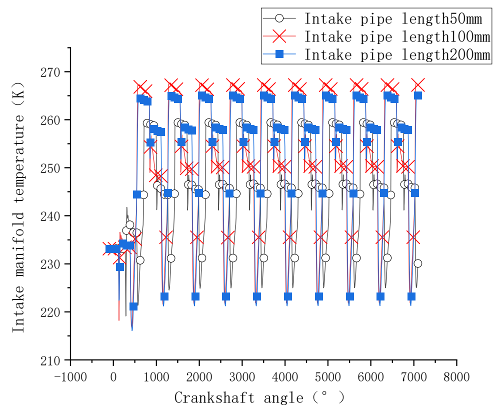


Figure 12. Temperature curves corresponding to different lengths of the intake pipe.

4.2.4. Intake Pipe Pressure

Figure 13 shows the temperature rise trend of the intake pipe under different intake pipe lengths. As shown in this figure, the pressure of the intake pipe varies with the length of the intake pipe. When the length of the intake pipe is 50 mm, the pressure drops the most, and when the length of the intake pipe is 200 mm, the pressure drops the least. The results indicate that as the length of the intake pipe decreases, the pressure of the intake pipe decreases further, which is beneficial for ensuring that the compressed and heated air flows back into the intake pipe. However, if the intake pipe is too short, the formed space is insufficient to fully accommodate the compressed air flowing back from the cylinder.

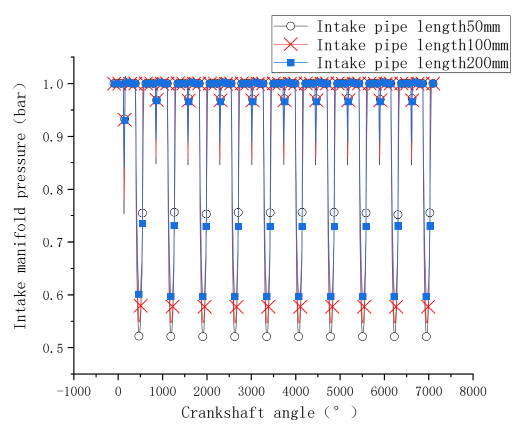


Figure 13. Pressure curves corresponding to different lengths of the intake pipe.

5. Results and Discussion of Low- and Medium-Speed Operating Conditions

In this chapter, simulations are carried out under low- and medium-speed conditions. Based on the simulation model, the cylinder pressure, cylinder temperature, intake air temperature, and intake air pressure are obtained, and the results under different working conditions are compared.

5.1. Impact of the Twice-Open Control Method on Low-Speed Conditions

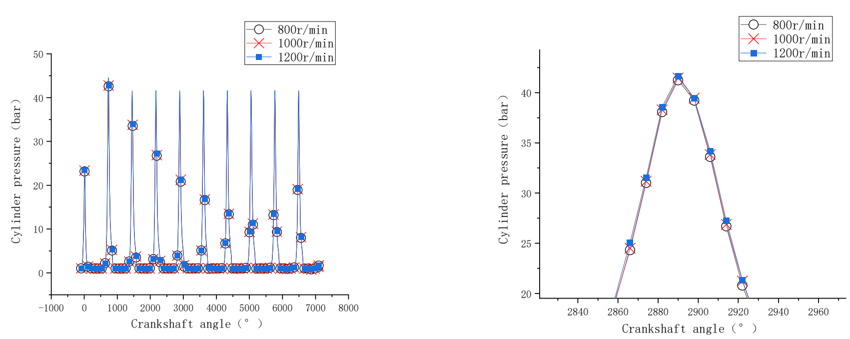
In this paper, low-speed conditions represent an engine speed below 1200 r/min. Due to the low amount of fuel being injected under low-speed conditions, the temperature of the engine cylinder is low, resulting in a low exhaust pipe temperature. It is necessary to increase the temperature of the cylinder as soon as possible in order to increase the exhaust pipe temperature, and thus improve the catalytic conversion efficiency of the SCR. In this section, the intake valve is still opened twice to realize a temperature increase in the intake pipe, the cylinder, and the exhaust pipe under low-speed conditions. However, the throttle angle needs to be greater than 0° to ensure that fresh air flows into the cylinder. In this section, the throttle angle is thus set to 90°.

5.1.1. Cylinder Pressure

Engine speed may influence engine performance when the intake valve opens two times. In order to analyze the influence of engine speed on engine performance, a simulation is developed based on the model at different engine speeds, set to 800 r/min, 1000 r/min, and 1200 r/min, and the intake valve lift is set as shown in Figure 4. Figure 14 shows a comparison of the results of in-cylinder pressure under different speeds. As shown in this figure, the change trends of the in-cylinder pressure under different speeds are similar, and engine speed has little effect on the peak pressure if other parameters are the same. Therefore, in the following section, an analysis is performed with the engine speed set at a fixed value of 1000 r/min.

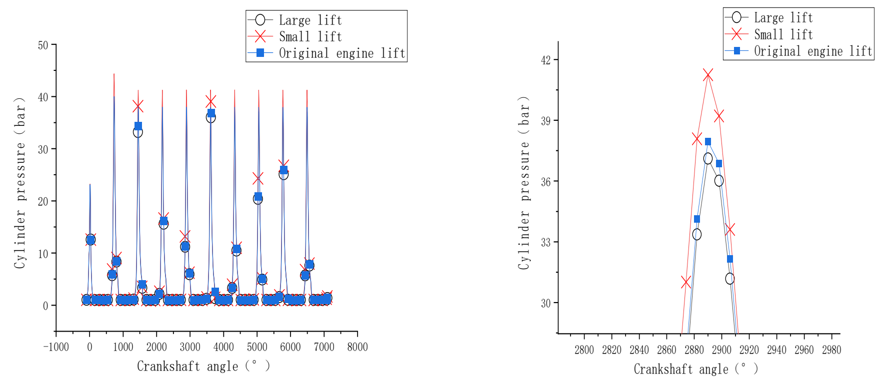
When the intake valve opens two times, the lift of the intake valve during the exhaust stroke may influence engine performance. In order to compare the influence of different intake valve lift conditions, a simulation is carried out under different valve lift conditions, as shown in Figure 4 and Figure 5, referred to as a small lift and a large lift, respectively. Also, with the aim of studying the effect of the twice-open control method, a simulation is also conducted under the original valve lift conditions of the engine, referred to as the original engine lift.

Figure 15 shows the comparison of in-cylinder pressure under different lift conditions. As shown in this figure, the change trends of in-cylinder pressure under different lift conditions are similar. The peak pressure is at its highest under the twice-open small lift conditions, while the peak pressure is at its smallest under the twice-open large lift conditions. The peak pressure value under the large lift conditions is similar to the peak pressure value of the original engine lift. The reason for this is that when the intake valve lift is large, the intake air flow area is similar to that in the original engine, and most of the exhaust will flow to the exhaust pipe.



(**a**) (**b**)

Figure 14. Comparison of in-cylinder pressure curves at different speeds: (**a**) original figure; (**b**) partial enlarged figure.

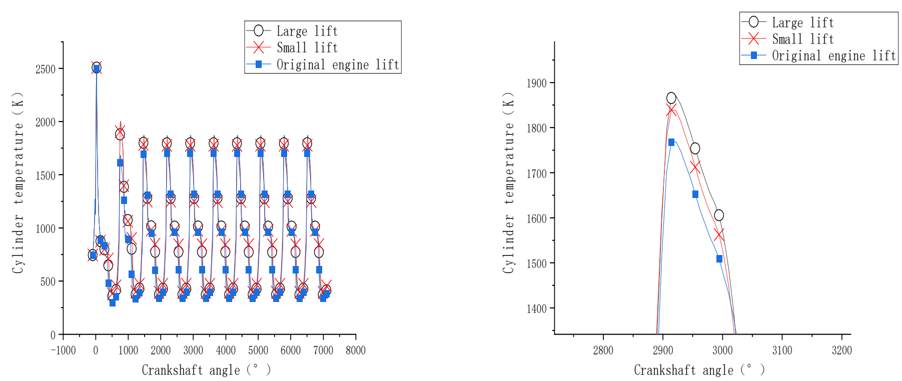


(**a**) (**b**)

Figure 15. Comparison diagram of cylinder pressure curves corresponding to different lift conditions: (**a**) original figure; (**b**) partial enlarged figure.

5.1.2. Cylinder Temperature

Figure 16 shows the cylinder temperature curves under different lift conditions. As shown in this figure, the cylinder temperature under different lift conditions becomes stable after three operating cycles, and the trends are similar. The cylinder temperature under a large lift is the highest, and the cylinder temperature under a small lift is similar to that under a large lift, while the temperature under the original engine lift is the lowest. This indicates that the twice-open control method is beneficial in increasing the temperature of the cylinder.



(**a**) (**b**)

Figure 16. Temperature curves in the cylinder corresponding to different lift conditions: (**a**) original figure; (**b**) partial enlarged figure.

5.1.3. Intake Pipe Temperature

Figure 17 shows the temperature curves of the intake pipe under different lift conditions. As shown in this figure, when the intake valve only opens during the intake stroke, the intake pipe temperature changes within a small range and the average value is close to the environmental temperature. However, the intake pipe temperature is much higher when the intake valve twice-open control method is applied. The temperature produced by the large lift is a little higher than the temperature produced by the small lift. The analysis shows that the twice-open control of the intake valve has a good effect on the temperature rise in the intake pipe under idle conditions, which is conducive to a rapid temperature rise in the intake pipe, a rapid temperature rise in the fresh gas entering the cylinder, the combustion of the mixed gas in the cylinder, and the improvement in the working performance of the diesel engine.

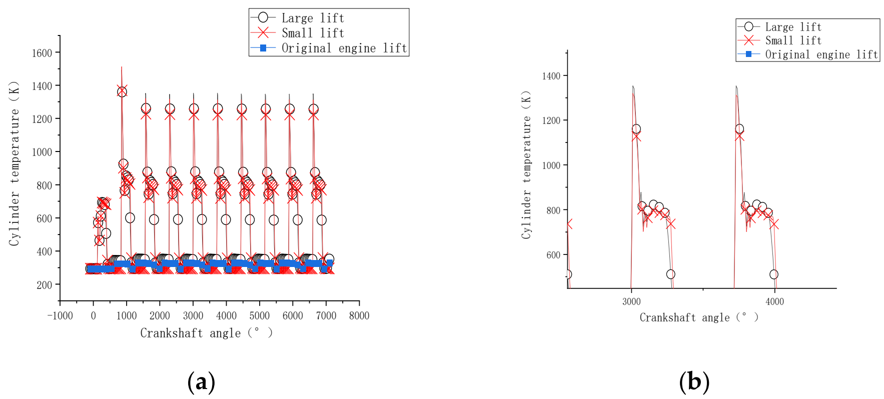


Figure 17. Temperature curves of intake pipe corresponding to different lift conditions: (**a**) original figure; (**b**) partial enlarged figure.

5.1.4. Exhaust Pipe Temperature

Figure 18 shows the temperature curves of the exhaust pipe under different lift conditions. As shown in this figure, after three working cycles, the exhaust pipe temperature becomes stable. The exhaust pipe temperature with a large lift is higher than that under the original engine and small lift conditions. The peak value of the exhaust pipe temperature under small lift conditions is lower than that under the original engine lift conditions; this may be due to the fact that some of the exhaust flows back into the intake pipe and the heat contained in the exhaust decreases in the exhaust pipe. For the large lift conditions, because most of the higher-temperature exhaust flows into the exhaust pipe, the exhaust pipe temperature is slightly higher than that under the other conditions.

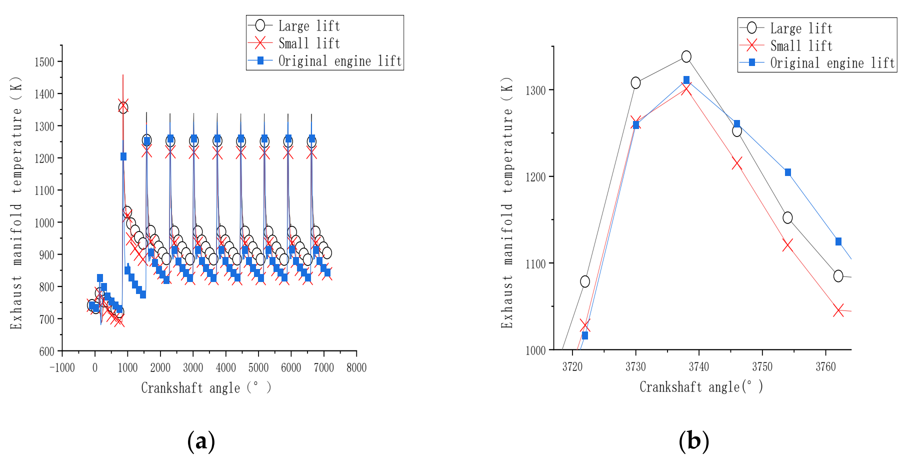


Figure 18. Exhaust pipe temperature corresponding to different lift conditions: (**a**) original figure; (**b**) partial enlarged figure.

5.2. Impact of the Twice-Open Control Method on Medium-Speed Conditions

When the studied diesel engine runs at a medium speed, the engine speed is normally between 1200 r/min and 1600 r/min. In this paper, the engine speed was set to 1200r/min. Under medium-speed conditions, the twice-open control method can also be used to improve the temperature of the diesel engine, so as to improve the engine's performance. With the aim of meeting the requirements of the engine under medium-speed conditions, the intake valve lift was set as shown in Figure 5.

5.2.1. Cylinder Pressure

Figure 19 shows the comparison curves of in-cylinder pressure under normal open and twice-open conditions. As shown in this figure, the peak pressure of the cylinder with the intake valve opened twice is much greater than that with the intake valve opened once. The reason for this is that when the intake valve opens during the exhaust stroke, some of the high-temperature air flows back into the intake pipe. Therefore, during the next cycle, the higher-temperature mixture flows into the cylinder, leading to a higher pressure compared to normal open conditions.

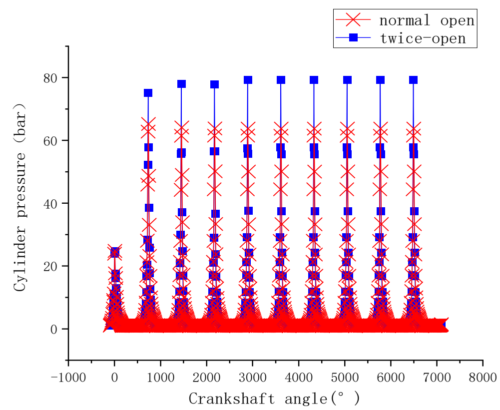


Figure 19. Comparison curves of cylinder pressure for different schemes.

5.2.2. Cylinder Temperature

Figure 20 shows the temperature curves of cylinder temperature under different open control methods. As shown in this figure, the cylinder temperature under the twice-open method is higher than that under the normal open method. The reason for this is discussed in the above sections. Our analysis also shows that the twice-open control strategy of the intake valve is conducive to the increase in the cylinder temperature. These results verify the effectiveness of the twice-open control method.

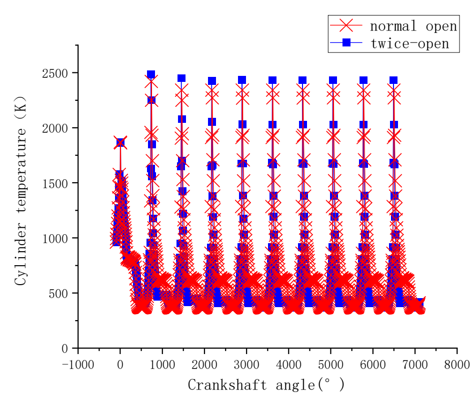


Figure 20. Comparison curves of cylinder temperature for different schemes.

5.2.3. Intake Pipe Temperature

Figure 21 shows the comparison of the intake pipe temperature under different schemes. As shown in this figure, the intake pipe temperature under the twice-open method is much higher than that under the normal open method. The results are similar to those in the above sections. This further verifies the effectiveness of the twice-open control method.

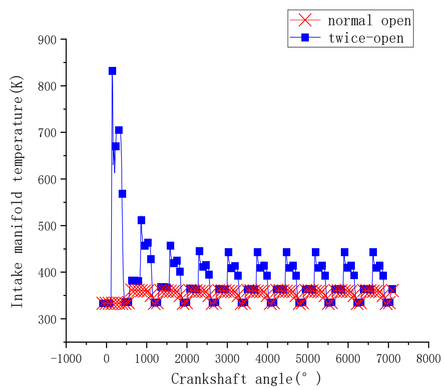


Figure 21. Comparison curves of intake pipe temperature for different schemes.

6. Conclusions

In this paper, the influence of a twice-open control method of a hydraulic variable valve system to improve the performance of diesel engines under cold-starting conditions and low- and medium-speed conditions is analyzed. The main conclusions are as follows:

(1) Compared with the normal open method of the intake valve, the peak pressure of the twice-open method is slightly lower under cold-starting conditions because the throttle is closed and the circulating intake air is reduced.

(2) A vacuum state can be formed in the intake pipe when the twice-open control method is applied and the throttle is closed under cold-starting conditions. The vacuum state can help most of the compressed air to flow back into the intake pipe. Our results show that the cylinder temperature and the intake pipe temperature are both increased. Compared with the normal open method, the twice-open control method can further improve the cold-starting performance.

(3) These results show that the twice-open control method can also accelerate the temperature rise in diesel engines at low and medium speeds, and can improve the performance of diesel engines under low- to medium-speed conditions.

The limitation of this study lies in the lack of relevant experiments on the analysis results. Future work will include further testing, installing a research diesel model, and testing its cold start performance at −40 °C and its performance at low and medium speeds.

Author Contributions: Writing—original draft preparation, D.G.; writing—review and editing, J.T.; validation, Z.X.; investigation, X.L. and X.C. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Postdoctoral Foundation of Shandong Province, China, [Grant Number SDCX-ZG-202203009] and the Training Program of Innovation and Entrepreneurship for Undergraduates [Grant Numbers CXCY2023110 and CXCY2024119].

Data Availability Statement: The data presented in this study are available upon request from the corresponding author. The data are not publicly available due to privacy reasons.

Conflicts of Interest: Author Xiaoxia Li was employed by the company Longkou Zhongyu Machinery Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest. The Longkou Zhongyu Machinery Co., Ltd. had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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