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Research on Cycle Cylinder Deactivation Technology Based on Hydraulic Variable Valve Mechanism

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Abstract. In this paper, a four-cylinder engine hydraulic variable valve mechanism test platform is built to study the torque fluctuation and intake pressure fluctuation caused by cycle cylinder deactivation. The results show that the intake valve is closed after the cylinder is stopped, resulting in a surge in the intake manifold pressure and an increase in the intake pressure fluctuation. The cycle cylinder deactivation will increase the torque fluctuation. The maximum torque under the 20 % stopping rate strategy is about 132 % larger than that without cylinder deactivation. At the same stopping time, the torque fluctuation is more uniform. The cycle cylinder deactivation strategy effectively reduces the heat transfer loss and pumping loss. Under the same cylinder deactivation rate and different strategies, the effective work and other losses of the same strategy at the cylinder stopping time are not much different from those of different strategies at the cylinder stopping time, but the heat transfer loss increases and the exhaust loss decreases.

Keywords. Gasoline engine, variable displacement, cycle cylinder deactivation, torque fluctuation

1. Introduction

Cycle cylinder deactivation technology can stop part of the cylinder under partial load, reduce pumping loss and heat loss, which can improve fuel economy and improve the effective thermal efficiency of the engine. It has gradually become a hot field in the new technology of efficient and clean internal combustion engine [1-4]. Therefore, it is the development trend of variable displacement technology in the future to dynamically jump and stop the cylinder in a certain mode [5]. This means that the non-working cylinder is not a continuous cylinder stop, but each cylinder (or each group of cylinders) stops the cylinder in a cyclic mode [6-7].

Variable displacement technology can effectively improve the engine fuel economy [8-9], but with the variable displacement working mode switching, it will cause the engine torque and speed fluctuation [10-11]. In order to improve the vibration under the variable displacement mode conversion, Bolander et al. and Gush B et al. used to adjust the slip rate of the hydraulic torque converter and increase the rotational inertia of the rotating parts to reduce the vibration, which improved the NVH (Noise,

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Vibration, Harshness) performance under the variable displacement mode conversion to a certain extent [12-13].

2. Research Platform Construction

2.1. Hydraulic Variable Valve Mechanism System Composition

The self-developed hydraulic variable valve mechanism based on electro-hydraulic drive is suitable for 1.4 L four-cylinder engine, and its three-dimensional rendering is shown in figure 1.

It mainly includes tappet piston group, valve piston group, throttle valve, seating buffer mechanism and oil compensation group. According to the control signal, the throttle valve discharges the oil in the oil channel to the external oil tank through the oil discharge channel in a timely manner for recycling. Driven by the original cam of the engine, the motion state of the valve plunger can be changed to achieve the function of closing the valve in advance. By adjusting the opening and closing time of the throttle valve, the valve lift and closing time can be continuously variable.

2.2. Hydraulic Variable Valve Motion Characteristic Test Platform

The flexible variable valve motion characteristics test platform is shown in figure 2. The hydraulic variable valve mechanism is mainly composed of low pressure system, high pressure system, stepping motor control system, drive system, frequency conversion motor control system and lubrication system. The low pressure system is composed of low pressure oil pump, drive motor, relief valve, hydraulic meter and oil tank. Its function is mainly to replenish oil for high pressure system. The high-pressure system is mainly composed of a tappet piston group, a valve piston group, a throttle valve, a stepper motor control system, a seating buffer mechanism, and a related one-way valve. Its main function is to establish a high-pressure system pressure to complete the valve opening, and the valve closing later. The seating buffer mechanism is responsible for reducing the valve seating speed to make it sit smoothly. The drive system is composed of variable frequency motor, frequency converter and related transmission components, which is used to control the reverse drag speed. The lubrication system is composed of oil supply tank and oil return pump, which is used for the lubrication of camshaft.

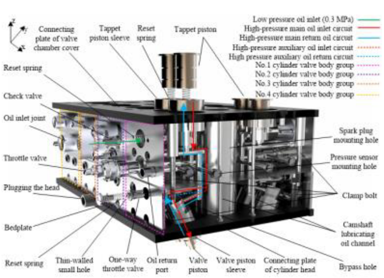

Figure 1. Independent research and development of hydraulic variable valve mechanism of four-cylinder engine.

Figure 2. Flexible variable valve motion characteristics test platform.

3. Analysis of Non-Uniformity of Intake Air in Cycle Cylinder Deactivation

3.1. Analysis of Intake Pressure Fluctuation

Under the condition of 1200 r/min and 20 Nm, the control strategy of 20 % cylinder stopping rate at the same cylinder stopping time is adopted to analyze the increase and decrease of intake manifold pressure caused by different cyclic cylinder stopping strategies. The intake pressure fluctuation and the intake valve lift curve of each cylinder are shown in figure 3. The cylinder stopping period of 20 % cylinder stopping rate is 5 cycles.

It can be seen from figure 3 that the intake pressure fluctuation is periodic, and each cycle includes 5 strokes. The maximum intake pressure is 0.92 bar, and the minimum intake pressure is 0.83 bar, with a difference of 0.09 bar. In the first cycle, with the opening of the intake valve of No.4 cylinder and No.2 cylinder, the intake pressure decreases evenly. After the intake valve of No.1 cylinder is closed, the intake pressure rises rapidly and reaches the maximum. The pressure change in the subsequent cycle is due to the opening or closing of the intake valve. By analyzing the strategy of 20 % cylinder deactivation rate when the cylinder deactivation time is the same, it is found that the intake air is stopped once every 5 strokes on average, and the time of each intake stop is the same, so the intake pressure appears in a cycle of 5 strokes, and the fluctuation of intake pressure in each cycle is the same. By analyzing other cylinder stopping strategies with the same cylinder stopping time, it is found that the cylinder stopping cycle of each cylinder is evenly distributed throughout the cycle because of the same cylinder stopping time, which can effectively reduce the fluctuation range and other fluctuations for the intake pressure.

As shown in figure 4, the intake pressure fluctuation of the 25 % cylinder deactivation rate strategy with different cylinder deactivation time is observed. The cycle of the 25 % cylinder deactivation rate strategy is 4 cycles. It can be seen that the intake pressure fluctuation also takes four cycles. The maximum is 0.94 bar, the minimum is 0.82 bar, and the difference is 0.12 bar. Compared with the 20 % cylinder deactivation strategy with the same cylinder deactivation time, the range of intake pressure fluctuation increases. The 25 % cylinder stopping rate strategy at different cylinder stopping times is analyzed. On average, the intake air is stopped once every 4 strokes, and each intake stop time is different. The order is 1-3-4-2, so the intake pressure fluctuation changes every small cycle, resulting in an increase in the fluctuation range.

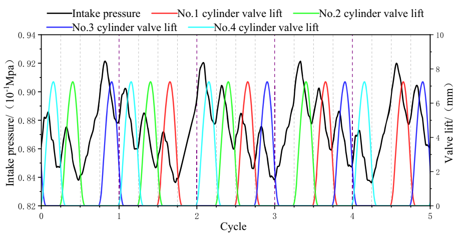

Figure 3. 20 % cylinder deactivation rate intake pressure.

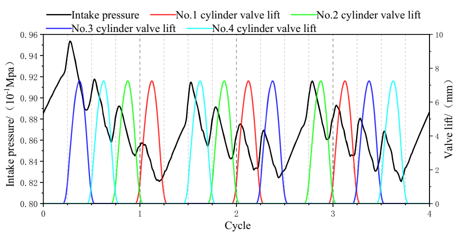

Figure 4. 20 % cylinder deactivation rate intake pressure.

Figure 5 is the intake pressure fluctuation comparison chart of 33 % cylinder deactivation rate strategy and 33 % cylinder deactivation rate strategy when the cylinder deactivation time is the same and the cylinder deactivation time is different. When the cylinder deactivation time is the same, the maximum intake pressure is 0.92 bar, the minimum intake pressure is 0.84 bar, and the difference is 0.08 bar; when the cylinder is stopped, the maximum intake pressure is 0.93 bar, the minimum intake pressure is 0.82 bar, the difference is 0.11 bar, and the fluctuation range becomes larger. From the diagram, it can also be found that the intake pressure takes three strokes as a small cycle when the cylinder stopping time is the same, and there is no obvious periodicity when the cylinder stopping time is different.

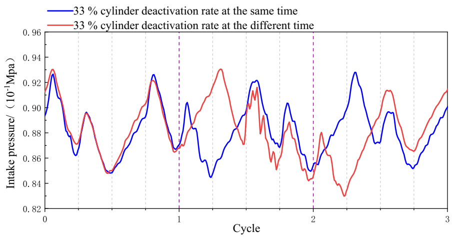

Figure 5. Comparison of intake pressure of different strategies with the same cylinder deactivation rate.

3.2. Analysis of In-cylinder Gas Quality

Under the condition of 1200 r/min and 20 Nm, the above 20 % cylinder deactivation rate control strategy is adopted to further analyze the change of in-cylinder gas mass under the change of intake pressure fluctuation during cyclic cylinder deactivation. As shown in figure 6 (A represents the intake stroke, B represents the compression stroke, C represents the expansion stroke, D represents the exhaust stroke), it can be seen from the diagram that the in-cylinder gas mass law of the four cylinders is the same, the order is 1-3-4-2, and the phase difference is 5 strokes. Specific analysis of 1 cylinder, the pink in the picture is the cylinder stop cycle. From a strategic point of view, 1 cylinder stops from the expansion stroke in the first cycle, and the gas in the cylinder is not discharged, so the gas quality in the cylinder is very large. In the next cycle, the intake and exhaust valves are opened and returned to normal. From the diagram, it can also be found that the gas mass in the cylinder increases slightly in the second cycle after the cylinder stop cycle of each cylinder, and the order is also 1-3-4-2.

Under the condition of 1200 r/min and 20 Nm, the above 25 % cylinder deactivation rate control strategy is adopted to analyze the change of in-cylinder gas quality under the fluctuation of intake pressure during cyclic cylinder deactivation. As shown in figure 7, pink is the one-cylinder cylinder deactivation cycle. It can be seen from the figure that compared with the same cylinder deactivation strategy at the time of cylinder deactivation, the in-cylinder gas quality of the 25 % cylinder deactivation rate strategy changes greatly, and the continuous low gas quality of one cylinder occurs. By analyzing the cylinder deactivation strategy, it is found that the cylinder 1 starts to stop at the upper dead center of the intake valve, so the in-cylinder gas quality is low. The cylinder stopping time of 2-cylinder, 3-cylinder and 4-cylinder are compression bottom to point, exhaust bottom to point and expansion top to point respectively. In the cylinder stopping cycle, the exhaust stroke is before the intake stroke, so this situation will not occur. The in-cylinder gas mass of the same strategy at the cylinder stopping time will not show a continuous lower state than that of different strategies at the cylinder stopping time, which is more uniform and stable.

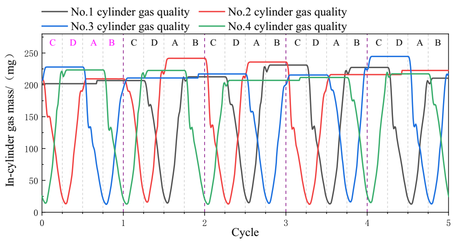

Figure 6. In-cylinder gas quality in 20 % cylinder deactivation rate.

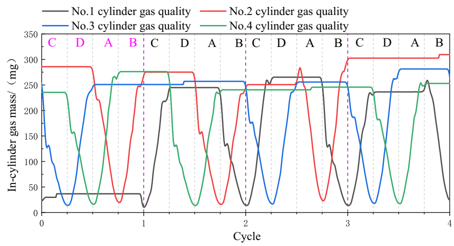

Figure 7. In-cylinder gas quality in 25 % cylinder deactivation rate.

3.3. Analysis of In-Cylinder Pressure

Under the operating conditions of 1200r/min and 20Nm, the in-cylinder pressure of No.1 cylinder with 20 % cylinder deactivation rate is shown in figure 8. Blue is the cylinder pressure, orange is the fuel injection volume per cycle, and pink and green are the intake and exhaust valve lifts, respectively.

Under the cycle stop strategy of 20 % stop rate. In the first cycle, the cylinder stops from the intake stroke to the exhaust stroke. The maximum cylinder pressure in the first cycle is 20.4 bar, which appears at the compression and intake TDC, and there is no fuel injection. In the second cycle, the intake air and fuel injection began to recover. At this time, due to the influence of the first cycle of cylinder deactivation, the intake air and fuel injection were less, so the cylinder pressure increased but did not fully recover. In the third cycle, the intake air and fuel injection continued to increase, and the cylinder pressure continued to increase. In the fourth and fifth cycles, the cylinder pressure fully recovered to 44.2 bar.

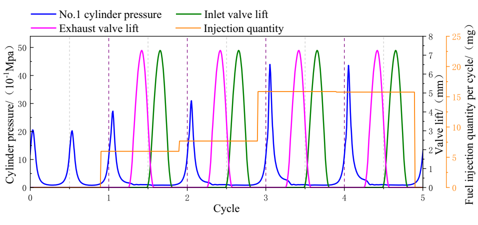

Figure 8. Cylinder pressure of No.1 cylinder under 20 % cylinder stopping strategy.

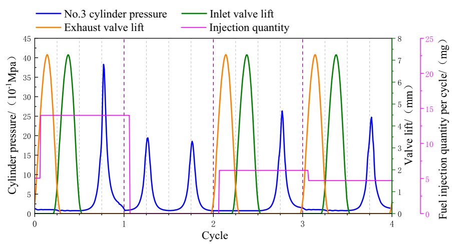

Figure 9. Cylinder pressure of No.3 cylinder under 25 % cylinder stopping strategy.

As shown in figure 9, under the operating conditions of 1200 r/min and 20Nm, the in-cylinder pressure of No.3 cylinder with 25 % cylinder deactivation rate and the No.3 cylinder with 25 % cylinder deactivation rate strategy start from the second cycle exhaust stroke to the expansion stroke. It can be seen in the figure that the maximum pressure in the cylinder is reduced to 19.6bar, the intake and fuel injection volume in the third cycle begin to increase, and the cylinder pressure is also increased accordingly. The cylinder pressure in the fourth cycle is slightly less, and the first cycle is greatly increased to 37.8bar, basically returning to normal cylinder pressure. Both strategies will have the problem of cylinder pressure fluctuation, and the cylinder pressure fluctuation of the two strategies is almost equal, and there is no obvious better one.

4. Analysis of Cycle Cylinder Deactivation Torque Fluctuation

The cyclic cylinder deactivation technology aims to temporarily close part of the cylinder at low load or idle speed during vehicle operation to reduce fuel consumption and emissions of the engine. However, this technology may cause torque fluctuations, that is, the torque output of the engine changes within a specific speed range. This torque fluctuation will affect the dynamic performance and driving experience of the vehicle to a certain extent.

4.1. Analysis of Torque Fluctuation under different Cylinder Deactivation Rates

According to the torque fluctuation data under different cylinder deactivation strategies in figure 10, it can be observed that the torque fluctuation of the engine increases with the increase of the cylinder deactivation rate. Specifically, at 20% cylinder deactivation rate, the maximum torque fluctuation is 428.1 Nm; at 33 % cylinder deactivation rate, the maximum torque fluctuation increases to 488.8 Nm. At 50% cylinder deactivation rate, the maximum torque fluctuation is further increased to 535.7 Nm. This trend indicates that a higher cylinder deactivation rate will lead to greater torque fluctuations, which may affect the stability of the engine and the smoothness of the power output. Therefore, in the design of the cyclic cylinder deactivation system, it is necessary to balance the relationship between the cylinder deactivation rate and the torque fluctuation to ensure that the engine can provide stable and reliable performance under different operating conditions.

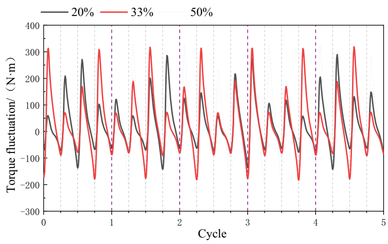

Figure 10. Torque fluctuation at different cylinder stopping rates.

4.2. Torque Fluctuation Analysis of different Cylinder Deactivation Strategies with the same Cylinder Deactivation Rate

Under the same cylinder stopping rate, different cylinder stopping strategies will also have different effects on torque fluctuation. For the cyclic cylinder deactivation strategy, different cylinders are deactivated in different cycles, resulting in different torque fluctuations. Cylinder stopping strategy usually includes different cylinder stopping modes and sequences, which will directly affect the torque output characteristics and stability of the engine. As shown in figure 11, under the 33 %

cylinder deactivation rate, the torque fluctuation under the two strategies of the same cylinder deactivation time and the different cylinder deactivation time can be seen from the diagram. The maximum torque fluctuation of the two strategies is not much different, and the specific fluctuation of each cycle is different.

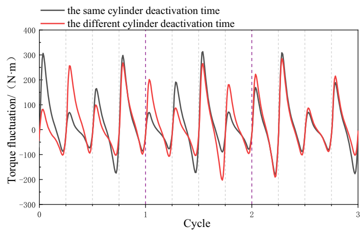

Figure 11. Torque fluctuation of different cylinder deactivation strategies under the 33 % cylinder deactivation rate.

Taking the same strategy of cylinder stopping time as an example, the influence of cylinder stopping strategy on torque fluctuation is analyzed. The torque mainly comes from the expansion stroke of each cylinder, and the cylinder stopping sequence of the expansion stroke is analyzed emphatically. As shown in table 1 (C1 represents the expansion stroke of No.1 cylinder, C2 represents the expansion stroke of No.2 cylinder, C3 represents the expansion stroke of No.3 cylinder, C4 represents the expansion stroke of No.4 cylinder), the number and sequence of cylinder stopping in each working cycle under this strategy can be seen. Stop once every two strokes, which is consistent with the torque diagram. Compared with different strategies at the stopping time, the strategy has more obvious periodicity and smaller overall fluctuation.

Table 1. The 33 % deactivation rate strategy when the stopping time is the same.

Cycle 1				Cycle 2				Cycle 3			
C1	C3	C4	C2	C1	C3	C4	C2	C1	C3	C4	C2

As shown in figure 12, the torque fluctuations under the two strategies of the same cylinder stopping time and different cylinder stopping time at 50 % cylinder stopping rate. It can be seen from the figure that the maximum torque fluctuations of the two strategies are not much different, and the specific fluctuations of each cycle are different. According to the analysis and restraint of the above two strategies, the expansion stroke of the cylinder stopping strategy with the same cylinder stopping time is more dispersed and has less influence on the torque fluctuation.

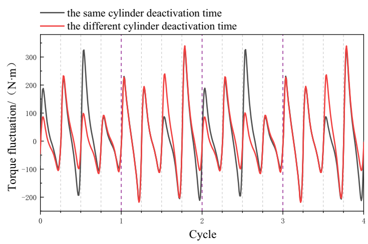

Figure 12. Torque fluctuation of different cylinder deactivation strategies under the 50 % cylinder deactivation rate.

5. Energy Conservation Analysis of Cycle Cylinder Deactivation

5.1. Energy Conservation Analysis of different Cylinder Deactivation Rates

As shown in figure 13, under the operating conditions of 1200 r/min and 20Nm, the proportion of various energy of the engine without cylinder stopping and different cylinder stopping rates, the fuel injection volume per cycle of the working cylinders under normal working condition, 20 % cylinder stopping rate, fixed one cylinder stopping rate, 33 % cylinder stopping rate and 50 % cylinder stopping rate are 6.21 mg, 7.77 mg, 8.47 mg, 9.32 mg and 12.42 mg, respectively. It can be seen from the diagram that with the increase of the cylinder deactivation rate, the exhaust loss increases, the heat transfer loss decreases, the other losses increase, and the effective work increases. This is because the increase of the cylinder stopping rate means that the number of cylinders working at the same time is reduced. The same as the fixed cylinder stopping law, the less the working cylinder, the smaller the heat transfer area and the smaller the heat transfer loss. At the same time, it is necessary to keep the torque constant, the throttle opening becomes larger, the intake fuel injection of the working cylinder increases, and the combustion temperature becomes higher, so the exhaust loss increases, the other losses increase, and the effective work increases.

As shown in figure 14, the average pressure index of the engine under different cycle stop rates at 1200 r/min and 20Nm operating conditions. It can be seen from the figure that the IMEP gap is very small, and basically does not change with the cylinder stop rate. This is because the torque is equal, and the average indicated pressure is basically equal. FMEP increases with the increase of cylinder deactivation rate, which is because the gas combustion pressure in the working cylinder increases with the increase of cylinder deactivation rate. Although the cylinder pressure in the non-working cycle decreases, the friction loss caused by the increase of gas combustion pressure is greater, which makes the sum of FMEP increase. PMEP decreases with the increase of cylinder stopping rate, which is the same as the fixed cylinder stopping law. The less the cylinders working at the same time, the larger the throttle opening, and the smaller the PMEP.

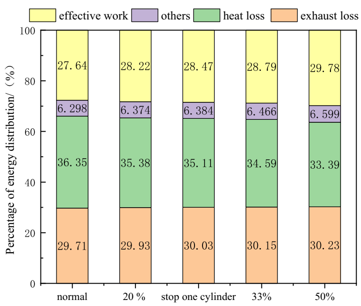

Figure 13. The proportion of engine energy with different cylinder deactivation rates.

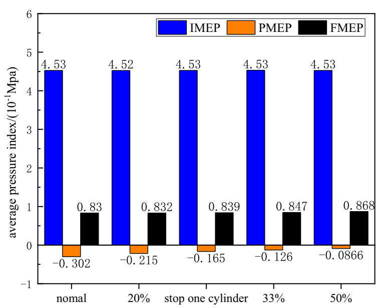

Figure 14. The average pressure index of the engine under different cycle stop rates.

At 1200 r/min and 20Nm operating conditions, the proportion of various energy of the engine at different speeds at a cycle stop rate of 20 % is shown in figure 15. 1200 r/min, 1600 r/min, 2000 r/min, 2400 r/min, 2800 r/min, 3200 r/min, 3600 r/min working cylinder fuel injection per cycle were 7.77 mg, 8.12 mg, 8.32 mg, 8.67 mg, 8.97 mg, 9.61 mg and 9.88 mg. It can be seen from the diagram that with the increase of rotational speed, the exhaust loss increases, the heat transfer loss decreases, the other losses increase, and the effective work decreases as a whole. Because under the condition of constant torque, as the engine speed increases, the combustion temperature in the cylinder increases, the exhaust temperature and exhaust volume increase, the exhaust loss and other losses increase, the corresponding heat transfer loss decreases, and the effective work decreases.

Under the operating conditions of 1200 r/min and 20Nm, the average pressure index of the engine at different speeds with the same cylinder stop rate is shown in figure 16. It can be seen from the figure that IMEP increases with the increase of rotational speed. This is because when the low-speed torque is constant, the gas pressure generated by each combustion can be better converted into engine output power. FMEP increases with the increase of rotational speed, which is because the mechanical friction loss occupies a large proportion at low rotational speed, and increases with the movement of the piston in the cylinder. The sum of FMEP is increased. PMEP increases with the increase of rotational speed, which is the same as the fixed cylinder stopping rule, because higher rotational speed means more intake and exhaust processes, which increases the pumping loss.

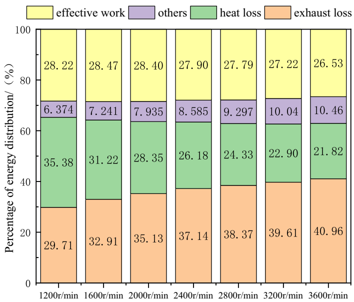

Figure 15. The proportion of engine energy with the same cylinder stop rate and different speed.

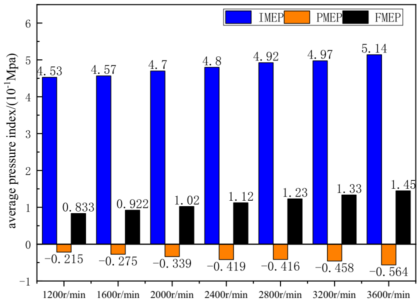

Figure 16. The average pressure index of the engine at different speeds with the same cylinder deactivation rate.

5.2. Energy Conservation Analysis of different Cycle Deactivation Strategies

The energy conservation analysis of different cycle stopping strategies will also be different. Different stopping modes will lead to different ways of fuel utilization in the cycle process, which will affect the results of energy conservation analysis. It will also change the flow characteristics in the cylinder, including gas inlet and outlet speed, vortex structure and so on. These changes will affect the combustion process and thermal energy conversion efficiency, thus affecting the results of energy conservation analysis. Heat transfer and exhaust system: Different cylinder deactivation strategies may affect the working mode of the exhaust system and the cooling system, which in turn affects the heat transfer and loss. These differences will also be reflected in the analysis of energy conservation. Therefore, this section analyzes the energy conservation of different cylinder stopping strategies.

Under the operating condition of 1200 r/min and 20 Nm, the proportion of various energy of the engine with the same cylinder stopping rate and different cylinder stopping strategies is shown in figure 17. From the figure, it can be seen that the effective work and other losses of the same strategy at the cylinder stopping time are not much different from those of different strategies at the cylinder stopping time, but the heat transfer loss increases and the exhaust loss decreases. This is because the strategy stops the cylinder in a relatively uniform order, the cylinder temperature drops less, the heat transfer loss is larger, and the exhaust loss is smaller.

Under the operating conditions of 1200 r / min and 20Nm, the average pressure index of the engine with the same cylinder deactivation rate and different cylinder deactivation strategies is shown in figure 18. It can be seen from the figure that the IMEP gap is very small, basically does not change with the cylinder stop rate, because the torque is equal. The same strategy FMEP is larger and PMEP is smaller, which is also because the strategy stops the cylinder more evenly, the intake pressure fluctuation is smaller, and the PMEP is smaller. At the same time, the combustion temperature is higher and the FMEP is larger.

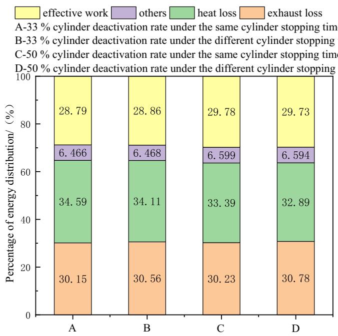

Figure 17. The proportion of various energy of the engine with the same cylinder deactivation rate and different cylinder deactivation strategies.

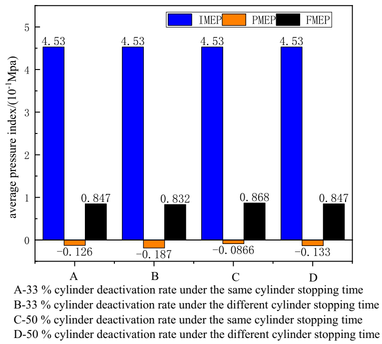

Figure 18. The average pressure index of the engine with the same cylinder deactivation rate and different cylinder deactivation strategies.

6. Conclusions

In this paper, aiming at the problem of torque fluctuation and intake pressure fluctuation caused by cyclic cylinder deactivation, the engine characteristics based on cyclic cylinder deactivation are studied, and the energy analysis under different cyclic cylinder deactivation strategies is carried out. The main contents are summarized as follows:

(1) The fluctuation of the intake pressure of the cycle stop cylinder is analyzed. The closing of the intake valve in each cylinder stop cycle will lead to a surge in the pressure of the intake manifold.

(2) The cyclic cylinder stopping will increase the torque fluctuation. The maximum torque under the 20 % cylinder stopping rate strategy is about 132 % larger than that without cylinder stopping. With the increase of cylinder stopping rate, the number of cylinder stopping increases, and the fluctuation range of torque increases.

(3) Under the same cylinder deactivation rate and different strategies, the effective work and other losses of the same strategy at the cylinder stopping time are not much different from those of different strategies at the cylinder stopping time, but the heat transfer loss increases and the exhaust loss decreases.

Acknowledgments

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