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Analysis of Characteristics of CI/HCCI Chemical Combustion Mode Switching of Automotive Engine

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In view of the problems appearing in cylinder average index pressure and the operating smoothness in the direct switching process of CI/HCCI chemical combustion mode in the cylinder of diesel engine, the injection compensation measures are drawn up for CI/HCCI direct switching to improve the average index pressure fluctuation, and the influence of injection compensation coefficient, transitional cycle number, fuel injection quantity and other parameters on CI/HCCI chemical combustion mode switching process analyzed. The conclusions are as follows. The CI/HCCI chemical combustion mode switching in the cylinder will lead to slow heat release in the cylinder, resulting in higher IMEP fluctuation ratio. The IMEP fluctuation ratio is the highest when the HCCI mode of the lower load zone is switched to the CI mode. The first cycle of cylinder using fuel injection compensation can improve the stable operation of the engine. IMEP fluctuation ratio is the lowest when fuel injection compensation coefficient is 1.06. The IMEP fluctuation ratio is the lowest, when the number of transition cycles is 2-3, as the fuel injection slightly lower than the linear decrease can improve the operating smoothness, and effectively reduce the emissions of NOx and particulates in tail gas.

1. Introduction

The worsening global climate and the consumption of non-renewable energy have become a worldwide problem. The automobile industry is also facing energy saving and emission reduction, improvement of the utilization rate of automobile energy, and other urgent tasks.
Compared with gasoline engine, diesel engine has the advantages of high fuel utilization and high torque. But its Compression Ignition (CI) characteristics make it obviously inferior to the gasoline engine, as it does not meet the automobile exhaust emission standards. Therefore, the reduction of NOx (NO1 and NO2) and Particulate Matter (PM) in exhaust emissions is an urgent problem to be solved for diesel engines (Ganesh et al., 2008; Singh and Agarwal, 2012; Yanagihara et al., 1997; Reitz, 2013).
At present, the improvement of the combustion mode of diesel engines is mainly achieved through fuel mixture, including gasoline / diesel dual fuel, gasoline/diesel mixture, low octane / high octane gasoline, etc. (Shi and Reitz, 2010; Youngchul et al., 2009; Yang et al, 2013). At the same time, researchers also improve the combustion efficiency of fuel by controlling the injection pressure, ERG, boost pressure, intake air temperature and other parameters in the diesel engine (Walter and Gatellier, 2006; Su et al, 2006; Gan et al., 2011).
Homogeneous Charge Compression Ignition (HCCI) is an effective technique to reduce the fuel consumption and pollutant emissions of diesel engines in recent years (Ganesh and Nagarajan, 2010; Bendu and Murugan, 2014; Yao et al., 2009), but it also inherently has flaws, as it burns unsteadily and it can hardly cover the operation of the whole engine. Some researchers have proposed to use CI/HCCI switching technology to solve the above problems of HCCI. That is to say, when the engine load is low, the HCCI combustion mode is selected, and the CI mode is selected when the load is high. However, CI/HCCI switching technology is not yet mature, and there are still many problems to be solved (Bunting et al, 2007; Lu et al., 2011; Kalghatgi and Hildingsson, 2011; Yang et al, 2013).
In view of the problems appearing in cylinder average index pressure and the operating smoothness in the direct switching process of CI/HCCI chemical combustion mode in the cylinder of diesel engine, the injection compensation measures are drawn up for direct switching of CI/HCCI to improve the average index pressure

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fluctuation, and the influence of injection compensation coefficient, transitional cycle number, fuel injection quantity and other parameters on CI/HCCI chemical combustion mode switching process analyzed.

2. Experimental device and experimental scheme

As shown in Figure 1, the experimental system mainly consist the central controller, I / O timer card, drive circuit, charge amplifier, intake and exhaust ports and other components. The diesel engine selected for the experiment is a single cylinder direct injection with a total of 4 valves, 6 injectors, and injection pressure of 80MPa. The experiment adopts high pressure common rail fuel injection device, with adjustable injection time, frequency and fuel quantity. The diesel engine has two combustion modes, CI and HCCI, which can be used to change the Indicated Mean Effective Pressure (IMEP) as the environment or experiment requires, and the control parameters such as EGR in the switching process are constant. With the first cycle fuel injection rate, fuel injection compensation coefficient and fuel injection cycle times taken as experimental objects, the switching stability of CI and HCCI of diesel engine are evaluated by using δIMEP, the fluctuation ratio. Its expression is as follows.

$$\delta_{\mathrm{IMEP}} = \frac{\mathrm{IMEP}_{\max} - \mathrm{IMEP}_{\min}}{\mathrm{IMEP}_{\max} + \mathrm{IMEP}_{\min}} \times 100\% \tag{1}$$

MEPmax and IMEPmin are the maximum and minimum IMEP respectively during the switching process from CI mode to HCCI mode.

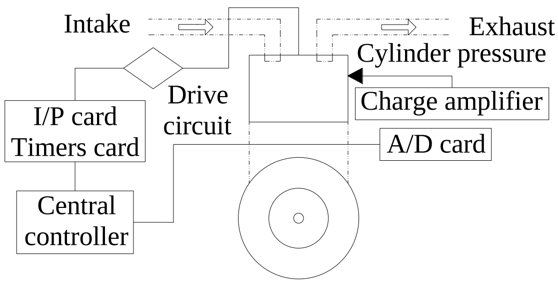

Figure 1: Experimental system of CI/HCCI mode switch

3. Analysis of chemical combustion characteristics

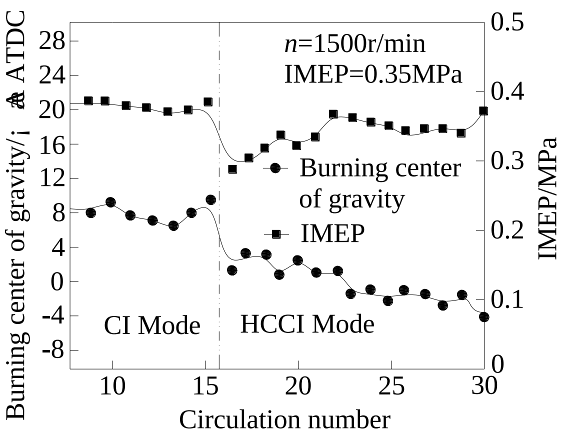

Figure 2: IMEP fluctuation of CI/HCCI mode direct switching

The fluctuation of the combustion center of gravity and the heat release rate of the average index cylinder pressure in the direct switching of the CI/HCCI in the diesel engine are as shown in Figure 2. It can be seen from the figure that when the mode is switched, a low-temperature heat release occurs in the engine, and there is big difference between the initial heat release rate and the post-heat release rate. The fuel injection ahead of time brought by HCCI mode result in the changes in combustion center of gravity, which gradually stabilizes until 8 times of the cycle. IMEP is significantly reduced, as the incomplete fuel combustion occurs due to lower engine load, lower temperature and the incomplete fuel evaporation. When the interior of the engine gradually transfers to HCCI mode, the fuel combustion and IMEP output are basically stable, and the overall fluctuation ratio of IMEP is about 14%.

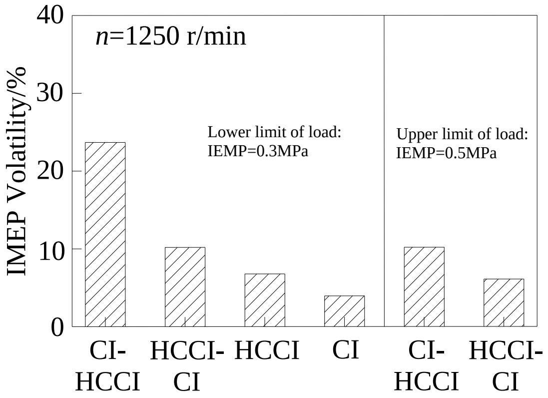

Figure 3: IMEP fluctuation ratio in different combustion of CI/HCCI mode direct switching

Figure 3 shows the comparison of ride stability during direct CI/HCCI direct mode switching in diesel engines. HCCI is only effective in the middle and lower load zone, and the CI/HCCI mode switch is essentially the switch between the lower load zone and the upper load zone. There is a CI-HCCI mixing zone between the two zones. In fact, there are CI mode, CI-HCCI switching mode, HCCI-CI switching mode and HCCI mode in the engine. As shown in Figure 3, the IMEP fluctuation ratio is the largest and the operating smoothness is the worst in the lower load area, followed by HCCI-CI, HCCI and CI-HCCI. The IMEP fluctuation ratio of CI is the smallest, and the IMEP fluctuation ratio of CI-HCCI in the upper load area is greater than that of HCCI-CI. The mode switching operating smoothness of load upper limit is better than that of the load lower limit. This is because the HCCI mode has higher requirements for the combustion environment, and the environment in the engine cylinder is easily changed when the combustion mode is switched to the lower load zone, resulting in the deterioration of the combustion, higher IMEP fluctuation ratio and other unfavorable situations.

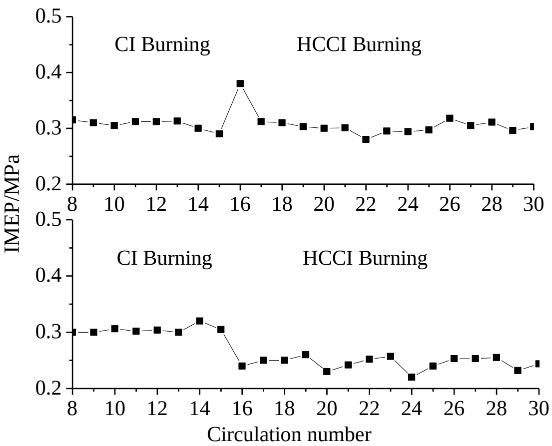

Figure 4: IMEP change with different fuel compensation coefficient

In the process of CI/HCCI mode switching, the IMEP can be effectively reduced by increasing the fuel injection quantity in the cylinder, thus increasing the stability of the CI/HCCI mode switching. The upper and lower diagrams in Figure 4 show the IMEP changes with the fuel injection compensation coefficient of 1.13 and without fuel injection compensation, respectively. As can be seen from the figure, when the compensation coefficient is 1.13, both the IMEP and the heat release rate in the HCCI combustion mode are higher, and the concentration of the mixed gas gradually increases, leading to a gradual advance of the combustion phase. Fuel injection compensation can help to improve incomplete fuel evaporation and unstable combustion in the cylinder, and other phenomena.

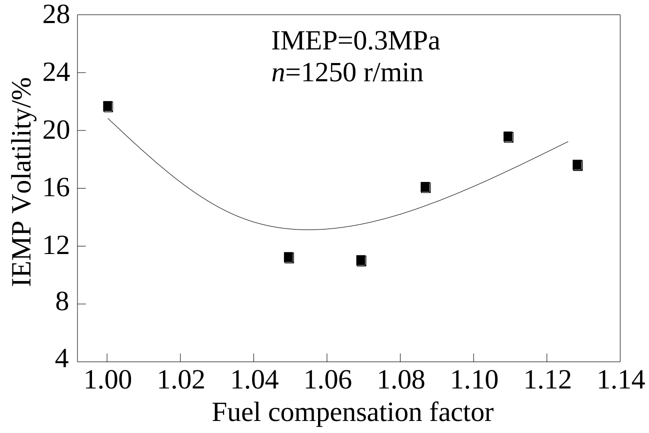

Figure 5: Relationship curve of IMEP fluctuation ratio and fuel compensation factor

The relationship between the different fuel injection compensation coefficients and the IMEP fluctuation ratio is shown in Figure 5. It can be seen from the figure that the fluctuation ratio of IMEP in the cylinder first increases and then decreases with the increase of the compensation coefficient. The fluctuation ratio in the cylinder reaches the minimum, when the coefficient of compensation is about 1.06. Compared with CI/HCCI direct switching in the lower load area, the fluctuation ratio of IMEP can be reduced by 46.8% using the fuel injection with a compensation coefficient of 1.06.
The transition cycle will affect the IMEP stability after the mode switching in the cylinder. Generally, when the number of transition cycles is 2-3, the fluctuation ratio of IMEP is the lowest, it is higher when the number of transition cycles is 0-1 times and 3 times or more. The curve of the relation between the number of cylinder cycles and fuel injection compensation coefficient when the quantity of fuel injection is reduced in different ways is shown in Figure 6. There are 5 cases where the fuel injection quantity of the first and final cycles in the cylinder is the same. As can be seen from the figure, the fuel injection compensation coefficient of the concave curve is smaller, but because of the large decrease of IMEP in its second cycle, the fluctuation ratio of IMEP will also increases. However, the reduction of fuel injection through arithmetic way will result in the lowest IMEP fluctuation ratio and the most stable operation.

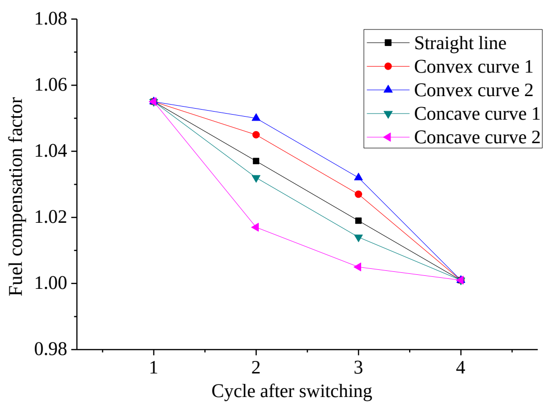

Figure 6: Fuel compensation rates of different curve form

The IMEP fluctuation ratio of the cylinder when the fuel injection quantity decreases in different ways is as shown in Figure 7. The abscissa 1-5 represents straight lines, convex curves 1 and 2, concave curves 1 and 2, respectively. As can be seen from the figure, the IMEP fluctuation ratio is the lowest, about 6.4%, at the concave curve 1, a decrease of 72% compared with the CI/HCCI direct switching, followed by the IMEP fluctuation ratio at the straight line, which is 8.3%. This is because there is a large step length in fuel injection quantity in the first cycle of the cylinder and more residual oil in the cylinder, so the stability is higher.

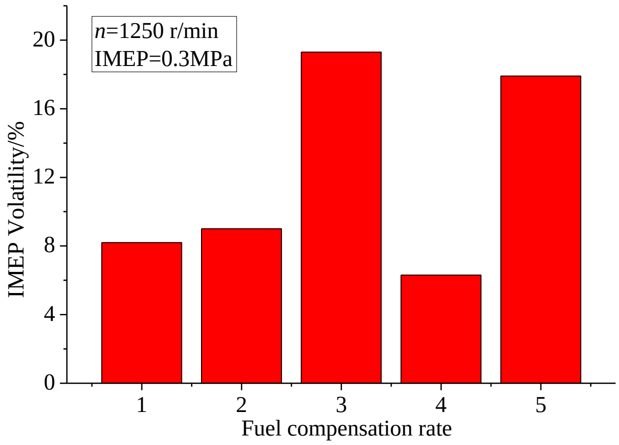

Figure 7: Relationship curve of IMEP fluctuation ratio in combustion switching and fuel compensation rate

4. Conclusions

In view of the problems appearing in cylinder average index pressure and the operating smoothness in the direct switching process of CI/HCCI chemical combustion mode in the cylinder of diesel engine, the injection compensation measures are drawn up for direct switching of CI/HCCI to improve the average index pressure fluctuation, and the influence of injection compensation coefficient, transitional cycle number, fuel injection quantity and other parameters on CI/HCCI chemical combustion mode switching process analyzed. The research conclusions are as follows.

(1) The CI/HCCI chemical combustion mode switching in the cylinder will lead to slow heat release in the cylinder, resulting in higher IMEP fluctuation ratio. The IMEP fluctuation ratio is the highest when the HCCI mode of the lower load zone is switched to the CI mode.

(2) The first cycle of cylinder using fuel injection compensation can improve the stable operation of the engine. IMEP fluctuation ratio is the lowest when fuel injection compensation coefficient is 1.06.

(3) The IMEP fluctuation ratio is the lowest, when the number of transition cycles is 2-3, as the fuel injection slightly lower than the linear decrease can improve the operating smoothness, and effectively reduce the emissions of NOx and particulates in tail gas.

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