COLD START CHARACTERISTICS STUDY BASED ON REAL TIME NO EMISSIONS IN AN LPG SI ENGINE

by

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Normally, cylinder pressure was used as a criterion of combustion occurrence, while in some conditions, it may be unreliable when identifying lean mixture combustion. This is particularly important for fuels like liquefied petroleum gas, which has good capacity for lean combustion. In this study, a fast response NO detector, based on the chemiluminescence method, was used to measure real time NO emissions in order to evaluate the technique as a criterion for establishing combustion occurrence. Test results show that real time NO emissions can be used to identify the cylinder combustion and misfire occurrence during engine cranking, and real time NO emissions can be used to understand the combustion and misfire occurrence. Real time NO emissions mostly happened in first several cycles during cold start, and NO emissions increased with the spark timing advancing.

Key words: *liquefied petroleum gas, spark ignition engine, cold-start, the first firing cycle, NO emissions*

Introduction

Nowdays, demands for emission reduction of the vehicle became very urgent which lead to stricter emission regulation. The cold start emission at –7 °C environmental temperature was required in the Europe and the USA emission regulation [1]. The research shows that 50%~80% HC and CO emissions was produced during the cold start [2, 3]. Since the 1990s, many researches about HC emissions during the cold start were carried out of China. Recently, the similar research was carried on in China. Professor Huang [4, 5] *etc*. studied the HC emissions and their influencing factors during cold start. Yong [3, 6] *etc*., combined with study of the light off characteristic of the three-way-catalytic converter, studied the emissions and affecting factors during cold start and warm-up.

Those studies show that the excess air coefficient was the key parameter for the first firing cycle (FFC) during cold start. The mixture concentration being too rich or too lean will increase the HC emissions of the FFC during cold start sharply. Therefore, the main object was to optimize the excess air coefficient in the FFC during cold start. HC emissions were one of the judgments for the optimum mixture concentration. While, study of HC emissions were not

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enough to monitor formation of the mixture, combustion in the cylinder and the creation of emission in details on spark ignition (SI) engine. The real time NO emissions can judge whether the combustion in cylinder happened or not because NO emissions come out with combustion and increasing with the combustion temperature. Therefore, the real time NO emissions were another judgment for the optimization of the excess air coefficient except for cylinder pressure and HC. The study about the real time NO emissions started firstly by Peckham [7, 8] . He studied the real time NO emissions emitted from the cylinder and exhaust valve on SI engine equipped with the real time NO detection. Hands [9] studied the real time NO, CO, and HC emissions during the first 505 seconds of the FTP75 on four cylinders SI engine. So far, no paper were puplished about the real time NO emissions during cold start.

Equipments and test methods

The study was done in a four-stroke air-cooled port fueled injection SI single cylinder engine fueled with LPG (engine parameters are shown in tab. 1). A single injector was equipped on the intake port. The LPG was injected at gas phase on 0.14 MPa constant pressure. The rotation encoder of CHA-1 and Kistler6125b cylinder pressure (connected with WDF-3 charge amplifier) was equipped on the engine. The measurement resolution of cylinder pressure was 1 °CA. The test was done at the condition of 20 °C ambient temperature, standard atmosphere and 12 V battery voltage.

Table 1. The specifications of test engine

Maximum power	7.3 kW at 73 kW at 8500 rpm
Maximum torque	8.7 Nm at 8500 rpm
Cylinder diameter	56.5 mm
Stroke	49.5 mm
Compressive ratio	9.2

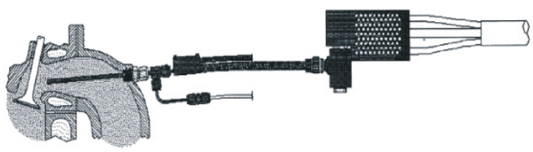

Figure 1. The location of the sample head

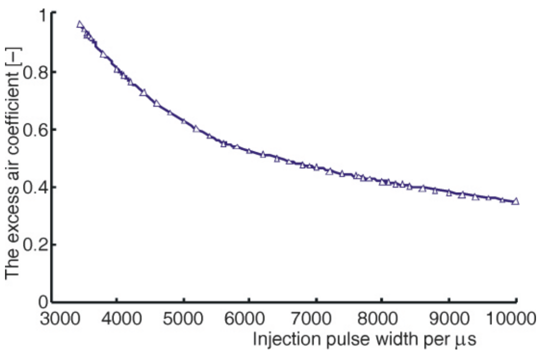

Figure 2. The relationship between fuel pulse time and excess air coefficient

The real time analysis and measure instrument – CombustionfNOx400 was used to test the NO emissions of the FFC during cold start. Compared with the traditional electronic chemistry methods, the response time of NO was shortened apparently by CombustionfNOx400. The response time for real time NO was about 4 ms. The position of NO probe was near the exhaust valve (fig. 1). The NO emissions signal, crankshaft rotation angle signal (CHA-1), cylinder pressure (Kistler6125b), and engine running parameter (the water and cylinder temperature, throttle open postion) were measured by the real time data acquisition system.

The research was carried out based on the cycle by cycle analysis of the first firing cycle during the cold start. The piston of the single cylinder engine usually stops before the compression top dead center (TDC). At that time, the intake valve closed, the fuel injection at that time will enter the cylinder in the next cycle. Therefore the first firing cycle in theory was the next cycle of the first injection happened with cranking, *i. e*. the second cycle during cold start. It was named as injecting then firing. In the first cranking cycle, fuel quantity of injection and the ignition advance angle was controlled by software. The real time data of engine parameters were measured by the high speed data acquisition system. The LPG injector was produced by KEIHIN. The relationship between injection pulse width and the excess air coefficient was shown in fig. 2.

Test results and analysis

The judgment of the firing during the cold start

Figure 3 shows the engine characteristic using 2.2 ms injection pulse width during cold start. From fig. 2, the excess air coefficient corresponding to that injection pulse width was a little bigger, which means the mixture concentration was very lean. Although each cycle had one time fuel injection, the mixture concentration was not increased immediately. The engine did not fire until the 5th cycle when cranking. The cylinder pressure and simultaneous crankshaft speed after combustion increased obviously compared to the other cycle. The real time NO increased to more than 1200 ppm, the peak value of cylinder pressure was 4 MPa, and speed was nearly 1600 rpm. Because of the leaner mixture, the following cycle misfired which can be judged by the cylinder pressure, speed, and NO emissions.

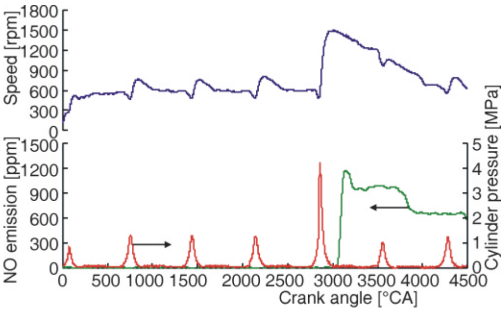

Figure 3. Cold start characteristic of continuous lean fuel injected

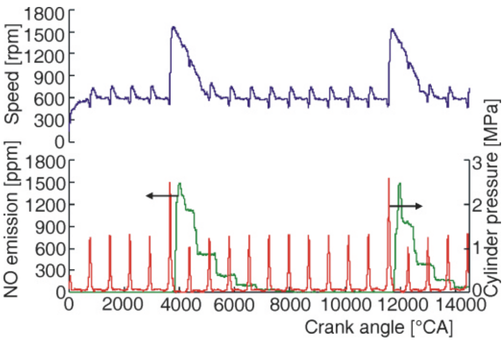

Figure 4. Transient characteristics of the engine during the special cold start

The fuel injection can be set on the defined cycle by engine control unit. As shown in fig. 4, the fuel was injected only in the 5th and 6th cycle during the cold start; the other cycle was cranking cycle with starter motor without fuel injection. Because the fuel was injected into the inlet air port before the compression TDC, the mixture can not enter into cylinder immediately but in the following cycle. Therefore, the engine fired in the 6th and 17th cycle after the injection in the 5th and the 16th cycle. Figure 4 shows the real time NO emission, the cylinder pressure, and the speed increased rapidly in the certain cycle. The two different firing cycles had almost 2.5 MPa peak value of cylinder pressure, and engine speed is greater than 1500 rpm. For two firing cycles, the real time NO emissions increased from 0 to 1500 ppm rapidly. Since no fuel injection in the following cycle, the speed and cylinder pressure in the cycle next to the two firing cycles drop quickly, and the real time NO emissions decreased gradually. It was seen that the residual NO in the cylinder dropped step by step, finally became zero.

The judgment of misfiring cycle during cold start

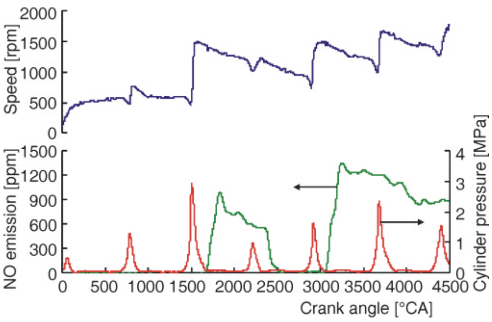

Figure 5. Characteristics of NO emissions for the misfiring cycle during cold start

Figure 5 shows that the engine speed, cylinder pressure, and the real time NO emissions change with the constant injection pulse width. That constant pulse width is shorter than normal which means the mixture fuel is lean. It shows that the first two dragging cycle fail to fire. It can be seen from lower cylinder pressure and cranking speed. Because no combustion, the NO emissions did not increase. Although there was no combustion in the first two cycles, the fuel mixture concentration became higher because of the residual fuel. It led to the firing in the third cycle. The corresponding peak value of cylinder pressure increased to 3 MPa, the speed increased to 1500 rpm and NO changed greatly to 1000 ppm. The 4th cycle misfired because of the lean mixture again. The NO emission dropped quickly, the cylinder pressure and speed decreased as well. The 1st firing cycle increased the cylinder temperature, made the combustion condition better. Therefore, the engine fired successfully after the 5th cycle. From fig. 5, the NO emission in the 5th cycle increased sharply. Compared with the 5th cycle, the NO emissions decreased obviously in the 6th cycle. It shows that the NO emission decreased when engine runs smoothly in idle. At that time, engine did not need too much fuel to sustain the combustion and combustion temperature decreased. Whether the combustion is successful or not can be judged clearly based on the real time NO emissions (fig. 5).

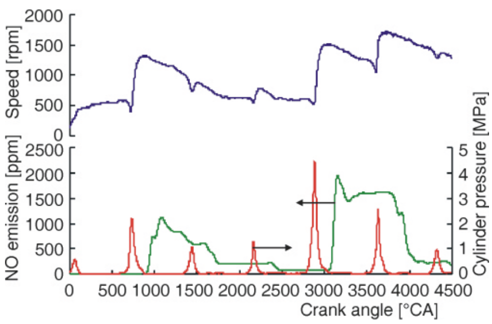

Figure 6. Characteristics of NO emissions for the misfiring cycle during cold start

Figure 6 shows the same curve as fig. 5. But the injection pulse width increased 100 ms compared with fig. 5. The engine succeed to fire in the 2nd cycle, the peak value of cylinder pressure exceeded the 2 MPa, the speed increased to 1400 rpm, the real time NO emission increased greatly from 0 to 1200 ppm. Due to the lean mixture, the 3rd and 4th cycle misfired after the 2nd cycle. The NO emissions decreased gradually. The 5th cycle had a violent firing. In that cycle, the peak value of cylinder pressure increased to 4.5 MPa rapidly, the NO emissions increased greatly to 2200 ppm, the speed increased to 1500 rpm. The 6th cycle belonged to the stable combustion cycle. The cylinder pressure decreased a little compared with the former cycle. The NO emissions had a small peak value before the opening of the exhaust valve. But the lean mixture made the unstable combustion and misfiring in the 7th cycle.

The characteristics of the real time NO emissions during cold start

The main quantity of the real time NO emissions came out in the 1st several cycles during cold start. The NO emissions decreased gradually in the following cycle. Because of the worse combustion condition during cold start, the richer mixture concentration was used for the 1st several cycles to make sure of the successful combustion. At that time, the cylinder pressure and combustion temperature increased sharply which lead to greats of NO emissions. When engine run smoothly in idle, the engine need less combustion heat to sustain as the 1st several cycles of cold start. The combustion heat and NO emissions decreased gradually. Figure 7 shows that the instantaneous crankshaft rotation speed, cylinder pressure, and the NO emissions when the excess air coefficient was 0.78 in the 1st cycle (using the same injection pulse width and ignition advance angle in the following cycle). As shown in figure, with the successful firing in the 1st cycle, the engine speed increased to 1500 rpm rapidly and was stable around the idle speed in the following cycle. The cylinder pressure increased to 4.4 MPa with the successful firing and decreased gradually in the following stable combustion. When the exhaust valve open in the 1st cycle, the real time NO emissions increased rapidly to 2200 ppm. It shows that the combustion temperature in the cylinder increased greatly which lead to a lot of NO emissions. Following the successful cold start, the cylinder pressure and engine speed come to stable, the NO emissions decreased. Because of the fast changing of the excess air coefficient and higher temperature in cylinder in the 1st several cycles, the NO emissions increased rapidly. That phenomenon was very similar to acceleration process. The rule can be found to optimize the combustion and reduce the real time NO emissions.

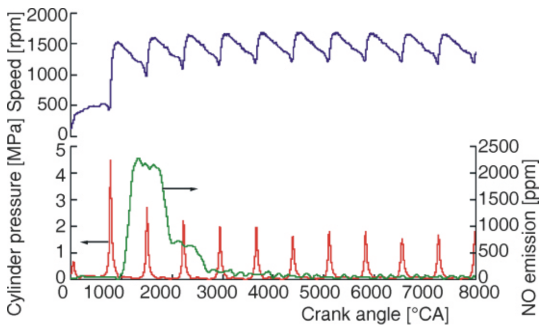

Figure 7. Transient characteristics during cold start

Figure 8 shows the real time NO emissions *vs*. the ignition advance angle at the 1st cycle. The excess air coefficient was 0.78 at the 1st cycle. The ignition advance angle was 20 °CA bTDC, 15 °CA bTDC, and 10 °CA bTDC at the 1st cycle. The following cycle had same ignition advance angle and fuel injection quantity. Only the real time NO emissions were shown in fig. 8, not including the cylinder pressure and engine speed curve corresponding to those three ignition advance angle. The engine had successfully stable idle after cold start (fig. 8 similar to fig.7). The NO emissions mainly came out from the early period of cold start (fig. 8). The NO emissions decreased gradually with the stable idle speed. After exhaust valve open at the first cycle, the real time NO emissions increased greatly in all three ignition advance angles. The 20 °CA bTDC had the highest peak value of NO emissions (2500 ppm). NO emissions at 15 °CA bTDC and 10 °CA bTDC are 2200 ppm and 2000 ppm, respectively. With the same fuel injection at the 1st cycle, the NO emissions increased with advancing of the ignition advance angle. The NO emissions in the following cy-

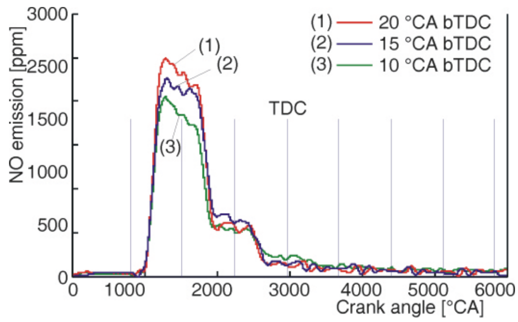

Figure 8. Variation in real time NO emissions during the cold start with the spark timing of the 1st firing cycle

cles decreased gradually and were almost same because of the same ignition advance angle and fuel injection quantity.

Conclusions

- Because the NO emissions coming out together with combustion, the real time NO emissions can be used as the criterion for the firing cycle during cold start.
- This test proved that the real time NO emissions can be used as the criterion for misfiring cycle during cold start because of no combustion in the misfiring cycle.
- Because the worse combustion condition, a richer mixture was used in the 1st several cycles to make sure the successful cold start. The real time NO emissions were mainly produced in the first several cycles during cold start, decreased gradually in the following cycles when engine speed came to stable.
- When the mixture concentration keeps constant during cold start, the real time NO emissions increased with the advancing of the ignition advance angle.

Acronyms

bTDC – before top dead centre
FFC – first firing cycle
LPG – liquid petroleum gas
TDC – top dead centre

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