International Journal of Automotive Technology, Vol. 8, No. 4, pp. 437–444 (2007)

1229–9138/2007/035–06

INVESTIGATION OF RUNNING BEHAVIORS OF AN LPG SI ENGINE WITH OXYGEN-ENRICHED AIR DURING START/WARM-UP AND HOT IDLING

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(Received 31 August 2006; Revised 9 July 2007)

ABSTRACT–This paper experimentally investigates the effects of oxygen-enriched air (OEA) on the running behaviors of an LPG SI engine during both start/warm-up (SW) and hot idling (HI) stages. The experiments were performed on an air-cooled, single-cylinder, 4-stroke, LPG SI engine with an electronic fuel injection system and an electrically-heated oxygen sensor. OEA containing 23% and 25% oxygen (by volume) was supplied for the experiments. The throttle position was fixed at that of idle condition. A fueling strategy was used as following: the fuel injection pulse width (FIPW) in the first cycle of injection was set 5.05 ms, and 2.6 ms in the subsequent cycles till the achieving of closed-loop control. In closed-loop mode, the FIPW was adjusted by the ECU in terms of the oxygen sensor feedback. Instantaneous engine speed, cylinder pressure, engine-out time-resolved HC, CO and NOx emissions and excess air coefficient (EAC) were measured and compared to the intake air baseline (ambient air, 21% oxygen). The results show that during SW stage, with the increase in the oxygen concentration in the intake air, the EAC of the mixture is much closer to the stoichiometric one and more oxygen is made available for oxidation, which results in evidently-improved combustion. The ignition in the first firing cycle starts earlier and peak pressure and maximum heat release rate both notably increase. The maximum engine speed is elevated and HC and CO emissions are reduced considerably. The percent reductions in HC emissions are about 48% and 68% in CO emissions about 52% and 78%; with 23% and 25% OEA, respectively, compared to ambient air. During HI stage, with OEA, the fuel amount per cycle increases due to closed-loop control, the engine speed rises, and speed stability is improved. The HC emissions notably decrease: about 60% and 80% with 23% and 25% OEA, respectively, compared to ambient air. The CO emissions remain at the same low level as with ambient air. During both SW and HI stages, intake air oxygen enrichment causes the delay of spark timing and the increased NOx emissions.

KEY WORDS : Running behavior, Oxygen-enriched air (OEA), SI engine, Startup, Hot idling, Emissions control

1. INTRODUCTION

SI engines are widely used as the power sources for passenger cars and light-duty vehicles. However, they are also major contributors of various air pollutant emissions such as hydrocarbons (HC), carbon monoxide (CO), nitrogen oxides (NOx) and other harmful compounds. With the more stringent emission regulations, substantial reductions of exhaust emissions from SI engines become extremely necessary, especially the HC and CO emissions discharged within the first one or two minutes following the startup of the engine. During this period, the engines are cold and normally run rich to overcome unexpected transients and poor mixture preparation. In the meantime, the three-way catalysts (TWC) are not fully effective until they reach operating temperature. As a result, the incomplete combustion is serious and lots of unburned and partially burned HC and CO emissions are produced and directly discharged into the atmosphere. According to Bielaczyc and Merkisz (1997; 1999), modern automobile powered by an SI engine equipped with a typical TWC and operating in closed-loop control, produced 60% to 80% of the total HC and CO emissions during the first phase of the FTP 75 driving cycle. Some researchers (Tang 2000; Isherwood *et al.*, 1998; Shen *et al.*, 1999) also emphasized the enormous contributions of emissions during the cold start and warm-up periods. Therefore over recent decades, a considerable amount of research effort has been made to reduce the cold start and warm-up exhaust emissions. One attempt is utilizing intake air oxygen-enrichment technology.

Many researchers have investigated the oxygen-enriched air (OEA) application for SI engines to assist combustion under steady state operations and proven that

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oxygen-enriched combustion is an effective method for improving combustion and decreasing exhaust emissions. The earliest attempt was made by Wartinbee *et al.* (1971). Their research results indicated substantial reduction in HC emissions and the accompanying NOx increase. Quader (1978) explained the effects of OEA on exhaust emissions and performance of SI engines with changes in flame temperatures and flame speeds. Kajitani *et al.* (1992) examined the in-cylinder reaction by using a high-speed dual-spectra infrared imaging system and found that addition of small amounts of oxygen into the fuel/air mixture noticeably increased thermal radiation (due to higher temperature) from the reaction zone throughout the combustion period. Maxwell *et al.* (1993) demonstrated that OEA could yield substantial reduction of HC and CO emissions for both gasoline and natural gas engines.

Some researchers (Ng *et al.*, 1993; Poola *et al.*, 1995) have utilized OEA to reduce the emissions within several minutes following the startup of SI engines. The research results indicated the benefits of intake air oxygen-enrichment for emissions reductions. In addition, Poola *et al.* (1996) also reported the substantial reductions of cold-phase emissions from a flexible fuel vehicle (FFV) operating on alcohol fuel under the oxygen-enrichment condition. With the development of membrane gas separation technology, some researchers (Callaghan *et al.*, 1999; Sekar and Poola, 1997), for the purpose of reducing cold start emissions, explored the application of membrane-based oxygen-enrichment technology to SI engines and attempted to utilize membrane modules to supply OEA for engines. Their study results showed the nice suitability of membrane modules for SI engines. The above body of research indicates the benefits of intake air oxygen-enrichment for SI engine cold-phase emission reductions and the promising perspective of the application of oxygen-enrichment membrane technology. However, there is little research on in-cylinder combustion process and behaviors of engine running parameters under the OEA operation within several minutes following the startup of SI engines, especially those burning alternative fuels.

Now liquefied petroleum gas (LPG) has been widely used as an alternative fuel for cars and motorcycles, and the research and development on using LPG is actively carried out by Lee *et al.* (2004) and Choi *et al.* (2005). Based on this background, the purpose of this study is to evaluate the effects of OEA on the running behaviors during both start/warm-up and hot idling stages of an LPG SI engine. To this end, an experimental study was performed on a single-cylinder, electronic fuel injection (EFI), LPG SI engine supplied with OEA containing 23% and 25% oxygen (by volume), respectively.

2. EXPERIMENTAL APPARATUS AND RESEARCH METHOD

2.1. Test Engine and Measurement System

The test engine and measurement instrumentation are depicted in Figure 1. The test engine is an air-cooled, single-cylinder, four-stroke SI engine whose major specifications are shown in Table 1. The engine was modified from gasoline to burn LPG fuel. The EFI system was especially developed for the test. The LPG fuel injector was a Keihin KN3-2B model located near the engine's inlet port. Standard market LPG was used as engine fuel. The main components of the fuel were propane (68.8%, by volume), n-butane (23.8%) and isobutane (7.4%). LPG fuel was supplied from an LPG cylinder which was modified from a standard one. The former pipe in the cylinder was replaced by a shorter one. One end of the new pipe lay on top of the cylinder, and the gaseous LPG fuel in the cylinder could be directly discharged through this pipe. A pressure regulator was used to control gas-phase LPG injection pressure at a constant value of 140 kPa. The regulator was developed by the author (Deng *et al.*, 2003) and had the function of keeping LPG flow rate stable.

The fuel injection pulse width (FIPW) spark timing could be set via the acquisition computer which communicates with the electronic control unit (ECU) through a series port cable. The setting values were sent into the ECU to control the fuel amount per cycle and spark timing. In addition, the acquisition computer can also obtain the real-time data of the FIPW, the oxygen sensor signal and the throttle position from the ECU. Fuel amount per cycle was a function of FIPW, and was calibrated by measuring the volume of the fuel which was injected into a volumenometer before experiments.

The cylinder pressure measuring devices included a Kistler 6125A piezoelectric pressure transducer and a Kistler 5051 charge amplifier. The 720 pulses per rotation

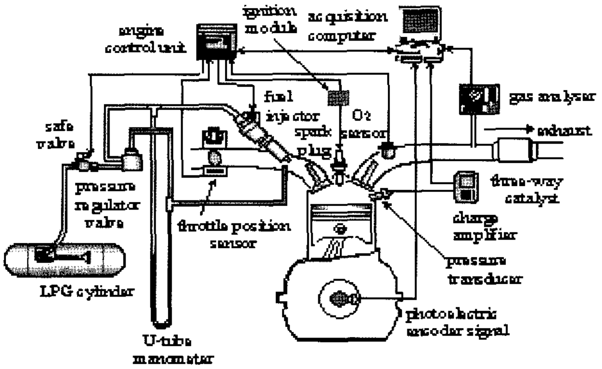


Figure 1. Schematic diagrams of the test engine and measurement instrumentation.

Table 1. Test engine specifications.

Engine type	SI, Single cylinder
Bore	56.5 mm
Stroke	49.5 mm
Displacement	125 ml
Compression ratio	9.2
Brake power(n)	7.3 kW (8500 r/min)
Brake torque(n)	8.7 N.m (8500 r/min)
Cooling system	Air-cooled
Valve train	OHC

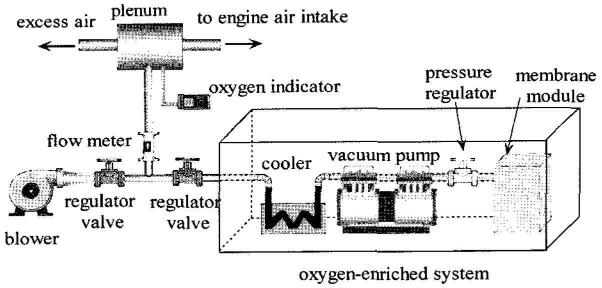


Figure 2. Schematic Diagram of intake air supply system.

from a shaft encoder on the engine crankshaft were used as the data acquisition clocking pulses to acquire the cylinder pressure data. The acquisition computer with a high-speed acquisition card was also used to record cylinder pressure data and crank angle pulse signal synchronously. The instantaneous engine speed was determined in terms of the instantaneous angular velocity of the crankshaft was which was obtained by calculating the duration time between the two successive pulse signal from the encoder.

The time-resolved HC, CO and NOx emissions emitted from the engine (hereafter referred to as "engine-out emissions") and the excess air coefficient (EAC) are measured with an FGA 4100 emission analyzer. The detection methods used are ionization for HC, magneto-dynamic for oxygen, infrared absorption for CO and CO_2, and chemiluminescene for NOx. EAC is given by the emissions measuring device which obtains the EAC of the mixture as a result of the actual ambient air/fuel ratio (AFR) over the stoichiometric ambient air/fuel ratio based on the exhaust gas analysis.

2.2. Intake Air Supply System

The engine intake air supply system fabricated for the experiments was mainly made up of a small membrane-based oxygen-enrichment system, a small blower, an oxygen indicator and a plenum, as shown in Figure 2. Before experiments, the system was turned on and make sure that it operated stably. The oxygen indicator was used to monitor the oxygen concentration of the air intake. The oxygen-enrichment system has the capability of producing enough OEA (up to 30% oxygen). By adjusting the pressure regulator which is between vacuum pump and membrane module, the pressure difference between the inlet and outlet of the membrane module can be changed. The OEA with the required oxygen concentration is then produced. 23% and 25% OEA were chosen for the experiments. The blower was used to supply ambient air (21% oxygen). Either ambient air or OEA was continuously supplied to the plenum. Intake air was controlled at the same flow rate with the regulator valves and the flow meter. One end of the plenum was connected to the intake air entrance of the test engine through which the engine drew the required intake air. The other end was open and the excess air was purged.

2.3. Research Method

The engine was cranked by its own electric starter and 12 volt battery. All the experiments were conducted at the ambient condition, which was at 24~26°C and 101.3 kPa. Before each experiment, the engine was soaked in ambient air for enough time to obtain the same start condition. The startup position of the piston was basically kept the same, which was near TDC in the compression stroke. The throttle valve was fixed at the actual idle position. The oxygen sensor was an electrically-heated one and heated immediately following the engine startup. Above 260°C, the oxygen sensor became completely active and the closed-loop control was achieved. The engine operation then came into closed-loop mode.

In order to quantitatively compare the effects of OEA on engine running behaviors, a fueling strategy consisting of fixed fuel injection pulse width (FIPW) mode during the SW stage and the following closed-loop control mode during HI stage was designed. The FIPW in the first cycle of injection was set at 5.05 ms. In the subsequent cycles, it was set at 2.6 ms until achieving closed-loop control was achieved. In closed-loop mode, the FIPW was adjusted by ECU programming in terms of the oxygen sensor feedback to maintain the EAC near 1.

For this test engine, the firing cycle is next to the corresponding injecting cycle because LPG fuel is injected at the compression TDC in every cycle. The first injection occurs in the first cranking cycle. Therefore, the first firing cycle is following the first cranking cycle. That is to say, the first firing cycle is the second cycle after startup if the in-cylinder combustion normally takes place. The 5.05ms FIPW in the first injecting cycle has been proven to be enough to make engine fire in the following cycle (the so-called the first firing cycle). The EAC of the mixture with 21, 23 and 25% oxygen concentrations intake air in the first firing cycle are 0.6213, 0.6797 and 0.7282, respectively. More information on EAC with

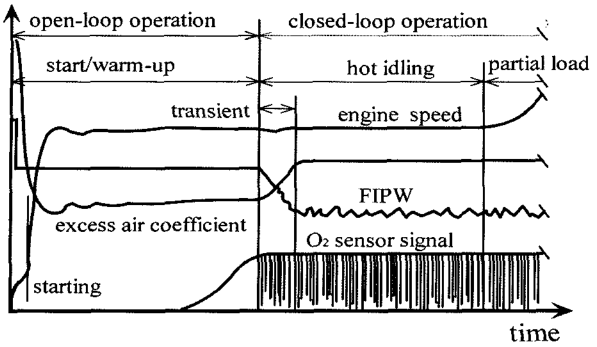


Figure 3. Engine running behaviors under the setting fueling strategy.

OEA can be obtained from the paper by the authors (Li *et al.*, 2006). After startup, the EAC is given from the exhaust gas analyzer.

The 2.6 ms was representative of the idle condition. The spark timing in the first firing cycle was fixed at 10A BTDC. Those in the successive cycles were adjusted by the ECU programming for the purpose of stabilizing engine at the idle speed of about 1400 rpm. When the engine speed exceeded the upper limit (1450 rpm) of the target speed (idle speed), spark timing was gradually retarded 2A every time. Under the lower limit (1350 rpm), spark timing was advanced.

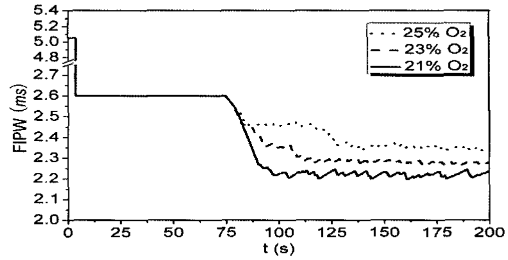
Under the above fueling strategy, the behaviors of FIPW, EAC, engine speed, and oxygen sensor signal throughout an experimental running process may be schematically described in Figure 3. During the SW stage, the FIPW is invariable, equal to the setting values. The initial part of the SW stage is the engine start-up followed by the warm-up. Once the closed-loop control is achieved, the engine comes into the HI stage where the FIPW is adjusted by the ECU programming.

This fueling strategy is somewhat different from that of a real engine in which the FIPW during the SW stage is set in terms of the MAP. However, this fueling strategy retains the essence of the actual fuel supply mode. By fixing the fuel amount per cycle during the SW stage, the effect of the ECU programming is decoupled as much as possible and the effects of OEA may be more accurately assessed.

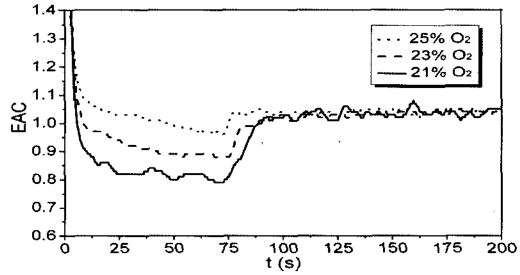
3. EXPERIMENTAL RESULTS AND DISCUSSIONS

3.1. FIPW and EAC

The traces for the FIPW and the EAC of the corresponding mixture at 21%, 23% and 25% oxygen concentrations during both SW and HI stages are presented in Figure 4(a) and (b), respectively. From Figure 4(a), it can be seen that before the 75th second, the FIPW at all three different oxygen concentrations are the same as at the 5.05 ms and 2.6 ms setting values. According to the above fueling strategy, it can be confirmed that the SW stage of the test engine is from the engine startup to the about 75th second. During this stage, the EAC of the mixture increases with the oxygen concentration as shown in Figure 4(b). This indicates that using OEA can make more oxygen available for oxidation.



(a) FIPW



(b) EAC

Figure 4. FIPW and EAC at different oxygen concentrations throughout the SW and HI stages.

Following the SW stage is the HI stage, in which due to the achievement of close-loop control, the FIPW is adjusted by the ECU programming to drop from the setting value 2.6 ms to eventually stabilize at about 2.22 ms, 2.28 ms and 2.34 ms, corresponding to the 21%, 23% and 25% oxygen concentrations, respectively. The increase of the FIPW with the oxygen concentration is due to the fact that during the HI stage, the fuel amount is controlled in terms of the oxygen sensor feedback for the purpose of maintaining the EAC of the mixture near 1, which can be seen from Figure 4(b). When using OEA, the mixture has more oxygen content and consequently more fuel is needed injecting.

From Figure 4(a), it can be noted that with the increased oxygen content, the FIPW takes a longer time before reaching the stable state. The reason is that the adjusting ability of the ECU programming is not adequately adaptive for the engine transient operation under OEA condition.

Based on the analysis, the effect of OEA on the in-cylinder mixture under the given test procedure can be summarized: during the SW stage, using OEA causes the

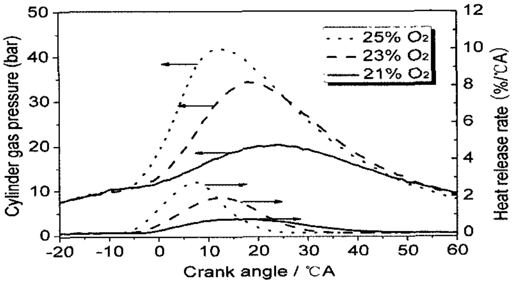


Figure 5. Cylinder pressure and heat release rate in the first firing cycle at different oxygen concentrations.

EAC of the mixture to increase; during the HI stage, the in-cylinder fuel amount in the mixture increases.

3.2. Engine Combustion and Speed during the SW Stage

The combustion in the first firing cycle with OEA is representative of the oxygen-enriched combustion. Figure 5 presents the cylinder pressures and corresponding heat release rate (burned fuel mass fraction per unit °CA) histories in the first firing cycle at 21%, 23% and 25% oxygen concentrations. It is clear that with the increase in the intake air oxygen concentration, the ignition time gradually advances and the maximum cylinder pressure and peak heat release rate remarkably increase. These changes are attributable to the stronger combustion reaction, higher flame temperatures and faster flame speeds caused by the increase of oxygen content.

Figure 6 shows the instantaneous engine speed during the initial part of the SW stage with the intake air of 21%, 23% and 25% oxygen concentrations. With 21% oxygen, the engine fires in the first firing cycle (the second injecting cycle). The firing of the two subsequent cycles accelerates the engine to 1400 rpm (the idle speed). Then, the engine stabilizes. Compared to 21% oxygen, OEA causes significant increase of engine speed and the speed increases with the oxygen concentration in the intake air. With 23% and 25% oxygen, the firing of the initial seven cycles accelerates the engine to about 1580 and 1850 rpm, respectively. After about 26 cycles, the speeds at 23% and 25% oxygen concentrations all return to the speed at 21% oxygen concentration. The evident increase of the engine speed results from the stronger and quicker combustion due to more available oxygen in the mixture. The retardation of spark timing leads to the engine to stabilize at idle speed after about 26 cycles.

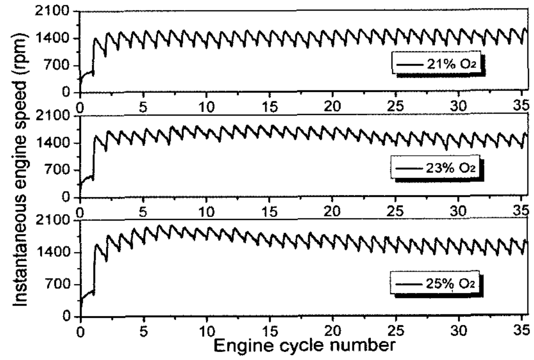
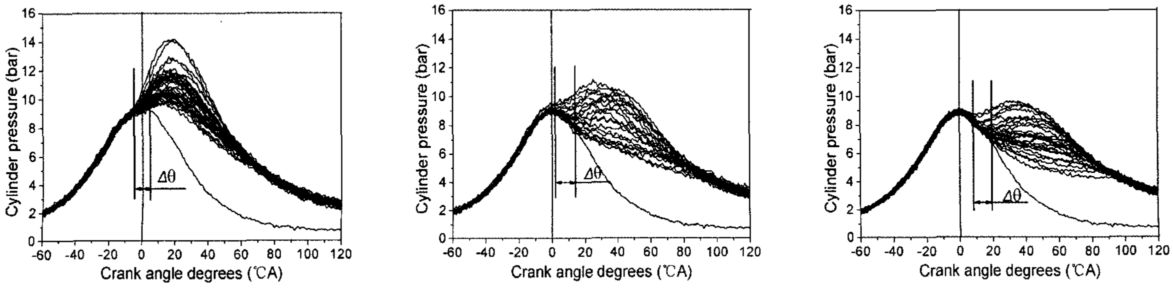


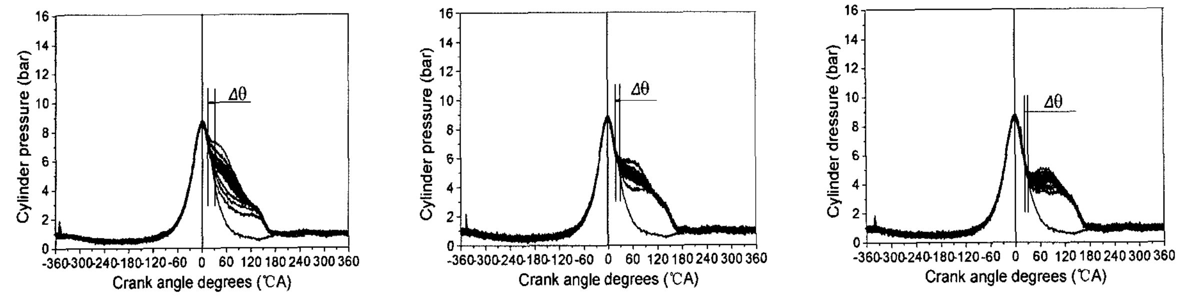
Figure 6. Instantaneous engine speeds at different oxygen concentrations during the SW stage.

The cylinder pressures with OEA in successive 50 cycles, which began from the 100th cycle after engine startup, were recorded. Their traces are overlapped and depicted in Figure 7. Here, the ignition timing is defined as the crank angle where the combustion pressure traces separates from the motored cylinder pressure trace. Ignition phase domain $\Delta\theta$ is defined as the range from the earliest ignition timing to the latest one in the successive 50 cycles. It can be seen that with increase in the oxygen concentration, $\Delta\theta$ evidently shifts backwards about 7 °CA and 15 °CA with 23% and 25% OEA, compared to ambient air. As pointed out above, for the test engine, the adjustment of spark timing is the measure to stabilizing the engine at the idle speed. OEA caused engine speed to increase. Consequently, the spark timing is retarded and the ignition takes place later. According to Russ *et al.* (1999) and Choi *et al.* (2000), moderate spark timing retard is desirable for the reduction of cold-phase HC emissions and shorter "light-off" time of catalysts. This means that use of OEA with proper oxygen concen-



(a) 21% oxygen concentration (b) 23% oxygen concentration (c) 25% oxygen concentration

Figure 7. Cylinder pressures at different oxygen concentrations during the SW stage.



(a) 21% oxygen concentration (b) 23% oxygen concentration (c) 25% oxygen concentration

Figure 8. Cylinder pressures at different oxygen concentrations during the HI stage.

tration, for example, 23% for the test engine, can directly bring the above benefits without any modification.

3.3. Engine Combustion and Speed during the HI Stage

Figure 8 shows the cylinder pressure traces in 50 successive cycles at different oxygen concentrations during the HI stage. The acquisition of the cylinder pressure began at basically the same time after engine startup. From Figure 8, it can found that spark timing is evidently retarded with the increase in the oxygen concentration in the intake air. Compared to ambient air, the spark timing with 23% and 25% OEA are averagely retarded 3 °CA and 7 °CA, respectively. The definition of Ignition phase domain $\Delta\theta$ in Figure 8 is same as that in Figure 7. It can be also noted that $\Delta\theta$ and the variation range of maximum cylinder pressure become smaller with the increase in the oxygen concentration. This suggests that the engine can run more smoothly.

Figure 9 shows that the engine speed increases with the oxygen concentration in the intake air. Compared to ambient air, the increasing degrees are 150 rpm and 350 rpm, corresponding to with 23% and 25% OEA. As discussed above, the fuel amount per cycle increases during the hot phase due to the use of OEA. Consequently the engine speed is elevated. From Figure 9, it can be found that with OEA, the engine speed fluctuations become smaller than with ambient air. This can be explained by the smaller $\Delta\theta$ and the variation range of maximum cylinder pressure as shown in Figure 8.

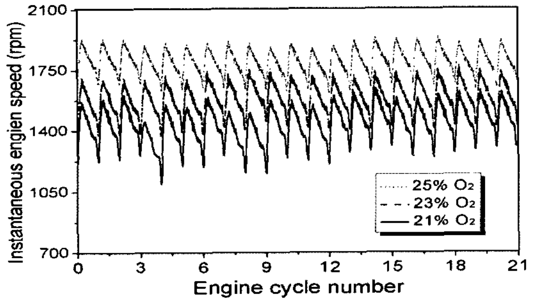


Figure 9. Instantaneous engine speeds at different oxygen concentrations during the HI stage.

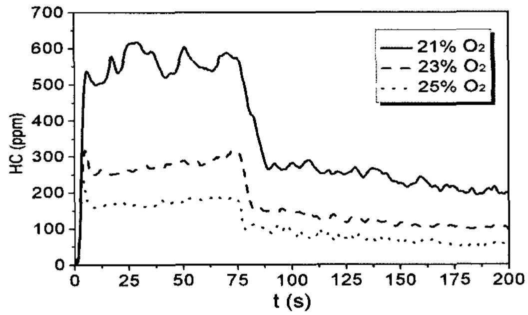
3.4. Engine-out HC, CO and NOx Emissions

The engine-out time-resolved HC, CO, and NOx emissions at the different intake air oxygen concentrations are presented in Figure 10. It can be seen that the HC and CO emissions discharged during the SW stage are evidently higher than those during the HI stage. One reason is that during the HI stage, the fuel amount per cycle is less and the mixture is near the stoichiometric one, which can be seen from Figure 4. Another reason is the higher in-cylinder and tailpipe temperatures. When the oxygen concentration in the intake air increases from 21%, the EAC of the combustible mixture during the SW stage increases and more oxygen is made available for oxidation. As a result, the HC and CO emissions are substantially reduced. On the average, the percent reductions in HC emissions are about 48% and 68% with 23% and 25% OEA, respectively. For CO emissions, the reductions are about 52% and 78% with OEA.

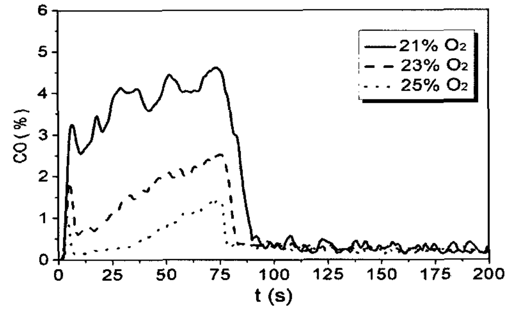
During the HI stage with OEA, the reduction of HC emissions is still noticeable at the average of 60% and 80% and maintains the value at the same low level as with ambient air. However, the CO emissions rarely changed. Considering the over-retarded spark timing and more fuel amount per cycle than those with ambient air, it can be deduced that using OEA during the HI stage also has potential to decrease the CO emissions even if the EAC during this stage is maintained near 1. The reductions of HC emissions with OEA are attributable to the improved combustion and higher flame temperatures which can both decrease flame-quenching and promote post-flame oxidation.

In the case of NOx emissions, Figure 10(c) shows that the increase in the intake air oxygen concentrations results in the increase of NOx emissions. However, the level of NOx emissions with OEA is still less than 250 ppm.

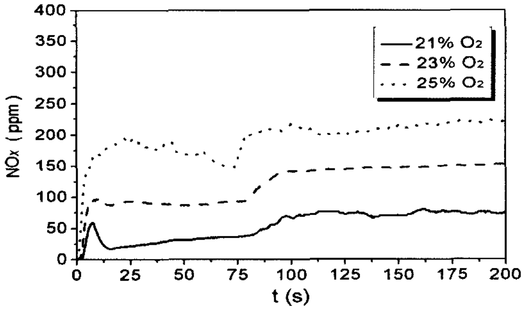
From the above experimental results, it can be also found that with 23% OEA, the reduction in HC and CO



(a) Engine-out HC emissions



(b) Engine-out CO emissions



(c) Engine-out NOx emissions

Figure 10. Engine-out HC, CO and NOx emissions at three different oxygen concentrations throughout the SW and HI stages.

emissions was significant. However, with 25% OEA, percent reduction was less than that obtained with 23%. Furthermore, the increase in oxygen level from 23% to 25% resulted in greater increase in NOx emissions. This suggests that the oxygen concentration of 23%, compared to 25%, is more proper because of the more effective reduction of HC and CO emissions.

4. CONCLUSIONS

This study was undertaken to investigate the engine responses to the intake air oxygen enrichment during both start/warm-up and hot idling stages. A laboratory specially-designed engine fueling strategy was used to assess the effects of OEA on the running behaviors. Based on the above results, the main conclusions can be obtained as follows:

(1) With the increase in the oxygen concentration in the intake air, the EAC of the in-cylinder mixture during the SW stage becomes higher and the fuel amount per cycle during HI stage increases.
(2) Intake air oxygen-enrichment can improve the in-cylinder combustion. With OEA, the combustion in the first firing cycle starts earlier and the maximum cylinder pressure and peak heat release rate notably increase.
(3) Using OEA, the spark timing is evidently retarded by ECU programming for the purpose of stabilizing the engine at idle speed during both SW and HI stages.
(4) With OEA, the maximum engine speed during the engine startup significantly increases. The engine speed during the HI stage increases with oxygen concentration in the intake air and the stability of engine speed can be improved.
(5) Compared to ambient air, the engine-out HC emissions with OEA decrease considerably during both SW and HI stages. The CO emissions are reduced substantially during the SW stage and maintain at the same low level as with ambient air during the HI stage.
(6) With OEA, the NOx emissions become higher than with ambient air but are still very low and thus not problematic.
(7) On a whole, 23% OEA is more suitable for the SI engine.

ACKNOWLEDGEMENTS–This study was financially supported by the National Nature Science Foundation of China (No. 50276035). The authors wish to express their gratitude to Chen Zong-peng for his contribution to this paper.

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