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Study on the Combustion Characteristics of Light-Load RI-CNG Engine
저부하 라디칼 착화 압축천연가스 엔진의 성능연구

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류우 · 동용 · 염정국 · 정성식

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주요용어 : 라디칼 착화(Radical Ignition), CNG(Compressed Natural Gas), 부실(Sub-chamber), 분사시기(Injection Timing), 공기과잉률(Excess Air ratio)

요 약 : 본 연구는 라디칼 착화(Radical Ignition이하 RI) 기술을 적용한 부실직분식 CNG(Compressed Natural Gas)엔진의 구동특성에 관한 것이다. 실험엔진은 단기통 디젤엔진을 개조하여 사용하였으며, 이는 부실식 디젤엔진처럼 연소실이 주실과 부실로 나누어져 있다. 부실에 분사된 CNG는 스파크플러그로 점화하며, 부실로 부터의 연소가스가 주실 희박 혼합기를 시켜 구동하는 엔진이다. RI 기술은 연소속도를 향상시킬 수 있다. 본 연구는 주로 저부하 RI-CNG 엔진의 성능을 연구하였다. 연료분사기간은 9 ms, 공기과잉률은 1.0, 1.2, 1.4로 하였다. 연료분사시기는 엔진의 배기밸브가 닫히는 ATDC 20 °CA 부터 120 °CA 사이로, 20 °CA 간격으로 지각시켜 가며 실험하였다. 본 연구는 연료분사시기 및 공기과잉률이 연소최고압력(P_{max}), 연소최고압력시기(Θ_{pmax}), 도시평균유효압력(IMEP), 사이클 변동계수(COV_{imep}), 연소속도에 미치는 양향 등을 구하고 분석하였다.

1. 서 론

RI (Radical Ignition) combustion method was applied into a sub-chamber type CNG (Compressed Natural Gas) injection engine which is a modified DI diesel engine. The volume of the sub-chamber is 1~2% of the main-chamber. The sub-chamber has about 4 passage holes of about 1.8 mm in diameter. A spark-plug and a CNG injector were installed in the sub-chamber. The ignition occurs in the sub-chamber first and then the combustion gas containing a number of active radicals is forced out of sub-chamber through the holes into the main-chamber to ignite the unburned mixture. It is predicted that the RI combustion method can improve combustion velocity[1~4).

To investigate the combustion characteristics of the RI-CNG engine, a series of experiments have been carried out. In the previous report[5~7), combustion characteristics of RI-CNG engine was investigated under middle load. RI-CNG engine showed higher combustion stability at certain conditions. But relatively longer combustion duration was observed under the middle load condition and the NO_X emission was a little higher.

There are some problems when using the CNG fuel which is used as the fuel for the RI-CNG engine. Its energy density is lower compared with liquid fuel such as gasoline and diesel, so longer injection duration is needed. The longer injection duration results in shorter mixing duration of the direct-injected CNG and the air. If the CNG is directly injected into the sub-chamber, the direct-injected CNG in the sub-chamber prevents the possibility entry of the fresh air from the

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main-chamber, which also affects the CNG-air mixture formation in the sub-chamber. All of these have a significant effect on the engine combustion characteristics and performance.

The purpose of this paper is to study the combustion characteristics of the RI-CNG engine under a light load. The engine speed was set at 1000 rpm. Under a light load condition, less CNG fuel is needed to be injected into the sub-chamber. So the injection duration is shorter compared with a middle load condition. In the experiment, the injection duration was set at 9 ms and the injection timing was changed every 20 °CA from EVC (Exhaust Valve Close) to the limit injection timing. The limit injection timing means that the engine can operate steadily until the limit injection timing. The effects of injection timing and excess air ratio on the cylinder pressure, P_{max}, θ_{pmax}, COV_{imep}, frequency distribution of P_{max} and θ_{pmax}, combustion duration were analyzed.

2. Experimental setup

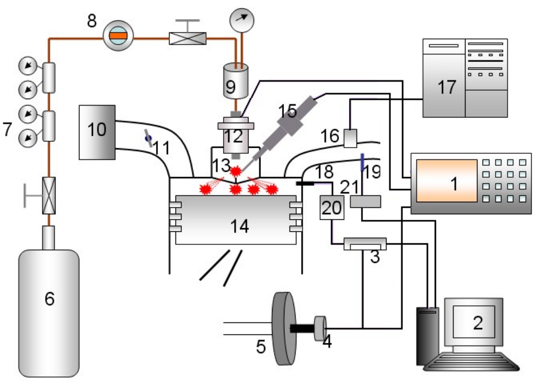
2.1 Experimental apparatus

A DI (Direct Injection) diesel engine was modified into an experimental RI engine. The specifications of the DI engine and the modified RI engine are shown in table 1.

Fig. 1 shows the experimental apparatus which consists of the RI engine, an ECU (Electric Control Unit), data acquisition system, fuel supply system and exhaust analysis system. Two regulators were used between the high pressure CNG tank and CNG injector to obtain steady injection pressure. A CNG injector and a spark-plug were installed in the sub-chamber. CNG is injected into the sub-chamber during the intake stroke and the pre-mixture is formed during the compression stroke. Then the pre-mixture in the sub-chamber is ignited by the spark-plug. All of engine speed, injection duration and injection timing can be controlled by the ECU.

Table 1 The experimental engine specification

	Base engine (ND80DI)	Modified engine
Type	DI diesel engine (single cylinder)	RI CNG engine
Bore×stroke(mm)	92×95	92×95
Displacement(cc)	632	632
Shape of piston cavity	Toroidal	Flat
Compression ratio	19	10.56
Intake valve open and close	BTDC 20° and ATDC 224°	BTDC 20° and ATDC 224°
Exhaust valve open and close	ATDC 136° and ATDC 20°	ATDC 136° and ATDC 20°



1. ECU controller 2. Data acquisition PC
3. A/D converter 4. Encoder 5. Dynamometer
6. CNG tank 7. Regulator 8. CNG flow meter
9. Surge tank 10. Air filter 11. Air throttle
12. GDI injector 13. Sub-chamber 14. Test engine
15. Spark plug 16. Exhaust gas sampling
17. Exhaust gas analyzer 18. Cylinder pressure sensor
19. λ sensor 20. Amplifier 21. λ indicator

Fig. 1 Schematic diagram of experimental system

Fig. 2 shows the relative location of the sub-chamber, the CNG injector and spark plug in cylinder head. The sub-chamber with a spark plug was set at the original injector place of the DI engine. The CNG injector was installed in the upper part of the sub-chamber. For this study, the CNG is injected into the sub-chamber directly. The direct injected CNG has the function of scavenging residual gas of the last cycle and supplying fuel for the new cycle. The sub-chamber has 4 passage holes of 1.8 mm in diameter. The volume of the sub-chamber is 2.45 cc.

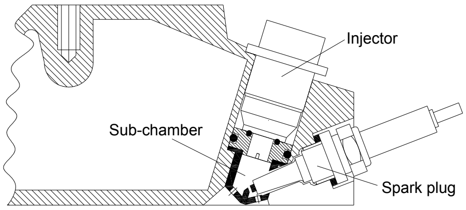


Fig. 2 Injector, sub-chamber and spark plug distribution in the RI-CNG engine

2.2 Experimental methods

The injection duration was set at 9 ms. Air excessive ratio was set at λ= 1.0, λ= 1.2 and λ= 1.4, respectively. The table 2 shows the specific experimental conditions.

Table 2 Experimental conditions

Item	Condition
Fuel	CNG
Cooling water temperature (°C)	75
Spark timing	MBT
Excess air ratio (λ)	1.0, 1.2, 1.4
Engine speed (rpm)	1000
Injection timing	ATDC 20°-limit injection timing

3. Experimental results and discussion

3.1 Effects of injection timing on cylinder pressure

In the case of the RI-CNG engine, the curves of cylinder pressure versus crank angle are given in Fig. 3. Each pressure curve is the average value calculated from the data measured for 50 cycles. When λ is 1.0, Fig. 3 shows the changes of cylinder pressure with different injection timings. To meet the MBT (Maximum Brake Torque), the ignition timing was set at BTDC (Before Top Dead Center) 45 °CA (Crank Angle) for the injection timing from ATDC (After Top Dead Center) 20 to 100 °CA and the ignition timing was set at BTDC 38 °CA for the injection timing from ATDC 120 to 200 °CA. Different ignition timings lead to different combustion characteristics. When the ignition timing is set at BTDC 45 °CA, the P_{max} is relatively higher and the maximum pressure occurs a little farther away from the TDC. When the ignition timing is set at BTDC 38 °CA, the P_{max} is relatively lower and the maximum pressure occurs close to the TDC(Top Dead Center). The smallest Θ_{pmax} occurs when the injection timing is set at ATDC 140 °CA. When injection timing is set at ATDC 200 °CA, the misfire happens.

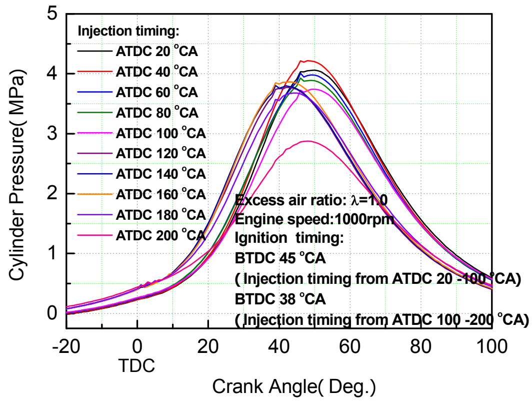


Fig. 3 Measured cylinder pressure versus injection timing as λ= 1.0

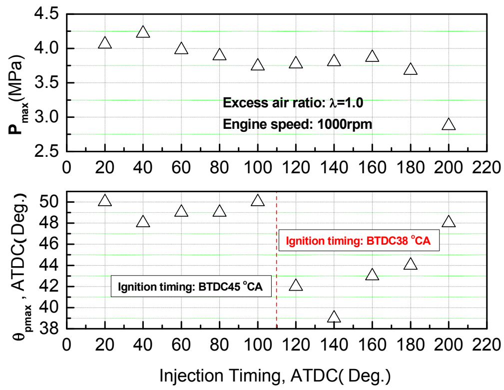


Fig. 4 Maximum cylinder P_{max} and Θ_{pmax} versus injection timing as λ= 1.0

When λ is 1.2, with the same injection duration, more air should be inducted into the cylinder, so the open rate of throttle valve should be increased. Fig. 5 shows the effects of injection timing on the cylinder pressure. To meet the MBT, the ignition timing was set at BTDC 32 °CA for the injection timing from ATDC 20 to 100 °CA and the ignition timing is set at BTDC 28 °CA for the injection timing from ATDC 120 to 210 °CA. Shown in Fig. 6, it is found that the

P_{max} values are almost the same for the injection timing between ATDC 20 and 180 °CA, but their Θ_{pmax} values are different, just when the injection timing is set from ATDC 120 to 180 °CA, the maximum pressure occurs close to TDC. From the experiment result, it shows that even at lean burn conditions. The engine can still obtain relatively high combustion velocity by adjusting injection timing. But with much delayed injection timing, an unsteady combustion or misfire will happen.

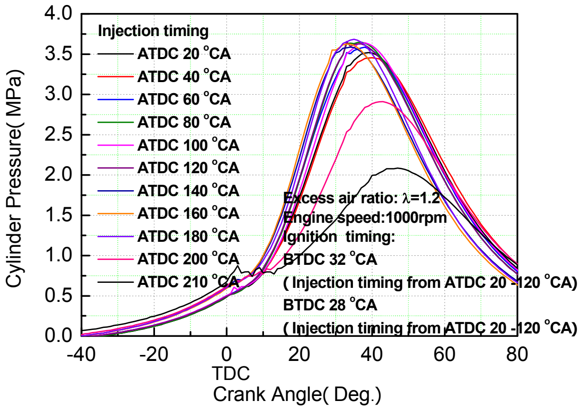


Fig. 5 Measured cylinder pressure versus injection timing as λ= 1.2

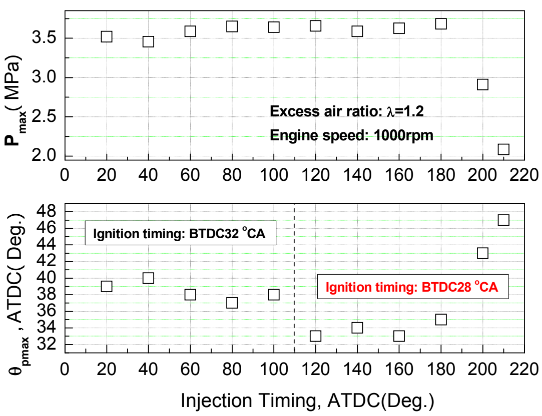


Fig. 6 Maximum cylinder P_{max} and Θ_{pmax} versus injection timing as λ= 1.2

As λ is 1.4, it is shown that the maximum cylinder pressure is much affected by the injection timing, and the maximum cylinder pressure decreases rapidly when the injection timing is set at ATDC 220 °CA which means the misfire occurs. Generally, the engine can reach its highest efficiency when maximum pressure occurs at ATDC 10~15 °CA, so a small Θ_{pmax} is good for engine efficiency. Fig. 7 shows the effects of injection timing on P_{max} and Θ_{pmax}. When the injection timing is ATDC 120 °CA, the engine has the highest maximum cylinder pressure P_{max} which leads to a rapid combustion and the Θ_{pmax} is the smallest which means the maximum pressure occurs close to TDC and the engine has relatively high efficiency.

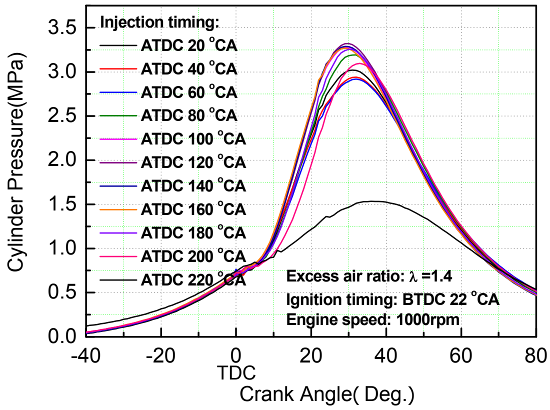


Fig. 7 Measured cylinder pressure versus injection timing as λ= 1.4

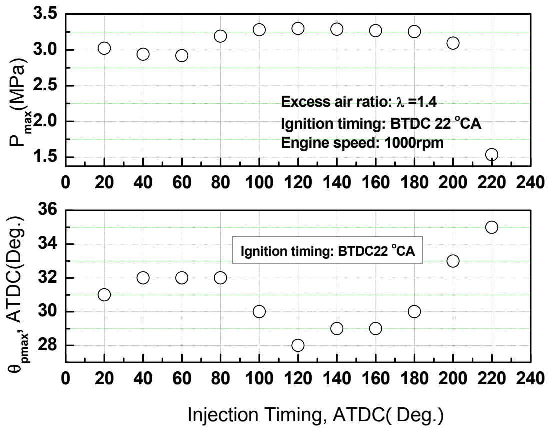


Fig. 8 Maximum cylinder P_{max} and Θ_{pmax} versus injection timing as λ= 1.4

3.2 Effects of injection timing on IMEP

Fig. 9 shows the effects of injection timing on IMEP (Indicated Mean Effective Pressure) with different excess air ratios. When λ is 1.4, the value of IMEP fluctuates slightly versus injection timing until the misfire occurs. For λ is 1.2, the peak IMEP value occurs when the injection timing is set at ATDC 100 °CA and ATDC 120 °CA. Shown in the Fig. 6, the corresponding Θ_{pmax} is ATDC 30 °CA and ATDC 28 °CA. As λ is 1.0, the value of IMEP decreases with the delay of injection timing. The IMEP value decreases with the increase of excess air ratio.

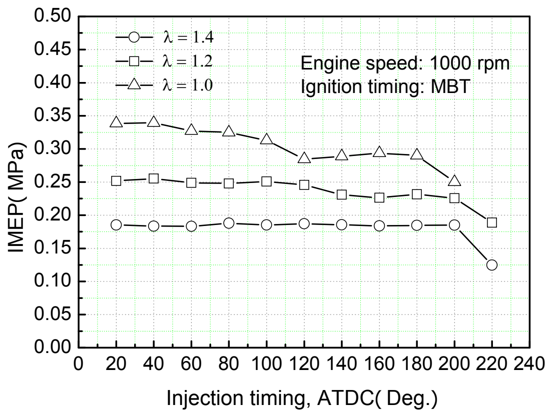


Fig. 9 The effects of injection timing on IMEP with different excess air ratios

3.3 Effects of injection timing on engine operation stability

Fig. 10 shows the combustion stability of the engine under given experiment conditions. The COV (Coefficient of Variation) of IMEP indicates engine operation stability. This RI engine shows high operation stability with different λ values, especially at lean burn condition when λ is 1.4, it still can operate steadily. So the RI combustion method can improve engine operation stability.

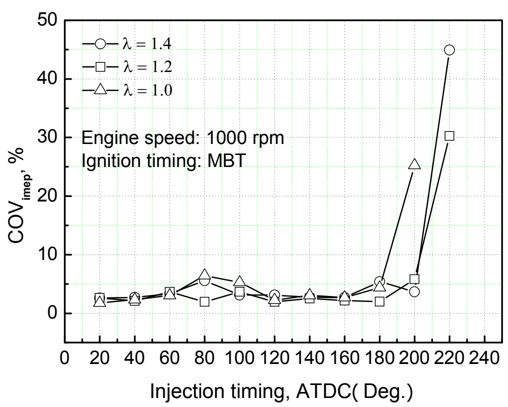


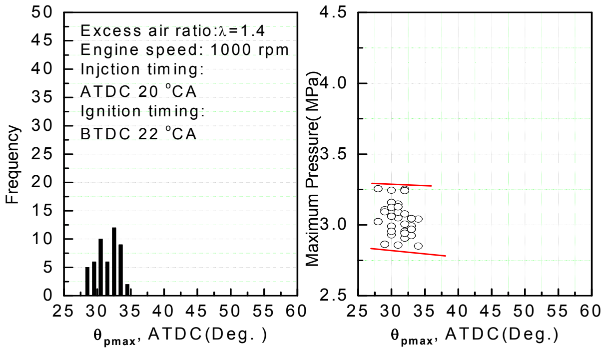
Fig. 10 The effects of injection timing on COV_{imep} with different excess air ratios

3.4 Frequency distribution of P_{max} and Θ_{pmax}

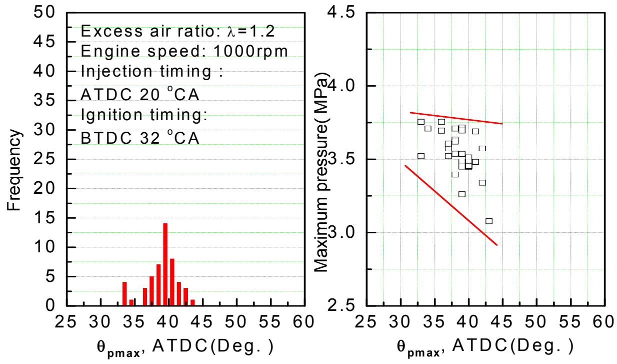
Fig. 11 shows the frequency distribution of Pmax and Θpmax, for 50 cycles of the RI engine with different λ values. The injection timing was fixed at ATDC 20 °CA. Shown in Fig. 11, with the decrease of λ value, the distribution of Θ_{pmax} becomes wider and the distribution of Θ_{pmax} becomes farther away from the TDC. When the λ is 1.4, the distribution of Θ_{pmax} is from ATDC 28 °CA to 35 °CA. When the λ is 1.2, the distribution of Θ_{pmax} is from ATDC 33 °CA to 43 °CA. When the λ is 1.0, the distribution of Θ_{pmax} is from ATDC 46 °CA to 54 °CA. The distribution of P_{max} also becomes wider and the value of P_{max} increase with the decrease of λ. When the λ is 1.4, the distribution of P_{max} is from 2.8 MPa to 3.3 MPa. When the λ is 1.2, the distribution of Θ_{pmax} is from 3 MPa to 3.8 MPa. When λ is 1.0, the distribution of Θ_{pmax} is from 3.6 MPa to 4.4 MPa. By comparing the distribution of P_{max} and Θ_{pmax} of different excess air ratios with the fixed injection timing, the cycle-by-cycle variation of 1.4 excess air ratio is small which means the engine operation is much steadier than that of other λ conditions.

When the injection timing is changed to ATDC 120 °CA, the frequency distribution of P_{max} and Θ_{pmax} for 50 cycles of the RI engine is shown in Fig. 12. When the λ is 1.4, the distribution of Θ_{pmax} is from ATDC 28 °CA to 36 °CA and the distribution of P_{max} is from 3 MPa to 3.5 MPa. When the λ is 1.2, the distribution of Θ_{pmax} is from ATDC 33 °CA to 37 °CA and the distribution of P_{max} is from 3.4 MPa to 4 MPa. When the λ is 1.0, the distribution of Θ_{pmax} is from ATDC 39 °CA to 48 °CA and the distribution of P_{max} is from 3.4 MPa to 4.2 MPa.

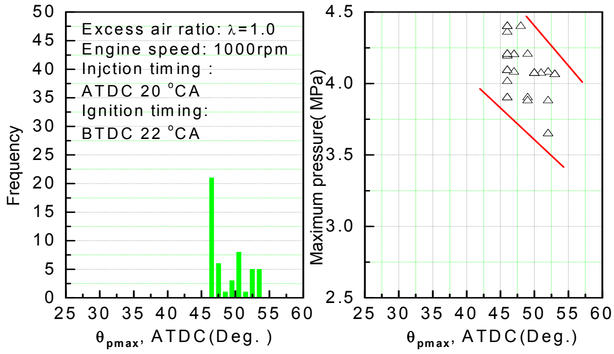
It is found that for both fixed injection timings, decrease in λ value makes the distribution of Θ_{pmax} to become wider and the Θ_{pmax} to become farther away from the TDC. It also makes the distribution of P_{max} to become wider and the value of P_{max} to increase.



(a) λ= 1.4

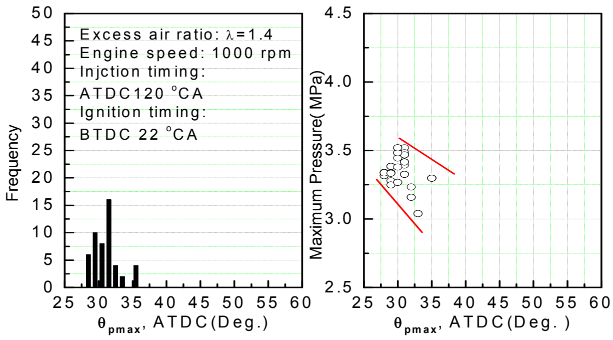


(b) λ= 1.2

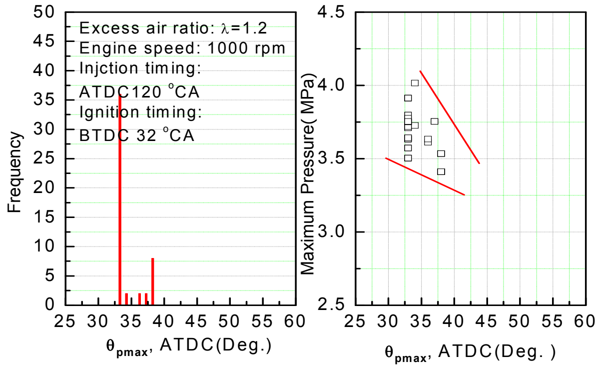


(c) λ= 1.0

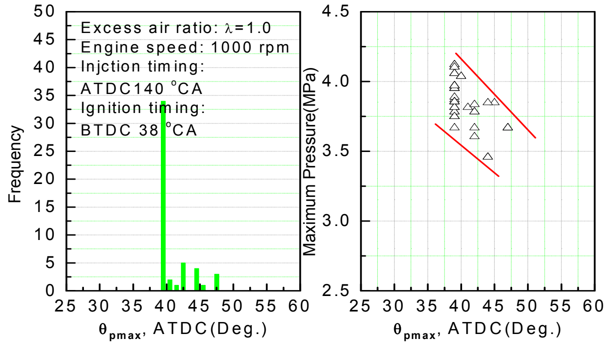
Fig. 11 Distribution of P_{max} and Θ_{pmax}, for 50 cycles of the RI engine under different λ values with fixed ATDC 20 °CA injection timing



(a) λ= 1.4



(b) λ= 1.2



(c) λ= 1.0

Fig. 12 Distribution of P_{max} and Θ_{pmax}, for 50 cycles of the RI engine under different λ values with fixed ATDC 140 °CA injection timing

3.5 Combustion duration

Fig. 13 illustrates the detailed combustion histories. The combustion duration is consisted of the flame development angle and the rapid burning angle. Shown in Fig. 13, the flame development angle is relatively long for this light load combustion. It is about 30 °CA, 40 °CA and 60 °CA for 1.4, 1.2 and 1.0 excess air ratio, respectively.

For each λ, the flame development angle changes with the increase of injection timing. As λ is 1.4, the fluctuation of the flame development angle is small; as λ is 1.2, when the injection timing is set from ATDC 120 °CA to 180 °CA, the flame development angle is shorter. For λ=1.0, the flame development angle is shorter when the injection timing is set from ATDC 120 °CA to 200 °CA and the difference of the flame development angle is more obvious. For all combustions with different excess air ratios and injection timings, they have almost the same rapid burning angle.

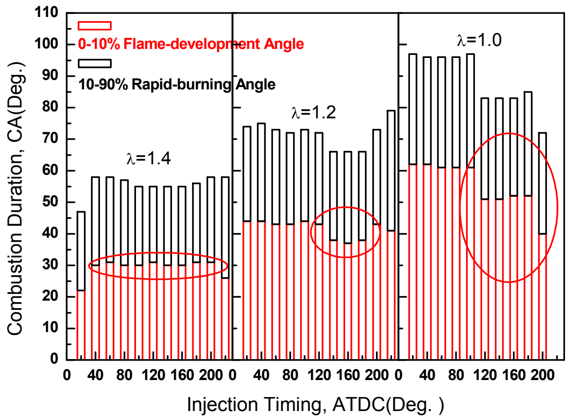


Fig. 13 Combustion duration versus injection timing with different excess air ratios

4. Conclusions

The RI method was applied in a modified DI diesel engine to achieve rapid bulk combustion, and the CNG fuel was directly injected into the sub-chamber to scavenge the residual gas that from the previous cycle. The effects of injection timing and excess air ratio on engine characteristics and performance were investigated under a light load condition. The following summarizes the results:

The maximum cylinder pressure is much affected by the injection timing. The maximum cylinder pressure decreases rapidly when the injection timing is set at ATDC 200 °CA which means the misfire occurs. It is found that for both fixed injection timings, decrease in λ value makes the distribution of Θ_{pmax} to become wider and the Θ_{pmax} to become farther away from the TDC. It also makes the distribution of P_{max} to become wider and the value of P_{max} to increase.

This RI engine shows high operation stability with different λ values, especially at lean burn condition. When λ is 1.4, the value of IMEP fluctuates slightly with injection timing until the misfire occurs; by comparing the distribution of P_{max} and Θ_{pmax} of different excess air ratios with the fixed injection timing, the cycle-by-cycle variation of 1.4 air excessive ratio is small; as λ is 1.4, the fluctuation of flame development angle is small. So RI combustion method can improve engine operation stability at lean burn combustion condition.

Acknowledgement

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