Combustion Characteristics of HCCI in Motorcycle Engine

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Homogeneous charge compression ignition (HCCI) is recognized as an advanced combustion system for internal combustion engines that reduces fuel consumption and exhaust emissions. This work studied a 150 cc air-cooled, four-stroke motorcycle engine employing HCCI combustion. The compression ratio was increased from 10.5 to 12.4 by modifying the cylinder head. Kerosene fuel was used without intake air heating and operated at various excess air ratios (λ), engine speeds, and exhaust gas recirculation (EGR) rates. Combustion characteristics and emissions on the target engine were measured. It was found that keeping the cylinder head temperature at around 120–130°C is important for conducting a stable experiment. Two-stage ignition was observed from the heat release rate curve, which was calculated from cylinder pressure. Higher λ or EGR causes lower peak pressure, lower maximum rate of pressure rise (MRPR), and higher emission of CO. However, EGR is better than λ for decreasing the peak pressure and MRPR without deteriorating the engine output. Advancing the timing of peak pressure causes high peak pressure, and hence increases MRPR. The timing of peak pressure around 10–15 degree of crank angle after top dead center indicates a good appearance for low MRPR.
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1 Introduction

Motor vehicle exhaust emissions are significant sources of air pollution with important implications for human health and global warming effects. Exhaust emission and fuel economy regulations are increasingly stringent, not only for automobiles, but also for motorcycles. Taiwan Environmental Protection Administration (EPA) implemented a new emission standard for motorcycles on July 1, 2007, which is the same rule as European Community Emission Standard EURO 3. The standards for motorcycles smaller than 150 cc are as follows: CO=2.0 g/km, HC =0.8 g/km, and NO_x=0.15 g/km. They evaluated the technology to achieve this standard by testing 49 of the most popular types of motorcycles in the market. The average value of the exhaust emissions of these 49 motorcycles were: CO =2.54 g/km, HC=0.48 g/km, and NO_x=0.20 g/km [1]. It shows that nitrous oxides (NO_x) is the most difficult to achieve.

NO_x is also difficult to reduce in a lean burn engine, which has been a good technology for improving the fuel economy of automobiles. Several approaches reduce NO_x emission, including exhaust gas recirculation (EGR), catalytic converter, selective catalytic reduction (SCR) system, NO_x trap, plasma reactor, water injection, water/fuel emulsions, homogeneous charge compression ignition (HCCI), etc.

HCCI produces very low NO_x emission and is accompanied by high thermal efficiency. A HCCI engine is similar to a combination of a spark ignition (SI) and a compression ignition (CI) engine. Fuel air mixture is premixed, as in a traditional SI engine, while its combustion is initiated by auto-ignition, which is like a CI engine. Therefore, HCCI is considered a high-efficiency alternative to SI engine [2] and as a low-emission alternative to the traditional CI engine [3]. Its advantages are as follows: high thermal efficiency and very low NO_x and particulate emissions. On the other hand, it has the following disadvantages: limited operation range, difficulty in controlling the ignition, too high combustion rate at high loads [4–6].

The problem in controlling combustion in a HCCI engine comes from the extreme sensitivity of HCCI combustion to temperature, pressure, and composition during the compression stroke [6]. There are many possibilities for HCCI engine control: variable compression ratio [7,8], variable valve timing [8,9], operation with multiple fuels [4,10,11], and thermal control [6,11–13].

Many studies have been done on automobile engines on either modified CI or SI engines. However, very few studies have focused on the characteristics of HCCI for motorcycle engines. The work discussed in this paper studied combustion characteristics of HCCI in an air-cooled, single-cylinder motorcycle engine. It focused on using an existing SI engine without significantly changing for HCCI operation.

2 Experimental Setup

For the experiments carried out with a 150 cc single-cylinder, air-cooled motorcycle engine, the compression ratio was increased from 10.5 to 12.4 by modifying the cylinder head. Increased compression ratio produces a higher compression temperature, which is good for compression ignition. The original fuel system and spark plug were kept in the original location for starting the engine. An additional injector was installed near the intake port for injecting fuel for HCCI operation. After starting the engine using gasoline with spark ignition and achieving a stable cylinder head temperature, the operation was shifted to HCCI combustion. Detail specifications of the test engine are shown in Table 1.

The experimental setup for engine testing is shown in Fig. 1. For the engine test, a Borghi & Saveri Srl FE150-S eddy-current engine dynamometer was employed to measure the engine output torque and speed. The fuel flow rate was measured by using ONO SOKKI FX-1110 mass burette flow detectors. The exhaust emissions included CO, HC, NO_x, O_2, and excess air ratio (λ) was measured with HOROBA MEXA-584L. The concentration of NO_x in this research was too low to be measured by this emission analyzer, so NO_x data are lacking in the results. An EGR analyzer, EGR 5230 by ECM, and K-type thermocouples were used for measuring the EGR rate and temperature.

The cylinder pressure was measured using a Kistler 6051B air-cooled piezoelectric pressure transducer. The crank angle (CA) was detected by a shaft encoder (BEI H25). The output signal of the pressure transducer was amplified using a charge amplifier. This amplified signal was transmitted to a data acquisition system, which was an AVL IndiCom 619 combustion analyzer. The cylinder pressure was recorded every 1 deg CA for 100 cycles. The measured pressure data were then used for calculating the heat release rate.

Engine control was accomplished by using a Motohawk ECU

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Table 1 Engine specifications

Engine type	4-stroke, 4-valve, single-cylinder/OHC, forced air-cooling
Displacement	150 cc
Compression ratio	12.4:1
Bore × stroke	57.4 × 57.8 mm
Intake valve open[a]	10 deg bTDC
Intake valve close[a]	20 deg aTDC
Exhaust valve open[a]	30 deg bTDC
Exhaust valve close[a]	10 deg aTDC

[a]Valve timing is defined at 1 mm of the valve lift.

555–80 controller produced by Woodward (USA) to control the fuel injection rate and injection timing. The MotoHawk allows the user to automatically generate machine code from SIMULINK diagrams and operate control hardware in real-time operation. The test procedure included warming up the engine with original spark and fuel systems, then switch to HCCI mode with various excess air ratios (λ), EGR rates, and engine speeds. There was no heating for the intake charge.

3 Results and Discussion

Initial test. The initial test was performed to select the appropriate fuel for HCCI operation and determine the basic parameters to run the engine. Three common fuels—gasoline, diesel, and kerosene—were considered for running HCCI in motorcycle engine. Fuel properties are shown in Table 2. After comparing the three different fuels, kerosene was selected due to its ignition characteristics and low viscosity. Gasoline is not easy for autoignition due to its high octane number, and diesel is not good for atomization due to high viscosity; so they are not suitable for HCCI in motorcycle engine.

Many factors influence HCCI combustion and some must be kept constant to eliminate their interference on the experiment. In the initial test, the influences of engine temperature and fuel injection timing were clarified. Temperature is the most important factor for HCCI combustion [4]; however, the engine temperature of an air-cooled engine is not as stable as that of a water-cooled engine and can seriously influence the experimental data. Hence, the engine temperature effect was evaluated by equipping the target engine with a temperature sensor on the cylinder head for indicating engine temperature, as shown in Fig. 1. The cylinder head temperature was varied by a blower for cooling and an insulation material on the engine to keep it warm.

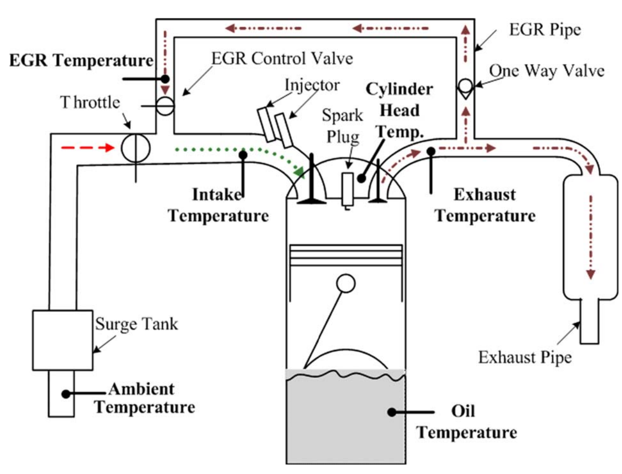

Fig. 1 Schematic diagram of the experimental setup

Table 2 Fuel properties[a]

Fuel	Specific gravity at 15°C	Boiling point (K)	Lower heating value (MJ/kg)	Kinematic viscosity at 40°C (cS)
Gasoline	0.7572	303–483	44	NA
Diesel	0.8	436–630	NA	2.0–4.5
Kerosene	0.8	403–561	43.4	1.0–1.9

[a]Source: China Petroleum Corporation, Taiwan.

Table 3 Effect of cylinder head temperature on combustion

Temparature[a] (°C)	COV (%)	P_{max} (bar)	CA of P_{max} (aTDC)	MRPR (bar/deg)
120	2.7	42.9	14	2.6
130	1.7	45.8	12	3.8
140	1.2	51.8	8	6.6

[a]"Temparature" is the cylinder head temperature.

The effect of cylinder head temperature on combustion is shown in Table 3. When the cylinder head temperature was lower than 110°C, it was very difficult to run HCCI, its cycle variation, which is the coefficient of cyclic variation (COV), is very high, so the temperature range in this test was raised from 120°C to 140°C. As the cylinder head temperature increased, the peak pressure and MRPR increased. Comparing the data in Table 1, the cylinder head temperature was kept at 120–130°C in the following tests.

The fuel injection timing for most port-injection SI engines is set to end the injection before intake valve opening to avoid the liquid fuel from entering into the cylinder directly [14–16]. The HCCI engine with port-injection has a similar effect. The top dead center (TDC) of compression stroke was defined as 0 deg CA, and hence the intake valve opening from −370 deg aTDC (degree after TDC) to −160 deg aTDC.

The emissions of HC and CO, and the COV of IMEP are all decreased during the closed valve injection, as shown in Table 4. However, in such an instance, the maximum rate of pressure rise increases. As a consequence, the injection timing of −90 deg aTDC (i.e., 90 deg bTDC) was chosen for the following experiments.

Effect of λ and EGR. The excess air ratio λ was varied at wide open throttle (WOT) while changing the fuel injection duration without EGR. The exhaust gas was induced into the intake manifold by partially closing the throttle. In such circumstances, the EGR rate increased as the throttle opening decreased. The fuel duration was kept constant during EGR testing.

The effect of λ ranging from 2.4 to 3.2 on heat release rate (HRR) is shown in Fig. 2. The HRR was calculated from experimental cylinder pressure data by using the model developed by Wu et al. [17]. It was a fuel injection duration sweep with fixed WOT. Peak HRR slows down when the excess air ratio increases. Two-stage heat release are found in the kerosene HCCI combus-

Table 4 Effect of fuel injection timing on combustion

Injection (aTDC)	COV (%)	IMEP (bar)	P_{max} (bar)	MRPR (bar/deg)	CO (%)	HC (ppm)
−360	3.97	5.05	38.7	1.55	0.31	422
−270	2.95	5.10	40.9	2.25	0.25	372
−180	2.65	5.22	42.7	2.84	0.22	340
−90	2.27	5.22	44.0	3.06	0.23	348
0	2.13	5.19	44.0	3.05	0.23	352
90	2.04	5.15	44.1	3.49	0.22	356
180	2.00	5.09	43.4	3.06	0.22	362
270	1.94	5.14	45.3	3.30	0.22	404

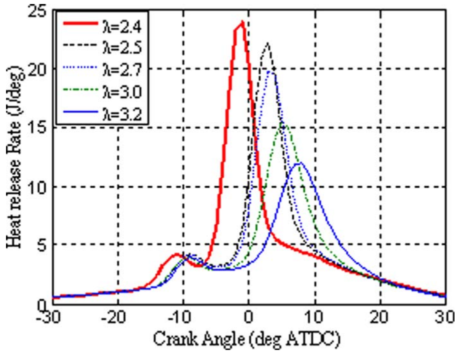

Fig. 2 Effect of excess air ratio (λ) on the heat release rate at 1500 rpm

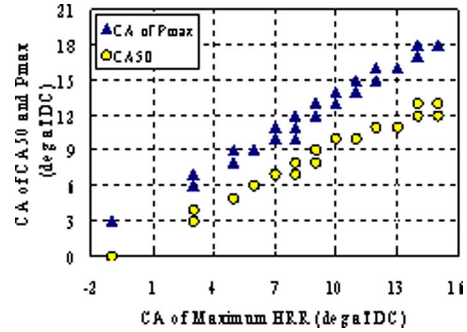

Fig. 3 Relationship between the timings of CA50, cylinder peak pressure, and maximum HRR

tion, as shown in Fig. 2. Low temperature heat release adds to heat in the cylinder early in the compression stroke and has the effect of enhancing ignition and advancing combustion phasing [18].

The peak pressure and MRPR decrease and the COV increases when λ or EGR increase (see Tables 5 and 6). This is because lower concentration of fuel or in-cylinder O_2 slows down the reaction rate. Fuel concentration decreases with increasing λ, and the in-cylinder O_2 concentration decreases with increasing EGR. As the concentration of fuel or O_2 decreases further, the ignition will be too late and even causes misfire. It is interesting to note that the indicated mean effective pressure (IMEP) keeps almost constant with increasing EGR at constant fuel injection duration (see Table 6). This means that a part of the exhaust gas that replaces fresh air may decrease peak pressure and MRPR without deteriorating the engine output. By the way, the COV does not increase much, as shown in Table 6.

The MRPR and COV of the IMEP are used as an index for the combustion quality in this paper. At higher loads, the maximum rate of cylinder pressure rise is too high. The high MRPR not only causes combustion noise [19], but also exceeds the material limits of the rings on a piston engine [4]. Some previous researchers set the limit of MRPR at 5 bar/deg [10] or 6 bar/deg [19]. On the opposite side, at low loads, the combustion becomes unstable, leading to high COV and emissions of HC and CO. Sun et al. [19] reported that the level of 3% COV of the IMEP would be considered acceptable in the industry for a throttled SI engine or diesel engine in the development stage.

Table 5 Effect of excess air ratio on combustion

λ	COV (%)	IMEP (bar)	P_{max} (bar)	MRPR (bar/deg)	CO (%)	HC (ppm)
2.4	2.90	5.29	42.1	9.57	0.08	402
2.5	2.72	5.32	47.1	7.93	0.13	410
2.7	2.64	5.12	52.2	5.93	0.17	386
3.0	3.75	4.74	54.2	3.81	0.25	412
3.2	4.69	4.41	57.1	2.26	0.47	430

Table 6 Effect of EGR rate on combustion

EGR (%)	COV (%)	IMEP (bar)	P_{max} (bar)	MRPR (bar/deg)	CO (%)	HC (ppm)
15	1.51	5.16	50.1	5.42	0.23	490
20	1.60	5.00	47.0	4.33	0.27	494
25	1.57	5.01	47.6	4.20	0.26	498
30	2.09	4.88	39.5	2.04	0.41	528
35	2.32	4.98	36.9	1.49	0.44	542

The emission of CO increases with increasing λ or EGR (see Tables 5 and 6) due to the low combustion temperature. Sjöberg and Dec [20] reported that CO oxidation does not reach completion with a peak temperature below 1500 K, since the OH level becomes too low.

Overall combustion characteristics. All experimental data which include a speed range of 1500 rpm, 2000 rpm, and 2500 rpm, with various excess air ratios and EGR rates, were analyzed to observe the overall combustion characteristics. The total number of data sets is 39.

CA50 is used as a good index for the combustion phasing, which is defined as the engine's crank angle position, where 50% of the cumulative heat release is achieved [4,21]. The timings of CA50, maximum HRR, and peak pressure are correlated with each other very well, as shown in Fig. 3. They have very good linear correlations.

As shown in Fig. 4, high peak cylinder pressure causes high MRPR, but when the peak pressure is lower than 40 bar, the MRPR is pretty low and not affected by the peak pressure. One of the factors increasing MRPR is the early timing of peak cylinder pressure, as shown in Fig. 5. The timing of cylinder peak pressure around 10–15 deg CA aTDC is correlated with the cylinder peak pressure ranging between 40–50 bar, which causes the MRPR to be less than 6 bar/deg.

4 Conclusion

HCCI combustion was operated on a 150 cc air-cooled, four-stroke motorcycle engine. Kerosene fuel was used without intake air heating and operated at various excess air ratios, engine speeds, and EGR rates. Measurements of various combustion characteristics and emissions on the target engine have led to the following conclusions:

(1) The cylinder head temperature of air-cooled engines varied

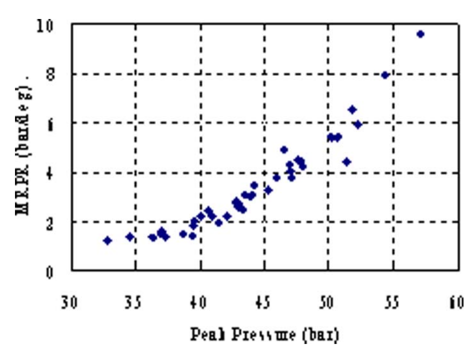

Fig. 4 Relationship between MRPR and peak pressure

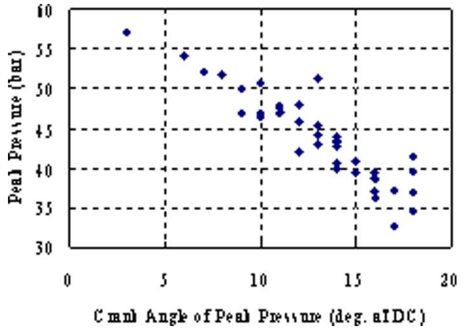

Fig. 5 Relationship between peak pressure and timing of peak pressure

very much according to the ambient temperature. It is important to keep at a certain value in order to conduct a stable experiment in HCCI combustion.

(2) Injecting fuel during the intake valve closing is better for air-fuel mixing. An injection timing of 90 deg bTDC of compression stroke was selected for this study.

(3) Higher λ or EGR causes lower peak pressure, lower rate of pressure rise, and higher CO emission. However, EGR is better than excess air for decreasing the peak pressure and MRPR without deteriorating the engine output.

(4) The timings of CA50, maximum HRR, and peak cylinder gas pressure are correlated with each other very well. When the cylinder peak pressure occurs at around 10–15 deg CA aTDC, it indicates a good appearance for low MRPR.

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Nomenclature

P = pressure
T = temperature

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