Combustion Control of a Small HCCI Engine 
Fuelled with DME 
using Hot and Cold EGR Gas*

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Abstract
One of the main challenges of HCCI engine research is developing a system to control the combustion phasing to achieve a stable operation. Though some HCCI combustion control systems have been suggested, they are heavy in weight and complex in mechanism. In this study, a simple combustion control system and an algorithm for a lightweight small-sized handy electrical generator HCCI engine fuelled with DME were developed and evaluated experimentally. In this system, the ratio of stoichiometric DME/air pre-mixture, Hot EGR gas and Cold EGR gas were adjusted by throttles. The experimental results showed that combustion phasing can be controlled through adjusting the mass-averaged in-cylinder gas temperature at intake valve closure timing by changing the ratio of Hot EGR gas and Cold EGR gas. Moreover, IMEP was PI (Proportional and Integral) feedback controlled by fuel flow rate, while the combustion phasing and equivalence ratio were PI feedback controlled by throttles. As a result, it is possible for these parameters to follow their set values.

Key words: Homogeneous Charge Compression Ignition Engine, HCCI, DME, EGR, Cyclic Variability, Rebreathing, Ignition Timing

1. Introduction

HCCI (Homogeneous Charge Compression Ignition) engine has the potential to achieve lower NOx and PM emissions with high thermal efficiency. In HCCI engine, air and fuel are charged homogeneously in the combustion chamber. Then the temperature of the mixture is increased during the compression stroke. Ignition occurs when the in-cylinder temperature reached the auto-ignition temperature of the fuel (1). Despite the merits, HCCI engine has some challenges. Firstly, as the ignition is determined by chemical kinetics, a system to control the combustion phasing should be developed. Secondly, as the auto-ignition occurs simultaneously in the combustion chamber, knocking is caused by excessive pressure rise rate at high load. Additionally, the low combustion temperature leads to higher HC and CO emission than SI and Diesel engines. CA50 is very important in controlling the combustion phasing of HCCI engine. And controlling CA50 in expansion stroke will lead to high thermal efficiency and avoid an excessive pressure rise rate. Some HCCI combustion control systems have been proposed using Variable Valve Timing System (2), Variable Compression Ratio System (3) or dual fuel system (4)(5). However, they are too heavy and complex to be suit for a lightweight and small-sized handy electrical
generator HCCI engine. In this paper, we developed a simple combustion control system and an algorithm for this kind of small HCCI engine fuelled with DME. In this system, the ratio of stoichiometric DME/air pre-mixture, Hot EGR gas and Cold EGR gas was adjusted only by throttles. Moreover, the performance of this system as well as its algorithm was experimentally evaluated.

2. HCCI Combustion Control Concept

Figure 1 shows the concept of the HCCI combustion control system of this study. As is shown, IMEP, dependent on input heat quantity per cycle, is controlled by the amount of stoichiometric DME/air pre-mixture. CA50, an index of combustion phasing, is controlled through adjusting the mass-averaged in-cylinder gas temperature at intake valve closure timing by changing the ratio of Hot EGR gas and Cold EGR gas. Additionally, the maximum pressure rise rate is controlled under the knocking limit through adjusting the amount of Cold EGR gas which consists of lots of inert gases. And in order to maintain high combustion efficiency, the maximum in-cylinder gas temperature is controlled above 1500K by controlling the quantity of the stoichiometric DME/air pre-mixture. Consequently, the HCCI operation with high thermal efficiency and exempt from knocking is realized by changing the ratio of stoichiometric DME/air pre-mixture, Hot EGR gas and Cold EGR gas.

3. HCCI Combustion Control System

3.1 Test fuel

For lightweight and small-sized engines, compression ratio must be low considering the engine strength. Therefore, the fuel that is superior in ignition characteristics is needed. In this study, we choose DME as the fuel. DME has two step heat release, called LTHR (Low Temperature Heat Release) and HTHR (High Temperature Heat Release), respectively. Moreover, it has low auto-ignition temperature compared with n-Butane and Methane. As a result, it is superior in ignition characteristics.

3.2 Test engine

Engine used in this study is based on a HONDA GX340K1 four-stroke single cylinder gasoline engine. Its specifications are given in Table 1.
Table 1  Configuration of the single cylinder engines(IVO, intake valve opening; IVC, intake valve closing; EVO, exhaust valve opening; EVC, exhaust valve closing; ABDC, after bottom dead center; EVRO, exhaust valve rebreathing opening; EVRC, exhaust valve rebreathing closing)

<table>
<thead>
<tr>
<th>Base Engine</th>
<th>HONDA GX340K1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bore × Stroke</td>
<td>82mm × 64mm</td>
</tr>
<tr>
<td>Displacement</td>
<td>337cc</td>
</tr>
<tr>
<td>Compression Ratios</td>
<td>8.13, 9.12, 10.76</td>
</tr>
<tr>
<td>Cooling Type</td>
<td>Air Cooling</td>
</tr>
<tr>
<td>Number of valves</td>
<td>2</td>
</tr>
<tr>
<td>IVO, IVC</td>
<td>175˚, 35˚ABDC</td>
</tr>
<tr>
<td>EVO, EVC</td>
<td>-35˚, -175˚ABDC</td>
</tr>
<tr>
<td>EVRO, L2.1</td>
<td>-155˚, 5˚ABDC</td>
</tr>
<tr>
<td>EVRC, L1.6</td>
<td>-131˚, 5˚ABDC</td>
</tr>
<tr>
<td>EVEC, L1.0</td>
<td>-119˚, 5˚ABDC</td>
</tr>
<tr>
<td>L0</td>
<td>- , -</td>
</tr>
</tbody>
</table>

3.3 Two stage exhaust cam system

A two stage exhaust cam system is used to introduce Hot EGR gas. Exhaust gas is re-breathed from the exhaust port into the combustion chamber as Hot EGR gas by re-opening the exhaust valve during the inlet stroke. In this work, four kinds of camshaft, with different exhaust valve profile during the inlet stroke, are produced. And each camshaft is named according to the maximum lift of the exhaust valve during the inlet stroke. Figure 2 shows the profiles of these cams.

![Fig. 2](image)

3.4 Gas mixing ratio control system

The schematic diagram of the HCCI combustion control system is shown in Figure 3. In this system, Cold EGR, cooled by water-cooling heat exchangers, and stoichiometric DME/air pre-mixture are mixed in the inlet manifold. Then, the mixture is introduced into the combustion chamber through the inlet port. Additionally, as stated above, Hot EGR gas is introduced into the combustion chamber by using the two stage exhaust cam system. The ratio of stoichiometric DME/air pre-mixture, Hot EGR gas and Cold EGR gas was adjusted by four throttles. As shown in the figure, Air Throttle A and Intake Throttle B are placed in the inlet manifold, while Exhaust Throttle C and Cold EGR Throttle D are placed in the exhaust pipe and the flow path of Cold EGR gas, respectively. Besides, a stepping motor, with a set speed of 20rpm (the throttle rotate .6deg during an engine cycle), is fixed on each throttle to control its position. Fuel is introduced by a fuel injector(spray hole $\Phi=2mm$), which is mounted in the inlet port. And the fueling rate is under the control of the digital mass flow controller. The fuel injection start timing is 20ATDC deg and the injection duration is 80deg.
**Fig. 3** Single cylinder HCCI combustion engine with 4 throttles and rebreathing exhaust cam profile (cold and hot EGR management and rebreathing exhaust cam operation for CA50 and IMEP control)

### 3.5 Measurement system

The in-cylinder gas pressure $P(\theta)$ is measured by a piezoelectric transducer, which is equipped at the top of the cylinder head and connected to an external charge amplifier. A strain gauge absolute pressure sensor is used to measure the intake gas pressure in the inlet port, $P_{in}$. A rotary encoder is fixed at the crankshaft, and both the in-cylinder gas pressure and the inlet gas pressure are measured with a timing resolution of 1 crank angle degree. Intake gas temperature $T_{in}$ and exhaust gas temperature $T_{ex}$ are measured by K type thermocouples, equipped in the inlet port and the exhaust port, respectively. Consequently, based on the inputs from the laminar flow meter, the piezoelectric transducer, the strain gauge absolute pressure sensor, and the set value of mass flow controller and the stepping motors, PXI system from National Instruments, as well as the Lab VIEW 7.1 software, is used for data acquisition, real-time analysis and control.

### 4. Results and Discussion

#### 4.1 Experimental condition

In this study, all experiments were conducted with the engine speed $Ne=1500$rpm, and the compression ratio $\varepsilon=10.76$. And Cam L2.1 (lift = 2.1mm) was used. In addition, Intake Throttle B and Exhaust Throttle C were held fully open, while the position of Air Throttle A $\Theta_A$ and Cold EGR Throttle D $\Theta_D$ were variables.

#### 4.2 HCCI combustion characteristics

This section shows the experimental results of steady state HCCI combustion with different Air Throttle A and Cold EGR Throttle D positions. In this study, the histories of in-cylinder gas pressure are the average value of the in-cylinder gas pressure measured in 64 cycles. And other analysis were based on these average values.

#### 4.2.1 CA50 control with mixing ratio of Hot EGR gas and Cold EGR gas

Firstly, we evaluate the validity of this HCCI combustion control system. Figure 4 shows many information about this system, such as, gas mass ratio $\gamma$, mass-averaged in-cylinder gas temperature at intake valve closure, rate of heat release, and combustion duration with different and, while the fueling rate $Q_{in}=370.5\pm0.3$J/cycle. As both Air Throttle A and Cold EGR Throttle D were opened, Hot EGR gas mass ratio decreased while...
Cold EGR gas mass ratio increased. Consequently, $T_{IVC}$ fell with constant $Q_{in}$. It was found that the LTHR and HTHR appearance timing and CA50 was delayed with the fall of $T_{IVC}$. In these conditions, $T_{LTHR}$, $T_{HTHR}$ and $Q_{LTHR}$ were almost constant ($T_{LTHR}$=799±9K, $T_{HTHR}$=992±8K, $Q_{LTHR}$=27.2±0.8J). Therefore, CA50 can be controlled through adjusting the mass-averaged in-cylinder gas temperature at intake valve closure $T_{IVC}$ by changing the ratio of Hot EGR gas and Cold EGR gas with constant $Q_{in}$.

4.2.2 Optimum CA50 validation

Figure 5 shows the effects of CA50 on indicated thermal efficiency $\eta_i$, maximum pressure rise rate ($\frac{dP}{d\theta}$)$_{max}$, and coefficient of variation of IMEP $CV_{IMEP}$ during 64 cycles when $Q_{in}$ is 390-400, 360-370 and 310-320 J/cycle. As shown in the figure, indicated thermal efficiency increased with the delay of CA50 and had the maximum value (42%) around 6 ATDC deg. And the maximum pressure rise rate was also strongly relevant to CA50 and decreased with the delay of CA50. For the developed engine, the knocking limit of the maximum pressure rise rate is 0.45MPa/deg (4MPa/ms). Moreover, $CV_{IMEP}$ stayed...
below 4% when CA50=0-6 ATDC deg, and increased rapidly after CA50 was delayed to more than 8 ATDC deg, where misfire nearly occurred. Therefore, CA50 should be controlled around 6 ATDC deg for the developed engine, considering the indicated thermal efficiency, the maximum pressure rise rate and $CV_{\text{IMEP}}$.

4.2.3 Developed HCCI engine performance

Figure 6 shows the performance of the developed engine compared with that of its conventional counterparts, whose specifications are shown in Table 2. As is shown, the indicated thermal efficiency of developed engine is over 38%, which is higher than that of the SI engine, from which the HCCI engine was modified. As for IMEP, developed HCCI engine is able to achieve the value from 0.32MPa to 0.49MPa under stoichiometric DME/air pre-mixture condition.
4.2.4 Analysis of cyclic dispersion

Figure 7 shows the IMEP and CA50 of 20 cycles which include misfire condition. And Figure 8 shows the histories of rate of heat release from 13th to 17th cycle. In these experiments, the position of Air Throttle $\Theta_A=13\text{deg}$, the position of Cold EGR Throttle $\Theta_D=0\text{deg}$, and fueling rate $Q_{in}=254.61\text{J/cycle}$. As shown in the figures, the IMEP of 14th and 15th cycle are lower than that of other cycles. Moreover, in 15th cycle, only low temperature heat release can be observed. And it is thought that exhaust gas temperature began decreasing from 14th cycle. However, although misfire happened in 15th cycle, knocking occurred in 16th cycle due to the excessive rate of heat release. The reason is that the introduced Hot EGR gas of 16th cycle contained a lot of unburned fuels of 15th cycle. Therefore, high temperature Hot EGR gas was introduced in 16th cycle, and consequently, HCCI combustion was persistent.

![Fig. 6 Performance of the modified HCCI engine compared with that of conventional engines](image)

![Fig. 7 Cyclic variations patterns of IMEP and CA50 with weak (misfire) cycles](image)
4.3 HCCI combustion control

In this section, control algorithm is developed base on the results of steady state HCCI combustion. And this algorithm is evaluated by experiment.

4.3.1 Construction of HCCI combustion control algorithm

Figure 9 shows the block diagram of constructed HCCI control algorithm. In this study, equivalence ratio, CA50 and IMEP are controlled parameters, and PI(Proportional and Integral) feedback control method is used. IMEP is controlled by the fuel flow rate $F_{\text{fuel}}$. Equivalence ratio $\phi$ is controlled by the position of Air Throttle $\Theta_A$ which adjusts the air flow rate $F_{\text{air}}$. CA50 is controlled by the position of Cold EGR Throttle $D \Theta_D$ which adjusts the amount of Cold EGR gas. Although these controllers interfere with each other, the effects of the interference are neglected. Additionally, the feedback signal of equivalence ratio is calculated from the air flow rate measured by laminar flow meter and the fuel flow rate set value of mass flow controller. Feedback signals of CA50 and IMEP are calculated from in-cylinder gas pressure $P(\theta)$. Considering cyclic dispersion, the average value of past three cycles is used as the feedback signal. The position of Air Throttle A and Cold EGR Throttle are controlled every cycle. However, the fuel flow rate is controlled every three cycles, since there is a communication interval between computer and mass flow controller. The proportional gain and the integral gain in Fig 9 are determined by try and error of step change of IMEP and CA50. Furthermore, in HCCI engine, a control algorithm relating knocking and misfire is necessary. Therefore, in this study, other algorithms are applied preferentially to fuel flow rate control when knocking and/or misfire occurs.
a. In case of knocking

An algorithm which forcibly reduces fuel flow rate when knocking occurs is developed. When the maximum pressure rise rate of the past three cycles exceeds 0.45MPa/deg, it is judged as knocking and the set value of fuel flow rate will be reduced by 0.5ml/cycle (2.4J/cycle) from that of the previous cycle. By doing this, knocking will be avoided and IMEP will fall in the next cycle. However, the optimization of CA50, realized by adjusting the amount of EGR gas, will keep IMEP constant with high efficiency and new set value of fuel flow rate. The reducing magnitude of fuel flow rate was based on experiment results.

b. In case of misfire

In this study, IMEP is PI controlled by fuel flow rate. Therefore, when misfire occurs, IMEP will be very small and the set value of fuel flow rate for the next cycle will increase precipitously, which will lead to hunching. However, for the developed engine, as verified in 4.2.4, when misfire occurs, combustion is persistent without any control. Considering this, when indicated thermal efficiency falls below 30% of the past three cycles’ average value, it is judged as misfire, and the set value of fuel flow rate is kept the same as that of the previous cycle.

Fig. 9 Block diagram of Equivalence ratio, CA50 and IMEP feedback control

4.3.2 Results of HCCI combustion control

Figure 10 and 11 show the results of positive and negative step change of IMEP, respectively. In both experiments, the set value of CA50 was 6 ATDC deg and the set value of IMEP was changed between 0.35MPa and 0.45 MPa. Moreover, the ● plots in Figure 10 indicates the cycles where knocking algorithm was run, while the × plot in Fig 11 indicates the cycle where misfire algorithm was run. As shown in Fig 10, when positive step change was imposed on IMEP set value, fuel flow rate increased precipitously, as a result, equivalence ratio increased and CA50 advances. Then, in order to follow the set value of equivalence ratio and CA50, the position of Air Throttle A and Cold EGR Throttle D were changed. However, there was a time-lag before IMEP followed its new set value, since the position of Air Throttle A and Cold EGR Throttle D interfered with each other and it is impossible to enlarge the control gain. Moreover, knocking occurred mainly from 270th cycle to 470th cycle, since it was impossible to follow the set value of CA50, which was advanced due to the increase of fuel flow rate. If the knocking algorithm were not applied, fuel flow rate would be increased persistently, and, as a result, the maximum pressure rise rate would be continuously beyond
the knocking limit. Therefore, it can be claimed that the knocking algorithm was effective for avoiding knocking. However, there is a time-lag effects, as shown above. The reason for this is considered to be that in the fuel rich combustion condition, IMEP was increased while fuel flow rate was decreased. Under this condition, the influence of equivalence ratio, changed by the air flow rate, is larger than that of the change of fuel flow rate.

Fig. 10  Cyclic variations of IMEP, CA50, Equivalence ratio, Opening angle of throttle A and throttle D, Fuel flow rate and Maximum PRR when changing IMEP set value from 0.35 to 0.45MPa
Fig. 11 Cyclic variations of IMEP, CA50, Equivalence ratio, Opening angle of throttle A and throttle D, Fuel flow rate and Maximum PRR when changing IMEP set value from 0.45 to 0.35MPa

Similar as in Figure 10, in Figure 11, both CA50 and equivalence ratio were influenced by the change of fuel flow rate. Besides, there was also a time-lag effect in the negative step change condition. However, the transient performance of negative step change is better than that of the positive one. In the positive step change it takes 250 cycles (20s) for IMEP to follow its set value, while, in the negative step change, it takes only 100 cycles (8s). This is because, in negative step change, it is air rich condition, and the change of fuel flow rate affects on combustion rapidly. Furthermore, the misfire algorithm was applied around 300th cycle, which prevented hunching.

In this study, equivalence ratio, CA50 and IMEP are feedback (PI) controlled by the position of Air Throttle A, Cold EGR Throttle D and fuel flow rate. However, there are some problem, such as interference and time-lag. To improve the transient performance and the stability of the control system, it is necessary to combine feedback control, feed forward control and the model predicting the position of throttles together to provide optimum gases mixing ratio against the change of fuel flow rate.
4. Conclusions

In this study, a simple control system and an algorithm for a lightweight small-sized handy electrical generator HCCI engine fuelled with DME were proposed and evaluated experimentally. In this system, the ratio of stoichiometric DME/air pre-mixture, Hot EGR gas and Cold EGR gas was adjusted by throttles. Consequently, CA50 and IMEP of the developed engine were controlled. The results are summarized as follows:

1. By designing and constructing intake and exhaust system that provide wide control range of mixing ratio of three gases by throttles, developed system achieved from IMEP=0.32MPa to 0.49MPa under $\varepsilon=10.76$ and stoichiometric premixture condition keeping high indicated thermal efficiency as diesel engine.

2. In developed HCCI engine, it is necessary to control CA50 around 6 ATDC deg in order to maintain high indicated thermal efficiency with low maximum rate of pressure rise and COV of IMEP. It is possible to control CA50 by adjusting the mixing ratio of Hot EGR gas and Cold EGR gas.

3. In an engine which uses a large amount of Hot EGR gas, even if misfire occurs, combustion continues without any control, because much unburned fuel is contained in Hot EGR gas.

4. Under the constant engine speed, it is possible to follow the set value of IMEP, CA50 and equivalence ratio by feedback controlling fuel flow rate and position of throttles. However it is necessary to combine feedback control and feed forward control with model because there are some problems such as interfere and time -lag.

5. An algorithm which decreases fuel flow rate forcibly when knocking and an algorithm which keeps fuel flow rate same as previous cycle when misfire are applied to feedback control. These algorithms enable avoidance of knocking and prevent hunching caused by misfire.

References