

Extension of Operating Range of a Multi-Cylinder Gasoline HCCI Engine using the Blowdown Supercharging System

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ABSTRACT

The objective of this study is to develop a practical technique to achieve HCCI operation with wide operation range. To attain this objective, the authors previously proposed the blowdown supercharge (BDSC) system and demonstrated the potential of the BDSC system to extend the high load HCCI operational limit. In this study, experimental works were conducted with focusing on improvement of combustion stability at low load operation and the reduction in cylinder to cylinder variation in ignition timing of multi-cylinder HCCI operation using the BDSC system. The experiments were conducted using a slightly modified production four-cylinder gasoline engine with compression ratio of about 12 at constant engine speed of 1500 rpm. The test fuel used was commercial gasoline which has RON of 91.

To improve combustion stability at low load operation, the valve actuation strategy for the BDSC system was newly proposed and experimentally examined. With the newly proposed valve actuation strategy, only intake valve lift was varied and EGR and exhaust valve lifts were fixed with variation in target load. Compared to the previously proposed valve actuation strategy for the BDSC system, relatively late EGR valve opening timing with early intake valve closing timing is applied at low load condition in the proposed strategy.

This provides high in-cylinder temperature and relatively rich fuel concentration at low load operation while providing a large amount of diluted mixture at high load operation. Additionally, effect of coolant water temperature on combustion stability was experimentally investigated. Coolant water temperature was varied from 85°C to 105°C. Experimental result showed that for low load HCCI operation, the valve timing with early intake valve closing and relatively late EGR valve opening was effective to increase combustion stability due to increases in in-cylinder temperature and fuel concentration. With early intake valve closing and relatively late EGR valve opening, a stable HCCI operation at net IMEP of 200 kPa was achieved. However, brake thermal efficiency was slightly deteriorated due to increase in pumping work utilized to increase in in-cylinder temperature. The increase in coolant water temperature also improved combustion stability and extends the low load operational limit due to increase in in-cylinder temperature. With a cooling water temperature of 105°C, the low load HCCI with net IMEP of 134 kPa was attained.

In addition, to reduce the cylinder to cylinder variation in ignition timing which restricts HCCI operating range with multi-cylinder operation, the secondary air injection system in which air is injected into an exhaust port of each cylinder to

control recharged EGR gas temperature using gas fuel injector was proposed and examined to control ignition timing of each cylinder independently. As a result, the cylinder to cylinder variation in ignition timing was successfully reduced and the high load HCCI operational limit with four-cylinder operation was extended up to net IMEP of 570 kPa. Compared to conventional SI operation, brake thermal efficiency was improved by about 15% using the newly proposed strategy with more than 99% reduction in NO_x emission.

INTRODUCTION

Homogeneous charge compression ignition (HCCI) combustion has a high potential to increase thermal efficiency of internal combustion engines with low NO_x and particulate emissions. Due to limited operational range in terms of engine speed and load, HCCI operation is regarded as a part load operation strategy. To apply HCCI combustion into practical engine operation strategy, operation mode switching between HCCI operation and conventional SI operation at low load and high load would be necessary. To take advantage in low fuel consumption rate of HCCI operation, extending HCCI operating range and reducing frequency of the operation mode switching are important.

The negative valve overlap in which a large amount of high temperature burned gas is trapped inside the cylinder before intake valve opening is widely used to attain HCCI operation[1]. So called the rebreathing method in which the exhaust gas is directly recharged from exhaust manifold by reopening exhaust valve during the intake stroke is also one of the common techniques to attain HCCI operation[2]. Urata et al[3] reported that the high load operational limit of HCCI operation using the NVO method with compression ratio of 11.5 was about 400 kPa in *gross IMEP* at 1500 rpm. Hiraya et al[4] also showed the high load limit with NVO method was 430 kPa. Fuerhapter et al.[2] showed the upper load limit using the rebreathing method was IMEP of 470 kPa (*gross* or *net IMEP* is not specified in [reference \[2\]](#) and [4]). The upper load limit of HCCI operation attained by the NVO or the rebreathing method is much lower than that required in practical usage[3].

The high load HCCI operation is restricted by increase in in-cylinder pressure rise rate ($dP/d\theta$) and NO_x emission due to lack of dilution gas consisting of intake air and EGR gas. Thereby, supercharging is effective to achieve much higher load HCCI operation [5]. In early studies about supercharged HCCI operation, Cristensen et al.[6] extended the upper load limit up to *gross IMEP* of 1.6 MPa using natural gas as a test fuel. In recent studies, supercharged HCCI operation with cooled EGR at *gross IMEP* of 1.6 MPa was experimentally demonstrated with conventional gasoline by Dec et al.[7]. However, using mechanical supercharger, brake thermal efficiency decreases and maximum *BMEP* decreases due to the high mechanical loss of superchargers [5], [8]. On the other hand, turbocharger would not be effective for HCCI operation because providing effective intake boost pressure using

turbocharger is supposed to be difficult because of low exhaust energy of the HCCI combustion. Takanashi et al. [9] developed the inter-cylinder EGR boost system to obtain a large amount of dilution gas without external supercharger. Using this system, the upper load limit defined by maximum pressure rise rate ($dP/d\theta_{\max}$) of 400 kPa/degree was extended up to *gross IMEP* of 600 kPa. However, this system is difficult to be applied into a production engine because the fully variable valve actuation with large degree of freedom with the special exhaust system used in this system requires complex constructions in the hardware and controlling system. In-cylinder thermal stratification is also shown to have a possibility to reduce $dP/d\theta_{\max}$ and to extend the upper load limit of HCCI operation. Sjöberg and Dec [10], [11], [12], [13] investigated the effect of in-cylinder thermal stratification mainly generated by heat transfer between the cylinder wall and in-cylinder mixture on $dP/d\theta_{\max}$ by experimental and numerical methods. The potential of the in-cylinder thermal stratification for reducing $dP/d\theta_{\max}$ was quantitatively demonstrated using a multi-zone chemical kinetics model. The multi-zone numerical analysis result revealed that providing a wider temperature distribution of the core of the in-cylinder mixture, combustion duration prolonged and $dP/d\theta$ decreased[11]. Also, it is experimentally revealed that thermal stratification within the bulk gas controls $dP/d\theta_{\max}$ and that temperature distribution generated by the heat transfer to the cylinder wall plays less role in reducing $dP/d\theta_{\max}$ [13]. It is considered that to generate a large thermal stratification within the bulk gas zone, techniques to reduce mixing between relatively low temperature intake mixture and hot EGR gas is necessary. However, insufficient mixing between fresh air-fuel mixture and EGR gas provides a spatial distribution of in-cylinder mixture composition [14][15]. Krasselt et al. [16] and Herold et al. [17] investigated the effect of in-cylinder stratifications of temperature, fuel concentration, A/F and specific heat ratio on $dP/d\theta$ using a single cylinder engine and an optical engine. The result revealed that the effect of the stratification of in-cylinder mixture temperature on $dP/d\theta$ could be canceled out by the competing effect of the distributions of fuel concentration and A/F . From these result, they suggested that the in-cylinder stratification is not introduced into a production engine because the magnitude of stratification maintained until combustion commenced is quite limited and the temperature stratification is accompanied by distributions of fuel concentration and A/F . By contrast, the simulation result carried out by Babajimopoulos [14],[15] using 3-D simulation of in-cylinder flow and multi-zone chemical kinetics showed that though the distribution of equivalence ratio has competing effect against the effect of temperature distribution on ignition, temperature distribution is still dominant factor that determines ignition timing.

The limiting factors for the low load HCCI operation is the decrease in combustion stability and the increases in unburned HC and CO emissions due to the decrease in fuel concentration with decreasing the amount of supplied fuel. One of the

common techniques to extend the lower load limit is direct fuel injection during the NVO period proposed by Willand et al.[1]. This technique was experimentally demonstrated to improve combustion stability and extend the lower load limit [18]. Using the direct injection during the NVO period, stable HCCI operations at an *gross IMEP* of 150 kPa with compression ratio of 15.0 and *gross IMEP* of 250 kPa with compression ratio of 11.5 have been reported [3], [18]. The chemiluminescence images observed during the NVO period indicate that fuel injected during the NVO period partially reacts during the NVO period. This partial heat release would increase in internal EGR gas temperature and thereby combustion stability would be improved [3][18]. However, as mentioned above, limited higher load operation and difficulty of operation mode switching between HCCI and SI due to large difference between the valve timing between NVO method used and that conventional SI operation mode are issues of HCCI operation with NVO technique. Dec [19] investigated the main source of CO and HC emission in low load HCCI operation using 0-D chemical kinetics simulation and revealed that CO and HC emission in HCCI combustion with well mixed mixture is mainly produced by incomplete bulk gas reaction due to decrease in in-cylinder fuel concentration with decreasing operation load. This implies that stratified fuel concentration with local fuel rich zone is possible to improve combustion efficiency at low load HCCI combustion. It has been reported that direct fuel injection during the latter part of compression stroke could control ignition timing leading to improved combustion stability and combustion efficiency at low load HCCI operation. However, NO_x emission generally increased with fuel stratification [20], [21], [22], [23], [24]. Intake throttling has been also examined to improve combustion stability and combustion efficiency at low load HCCI operation [25], because the intake throttling increases fuel concentration and exhaust gas temperature at given operation load. In summary, to extend the upper load limit of HCCI operation, a technique capable of obtaining a large amount of intake mixture would be necessary, even though turbocharger is applied. Also, providing a strong thermal stratification within the bulk gas zone has potential for allowing much higher load HCCI operation by decreasing $dP/d\theta_{\max}$. On the other hand, to attain stable low load HCCI operation and to reduce HC and CO emissions at low load HCCI operation, relatively high fuel concentration and high in-cylinder temperature are required. This indicates that the amount of dilution gas has to be appropriately controlled with variation in target load so that the fuel concentration is relatively leaner for high load operation and richer for lower load operation.

Additionally, cylinder to cylinder variation in ignition timing is also one of the limiting factors of operating range with multi-cylinder HCCI engines. In the four-cylinder HCCI operation test conducted by Flowers et al.[26], there was significant cylinder to cylinder variation in combustion timing, and the difference in combustion timing between cylinders increased with combustion timing retarding. It is concluded

that reducing the phase difference in combustion timing between the cylinders is necessary to achieve higher *BMEP*. The benefit of reduction in the cylinder variation in combustion timing can be seen in reference [27]. Closed loop control system which controls fuel injection duration and spark ignition timing of each cylinder and the amount of external EGR gas was developed to reduce the cylinder to cylinder variation in ignition timing of SI-CI engine. It is found that the cylinder variation in air-fuel ratio significantly affects the cylinder variation in ignition timing. It is also shown that combustion phasing control could decrease the average ringing intensity which is an indicator of the combustion noise associated $dP/d\theta_{\max}$ without decreasing combustion stability by providing stable retarded combustion. Considering practical usage, reducing the cylinder to cylinder variation in combustion timing is necessary to extend the operating range with multi-cylinder HCCI engine.

The objective of this study is to develop a practical technique to achieve HCCI operation with wide operating range. To attain this objective, the authors proposed the blowdown supercharge (BDSC) system and the EGR guide which can obtain a large amount of dilution gas without external supercharger and a strong in-cylinder thermal stratification as a practical technique to extend the high load HCCI operational limit [28], [29]. The in-cylinder thermal stratification generated by reducing mixing between intake gas and EGR gas using the proposed technique successfully decreased $dP/d\theta_{\max}$ at high load HCCI operation. As a result, high load HCCI operational limit was extended up to *net IMEP* of 580 kPa (*gross IMEP* of 615 kPa) which covers almost whole operating range used in typical urban driving with the acceptable levels of $dP/d\theta_{\max}$ and NO_x emission [29]. However, the details of low load HCCI operation using the BDSC system have not been investigated, yet. Also, the in-cylinder pressure analysis in the previous study was conducted focusing attention on only one cylinder of four-cylinder engine. Considering practical usage, low load limit and performance of multi-cylinder HCCI operation should be clarified. In the present study, the valve actuation strategy which improves the combustion stability at low load HCCI operation using the BDSC system was examined. Also, basic performance of four-cylinder HCCI engine using the BDSC system was investigated with reduced cylinder to cylinder variation in ignition timing using the newly developed ignition timing control system.

BLOWDOWN SUPERCHARGING (BDSC) SYSTEM AND SECONDARY AIR INJECTION SYSTEM

BLOWDOWN SUPERCHARGING SYSTEM WITH EGR GUIDE

The concept of the blowdown supercharge (BDSC) system is to obtain a large amount of diluted mixture without an external



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supercharger for extending the high load operational limit of HCCI gasoline engines whilst keeping $dP/d\theta$ and NO_x emissions low. Figure 1(a) and (b) show the idea of a four-cylinder BDSC system. This system has a 4-2-1 exhaust system, which is a common exhaust system for high performance production engines. The exhaust system is divided into two groups of cylinders # 1 & # 4 and # 2 & # 3. This provides a blowdown pulse separation for each pair of cylinders of 360 deg phase difference. Figure 1(b) shows an example of the valve timing used in the BDSC system. The exhaust valve is reopened during the early stages of the compression stroke to charge hot exhaust gas into the cylinder. At the beginning of the compression stroke in the cylinder # 4, the exhaust valve of the cylinder # 1 opens, and exhaust blowdown pressure wave from the cylinder # 1 causes an increase of pressure in the exhaust system. At this timing, the exhaust valve of the cylinder # 4 opens again. Then, some amount of the exhaust gas is recharged into the cylinder # 4 through the exhaust port by the high exhaust pressure wave from the cylinder # 1. Figure 1(c) shows temporal variations of in-cylinder pressure of the HCCI operation using the BDSC system. The in-cylinder pressure, intake pressure, the exhaust pressure and the valve lift profiles are shown. The in-cylinder pressure largely increases during the EGR valve opening period due to EGR gas recharging by the exhaust pressure. Also, it is found that the amount of recharged EGR gas is determined by the magnitude of the exhaust blowdown pressure wave and mean exhaust pressure. The BDSC system allows a large amount of intake air-fuel mixture to be inducted into a cylinder. Since EGR gas is supercharged into a cylinder just after the intake stroke, volumetric efficiency is not affected. This allows more fuel to be supplied. Furthermore, because EGR gas is pushed into the cylinder at high pressure, the total mass of in-cylinder diluted mixture increases. Since a large amount of in-cylinder mixture is provided by the BDSC system, the word “supercharging” is used for the name of this system. A large amount of diluted mixture avoids an increase in $dP/d\theta$ as well as an increase in NO_x emission due to relatively slow heat release and low combustion temperature. The details of the system are presented in the reference [28].

In-cylinder thermal stratification has a high potential for reducing $dP/d\theta_{\max}$. The EGR guide was developed to generate a strong in-cylinder thermal stratification [29], [30]. The EGR guide is used together with the BDSC system. The EGR guide consists of half-circular rings attached on the edge of the exhaust ports and the piston head with a protuberant surface. The EGR guide controls the flow direction of EGR gas recharged through the exhaust port and reduces a mixing between the relatively low temperature intake mixture and the high temperature EGR gas for providing a strong thermal stratification inside the cylinder. The effects of the EGR guide on in-cylinder temperature distribution and $dP/d\theta_{\max}$ have been presented previously in references [29] and [30].

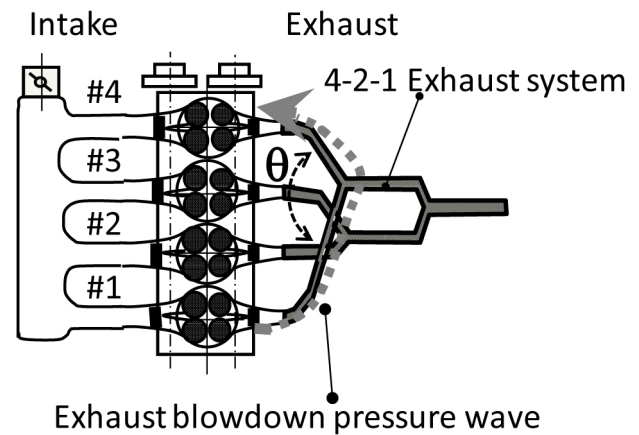


Figure 1(a). Configuration of four-cylinder blowdown supercharge system

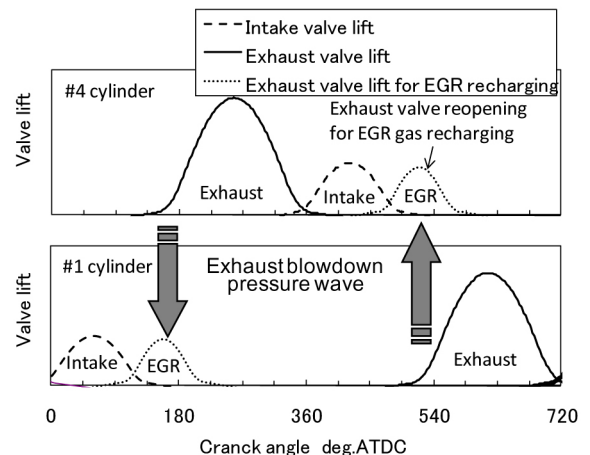


Figure 1(b). Exhaust valve reopening for EGR gas recharging

Figure 1. Concept of the blowdown supercharge system

VALVE TIMING

The valve timings used in the BDSC system for engine speed of 1500 rpm are shown in Figure 2. Exhaust valve timing is fixed with engine speed. Intake and EGR valve timings are varied according to a target load. During high load conditions, a large amount of intake air is necessary because more fuel has to be supplied to increase the operating load. By contrast, during low load conditions, because fuel concentration would be relatively leaner than high load conditions, a larger amount of high temperature recharged EGR gas and a smaller amount of intake air are required for increasing the in-cylinder mixture temperature. Hence, with increasing target load, intake valve closing timing and EGR valve opening timing retard, and a higher intake valve lift and a lower EGR valve lift are used for a higher target load. In this study, valve timings were varied by

changing a pair of intake and exhaust camshafts. In this study, three pairs of intake and exhaust camshafts for different target loads were used. The valve lift called C500 was designed for the highest target load, and that called C100 was designed for the lowest target load. The valve timings for each target load were numerically optimized for obtaining suitable in-cylinder temperature and fuel concentration which provide lower fuel consumption, lower maximum in-cylinder temperature to avoid NO_x production and sufficiently high in-cylinder temperature to ignite at suitable timing. The optimization was carried out using a commercially available 1-D simulation code; GT-POWER and an optimizer software; mode-FRONTIER. The details of the optimized process have been reported previously [28].

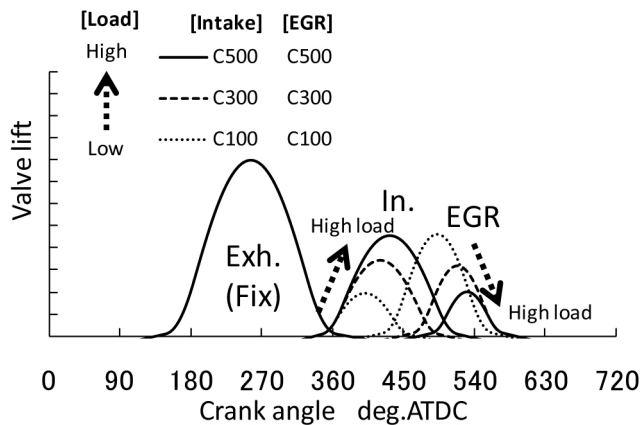


Figure 2. Valve actuation strategy of the BDSC system (previously proposed normal strategy)

SECONDARY AIR INJECTION SYSTEM

Controlling the ignition timing is one of the main issues of a HCCI engine. The EGR gas temperature strongly affects in-cylinder temperature. Therefore, ignition timing is supposed to be controlled by controlling EGR gas temperature appropriately. In this study, to control ignition timing, the secondary air injection system was developed. Figure 3 shows the configuration of the secondary air injection system. As shown in this figure, a commercially available gas fuel injector was installed to the exhaust manifold. Using the gas injector, relatively lower temperature air was injected into exhaust gas before the EGR valve closing timing to control recharged EGR gas temperature. A gas injector has high enough responsivity to vary injection duration cycle by cycle. Therefore, using the secondary air injection system, the ignition timing of each cylinder could be controlled independently cycle by cycle.

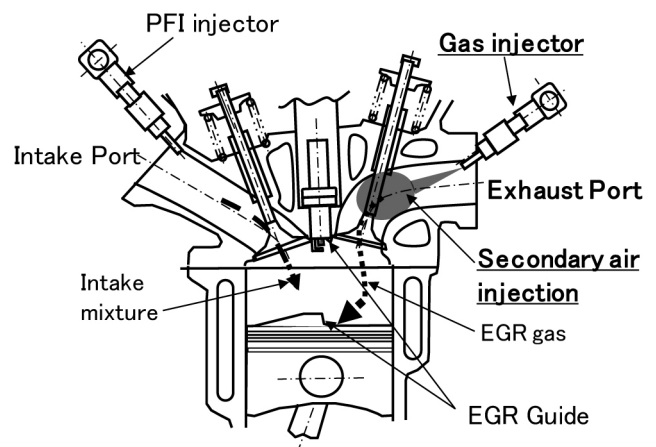


Figure 3. Configuration of the secondary air injection system

EXPERIMENTAL SET UP

TEST ENGINE

A commercially available 2.0 L four-cylinder gasoline engine with a port fuel injection system (HONDA K20A) was used as a test engine. Some basic specifications of the test engine are summarized in Table 1. The engine has a bore of 86 mm, a stroke of 86 mm, and a displacement volume of 1998.2 cm^3 (499.6 $\text{cm}^3/\text{cylinder}$). In the base engine, VTEC (variable valve timing and lift electronic control) system is originally installed in the exhaust valve train. The exhaust VTEC was used to control EGR valve lift actuation to switch an operation mode between HCCI and SI (spark ignition). In the experiment, the engine was operated with SI mode without the EGR valve lift for warming up the engine components. After the warming-up run, the EGR valve lift was activated by exhaust VTEC to switch the engine operation mode from SI to HCCI. The exhaust manifold of the test engine was newly designed for the BDSC system based on one-dimensional simulation result [28]. To obtain a large exhaust blowdown pressure pulse, the diameter of the manifold was decreased from $\phi 38$ mm to $\phi 30$ mm, and the joint angle between two exhaust pipes (θ in Figure 1) was changed to 180 degrees. A compression ratio of the test engine was changed by changing the piston head geometry. The piston head which has the EGR guide wall was newly designed. Considering the practical usage, a HCCI operation would be used partially, switching to and from a conventional SI operation because whole operation range in terms of load and speed is difficult to be covered with only the HCCI operation. Therefore, compression ratio could not be increased so much. In this study, piston head was designed with a target compression ratio of 12.

Table 1. Test engine specifications

Engine type	Inline 4-cylinder
Displaced volume	1998 cm ³
Stroke	86 mm
Bore	86 mm
Compression ratio	12:1
Fuel supply	Port injection

MEASUREMENT SYSTEM

In the present study, to eliminate the effect of the variation in engine performance between the cylinders, the experiments were conducted by two-cylinder operation with focusing attention on one cylinder among the four cylinders, in advance. After the two-cylinder operation tests, total performance in terms of specific fuel consumption rate and exhaust emissions of the HCCI operation using the BDSC system were investigated with the four-cylinder operation. In the two-cylinder operation, only the cylinders #4 and #1 were activated, and the cylinders #2 and #3 were deactivated by stopping fuel supply and valve actuation. The cylinder pressures of all activated cylinders were measured by a piezoelectric pressure transducer (Kistler 6052C or 6117B). A piezo-resistive pressure transducer (Kistler 4005A) was mounted on the exhaust manifold and on the intake manifold of the cylinders # 4 and #3 for the measurement of exhaust and intake pressure pulsations. In this study, an exhaust throttle valve additionally installed regulates the mean exhaust pressure. For exhaust emission measurements, FTIR (HORIBA, MEXA 6000FT) was used for NO_x (NO and NO₂) and CO, and FID (HORIBA, MEXA1170HFID) was used for unburned HC emission.

The measurement and in-cylinder pressure analysis with the two-cylinder operation were conducted using the cylinder #4, while those with the four-cylinder operation were conducted using all four cylinders. Also, it would be note worthy that indicated results are shown as net values, calculated on a 720 degrees CA basis, unless otherwise noted.

EXPERIMENTAL CONDITIONS

Table 2 shows the base experimental conditions in the present study. All experiments were conducted with conditions shown in Table 2 unless otherwise noted. Engine speed was set at 1500 rpm. Intake air temperature was kept at 25 °C and relative humidity was kept at 50 % for all measurements. Coolant water temperature was set at 85 °C as a base condition and varied from 85 °C to 105 °C. Conventional gasoline (RON 91) was used as a test fuel. For fuel injection, a port fuel injection (PFI) system was used. Injection pressure of PFI was set at 350 kPa (gauge). To obtain well mixed air-fuel mixture, the port fuel injection was completed before intake valve opening. Fuel injection timing was set at 10 degrees before intake TDC.

Table 2. Experimental conditions

Engine speed	1500 rpm
Intake temperature	25 °C
Intake air humidity	50 %
Coolant water temperature	85 °C ~ 105 °C
Port fuel injection pressure	350 kPa (gauge.)
Port fuel injection timing	-10 degrees ATDC (intake)
Test fuel	Gasoline (RON 91)

DEFINITION OF THE HCCI OPERATIONAL LIMIT

The limiting variables at the high load operation are maximum pressure rise rate ($dP/d\theta_{\max}$) and NO_x emission. Those at the low load operation are combustion stability and misfiring. In the present study, an acceptable HCCI operation condition was defined as follows:

$$dP/d\theta_{\max} \leq 400 \text{ kPa/degree}$$

$$COV \text{ of IMEP} \leq 5\%$$

$$ISNO_x \leq 0.1 \text{ g/kWh}$$

The acceptable $dP/d\theta_{\max}$ depends on the engine specifications and operating conditions. Ringing intensity [31] that correlates with $dP/d\theta_{\max}$ has been widely used to define the upper load limit of HCCI operation. Corresponding ringing intensity to $dP/d\theta_{\max}$ of 400 kPa/degree is about 2.0 for the experimental condition of the present study.

RESULTS AND DISCUSSION

IMPROVEMENT OF COMBUSTION STABILITY AT LOW LOAD HCCI OPERATION

Improvement of Combustion stability at low load HCCI operation by early intake valve closing and late EGR valve opening

In the previous study, the potential of the BDSC system to extend the upper load limit of HCCI operation was experimentally demonstrated and high load HCCI operational limit was successfully extended up to *net IMEP* of 580 kPa (*gross IMEP* of 615 kPa) with the acceptable levels of $dP/d\theta_{\max}$ and NO_x emission [29]. In the present study, low load HCCI operation performance using the BDSC system in terms of combustion stability and exhaust emission was investigated.

With decreasing operation load, combustion instability and CO and HC emissions increase due to the decrease in fuel