

A Study of Newly Developed HCCI Engine With Wide Operating Range Equipped With Blowdown Supercharging System

Tatsuya Kuboyama and Yasuo Moriyoshi
Chiba Univ.

Koichi Hatamura
Hatamura Engine Research Office

Junichi Takanashi and Yasuhiro Urata
HONDA R&D

Toshio Yamada
CD-adapco

ABSTRACT

To extend the operating range of a gasoline HCCI engine, the blowdown supercharging (BDSC) system and the EGR guide were developed and experimentally examined. The concepts of these techniques are to obtain a large amount of dilution gas and to generate a strong in-cylinder thermal stratification without an external supercharger for extending the upper load limit of HCCI operation whilst keeping $dP/d\theta_{\max}$ and NO_x emissions low. Also, to attain stable HCCI operation using the BDSC system with wide operating conditions, the valve actuation strategy in which the amount of dilution gas is smaller at lower load and larger at higher load was proposed. Additionally to achieve multi-cylinder HCCI operation with wide operating range, the secondary air injection system was developed to reduce cylinder-to-cylinder variation in ignition timing. As a result, the acceptable HCCI operation could be achieved with wide operating range, from IMEP of 135 kPa to 580 kPa. Compared to conventional SI operation, BSFC was improved by 14 % ~ 35 % with more than 99 % reduction in NO_x emissions.

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INTRODUCTION

Homogeneous charge compression ignition (HCCI) is one of the promising candidates to improve thermal efficiency of internal combustion engines with extremely low exhaust emissions. However, due to a limited operational range, the HCCI combustion has been regarded as a part load operation strategy. Operation mode switching between HCCI and conventional spark ignition (SI) operation at low load and high load would be necessary. To apply HCCI combustion into a production engine operating strategy, extending the HCCI operating range and reducing the frequency of the operation mode switching are necessary. Otherwise, the

advantage of the HCCI combustion as a high efficient combustion strategy would be sacrificed.

The negative valve over lap (NVO) method is one of the most common strategies to realize gasoline HCCI combustion [1,2,3]. The exhaust rebreathing is also well known strategy [4]. Using the NVO method or the rebreathing method, the upper load limit is about gross IMEP of 400 kPa [1,2,3,4]. The high load HCCI operation is restricted by the increases in in-cylinder pressure rise rate ($dP/d\theta$) and NO_x emissions mainly due to the lack of dilution gas. Consequently, supercharging has been widely used to realize much higher load HCCI operation [5]. T. Johansson et al. demonstrated that the pressure rise rate can be reduced and thereby the

capable HCCI operating range can be extended, by increasing the air dilution with turbocharger [6]. Also, it is mentioned that the peak cylinder pressure can be a limiting factor for the capable HCCI operation when the boost pressure is high [6]. In recent studies, Dec et al. demonstrated a HCCI operation at a gross IMEP of 1.6 MPa using a mechanical supercharger [7]. However, when using a mechanical supercharger, brake thermal efficiency is deteriorated and maximum BMEP decreases because of the high mechanical loss of superchargers. Also, a turbocharger would not be effective for HCCI operation because providing effective boost pressure using a turbocharger would be difficult due to the low exhaust energy of HCCI combustion. It is considered that developing a technique capable of providing a large amount of dilution gas without external supercharger is important. Takanashi et al. [8] proposed the inter-cylinder EGR boost system to obtain a large amount of dilution gas without an external supercharger. The upper load limit, defined by $dP/d\theta_{max}$ of 400 kPa/degree was extended up to a gross IMEP of 600 kPa. However, this system is difficult to be applied into a production engine because the fully variable valve actuation with the special exhaust system used in the system require complex construction in the hardware and controlling system.

A strong in-cylinder thermal stratification has been also shown to be effective to reduce $dP/d\theta$ and extend the upper load limit of HCCI operation. The potential of the in-cylinder thermal stratification to reduce $dP/d\theta$ has been well investigated by Dec and Sjöberg [9,10,11,12]. They applied a multi-zone chemical analysis to predict the effect of temperature distribution on HCCI combustion, and revealed that a wide temperature distribution of the core of the in-cylinder mixture prolongs the combustion duration and decreases $dP/d\theta$ [9, 10]. They also experimentally found that the thermal stratification within the bulk gas controls $dP/d\theta$ and that the temperature distribution generated by a wall heat loss plays a smaller role in reducing $dP/d\theta$ [12]. It is considered that to generate a large thermal stratification within the bulk gas zone, insufficient mixing between fresh air-fuel mixture and EGR gas would be effective. However, a strong in-cylinder thermal stratification provided by the insufficient mixing between intake air-fuel mixture and EGR gas is considered to be accompanied by stratified distributions of fuel concentration which has a competing effect on $dP/d\theta$ against the temperature distribution [13, 14]. Babajimopoulos claimed that even though the distribution of equivalence ratio has a competing effect against the effect of temperature distribution on ignition, the temperature distribution is still the dominant factor that determines ignition timing [15, 16].

The limiting factors for low load conditions are deteriorations in combustion stability and combustion efficiency because of a low fuel concentration and low in-cylinder temperature during low load conditions. A direct injection during the NVO period has been widely used to extend the low load HCCI operational limit. Using this

technique, a stable HCCI operation at a gross IMEP of 150 kPa with a compression ratio of 15.0 and a gross IMEP of 250 kPa with a compression ratio of 11.5 was experimentally demonstrated [2, 17]. The chemiluminescence images observed during the NVO period revealed that fuel directly injected during the NVO period partially reacts during the NVO period. This partial heat release would increase the in-cylinder temperature, leading to the improvement of the combustion stability [2, 17]. Also, a direct injection during the latter part of compression stroke which provide local fuel rich zone improves combustion efficiency and combustion stability at low load HCCI operation. However, such a strong stratified fuel distribution generally causes an increase in NO_x emissions [18,19,20,21].

For multi-cylinder HCCI operation, a cylinder-to-cylinder variation in ignition timing is also the limiting factor of the HCCI operating range [22]. Therefore, applying HCCI operation into a multi-cylinder engine, independent control of the ignition timing of each cylinder is also important. The benefit of reduction in the cylinder variation in combustion timing can be seen in reference [23]. A 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 an SI-CI engine. It was found that the cylinder variation in air-fuel ratio significantly affects the cylinder variation in ignition timing. It was also shown that combustion phasing control could decrease the average ringing intensity, which is an indicator of the combustion noise associated with $dP/d\theta_{max}$ without decreasing combustion stability by providing stable retarded combustion.

In summary, to extend the high load limit of HCCI operation, a technique capable of obtaining a large amount of intake mixture would be necessary. On the other hand, to obtain stable low load HCCI operation, a high in-cylinder temperature with a relatively fuel rich mixture is necessary. This implies that the total amount of dilution gas has to be appropriately controlled with a target load. Additionally, reducing the cylinder-to-cylinder variation in combustion timing is also required for extending the operational range with multi-cylinder HCCI engines.

The objective of this study is to develop a practical technique to attain HCCI operation with wide operational range. To achieve this, one of the authors previously proposed a new technique named “blowdown supercharging (BDSC) system” which allows a large amount of intake mixture and EGR gas to be inducted into the cylinder, and numerically evaluated the potential of the BDSC system [24]. In the present study, in addition to the BDSC system, the EGR guide for generating a strong in-cylinder thermal stratification was proposed. Also, to attain HCCI operation with wide operating range, valve actuation strategy for the BDSC system in which the amount of dilution gas is smaller at lower load and larger at higher load was proposed. Additionally, to reduce the cylinder-to-cylinder variation in

ignition timing during multi-cylinder HCCI operation, a new technique for individual control of ignition timing of each cylinder was proposed. The effect of the BDSC system with EGR guide on the high load limit of HCCI operation was numerically and experimentally demonstrated, at first. Secondly, to achieve a stable HCCI operation using the BDSC system during low load conditions, the effect of valve timing on combustion stability during low load operations was investigated. Finally, to reduce the cylinder-to-cylinder variation in ignition timing and to attain a wide range multi-cylinder HCCI operation, the secondary air injection was applied. Also, specific fuel consumption rate and exhaust emissions during the wide operating range achieved by the BDSC system were investigated using four-cylinder HCCI engine.

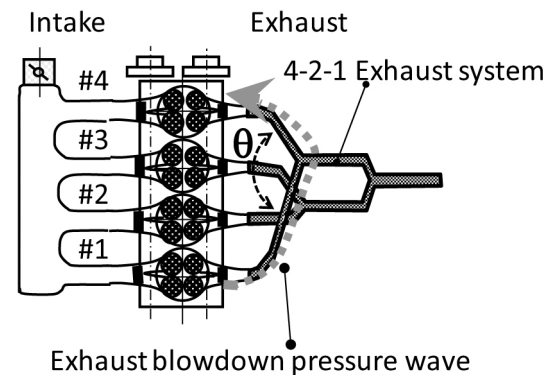
CONCEPTS OF BLOWDOWN SUPERCHARGING SYSTEM WITH EGR GUIDE AND SECONDARY AIR INJECTION

BLOWDOWN SUPERCHARGING SYSTEM WITH EGR GUIDE

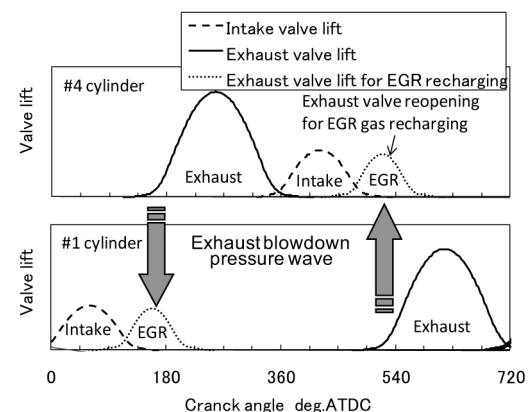
The details of the BDSC system were previously discussed [24]. In the previous study, two systems were proposed, the one is "BDSCac" and the other is "BDSCpw". Because the system configuration for the BDSCpw would be simpler and more practical than that of the BDSCac, the BDSCpw was adopted in the present study. Note that the BDSCpw is called simply "BDSC system" in this study.

Here, the concept of the BDSC is briefly described. The concept of the BDSC system is to obtain a large amount of diluted mixture without an external supercharger for extending the high load operating limit of HCCI gasoline engines whilst keeping $dP/d\theta$ and NO_x emissions low. Figure 1 shows 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 for cylinder # 4, the exhaust valve of cylinder # 1 opens, and the exhaust blowdown pressure wave from cylinder #1 causes an increase of pressure in the exhaust system. At this timing, the exhaust valve of cylinder # 4 opens again. Then, some amount of the exhaust gas is recharged into cylinder # 4 through the exhaust port by the high exhaust pressure wave from cylinder # 1. 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. A large amount of diluted mixture avoids an increase in $dP/d\theta$ as well as an increase in NO_x emissions due to relatively slow heat release and low combustion temperature.



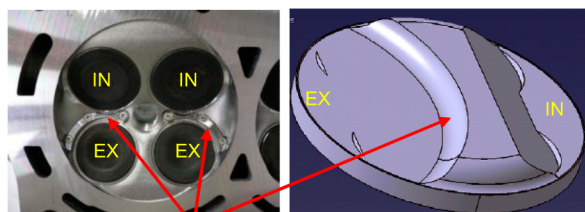
a. Configuration of four-cylinder BDSC system



b. Exhaust valve reopening for EGR gas recharging

Figure 1. Concept of the blowdown supercharging (BDSC) system

In addition, in the present study, the EGR guide was newly applied for providing a strong in-cylinder thermal stratification to decrease $dP/d\theta$ during high load operations. Figure 2 shows the geometry of the EGR guide. 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 flow direction of recharging EGR gas is restricted to reduce mixing between the relatively low temperature intake mixture and the high temperature EGR gas for providing a strong thermal stratification inside the cylinder.



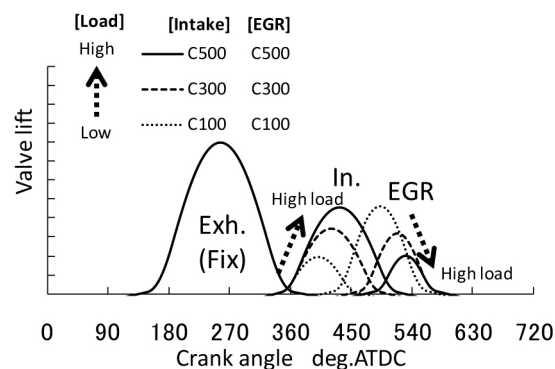
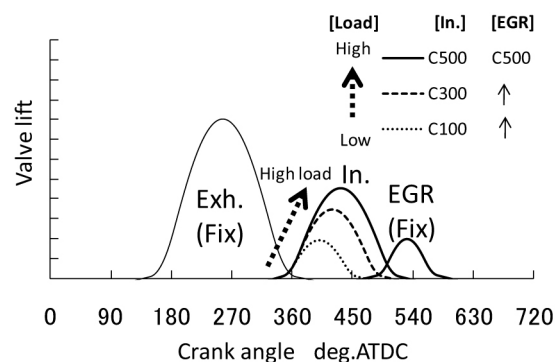
EGR Guide

Figure 2. Geometry of the EGR guide

VALVE ACTUATION STRATEGIES

In the present study, two valve actuation strategies shown in [Figure 3 \(a\)](#) and [\(b\)](#) were examined. Here, “C100”, “C300” and “C500” in these figures are labels for the different valve lift profiles. C100 indicates the smallest valve lift, C300 indicates medium valve lift and C500 indicates the largest valve lift profile. The first one shown in [Figure 3\(a\)](#) was proposed in the previous report [24]. In this strategy, intake and EGR valve timings were varied according to the target load. As the target load increases, intake valve closing timing and EGR valve opening timing retard. A higher intake valve lift and a lower EGR valve lift are used for a higher target load. This allows more air to be charged, and more fuel to be supplied. On the other hand, for low load conditions, a lower intake valve lift and a higher EGR valve lift are used so that a smaller amount of intake air and a larger amount of EGR gas are charged, in order to increase in-cylinder temperature. In this strategy, in-cylinder temperature increases, and fuel concentration decreases as the target load decreases.

The second strategy shown in [Figure 3\(b\)](#) was newly proposed so that the mixture temperature increases without decrease in fuel concentration as the target load decreases. In this strategy, the exhaust valve lift and the EGR valve lift are fixed and only the intake valve timing is varied with the target load. Because a smaller intake valve lift and a smaller EGR valve lift are used, the total amount of the dilution gas decreases with decreasing the target load. This provides a relatively richer fuel concentration and a higher in-cylinder temperature than the first strategy during low load conditions. For low load conditions, early intake valve closing and relatively late EGR valve opening are used, in comparison to the first strategy. Hence, in the following parts in this paper, the new valve actuation strategy shown in [Figure 3\(b\)](#) is called “EGR-R (retard) strategy”, and the valve actuation strategy proposed in the previous study (shown in [Figure 3\(a\)](#)) is called “normal strategy”. Here, it should be noted that with the EGR-R strategy, relatively late EGR valve opening timing is used for low load conditions, but the EGR valve timing is fixed and it is not varied with target load. Also, it should be noted that at high load operation with the EGR-R strategy, the similar valve timings to the previously proposed “normal strategy” are used.

**a. Valve actuation strategy for the normal strategy****b. Valve actuation strategy for the EGR-R strategy****Figure 3. Valve timing for the BDSC system**

SECONDARY AIR INJECTION

In-cylinder mixture temperature has a large impact on ignition timing. This suggests that the ignition timing could be appropriately controlled by controlling in-cylinder mixture temperature. In the present study, a secondary air injection into the EGR gas was examined to control the EGR gas temperature and ignition timing. [Figure 4](#) shows the schematic of the secondary air injection system. Gas fuel injectors installed to the exhaust manifold of each cylinder were used to supply secondary air in the exhaust port before the EGR valve closing. By varying the amount of supplied secondary air, ignition timing could be controlled. The amount of injected secondary air would depend on engine and its operating conditions. In the case of the present study, it was around 20 cm³ which is about 4% of the displacement volume of one cylinder of the test engine.

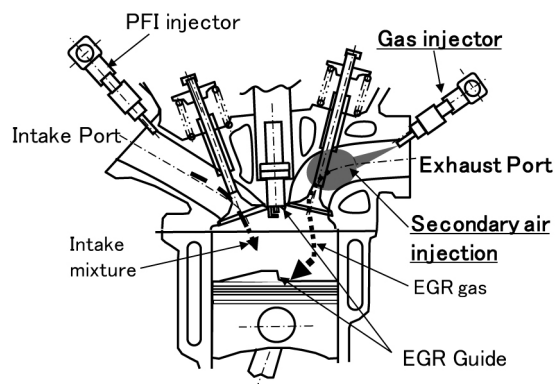


Figure 4. Schematic of the secondary air injection system

EVALUATION OF BLOWDOWN SUPERCHARGING SYSTEM

3-D NUMERICAL SIMULATION OF IN-CYLINDER TEMPERATURE DISTRIBUTION

In the newly proposed method, a spatial distribution of high temperature recharged EGR gas is controlled to generate a strong in-cylinder thermal stratification by using the EGR guide. A stronger thermal stratification would be more effective to decrease in-cylinder pressure rise rate ($dP/d\theta$) limiting the high load HCCI operation. To investigate the effect of the EGR guide geometry on the spatial distribution of in-cylinder temperature, a 3-D numerical simulation was conducted using a commercially available CFD code, STAR-CD [25]. In the 3-D numerical simulations, in-cylinder distributions of temperature and fuel concentration were predicted from the beginning of the intake stroke to the end of the compression stroke with approximately 1.3 million computational cells at bottom dead center. Ignition and combustion models were not implemented and chemical reactions were not considered in this 3-D simulation. The initial condition and the boundary conditions were given by the 1-D engine cycle simulation using the commercial code GT-POWER [26].

To estimate the thermal stratification quantitatively, a five-zone analysis was applied. In this method, the in-cylinder mixture was divided into five equal mass zones classified by the temperature distribution. The temperature difference (ΔT) between the highest temperature zone (zone 5) and the second lowest temperature zone (zone 2) was used as an indicator of the in-cylinder temperature stratification. In this method, a larger ΔT indicates a stronger thermal stratification. Since it is considered that the lowest temperature zone (zone 1) would be little affected by the EGR guide but by the wall heat loss, and that the lowest temperature zone (zone 1) has less effect on $dP/d\theta_{\max}$, the

lowest temperature zone (zone 1) was not considered in this analysis.

0-D MULTI-ZONE MODEL WITH DETAILED CHEMICAL KINETICS

To investigate the effect of spatial distributions of in-cylinder temperature and fuel concentration on $dP/d\theta$, a 0-D simulation with detailed chemical kinetics was conducted. In the 0-D chemical reaction simulation, to consider a stratified distribution of in-cylinder mixture in terms of temperature and fuel concentration, a multi-zone model was applied [10]. In this simulation, the in-cylinder mixture is divided into a number of equal mass zones with regard to temperature and fuel concentration which are predicted by 3-D numerical simulation. 0-D detailed chemical reactions are solved in each divided zone. Each zone has homogeneous temperature and chemical species concentrations. Heat release in each divided zone affects in-cylinder pressure. This means that the pressures in each zone are equal to the in-cylinder pressure. However, the chemical species and energy transfers between the each divided zone were not considered. Sjöberg et al. showed that the five-zone analysis has enough accuracy to predict $dP/d\theta$ of HCCI combustion [10]. In the present study, in order to investigate the effect of spatial distributions of temperature and fuel concentration on $dP/d\theta_{\max}$, the in-cylinder mixture was divided into twenty-five zone classified by temperature and fuel concentration. Firstly, the in-cylinder mixture was divided into five equal mass zones classified by the temperature distribution. Then, each temperature zone was divided again into five equal mass zones based on fuel concentration. In total, twenty-five zone were considered in this simulation. Chemical reactions were solved by using a commercial code: DARS [27]. A reaction model proposed by Golovichev [28] was employed in which 120 species and 619 reactions were considered.

TEST ENGINE AND EXPERIMENTAL CONDITIONS

Based on the simulation results, the performance of the BDSC system was experimentally demonstrated using a modified production four-cylinder gasoline engine (HONDA K20A). The specifications of the test engine are summarized in Table 1. The test engine has a displacement volume of 1998 cm³, a bore of 86 mm and a stroke of 85 mm. The piston head used in the experiments was designed with a target compression ratio of 12. A port fuel injection (PFI) system is employed for fuel supply. The exhaust manifold of the test engine was modified to obtain a large exhaust blowdown pressure pulsation [24]. Based on one-dimensional gas exchange simulation results, the diameter of the manifold was designed $\phi 30$ mm, and the joint angle between the two exhaust pipes (θ in Figure 2) was changed to 180 degrees.

Some of the experimental conditions are listed in Table 2. All experiments were conducted with conditions shown in