

Effect of Fuel and Thermal Stratifications on the Operational Range of an HCCI Gasoline Engine Using the Blow-Down Super Charge System

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ABSTRACT

In order to extend the HCCI high load operational limit, the effects of the distributions of temperature and fuel concentration on pressure rise rate ($dP/d\theta$) were investigated through theoretical and experimental methods. The Blow-Down Super Charge (BDSC) and the EGR guide parts are employed simultaneously to enhance thermal stratification inside the cylinder. And also, to control the distribution of fuel concentration, direct fuel injection system was used.

As a first step, the effect of spatial temperature distribution on maximum pressure rise rate ($dP/d\theta_{max}$) was investigated. The influence of the EGR guide parts on the temperature distribution was investigated using 3-D numerical simulation. Simulation results showed that the temperature difference between high temperature zone and low temperature zone increased by using EGR guide parts together with the BDSC system. Experiments were conducted by using a four-cylinder gasoline engine equipped with the BDSC with EGR guide system to investigate the effect of the EGR guide on the heat release rate and the in-cylinder pressure rise rate. Experimental results showed that 50% and 90 % mass

fraction burned timing (CA50 and CA90) were delayed and combustion duration became longer when the EGR guide was used to enhance thermal stratification. As a result, the maximum pressure rise rate could be decreased and the HCCI high load limit successfully extended. Meanwhile 10 % mass fraction burned timing (CA10) was not affected by the thermal stratification generated by the EGR guide. This is probably because the fuel is also spatially stratified such that the fuel concentration becomes lean in the high temperature zone.

Next, the effect of the fuel distribution on high load HCCI operation was investigated. Numerical analysis using a multi-zone combustion model considering detailed chemical reactions was carried out. The simulation results showed that the maximum pressure rise rate was decreased by 27 % when the fuel distribution was uniform with temperature distribution generated by the BDSC with EGR guide system. Then, to obtain a uniform fuel distribution while keeping the temperature distribution generated by the BDSC with EGR guide system, a direct injection system was employed and the effect of fuel direct injection on maximum pressure rise rate was experimentally investigated. As a result, if 20 % of the

total fuel was injected directly into the cylinder during the exhaust stroke, the spatial distribution of the fuel concentration (G/F; fuel mass ratio to the total mass of in-cylinder mixture) became more homogeneous and maximum pressure rise rate was decreased by 10%. And also, 20 % of the total fuel directly injected during the compression stroke, maximum pressure rise rate was decreased by 20 %.

Finally, a simple method to predict the ignition timing using Livengood-Wu integral and 1-D numerical simulation code was examined. It was found that the proposed method can predict the ignition timing with small deviation around ± 2 degrees.

INTRODUCTION

HCCI (Homogeneous charge compression ignition) is well known as a highly efficient and low exhaust gas emission engine operating strategy. However, to realize HCCI operation in a production engine, several issues remain to be addressed. The main issues of operating an engine in HCCI mode are the limited operational load range achievable and the difficulty in controlling ignition and combustion. Previous researchers have suggested several techniques to solve these issues. In order to achieve stable HCCI combustion, in-cylinder temperature has to be high enough to realize auto ignition. An intake heater has been widely used for pre-heating of the intake mixture [1]. However, intake heaters are not suitable for practical application because a large amount of electricity is required for the heating. Willand et al. proposed HCCI using negative valve over lap which retains hot exhaust gas in the combustion chamber to keep the in-cylinder temperature hot enough to realize auto ignition [2]. Variable valve actuation (VVA) is a promising candidate to control the auto ignition timing [2]. Internal EGR using negative valve overlap (NVO) has been demonstrated to control ignition timing without an external heater, also direct fuel injection into the cylinder during the NVO period was suggested to control ignition timing, and it was demonstrated to be efficient for the extension of the low load limitation[3], [4],[5]. However, when using either an intake heater or internal EGR, the amount of intake air-fuel mixture is generally restricted by the presence of the EGR and expansion of pre-heated air. As a consequence, at high load operation, the combustion temperature increases and thus NO_x emissions and the in-cylinder pressure rise rate increase.

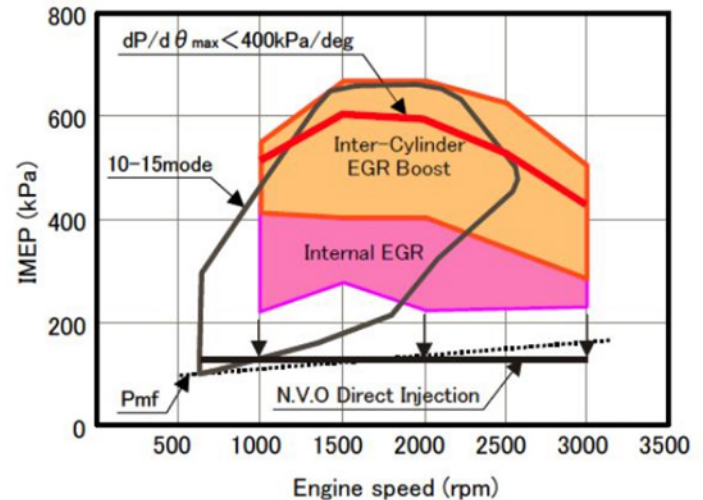


Fig. 1. Japanese 10-15 test driving mode range and HCCI operational range using the previous technique[8].

Hyvonen et al. indicates that increase in the compression ratio is useful for extending the operational HCCI load range from the experimental results by using a variable compression ratio engine [6]. They also shows that for the extension of the high load operation limit, using either a supercharger or a turbocharger is efficient [6] because the volumetric efficiency and the heat capacity of intake mixture increase. And also, the importance of the work efficiency of turbocharger is indicated. On the other hand an external supercharger is not suitable for practical applications, because the system becomes more complicated, costly, and there are mechanical power losses associated with the supercharger [3], [6]. Takanashi et al. developed a so called “Inter-Cylinder EGR Boost System”, which can realize the charge boost HCCI operation, and investigated the performance of the developed system by using an inline four-cylinder engine with a displacement volume of 1590 cc [8]. Figure 1 shows the IMEP vs. engine speed map under the Japanese 10-15 driving mode cycle, which covers a typical urban driving pattern, when a vehicle runs with an engine of a displacement volume 1590 cc and a vehicle weight of 1280 kg. The operational HCCI driving area using the “Inter-Cylinder EGR Boost System” and NVO (internal EGR, NVO direct injection) are shown in this map as well. It was shown that the “Inter-Cylinder EGR Boost System” can realize HCCI operations at an IMEP of 600 kPa which is still below the upper load of Japanese 10-15 driving mode area. They concluded that in order to realize operational HCCI at higher load, it is required to reduce the in-cylinder pressure rise rate. Thermal stratification has been found by both numerical and experimental investigations to reduce in-cylinder pressure rise rate [9], [10], [11]. Sjöberg et al. experimentally and numerically investigated the effect of thermal stratification on in-cylinder pressure rise rate [9], [10]. However, a practical

method to achieve large thermal stratification inside the cylinder has not been proposed as yet. In a previous work, one of the authors proposed a new system named as “Blow-Down Super Charging (BDSC) system” which can trap a large amount of EGR gas and intake air-fuel mixture without an external supercharger by using the exhaust blow-down pressure wave from another cylinder phased 360 degrees earlier in the firing order, and the potential of the BDSC system was estimated by 1-D numerical simulation [12]. In the present study, the BDSC with EGR guide system and a direct fuel injection system were applied to extend the high load HCCI operation limit up to an IMEP of 650 kPa, which corresponds to the upper load of urban driving during the Japanese 10-15 driving mode cycle. The effect of thermal and fuel stratification on the heat release rate and the maximum pressure rise rate ($dp/d\theta_{max}$) were investigated.

BLOW-DOWN SUPER CHARGING (BDSC) SYSTEM

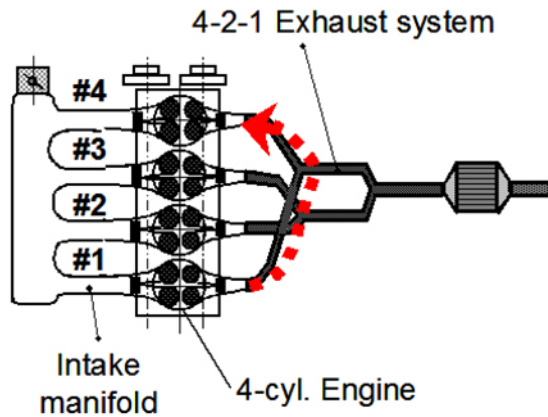
The concept of the BDSC-system is a new method to obtain a large amount of diluted mixture without external supercharging for extending the high load operation limit of HCCI engines whilst keeping the in-cylinder pressure rise rate and NOx emissions low. [Figure 2\(a\)](#) shows the idea of a four-cylinder 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 gives a blow-down pulse separation for each pair of cylinders of 360 deg. [Figure 2\(b\)](#) shows an example of the valve lift timing. The exhaust valve is opened for a second time during the early stages of the compression stroke (EGR-lift). At the beginning of the compression stroke, or the end of the intake stroke of cylinder # 4, the exhaust valve of cylinder # 1 is opened and its exhaust blow-down pressure wave causes an increase of pressure in the exhaust system. At this timing, the exhaust valve of cylinder # 4 opens again, and then some amount of the exhaust gas is charged into cylinder # 4 through the exhaust port by the exhaust pressure wave from cylinder # 1.

The BDSC system allows a large amount of intake air-fuel mixture to be inducted into the cylinder. Since the EGR gas is supercharged into the cylinder just after the intake stroke, the volumetric efficiency is not affected. This allows more fuel to be supplied, and HCCI operation at higher load can be attained. Furthermore, because the EGR gas is supercharged, the total mass of in-cylinder mixture increases, resulting in an increase in the heat capacity of the mixture. A large amount of diluted mixture avoids an increase in the rate of in-cylinder pressure rise as well as an increase in the NOx emissions due to the relatively slow heat release and low combustion temperature. The “Inter Cylinder EGR Boost System” which is a similar system to the BDSC system, but using a more complex exhaust system, has been experimentally proved to

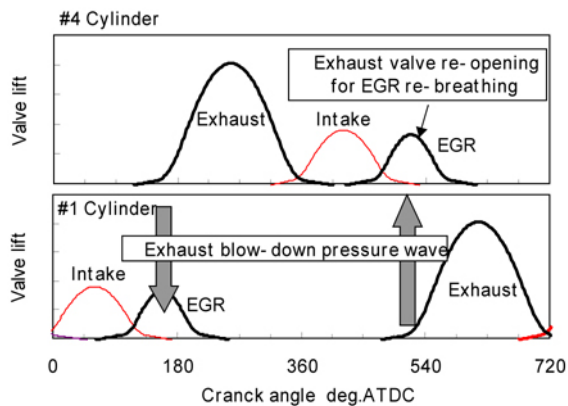
be efficient for high load HCCI operation with very low NOx emissions. However, in this system, the in-cylinder pressure rise rate ($dp/d\theta$) was still high at loads over an IMEP of 600 kPa [8]

IN-CYLINDER THERMAL STRATIFICATION USING EGR GUIDE

In-cylinder thermal stratification has a high potential for reducing the rate of in-cylinder pressure rise rate of HCCI operation [9],[10],[11]. In the present study, in order to generate a large thermal stratification in the cylinder, EGR guides are used to control mixing between the fresh air-fuel mixture and the high temperature EGR gas recharged through the exhaust port. In previous studies [13],[14], in order to investigate the effect of the geometry of the EGR guide attached on the edge of the exhaust port on in-cylinder temperature distribution, 3-D numerical simulations were carried out by using the commercial CFD code “STAR-CD 3.26”. The calculation conditions are summarized in [Table 1](#). The calculation geometry is the same as that of the test engine used in this experiment, which has a 86 mm bore, a 86 mm stroke and a compression ratio of 12. To take turbulence into account, the standard k - epsilon model was employed. The intake and exhaust pressure boundary conditions were obtained by 1-D cycle simulation results using the commercial code “GT-POWER 6.2”. The location of the EGR guide on the edge of exhaust port was varied to find the optimum geometry of EGR guide for generating large in-cylinder thermal stratification. As a result, a circular ring around the exhaust valves and a bank on the piston were attached to control the rebreathed gas flow, as shown in [figure 3](#).



(a). Blow-Down Super Charge (BDSC) system



(b). Valve lift and timing of the BDSC

Fig. 2. Blow-Down Super Charge system and valve lift timing of the system

<figure 3 here>

TEST ENGINE AND CONDITIONS

Table 1 shows the specifications of the test engine and test conditions. The test engine used for this study is based on a Honda K20A, which is an inline four-cylinder gasoline engine with port fuel injection. The engine has a bore of 86mm, a stroke of 86mm, a displacement volume of 499.6 cc per cylinder and a compression ratio of 11.5. The compression ratio is changed from 11.5 to 12 for HCCI operation. The coolant water temperature of the test engine was kept at 358 K. The intake gas temperature was 298 K and humidity was 50% for all measurements. Conventional gasoline (RON 91) was used as fuel. The fuel injection pressure was 350 kPa (gauge). Engine speed was set to 1500rpm. In this experiment, fuel injection into the intake port was ended before intake valve opening to obtain well mixed air-fuel mixture.

In this experiment, in order to vary the valve lift timing, three different pairs of intake and exhaust camshafts were used. Figure 4 shows valve lift curves used in the present study. In this study, fixed exhaust valve lift timing was used. The valve

lift timings of the intake valve and the EGR valve were varied according to the target IMEP. The camshaft for higher load operation has a larger intake valve lift with smaller EGR valve lift, while the camshaft for lower load operation has a lower intake valve lift with higher EGR valve lift. In order to obtain optimal valve actuation to give a suitable in-cylinder temperature for auto ignition and to minimize the combustion temperature for each of the target loads, IMEP of 350 kPa, 600 kPa, 650 kPa at engine speed of 1500 rpm, the valve lift and timing were optimized numerically by using a 1-D simulation code (GT-POWER 6.2) and an optimizer software (mode-FRONTIER). The details of the optimization process were reported previously[12].

Table.1. Engine specifications and test conditions

Base engine	Honda, K20A
Engine type	Inline 4 cylinder
Bore x Stroke	86 mm x 86 mm
Connecting rod length	139 mm
Displacement volume	499.6 cc/cyl.
Compression ratio	12 (HCCI) / 11.5 (Base)
Intake air temperature	298 K $\pm$ 1K
Intake air humidity	50 % $\pm$ 2%
Coolant water temp.	358 K $\pm$ 2 K
Fuel injection	Port injection
Fuel injection pres.	350 kPa (gauge)
Fuel	Gasoline (RON 91)
Engine speed	1500 rpm

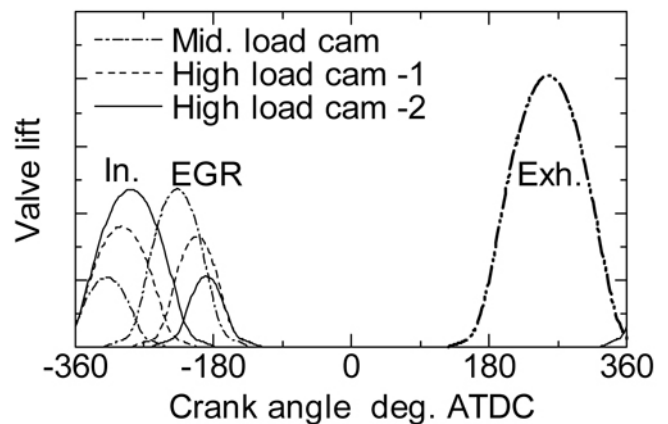


Fig. 4. Valve lift and timing used in the experiment

In this study, only two of the four-cylinder, cylinder # 1 and # 4, were used for the measurements. The others, # 2 and # 3, were not fired by stopping fuel supply and valve actuation. The cylinder pressure of the two fired cylinders (#1 and #4) was measured by piezoelectric pressure sensors (Kistler Type 6052C, 6117B). Piezo-resistive pressure sensors (Kistler 4005A) were mounted in the exhaust and the intake manifolds of # 4 cylinder for measurement of the exhaust and

intake pressure pulsations. The mean pressure in the exhaust pipe was regulated by using an exhaust throttle valve, installed after the silencer. NO_x (NO and NO₂) and CO concentration in exhaust gas were measured by using FTIR (HORIBA, MEXA 6000FT). For unburned HC measurement, FID (HORIBA, MEXA1170HFID) was used. In the present study, operational HCCI condition was defined as follows:

- $dP/d\theta_{max} \leq 400$ kPa/deg.
- COV of IMEP $\leq 5\%$
- ISNO_x ≤ 0.1 g/kWh

RESULTS AND DISCUSSION

EFFECT OF THE EGR GUIDE ON IN-CYLINDER TEMPERATURE DISTRIBUTION

In the previous studies[13],[14], the optimized geometry and location of the EGR guide parts were found by 3-D numerical simulation. However, the boundary conditions used in the previous studies were given from 1-D numerical simulation results. In the present study, to investigate spatial distributions of in-cylinder temperature more accurately, 3-D numerical simulation was carried out using measured intake and exhaust pressures for the boundary conditions of the simulation.

Figure 5 shows the effect of EGR guide on the spatial distribution of the in-cylinder temperature. Figure 6 shows a calculated histogram of the cylinder temperature at 20 deg. BTDC. From figure 5, it is found that in the case with EGR guide, mixing between rebreathed EGR gas and air-fuel mixture is constrained and the high temperature zone locally distributes around the exhaust port during over the compression stroke. In figure 6, it can be seen that in the case with EGR guide, mixture temperature is more heterogeneous than in the case without EGR guide. To evaluate the effect of the EGR guide on the spatial temperature distribution quantitatively, a five-zone analysis[9] was applied. In this method, the in-cylinder mixture is statistically divided into five equal mass zones classified by temperature. In this study, ΔT was defined as the temperature difference between the highest temperature zone (zone 5) and the second lowest temperature zone (zone 2), and ΔT was used as an indicator of the heterogeneity of the spatial temperature distribution. A larger ΔT indicates that a larger thermal stratification exists. Here the lowest temperature zone (zone 1) was not taken into account because the lowest temperature zone is presumed to be largely affected by the wall heat loss rather than the EGR guide. Figure 7 shows the temporal variation of ΔT . It can be seen that ΔT at 20 deg.BTDC can be increased about 60 % by using the EGR guide. From these results, it is confirmed that the EGR guide is effective to enhance the in-cylinder thermal stratification.

<figure 5 here>

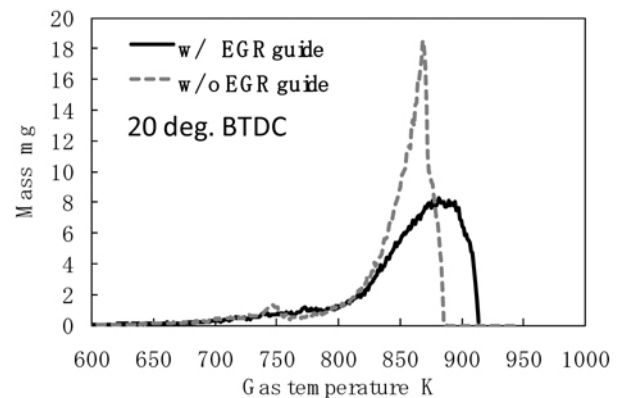


Fig. 6. Effect of the EGR guide on in-cylinder temperature histogram

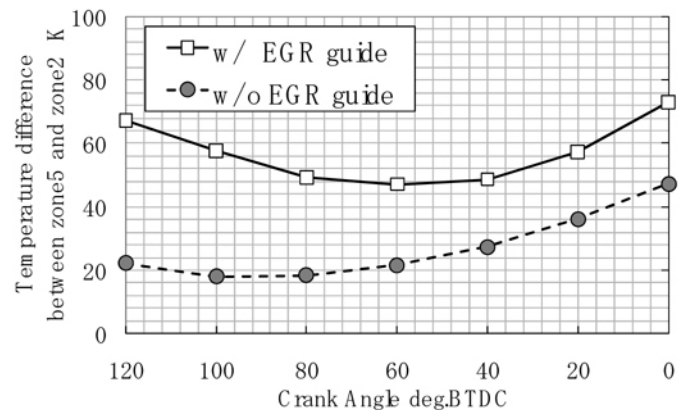


Fig. 7. Effect of the EGR guide on the temperature difference between zone 5 and zone 2

EFFECT OF EGR GUIDE ON HCCI OPERATIONAL RANGE

To investigate the effect of in-cylinder thermal stratification on the HCCI operational range, experiments were carried out by using an in-line four-cylinder engine equipped with both the BDSC system and the EGR guide. In this experiment, fuel was supplied into the intake port before the intake valve open to promote the mixing between fresh air and supplied fuel. The end of fuel injection was set at before the intake valve open. The profiles of the intake, the exhaust and the EGR valves were fixed. The valve profiles used in this experiment were high load cam -2 shown in figure 4. A mean exhaust pressure was varied as an experimental parameter to vary the EGR ratio.

Figure 8 shows the typical in-cylinder, exhaust and intake pressure when the BDSC system was used. The profiles of the intake, the exhaust and the EGR valves are also shown in this figure. As shown in the figure, in-cylinder pressure