

Evaluation of the Performance of a Boosted HCCI Gasoline Engine with Blowdown Supercharge System

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ABSTRACT

HCCI combustion can realize low NO_x and particulate emissions and high thermal efficiency. Therefore, HCCI combustion has a possibility of many kinds of applications, such as an automotive powertrain, general-purpose engine, motorcycle engine and electric generator. However, the operational range using HCCI combustion in terms of speed and load is restricted because the onset of ignition and the heat release rate cannot be controlled directly. For the extension of the operational range using either an external supercharger or a turbocharger is promising. The objective of this research is to investigate the effect of the intake pressure on the HCCI high load limit and HCCI combustion characteristics with blowdown supercharging (BDSC) system. The intake pressure (P_{in}) and temperature (T_{in}) were varied as experimental parameters. The intake pressure was swept from 100 kPa (naturally aspirated) to 200 kPa using an external mechanical supercharger. The experimental results showed that the maximum load successfully increased with increasing the intake pressure. The highest load in this study was 935 kPa in IMEP_g at the condition of 200 kPa in P_{in} and 32 °C in T_{in} . The maximum load of boosted BDSC-HCCI engine can be achieved comparable to the full load of naturally aspirated SI engine. In addition, for conditions with above 200 kPa in T_{in} , A/F and G/F could be almost the same. The comparison of heat release rate between with and without BDSC showed that the peak value of heat release rate decreased and the combustion duration was prolonged with BDSC by thermal stratification. Not only the pressure rise rate but also the peak cylinder pressure could be reduced by BDSC system. Moreover, the intake temperature was decreased while maintaining the conditions of G/F and intake pressure to investigate the intake temperature on heat release. The results showed that the $dP/d\theta$ max is reduced with T_{in} less than 50 °C.

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INTRODUCTION

Internal combustion engines are required to reduce damages to the environment and also improve thermal efficiency. Homogeneous Charge Compression Ignition (HCCI) combustion can provide low nitrogen oxide (NO_x) and particulate emissions and high thermal efficiency comparable to that of a diesel engine. HCCI combustion may

be an alternative to the throttled Spark Ignition (SI) engine so that engine efficiency increases drastically. Therefore, HCCI combustion has a possibility of many kinds of applications, such as an automotive powertrain, general-purpose engine, motorcycle engine and electric generator. However, the operational range using HCCI operation cannot be controlled directly. HCCI operation for practical use can be achieved by

controlling the chemical reaction of mixture which depends on the in-cylinder pressure and temperature histories, the fuel properties and mixture composition. The scope of this paper is to extend the upper load range limit. It is necessary to increase the power output while maintaining conditions such as low pressure rise rate ($dP/d\theta_{max}$) and NOx emissions.

Hyvönen et al.⁽¹⁾ examined the HCCI operational range with both mechanical supercharging and simulated turbocharging using a Variable Compression Ratio (VCR) engine. They showed the HCCI operating range can be extended with both mechanical supercharging and turbocharging, and the HCCI high load limit was comparable to that of a naturally aspirated SI operation. Dec et al.⁽²⁾ investigated the effects of intake pressure and temperature on the HCCI high load limit and HCCI combustion characteristics. They found the high load limit was extended by a combination of supercharging and adding external EGR, and the shape of heat release rate (HRR) was changed because intake boosting significantly enhances the early autoignition reaction⁽²⁾⁽³⁾. Thus, for the extension of high load limit using either a supercharger or a turbocharger is efficient due to increases in volumetric efficiency and heat capacity. However, the low exhaust energy caused by lean combustion results in low efficiency of turbocharger⁽⁴⁾. One of the technical challenges is the selection of turbocharger.

Andre et al.⁽⁵⁾ investigated the potential of boosted HCCI using combined boosting system (external air compressor and engine turbocharger). The result shows that the engine was run in HCCI mode up to 650 kPa BMEP load. Thomas et al.⁽⁶⁾ surveyed the operational region using a multi cylinder engine turbocharged by variable geometry turbine (VGT). As a result, the highest intake pressure was around 180 kPa (abs.), and the operational load range was increased in the whole speed range by turbocharging.

In the previous work, the authors proposed a system named "BlowDown SuperCharge (BDSC)" and "EGR guide"⁽⁷⁾. The BDSC system can trap a large amount of intake air-fuel mixture and exhaust gas recirculation (EGR) without an external supercharger by using the exhaust blowdown pressure wave from another cylinder with a phase-shift by 360 degrees. In addition, in order to generate strong thermal stratification in the cylinder, EGR guide is used to control mixing between the intake air-fuel mixture and the high temperature EGR gas recharged through the exhaust port. Using the proposed BDSC with EGR guide system, HCCI high load limit was successfully extended⁽⁷⁾⁽⁸⁾. Therefore, more extension of the HCCI operational region can be expected by combining the BDSC system and external supercharging. Also, to determine the potential of boosted HCCI for examining operational area and thermal efficiency are required.

The objective of this research is to investigate the effect of external supercharging on the high load limit of HCCI operation with the BDSC system, thermal efficiency and HCCI combustion characteristics.

EXPERIMENTAL SETUP AND CONDITIONS

The BDSC System

The concept of the BDSC system is to obtain a large amount of diluted mixture without an external supercharging for extending the high load limit of HCCI engines while maintaining conditions such as low $dP/d\theta$ and NOx emissions. Figure 1 shows the schematic of the BDSC system. This inline four-cylinder engine has a 4-2-1 exhaust system which is divided into two groups of cylinders #1 and #4, #2 and #3. Two cylinders in each group are operated in just 360 °CA phase difference from each other. Figure 2 shows an example of the valve timings of cylinder #1 and #4, which is one of the groups. The exhaust valve is opened twice each cycle during the exhaust stroke and the early stages of the compression stroke (EGR-lift). At the end of the intake stroke of cylinder #1, the exhaust valve of the cylinder #4 is opened and its exhaust blowdown pressure wave causes an increase of pressure in the exhaust manifold. At this timing, the exhaust valve of the cylinder #1 open, and then some amount the exhaust gas is recharged into the cylinder #1 through the exhaust port by the exhaust pressure wave from the cylinder #4. The BDSC system allows a large amount of intake air-fuel mixture to be inducted into the cylinder. Since the EGR gas is recharged into the cylinder just after the intake stroke, volumetric efficiency is not affected much. Furthermore, because the EGR gas is supercharged using blowdown pressure wave, the total mass of in-cylinder mixture increases.

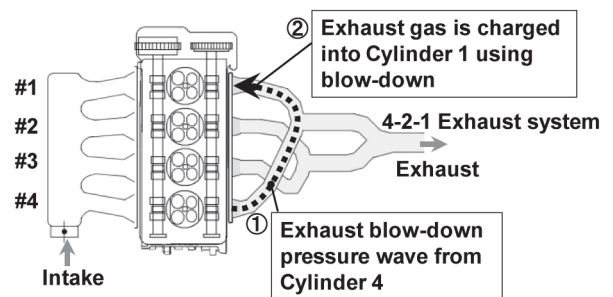


Fig. 1. Blow-Down SuperCharging system

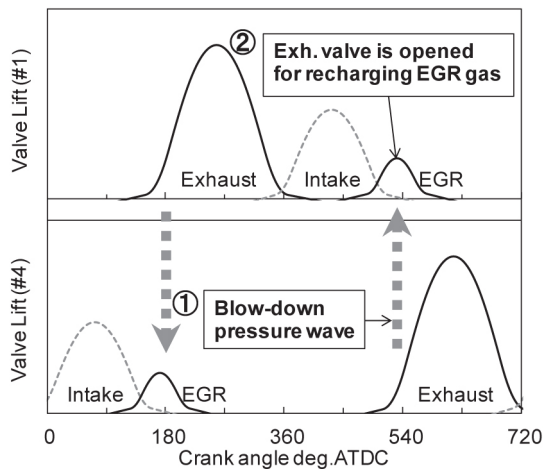


Fig. 2. Valve lifts timing of BDSC system

In addition, in order to generate a strong thermal stratification inside the cylinder, mixing between the fresh air-fuel mixture and high temperature EGR gas is reduced. In a previous study⁽⁵⁾, the geometry of the combustion chamber is optimized by using 3-D numerical simulations. Figure 3 shows the in-cylinder distributions of temperature at 120 deg.BTDC and 32 deg.BTDC, before ignition timing. 3-D numerical simulations were carried out by using the commercial CFD code “STAR-CD 3.26”. The differencing scheme was MARS. The standard k-e model was employed to take turbulence into account. The mixing between high temperature EGR gas and intake air is suppressed so that the high temperature EGR gas remains near the exhaust valves.

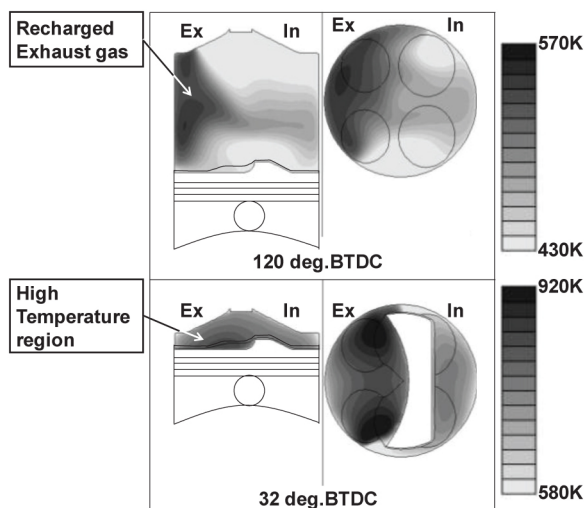


Fig. 3. Numerical results of spatial distribution of in-cylinder temperature.

A large amount of diluted mixture and in-cylinder thermal stratification avoid an increase in the rate of in-cylinder pressure rise as well as an increase in the NO_x emissions due to the relatively slow heat release and low combustion

temperature. As a result, the high load HCCI operational limit was successfully extended. The details of the BDSC system and generating the thermal stratification were previously reported in the references⁽⁷⁾⁽⁸⁾.

Test Engine And Conditions

The engine used in this study is a production inline four-cylinder gasoline engine. Engine specifications and some of the experimental conditions are listed in Table 1. Measurements setup for externally boosted operation is shown in Figure 4. To realize the HCCI operation with the BDSC, the engine was modified in regard to the valve timing, exhaust manifold and geometry of combustion chamber including compression ratio. The measured compression ratio is 12.0. Conventional gasoline (RON 91) was used as a test fuel. The fuel injection pressure was set at 350 kPa (gauge).

Table 1. Engine specifications and test conditions

Engine type	Inline-4 cylinder
Bore × Stroke	86 mm × 86 mm
Displacement	1998 cm ³
Compression ratio	12.0
Supercharger	Lysholm compressor
Fuel	Gasoline (RON91)
Fuel supply	Port injection
Engine speed	1500 rpm
Coolant water temperature	105 °C
Intake pressure (abs.)	100 – 200kPa
Intake temperature	32 – 105 °C
Valve timing and lift	deg.ATDC (mm)
IVO / IVC (Lift)	341 / 540 (5.5)
EVO / EVC (Lift)	156 / 373 (7.1)
EGR-VO / EGR-VC(Lift)	498 / 599 (2.2)

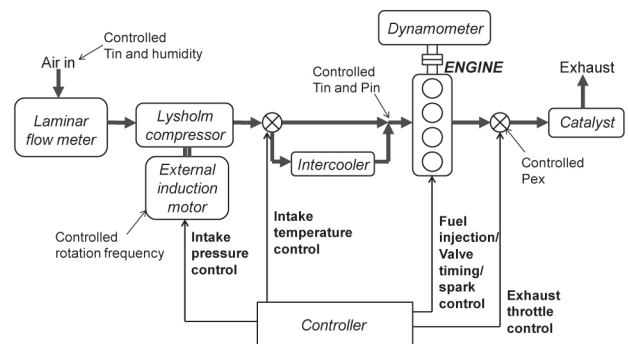


Fig. 4. Measurements set up for boosted operation

In this study, the intake pressure was varied from 100 kPa (abs.) to 200 kPa by using a mechanical supercharger driven by an external induction motor. The intake mean pressure could be adjusted by varying the motor drive speed. The intake gas temperature was adjusted by a water cooled intercooler. The partition ratio of a three-way valve was controlled to realize given intake temperature. Ambient temperature and humidity were maintained constant at 25 °C