

Closed-Loop Combustion Control of a HCCI Engine with Re-Breathing EGR System

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ABSTRACT

This study experimentally investigates the control system and the algorithm after constructing a HCCI combustion control system for the development of a small HCCI engine fuelled with Dimethyl Ether (DME). This system can control four throttles for the mixing ratio of three gases of in-cylinder (stoichiometric pre-mixture, hot EGR gas and cold EGR gas). At first, the combustion behavior for combustion phasing retarded operation with cold and hot EGR was examined. Then, the potential of model-based and feed back control for HCCI combustion with change of the demand of IMEP was investigated. In the end, the limit of combustion-phasing retard for IMEP and PRR was explored. Results shows that to get high IMEP with acceptable PRR and low coefficient of variation of IMEP, crank angle of 50% heat release (CA50) should be controlled at constant phasing in the expansion stroke. CA50 can be controlled by changing the ratio of pre-mixture, hot EGR gas and cold EGR gas with throttles. Due to the cycle-to-cycle variation, the change of total mass of fuel in cylinder has a big effect on IMEP. After misfire, unburned fuel and intermediates remain in exhaust gas, which is re-breathed as hot EGR gas, and unburned fuel and intermediates are supplied to next cycle. This leads to the total mass of fuel changes cycle-to-cycle. As a result of feedback control, transient performance is realized but high sensitivity of response cannot be achieved under the constant engine speed.

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INTRODUCTION

The HCCI combustion is the controlled autoignition of homogeneous mixture through compression. This combustion offers the potential to significantly reduce nitrogen-oxide (NO_x) and particulate emissions, while achieving good fuel economy [1]. Therefore, HCCI engine is considered as a high-efficiency alternative to spark ignition (SI) gasoline engine and as a low-emissions alternative to compression ignition (CI) diesel engine. However, several technical difficulties need to be overcome for the practical application of HCCI in production engines. Among these, controlling pressure-rise rate associated with excessive heat-release rate at high loads continues to be a major issue. HCCI combustion depends not only on the unique chemical-kinetic mechanisms of the fuel, but also on the thermal conditions that mixture goes through during compression process. Due to the self-accelerating nature of chemical-kinetic rates as the temperature rises, HCCI combustion tends toward nearly instantaneous heat release, which can result in rapid pressure rise leading to unacceptable pressure-rise rate particularly at

high loads. To mitigate pressure-rise rate at high loads, thus allowing higher-load HCCI operation, previous studies demonstrated the strong potential of combustion-phasing retard [2, 3]. The benefits of combustion-phasing retard could be realized when autoignition occurs during the expansion stroke, since the effects of the naturally occurring thermal stratification are amplified [4, 5]. However, there are limits to how far combustion-phasing retard can be exploited to reduce pressure-rise rate. Too much combustion-phasing retard leads to unstable combustion with misfire or partial-burn cycles due to piston expansion is very strong compared to the exothermic reactions of the autoignition process, resulting in unacceptable IMEP variations. To accomplish combustion-phasing retard in the same level of IMEP for acceptable pressure-rise rate, it is important to understand the exact limit of combustion-phasing retard, the behavior of combustion beyond this limit, and how easily stable combustion can be restored.

Combustion-phasing control has been demonstrated for a variety of techniques such as variable compression ratio [6], variable valve timing [7], and intake air heating [8]. Ultimately, all of these techniques adjust the compressed gas temperature so that the charge mixture autoignites at the desired crank angle. EGR has been shown to offer significant advantages for controlling combustion phasing in HCCI engines [9]. Cooled EGR (external EGR) is the recirculated gases that contain species as like carbon monoxide (CO), hydrocarbons (HC), partially oxidized hydrocarbons and unburned fuel, in addition to the major species CO_2 , H_2O and N_2 [10]. The use of cooled EGR tends to retard combustion phasing even at high loads mainly due to the presence of CO_2 and H_2O that stand out with high mole-specific heat capacity (C_v). A reduction of O_2 concentration associated with the addition of cooled EGR to intake air also directly influences combustion-phasing retard. Consequently, the combined effects of the increase of C_v and the reduction of O_2 concentration in the in-cylinder charge provides strong potential to retard combustion phasing even at high loads. Alternatively, hot EGR (internal EGR), usually in the form of retained residuals, is often used to advance combustion phasing, or to achieve autoignition of high-octane fuels in HCCI engines with the relatively low compression ratios that allow switching to SI operation at high loads. Less hot EGR is required at high loads due to the higher temperature of the residuals and the increased in-cylinder surface temperature, which can be expected to cause unacceptable pressure-rise rate [11]. However, the presence of hot residuals pockets from the previous cycle as a result of incomplete mixing has the potential to increase thermal stratification as well, unless the potentially more intense mixing homogenizes the core of the charge too quickly [2]. As mentioned above, it should be possible to broaden the naturally occurring thermal stratification, and this way more amplifies the benefits of combustion-phasing retard. Closed-loop control of the combustion phasing might become necessity to operate at high loads in the limit of combustion-phasing retard. This was accomplished by changing the ignition properties of the fuel by variable hydrogen addition [12]. Rapid combustion-phasing control can also be accomplished by fast thermal management [13], variable compression ratio [14], or variable valve timings [15]. Hence, these techniques should all have the potential to enable HCCI operation at high loads that fall in the limit of combustion-phasing retard.

OBJECTIVES

The main objective of this study is to experimentally investigate the combustion-phasing retard in a HCCI engine for understanding how combustion-phasing retard can be used to reduce excessive heat-release rate, thus allowing higher-load HCCI operation while maintaining acceptable pressure-rise rate. This investigation consists of three parts.

1. The benefits and limits of combustion-phasing retard on HCCI combustion are demonstrated and discussed in detail.
2. The behavior of HCCI combustion beyond the limit of combustion-phasing retard and the trend of increasing cycle-to-cycle variations are identified, and the source of these variations is explained.
3. Closed-loop control is applied to control combustion phasing in the limit of combustion-phasing retard for stable HCCI operation.

EXPERIMENTAL AND CHEMICAL-KINETICS MODELING SETUP

HCCI Research Engine

The engine used for this investigation is based on a HONDA GX340 K1 single-cylinder, air-cooled, gasoline engine with a displacement of 0.337 liters, which is applied to an electric generator. A schematic of the engine facility is shown in Fig. 1, and the engine specifications are listed in Table 1 with operating conditions. The engine is equipped with an EGR passage for cooled EGR and a two-stage exhaust cam for hot EGR (retained residuals and rebreathing EGR). Figure 2 shows valve lift profiles featuring a rebreathing valve lift resulting from a two-stage exhaust cam. In addition to cooled EGR and hot EGR systems, four butterfly valves were installed that can be used to fully or partially shut off the flow of air (Throttle A and Throttle B), cooled EGR (Throttle B and Throttle D) and hot EGR (Throttle C) for precisely controlling the in-cylinder charge mixture composition, and ultimately determine the temperature of in-cylinder charge at the time of intake valve close (T_{IVC}). Fig. 3 shows the schematic of thermocouple position for measuring Hot EGR temperature. Fig. 4 shows how to calculate the volume of charged gases for n cycle. As can be seen in Fig. 4, the in-cylinder charge gases of n cycle is calculated by integrating the gas flow rate from IVC of $n-1$ cycle to IVC. To serve as a fundament for the following sections, motored data are presented here to clearly show the effects of Throttle A and D on the mass ratio of in-cylinder charge at IVC when adjusting the angle of Throttle A and D from 0deg (Full close) to 90deg (Full open).

As Fig. 5 shows, opening Throttle D leads to a large increase of cooled EGR by replacing air and hot EGR over a range of Throttle A. This is especially pronounced at the smaller Throttle A angle, as indicated by the mass ratio of in-cylinder charge at IVC.

Test Fuel

DME was chosen as the test fuel for this study because it is two-stage ignition fuel that has the first heat-release “low-temperature heat release (LTHR)” associated with cool-flame chemistry before main heat-release “high-temperature heat

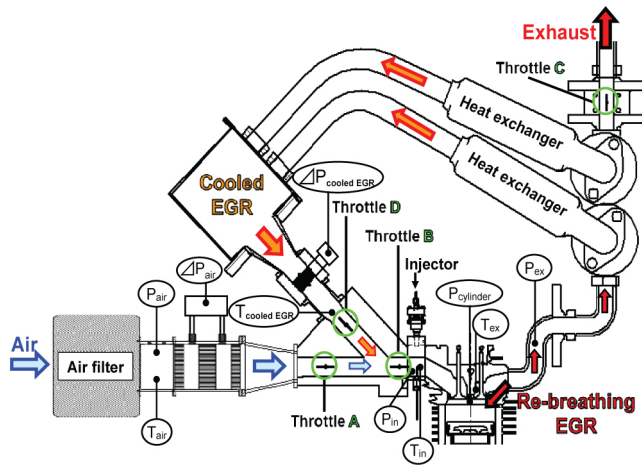


Fig.1. Schematic of the HCCI engine facility

Table 1. Engine specifications and operating conditions

Displacement (single-cylinder)	0.337liters
Bore	82 mm
Stroke	64 mm
Connecting rod length	112 mm
Compression ratio	10.76
No. of valve	2
Engine speed	1500 rpm

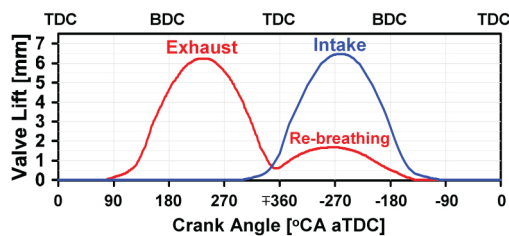


Fig.2. Valve lift profiles featuring re-breathing valve

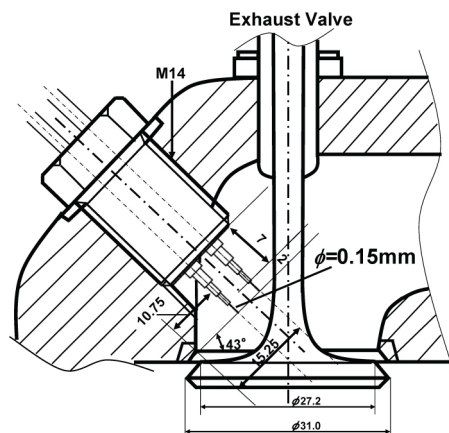


Fig.3. Schematic of exhaust(Hot EGR) thermocouple position

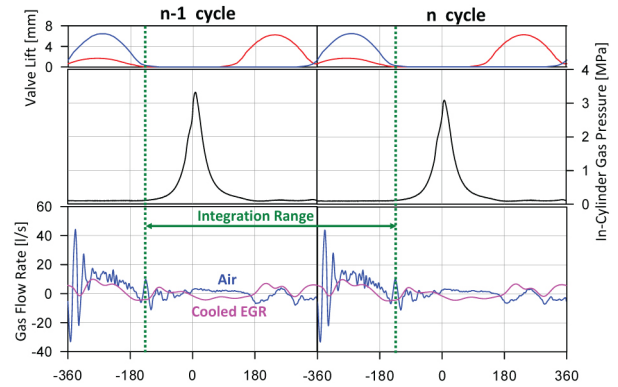


Fig.4. Integration range of in-cylinder charged gas for n cycle

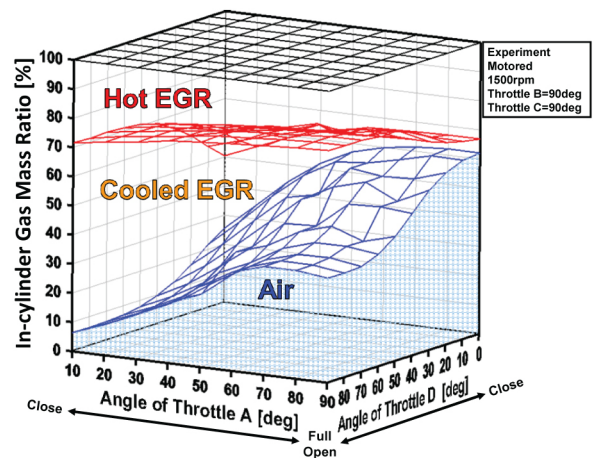


Fig.5. Effect of Throttle A and D on the mass ratio of in-cylinder charge at IVC under motored operation

Table 2. Fuel properties [16]

Property	DME	Diesel
Chemical formula	C_2H_6O	$C_{10.8}H_{18.7}$
Cetane number	55~60	40~55
Molecular weight	46.07	148.6
A/F Stoichiometric	9.0	14.7
Lower heating value [MJ/kg]	28.4	42.5
Boiling point [°C]	-24.9	71~193

release (HTHR)". Table 2 lists the properties of the DME compared against those of diesel that represents a typical two-stage ignition fuel. The two-stage ignition fuels have recently been investigated and shown to offer advantages for combustion-phasing control and reducing pressure-rise rate at high-load HCCI operation [3]. With two-stage ignition fuels, a HCCI engine has lower cycle-to-cycle variations when operated with extensive combustion-phasing retard because the LTHR leads to higher temperature-rise rates just prior to hot ignition. This could allow higher loads without engine knock since increased combustion-phasing retard produces significant reductions in the pressure-rise rate. Furthermore,

DME exhibits a characteristic of high-volatility (and gas-phase). The volatile fuels are relatively easy to form into homogeneous mixtures, which is advantageous for conventional premixed HCCI.

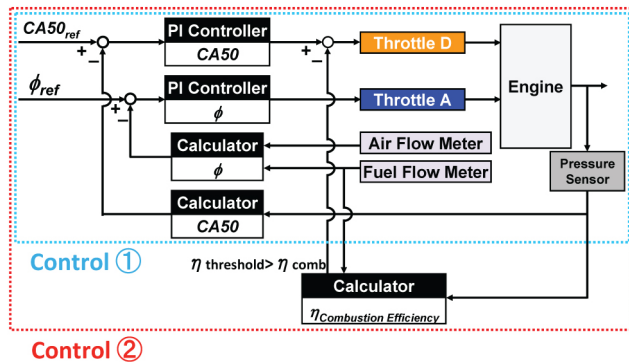


Fig.6. Schematic of the closed-loop control system

Closed-Loop Control

For controlling the combustion phasing in a HCCI engine, accurate closed-loop control would certainly be needed to precisely maintain the required combustion phasing due to no direct control mechanisms such as a spark discharge of SI engine or a fuel injection of CI engine [12]. Furthermore, since a brief disturbance of the combustion phasing in the limit of combustion-phasing retard leads to a large change in an initial condition, which then amplifies the initial disturbance and makes it impossible for the combustion phasing to return to the stable HCCI operation, so closed-loop control of the combustion phasing might become more a necessity for stable HCCI operation. Fig. 6 shows a schematic of closed-loop control system used for this investigation. As a tool for designing closed-loop control system, LabVIEW program was chosen due to its flexible and scalable design. As explained in Refs. [17, 18], practical and reliable feedback signals are necessary to achieve a fast response closed-loop control. For the control ①, the 50% burn point and equivalence ratio were selected as the feedback signal for this closed-loop control. For the control ②, the 50% burn point, equivalence ratio and combustion efficiency were selected as the feedback signal. Since these feedback signals have been indentified to be the practical and reliable feedback signals even for retarded combustion phasing, as shown in a recent study by the authors [19].

RESULT

All data for this investigation were acquired under naturally aspirated operation at 1500rpm. The fueling rates were kept constant at 346 ± 2 J/cycle using digital mass flow meter. This research engine is equipped with four butterfly valves (Throttle A, B, C and D) that can be used to control the combustion phasing by changing the in-cylinder charge

mixture composition. As mentioned in the description of the introduction, the combustion phasing is retarded proportional to the use of cooled EGR. Furthermore, for a given combustion phasing, hot EGR amplifies the benefits of combustion-phasing retard by increasing the degree of thermal stratification at IVC. On this research engine, since using Throttle D alone can significantly increase cooled EGR, this study only adjusted the angle of Throttle D from 0deg (Full close) to 38deg while maintaining the angle of other throttles at 30deg for Throttle A, and at 90deg (Full open) for Throttle B and C to better understand the function of cooled EGR on combustion-phasing retard. As Fig.5 shows, Throttle A directly influences on air mass ratio of in-cylinder charge at IVC leading up to a significant change of equivalence ratio (ϕ), especially over a range of Throttle D angle (0~38deg) considered in this study. Stoichiometric combustion with EGR addition represents a natural upper fueling limit for HCCI combustion. Therefore, the angle of Throttle A was kept at 30deg to investigate if it is possible to combust a stoichiometric charge with acceptable pressure-rise rate in the limit of combustion-phasing retard.

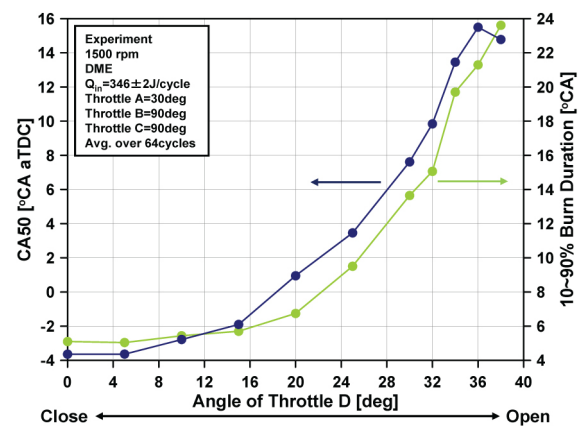


Fig.7. 50% burn point and 10-90% burn duration as a function of angle of Throttle D.

The combustion phasing was determined from the 50% burn point (CA50) of the cumulative apparent heat-release rate (AHRR). The AHRR was calculated from pressure traces using the typical first law and perfect gas analysis, assuming constant gas properties for each operating conditions and disregarding heat transfer [21]. It should be noted that LTHR is excluded when calculating AHRR for the 50% burn point, since it eliminates the need to correct for heat transfer during the weak low-temperature combustion phase which extends for many crank angles. Effectively, the reported combustion phasing refers to 50% burn point for HTHR, starting at the crank angle of minimum heat-release rate between LTHR and HTHR. Presenting the 50% burn point referring to HTHR is considered more relevant and consistent from the standpoint of quantifying the combustion phasing of main combustion.