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Characteristics of HCCI engine operation for additives, EGR, and intake charge temperature while using iso-octane as a fuel*

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Abstract: This work investigates the effects of exhaust gas recirculation (EGR) and operation parameters including engine speed, equivalence ratio, coolant-out temperature, and intake charge temperature on the basic characteristics of a single-cylinder homogeneous charge compression ignition (HCCI) engine powered with reformulated iso-octane fuels. The running range of iso-octane HCCI engine can be expanded to lower temperature and more load by adding di-tertiary butyl peroxide (DTBP) in the fuel. The combustion timing advances with the increase of DTBP concentrations, coolant temperature and equivalence ratio. The effects of EGR on the combustion and emissions are remarkable when the EGR rate is higher than 25%, and the combustion phase is sharply postponed and the UHC and CO emissions deteriorate. The intake charge temperature has a moderate effect on combustion and emissions when it is lower than 35 °C; but the combustion timing advances, the combustion duration shortens, and sometimes it leads to knock combustion when the intake charge temperature increases to above 35 °C.

Key words: Homogeneous charge compression ignition (HCCI), Iso-octane, Additive, Exhaust gas recirculation (EGR), Combustion characteristics
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INTRODUCTION

The degradation of the global environment and foreseeable future depletion of worldwide petrol reserves provides strong encouragement to research on advanced combustion technology of automobile engines. Identified as a distinct combustion phenomenon about 25 years ago (Onishi *et al*., 1979; Noguchi *et al*., 1979), HCCI is a promising alternative combustion model to traditional spark ignition engines and compression ignition engines. The homogeneous charge compression ignition (HCCI) combustion engine combines features of both SI and CI engines, guaranteeing the high efficiency of a diesel engine with virtually no NO_x and particulate emissions. Based on these reasons, HCCI combustion has been widely researched in experimentally and theoretically by the engine researchers all over the world (Lü *et al*., 2005; Santoso *et al*., 2005; Sjober *et al*., 2005; Peng *et al*., 2005; Yap *et al*., 2005). However, there several problems blocking the road to successfully integrate the HCCI concept into automotive applications: extending the operating range of HCCI to high loads; controlling ignition timing and burn rate over a range of engine speed and loads; cold starts and transient response of the HCCI engines; minimizing UHC and CO emissions; improving power density; cylinder-to-cylinder variation, and so on. The key to settlement of the problems lies in the control of the ignition timing and the burn velocity.

Iso-octane is a primary reference fuel (PRF) for octane rating in spark ignition engines, and when used in compression ignition engines, it has a cetane number of approximately 15. Currently, there is in-

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tense interest in using iso-octane as a fuel in the investigations of HCCI, in which iso-octane is used both as a clean fuel and as a component in a primary reference fuel blend. It is difficult to achieve HCCI combustion without accessorial methods. Several potential control methods have been proposed to control gasoline HCCI combustion (Yang *et al*., 2002; Kontarakis *et al*., 2000): intake charge heating system, exhaust gas recirculation (EGR), variable compression ratio (VCR), and variable valve timing (VVT) to change the effective compression ratio and/or the amount of hot exhaust gases retained in the cylinder, etc.

In this work new methods are tried to control the iso-octane HCCI combustion—improving the ignitibility and combustion efficiency of lean fuel/air mixture by adding additive DTBP in the iso-octane fuel, and decreasing the combustion velocity and NO_x emissions of rich fuel/air mixture by the cooled external exhaust recirculation gas.

EXPERIMENT SYSTEM

A four-cylinder, four-stroke high-speed direct injection (DI) diesel engine was employed as prototype engine. One cylinder of the prototype engine was designed to operate with HCCI combustion, the other cylinders running with original DI diesel engine. The intake pipe and exhaust system of the test cylinder were separated from the other cylinders, and an individual injection pump was used to supply the test fuel through port injection. Furthermore, a controllable EGR system was used to investigate the effect of cooled EGR on HCCI combustion. The specifications of the test cylinder are shown in Table 1.

To ensure the repeatability and comparability of the measurements for different fuels and operating conditions, the intake charge temperature was fixed at 20 °C (without EGR), held accurately within ±1 °C; while in the cooled EGR tests, inlet temperature was fixed at 30 °C, and held accurately within ±1 °C. The coolant-out temperature remained at 85 °C, held accurately within ±2 °C. The engine speed was kept at 1800 r/min.

The cylinder pressure was measured by a Kistler model 6125A pressure transducer. The charge output from this transducer was converted to an amplified voltage by a Kistler model 5015 amplifier. Emissions of UHC, CO_2, CO, and NO_x were measured with an AVL emission analyzer. The percentage of EGR rate was determined by comparing the CO_2 concentrated in the exhaust and intake pipe.

EXPERIMENTAL RESULTS AND DISCUSSION

Effect of additive on HCCI combustion

According to the chemical kinetics, for heavy hydrocarbons, HCCI combustion is featured with two-stage combustion and negative temperature coefficiency (NTC) region. At low temperature, reaction is initiated by the abstraction of H from a fuel molecule by O_2 to form an alkyl radical R and HO_2. After that, the addition reaction and isomerization reaction initiate a highly exothermic cycle producing H_2O and an alkylperoxide. As a result, the temperature of the fuel/air mixtures increases as the reactions proceed. When the temperature achieves the decomposition temperature of the ketohydroperoxide of between 800 K and 850 K, cool flame reaction occurs. After that, the HCCI combustion events can be observed only when the in-cylinder gas temperature reaches the H_2O_2 decomposition temperature of about 1000 K near the piston top dead center (TDC).

Any method that shortens the time for the mixture to attain the H_2O_2 decomposition temperature will advance the HCCI ignition timing. Use of additive is an efficient method. In general, the application of additive on ignition property has a number of

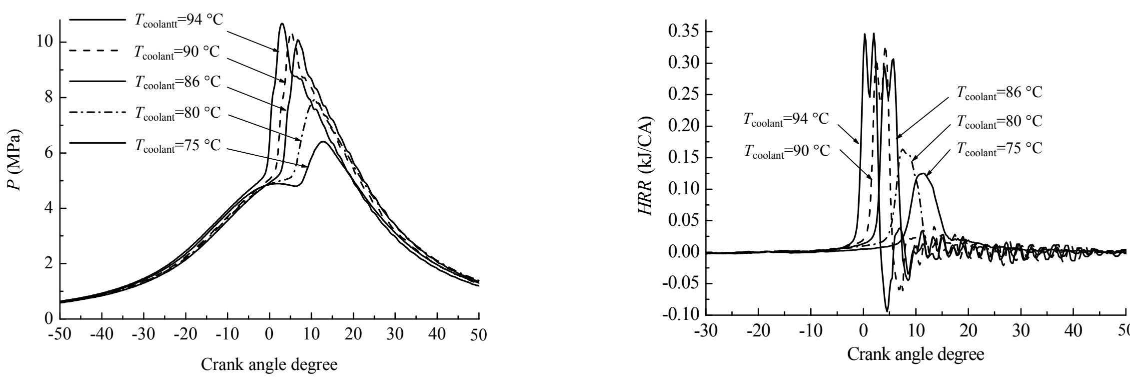
Table 1 Specifications of the single-cylinder HCCI engine

Parameter	Value	Parameter	Value
Bore×stroke	98 mm×105 mm	Advance angle of injector open	285 BTDC
Displacement (l)	0.782	Inlet valve open	16 BTDC
Compression ratio	18.5:1	Inlet valve close	52 ABDC
Nozzle type	Single-hole	Exhaust valve open	66 BBDC
Injector open pressure	5.5 MPa	Exhaust valve close	12 ATDC

effects. First, heat release effect—the temperature of the air/fuel mixture will slightly increase with the heat release in the additives decomposition reaction. Second, chemical effect—reaction velocities of the air/fuel mixture will be accelerated by the active radicals produced during the low-temperature decomposition.

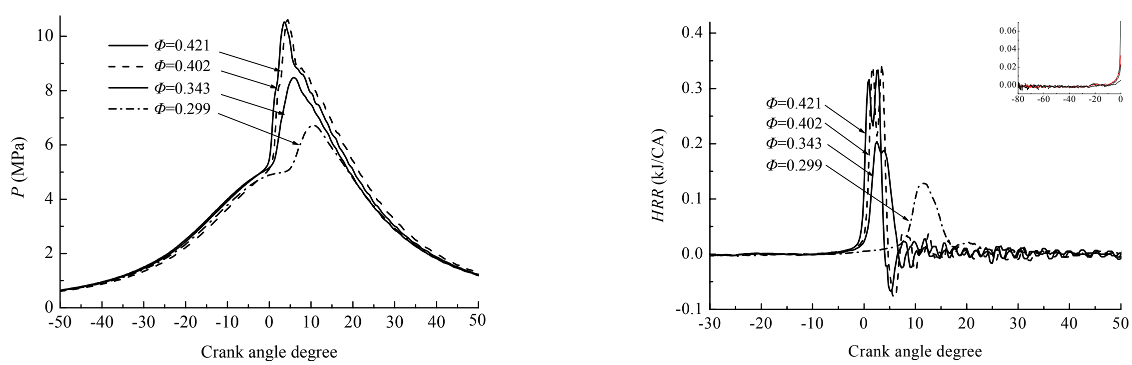
As shown in Fig.1, the iso-octane HCCI combustion can be expanded to a lower engine coolant temperature when 3% DTBP (by volume) is added to the fuel. Moreover, it can be found that the coolant temperature exerts important impact on HCCI combustion. With the increase of the coolant temperature, the temperature increasing rate of the in-cylinder gas mixture during the compression stroke, results in a short timescale for the mixture to attain the ignition timing. As a result, the ignition timing advances, the combustion velocity increases, and the maximum gas pressure and the peak value of the heat release rate increase. But it should be noted that when the coolant temperature reaches a certain value for a specific equivalence ratio, the super quick combustion will lead to a knock combustion, which will adversely affect the reliability of the engine. Furthermore, it could be seen that the falling edge of the heat release curves can be indicative noisy due to the acoustic phenomenon in the cylinder (knocking-like pressure oscillation). This phenomenon was also noted in other research reports.

Fig.2 shows the cylinder pressure and heat release rate as a function of crank angle and equivalence ratio for iso-octane with 4% DTBP additive. It is obvious that with the increase of the equivalence ratio, the maximum gas pressure and the peak value of the heat release rate increase remarkably, and that the mixture concentration has moderate effect on HCCI combustion characteristics when the equivalence ratio increases up to 0.4. For this operating condition, faint knock combustion can be observed. At the same time, it can be found from the heat release rate that iso-octane HCCI combustion only shows single-stage combustion. This is different from many heavy hydrocarbon fuels that show two-stage combustion and NTC phenomena.



(a) (b)

Fig.1 Cylinder pressure (a) and heat release rate (b) as a function of crank angle and engine coolant temperature



(a) (b)

Fig.2 Cylinder pressure (a) and heat release rate (b) as a function of crank angle and equivalence ratio *Φ* (1800 r/min, iso-octane+4% DTBP)

Fig.3a shows the influence of the DTBP volume and engine equivalence ratio on the maximum pressure rising rate. At same time, this figure also reflects the effect on the lean combustion limit. Obviously, with the addition of the DTBP additive, the HCCI combustion is expanded to the lean fuel/air mixture substantially; for a specific equivalence ratio, the combustion timing advances, and the combustion speed increases. As a result, the maximum pressure rising rate increases slightly and the rich fuel/air mixture is slightly reduced.

Fig.3b shows thermal efficiency as a function of the DTBP volume and equivalence ratio. With the addition of the DTBP, the combustion efficiencies at medium and lower equivalence ratio improve, so that the thermal efficiency increases substantially. Furthermore, the combustion timing is close to the top dead center for the rich mixture with the additive, the thermal efficiency also improves. However, when the equivalence ratio is up to 0.4, the increase of DTBP volume has little effect on thermal efficiency.

Effect of cooled EGR on HCCI combustion

EGR is widely used as the main method to decrease the NO_x emission from diesel engines, and is also used as the basic method to control the ignition timing and burn rate of HCCI combustion. This paper is mainly aimed at evaluating the effect of cooled EGR on HCCI combustion, when the mixture temperature of the fuel, fresh air, and recycled exhaust gas is kept at a constant temperature.

Fig.4 compares the gas pressure and heat release rate for different cooled EGR rate while a constant fuel supply rate is maintained for all the test points. The general tendency is that the ignition phase is delayed, and that the peak value and maximum gas pressure decrease with the introduction of EGR. Particularly, the combustion characteristics change substantially when the EGR rate is higher than 30%.

Fig.5 shows the variations of ignition timing and

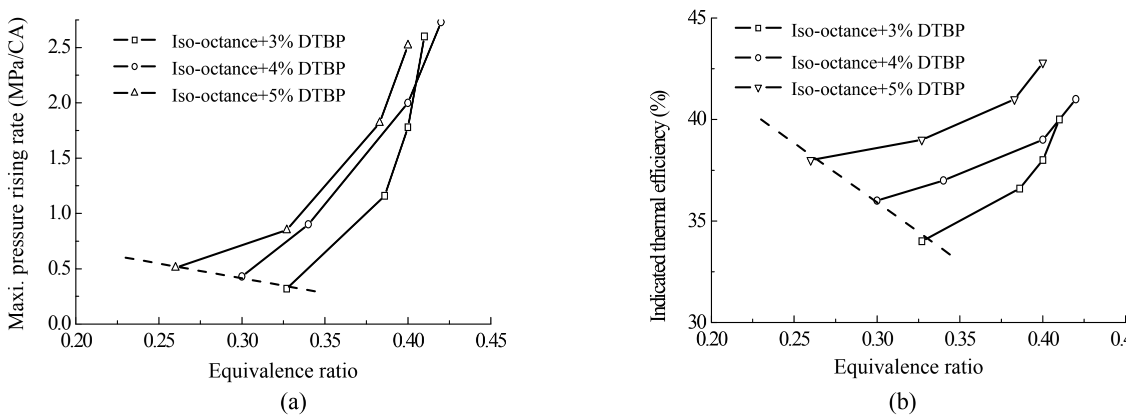


Fig.3 Effect of DTBP on the max pressure rising rate (a) and on the thermal efficiency (b)

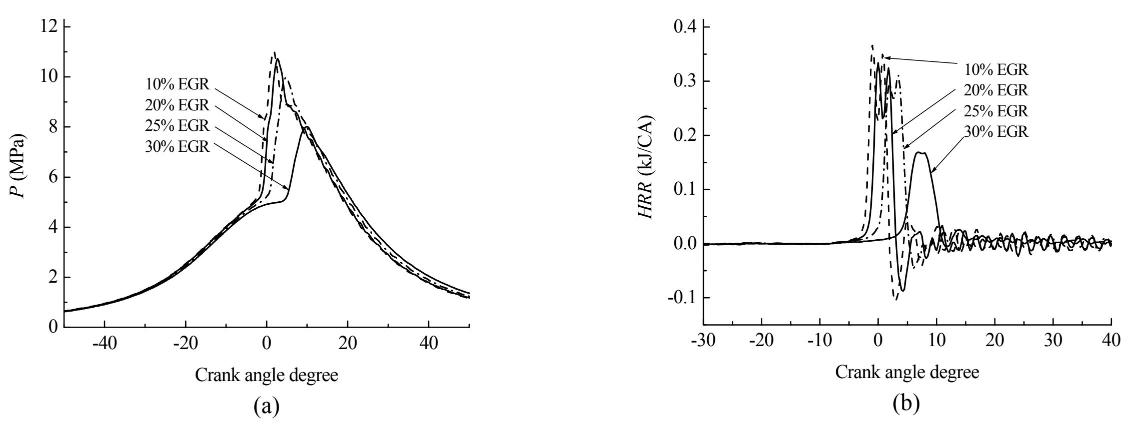


Fig.4 Effect of cooled EGR on HCCI combustion for iso-octane with DTBP addition (1800 r/min, iso-octane+4% DTBP, *b*=23.0 mg/cycle)

combustion duration for iso-octane HCCI combustion at the cooled EGR rate and DTBP volume in fuel. In this paper, the ignition timing is the specified crank angle corresponding to 20% of the magnitude of peak heat release on the rising side of the curve, and the combustion duration is defined as the distance between the ignition timing crank angle and the crank angle corresponding to 20% of the magnitude of peak of heat release on the falling side of the curve. For each test fuel, the combustion duration prolonged and the ignition timing is delayed with the increase of the cooled EGR rate. Particularly, the HCCI combustion parameters changes substantially when the EGR rate is higher than 25%. For a specific EGR rate and a fixed fuel supply rate, the ignition timing advances and combustion duration shortens with the addition of DTBP volume.

Fig.6 shows that the influence of cooled EGR on HCCI emissions including CO, UHC, and NO_x. UHC is mainly due to the chain termination during the chain propagation. With CO emission from internal combustion, the engine is primarily controlled by chemical reaction. It mainly comes from the low-temperature regions, such as boundary layer, near the walls, and crevice layer. Essentially, the main factor determining the UHC and CO level is the in-cylinder gas temperature. With increasing EGR rate, the ignition and combustion events occur near or after the TDC, and then the uncompleted reaction products in the boundary layer and crevice layer discharge into the exhaust pipe during the expansion stroke. Furthermore, the gas temperature decreases with the increase of EGR rate, and further oxidation in the exhaust pipe also reduces. These conditions lead to higher CO levels with the increase of EGR rate.

Regarding the NO_x emissions, the major advantage of HCCI combustion is ultra NO_x emissions. This can be verified in Fig.6b. Moreover, the NO_x emissions can be further decreased by the cooled EGR rate.

Effect of intake charge temperature

Intake charge temperature is a key factor affecting

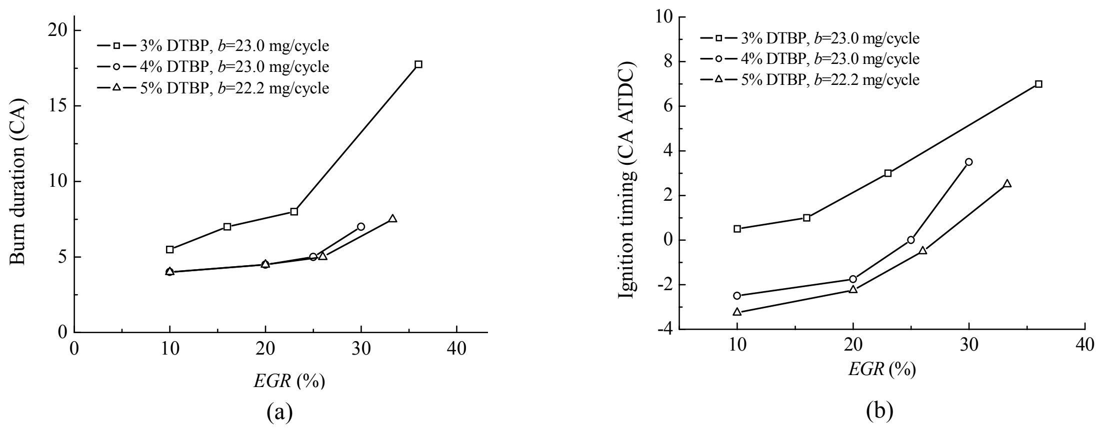


Fig.5 Effect of cooled EGR rate on combustion duration (a) and ignition timing (b) for iso-octane HCCI combustion with different additive volume

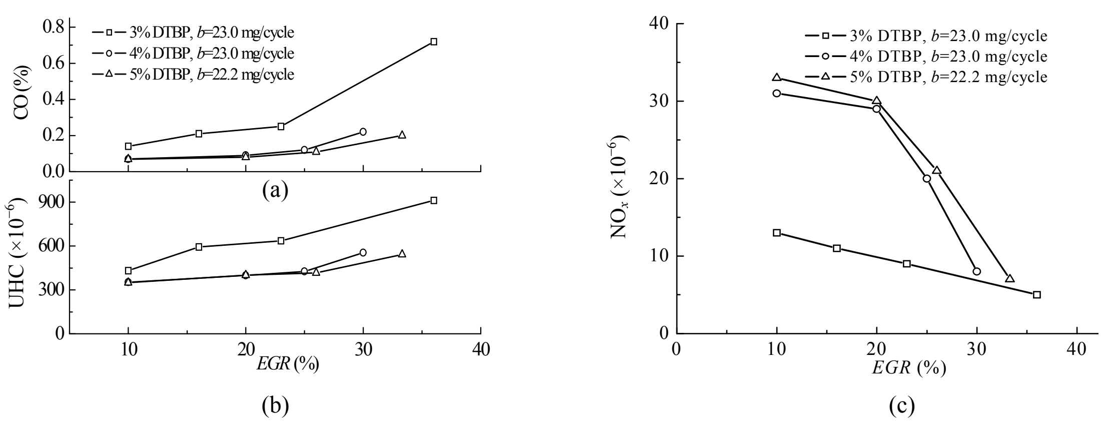


Fig.6 Influences of cooled EGR on HCCI emissions including CO (a), UHC (b), and NO_x (c)

the HCCI combustion and emission. This paper discusses the effects of the mixture temperature of the fresh air, fuel, and recycled gas on the HCCI combustion under a specific EGR rate. The temperature is changed by tuning the coolant flow rate of the cooling box. Fig.7 shows the experimental results. From Figs.7a and 7b, for a fixed fuel supply rate and a constant EGR rate, the ignition timing advances, and the maximum gas temperature and blast pressure increase notably with the increase of the intake charge temperature. When the intake charge temperature is higher than 45 °C, knock combustion can be observed. Figs.7c and 7d give the combustion parameters corresponding to the above operating conditions. When the temperature is lower than 35 °C, there is a moderate effect of temperature on combustion parameters. After that, intake charge temperature has important impact on HCCI combustion parameters.

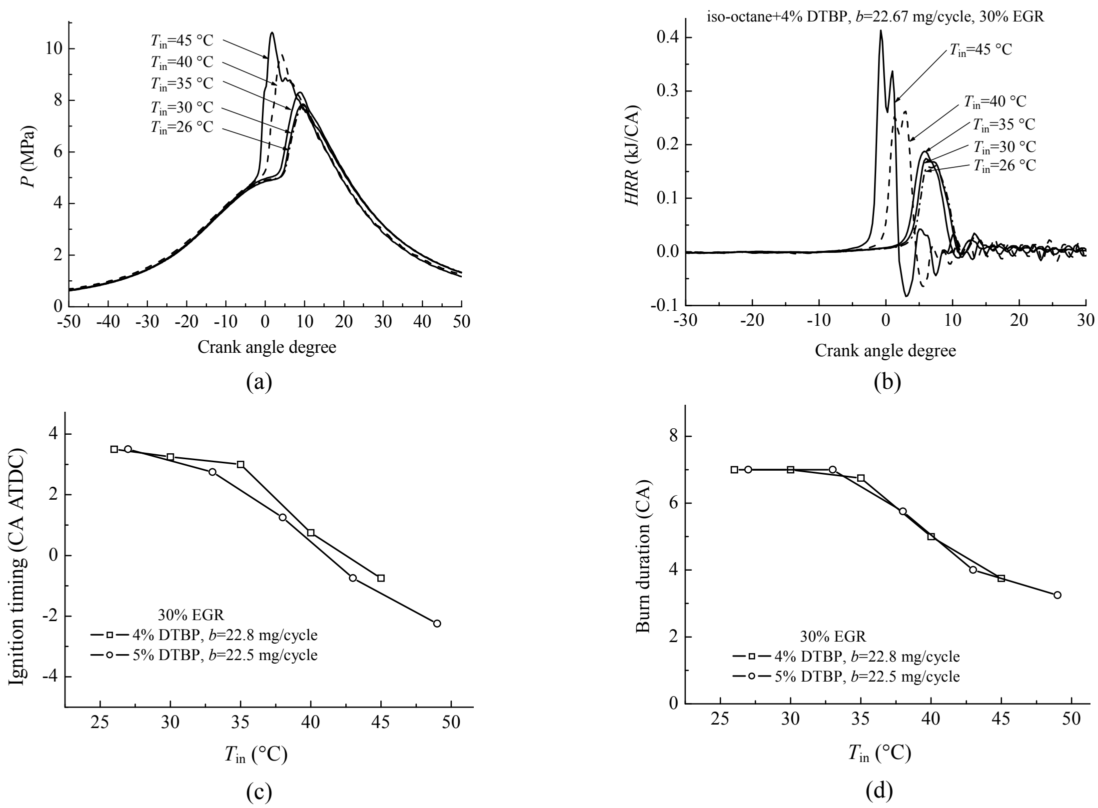


Fig.7 Effect of intake charge temperature on HCCI combustion characteristics. (a) In-cylinder pressure; (b) Heat release rate; (c) Ignition timing; (d) Combustion duration

CONCLUSION

(1) HCCI combustion operates stably by using clean iso-octane with DTBP addition (>3% by volume) without intake chare heating or any other accessory methods. Furthermore, the ignition timing advances with the increase of the DTBP addition, coolant temperature, equivalence ratio and intake charge temperature.

(2) Iso-octane HCCI combustion shows single-stage combustion for all operating conditions.

(3) Cool EGR causes ignition timing delays and combustion duration decreases for iso-octane HCCI combustion with DTBP addition in fuel, while EGR causes the CO and UHC level to increase gradually, and NO_x emission decreases under all operating conditions.

(4) The intake charge temperature has a moderate effect on combustion and emissions when it is lower than 35 °C; but the combustion timing advances and the combustion duration shortens, which sometimes leads to knock when the intake charge temperature increased above 35 °C.

References

Kontarakis, G., Collings, N., Ma, T., 2000. Demonstration of HCCI Using a Single Cylinder Four-stroke SI Engine with Modified Valve Timing. SAE, Paper 2000-01-2870.

Lü, X.C., Chen, W., Huang, Z., 2005. A fundamental study on the control of the HCCI combustion and emissions by fuel design concept combined with controllable EGR, Part 1: The basic characteristics of HCCI combustion. *Fuel*, **84**(9):1074-1083. [doi:10.1016/j.fuel.2004.12.014]

Noguchi, M., Tanaka, T., Takeuchi, Y., 1979. A Study On-gasoline Engine Combustion by Observation of Intermediate Reactive Products During Combustion. SAE, Paper 1979-01-0840.

Onishi, S., Jo, S.H., Shoda, K., 1979. Actived Thermo-Atmosphere Combustion (ATAC)—A New Combustion Process for Internal Combustion Engines. SAE, Paper 1979-01-0501.

Peng, Z.J., Zhao, H., Tom, M., Nicos, L., 2005. Characteristics of homogeneous charge compression ignition (HCCI) combustion and emissions of *n*-heptane. *Combustion Science and Technology*, **177**(11):2113-2150. [doi:10.1080/00102200500240588]

Santoso, H., Matthews, J., Cheng, W.K., 2005. Managing SI/HCCI Dual-Mode Engine Operation. SAE, Paper 2005-01-0162.

Sjober, M., Dec, J., Cernansky, N.P., 2005. Potential of Thermal Stratification and Combustion Retard for Reducing Pressure-Rise Rates in HCCI Engines, Based on Multi-Zone Modeling and Experiments. SAE, Paper 2005-01-0113.

Yang, J.L., Todd, C., Thomas, K., 2002. Development of a Gasoline Engine System Using HCCI Technology—The Concept and the Test Results. SAE, Paper 2002-01-2832.

Yap, D., Karlovsky, J., Megaritis, A., Wyszynski, M.L., Xu, H., 2005. An investigation into propane homogeneous charge compression ignition (HCCI) engine operation with residual gas trapping. *Fuel*, **84**(18):2372-2379. [doi:10.1016/j.fuel.2005.05.008]