EFFECTS OF INTAKE AIR TEMPERATURE ON HOMOGENOUS CHARGE COMPRESSION IGNITION COMBUSTION AND EMISSIONS WITH GASOLINE AND n-HEPTANE

by

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Original scientific paper
DOI: 10.2298/TSCI140524174Z

In a port fuel injection engine, optimized kinetic process technology is implemented to realize homogenous charge compression ignition (HCCI) combustion with dual-fuel injection. The effects of intake air temperature on HCCI combustion and emissions are investigated. The results show that dual-fuel control prolongs HCCI combustion duration and improves combustion stability. Dual-fuel HCCI combustion needs lower intake air temperature than gasoline HCCI combustion, which reduces the requirements on heat management system. As intake air temperature decreases, air charge increases and maximum pressure rising rate decreases. When intake air temperature is about 55 °C, HCCI combustion becomes worse and misfire happens. In fixed dual fuel content condition, HC and CO emission decreases as intake air temperature increases. The combination of dual-fuel injection and intake air temperature control can expand operation range of HCCI combustion.

Key words: *duel fuel, HCCI, n-heptane, intake air temperature, load expanding*

Introduction

Homogeneous charge compression ignition (HCCI) combustion shows high potential to reduce fuel consumption and emission. An HCCI engine can reduce fuel consumption through high compression ratio, un-throttling, and lean combustion. Meanwhile, NO_x emission can be suppressed due to low cylinder temperature in HCCI combustion. Many technologies are implemented to realize HCCI combustion. Controlled auto ignition is a common method for HCCI combustion, which traps hot residual gas from last cycle to increase gas temperature by negative valve overlap system [1, 2]. Another method to promote HCCI combustion is variable compression ratio [3]. Dual-fuel or fuel reformer could also be employed to realize auto ignition [4-7]. The ratio of two fuels should be changed under different operation conditions to control HCCI timing. Dual fuel HCCI combustion with diesel and n-heptane is studied in a single cylinder engine, and combustion process is analyzed [6, 8]. Yang and Kenney [9] proposed optimized kinetic process (OKP) technology to realize HCCI combustion, which using coolant and exhaust gas to heat intake air. The OKP technology was demonstrated in a single cylinder direct

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injection engine. Net indicated fuel efficiency was 30% higher than a prototype direct injection engine. For HCCI combustion with OKP technology, intake air should be heated to a relative high temperature, which brings challenge for intake air system and HCCI load expansion.

In the study, OKP technology is implemented in a 4-cylinder port fuel injection engine to realize HCCI combustion. Intake port has two independent injection systems with gasoline and n-heptane. The ratio of gasoline and n-heptane is changed due to different operating point. Intake air temperature is tuned to control HCCI combustion, and the effects of intake air temperature on HCCI combustion with gasoline and n-heptane are studied in experiments.

Experimental set-up

The test engine is a 1.5 liter port fuel injection engine. The engine parameter is shown in tab. 1.

Table 1. Engine specification

Engine type	PFI, 4 valve DOHC gasoline
Bore	75 mm
Stroke	84.8 mm
Displacement	1.498 liter
Compression ratio	13:1

The OKP technology with heat management system is employed to realize HCCI combustion in the experiment. The new coolant-intake air heat exchanger and exhaust-intake air heat exchanger are added. There are separate valves on pipe, which could be used for fast thermal management. The piston geometry is redesigned, which increases compression ratio from 10.5 to 13. Test engine has two independent injection systems with gasoline and n-heptane. The test bench has independent high pressure air source, which can be used for intake air pressure investigation experiment. The test bench schematic is shown in fig. 1. Four 611B Kistler cylinder pressure sensors are installed to measure HCCI combustion. The D2T Osiris combustion analyzer is used to process cylinder pressure sensor signals. The Bosch LS17025 lambda sensors are installed on intake and exhaust pipe, which are used to measure oxygen concentration and exhaust gas re-circulation rate. The AVL 4000 gas analyzer is used to measure HC, CO, and NO_x concentration in exhaust. The dynamometer control system is XiangYi FC2000 system.

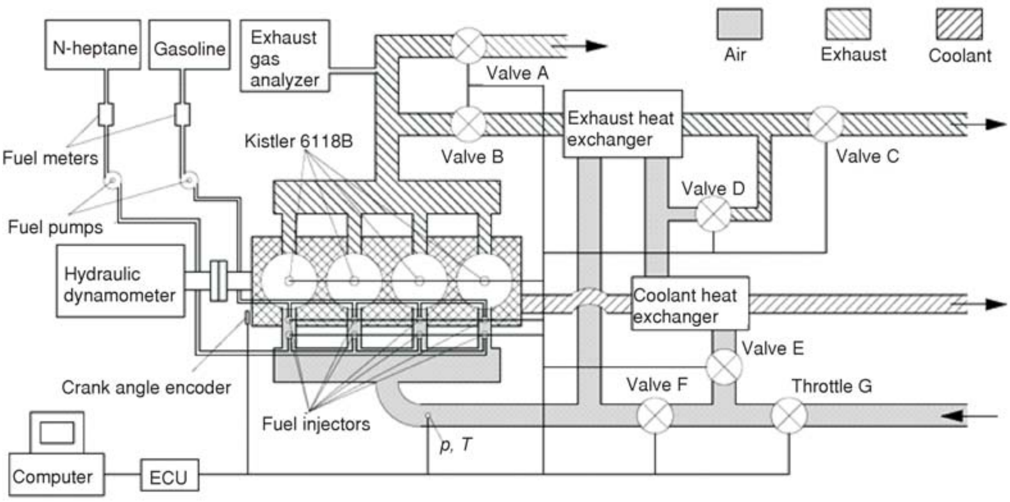

Figure 1. Schematic diagram of experimental apparatus

Gasoline and n-heptane were injected into intake port by two groups of injectors separately. Properties of gasoline and n-heptane are shown in tab. 2.

Table 2. Properties of gasoline and n-heptane

Property	Gasoline	n-Heptane
Cetane number	52	56
Octane number	93	0
Lower heating value [$MJkg^{-1}$]	44.1	44.5
Density [kgm^{-3}] at 20 °C	746	683
Viscosity [mPa·s] at 20 °C	0.567	0.376
Heat of evaporation [$kJkg^{-1}$]	290-315	310
Boiling point [°C] at 1 atm	–	98.5

In the experiment, when engine runs in spark ignition mode, valve E is closed and valve F is fully open, valve G is controlled as throttle. Intake air is conducted into cylinder without heating stage. When engine runs in HCCI combustion mode, valve E is open and valve F is closed. Intake air is heated by coolant and exhaust gas, the intake temperature rises to the desired value in short time. With high compression ratio and intake variable valve timing tuning, mixture could start auto ignition near engine compression top dead centre (TDC) position. The HCCI combustion timing is controlled and tuned by intake air temperature, injection quantity and exhaust gas recirculation (EGR) rate. The valve positions in hot air pipe and cold air pipe could be changed to realize different desired intake air temperature. Exhaust gas could be conducted to intake pipe by controlling valve D, which could be used for EGR experiments.

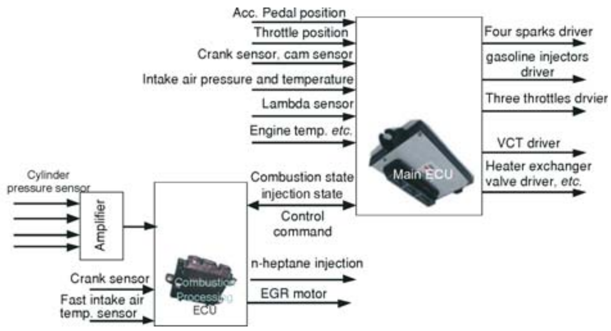

Figure 2. The HCCI engine control system structure

The control system for research engine is based on prototype electronic control unit (ECU). There are two prototype ECU for the demo engine, which are shown in fig. 2. First, 128 pin mototron ECU is used for main control ECU, which will control injection, ignition, throttle, *etc*. Second, 112 pin mototron ECU is used as cylinder pressure processing ECU, which also controls the n-heptane injection. There are control commands and states information exchange between two ECU by controller area network.

Gasoline and n-heptane are injected into intake port by two groups of injectors separately. Properties of gasoline and n-heptane are shown in tab. 3. The ratio of gasoline in the fuel injected was defined:

$$RG = \frac{m_g \mathrm{LHV_g}}{m_g \mathrm{LHV}_g + m_n \mathrm{LHV_n}} \tag{1}$$

where m_g is the mass of gasoline, $\mathrm{LHV_g}$ – the low heat value of gasoline, m_n – the mass of n-heptane, $\mathrm{LHV_n}$ – the low heat value of n-heptane.

In this study, coefficient of variation (COV) of combustion parameter is defined:

$$COV(x) = \frac{\sigma}{\bar{x}} 100\% \tag{2}$$

where σ is the standard deviation, $\bar{x}$ – the mean value.

In order to evaluate the combustion knock intensity of the HCCI engine, ringing intensity (RI) was employed in this investigation. The RI is defined [10]:

$$RI = \frac{1}{2\gamma} \frac{\left[0.05\left(\frac{\mathrm{d}P}{\mathrm{d}t}\right)_{\max}\right]^2}{p_{\mathrm{peak}}} \sqrt{\gamma \mathrm{R} T_{\max}} \tag{3}$$

where γ is the ratio of specific heats, $(\mathrm{d}P/\mathrm{d}t)_{\max}$ – the maximum of pressure rise rate, p_{peak} – the peak of in-cylinder pressure, and $T_{\max}$ – the peak of in-cylinder temperature.

In the experiment, engine operating conditions are shown in tab. 3. Intake air temperature is controlled by tuning throttle position of hot pipe and cold pipe. The RG is tuned by the ECU calibration software.

Table 3. Operating conditions

Parameter	Value
Intake air pressure	975 kPa
Coolant temperature	90 °C
Oil temperature	90 °C
Engine speed	1600 rpm
Fuel delivery	296.8 [J per cycle]
Intake air temperature	60~170 °C
RG	0.57~0.65

Test results

In the same operating conditions, threshold temperature for gasoline combustion is higher than n-heptane combustion. Gasoline combustion has only one exothermic reaction phase. The N-heptane combustion has two exothermic reaction phases, which are called low temperature exothermic reaction and high temperature exothermic reaction. As cylinder temperature reaches above 800 K, low temperature exothermic reaction starts. Low temperature exothermic reaction increases the cylinder temperature, which promotes high temperature exothermic reaction.

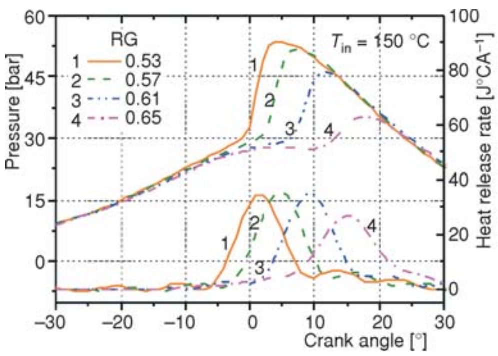

Figure 3. Effect of RG on pressure and heat release rate of dual-fuel HCCI engine

Figure 3 shows the influence of RG on cylinder pressure and heat release rate. As RG value increases, the content of n-heptane decreases. The ratio of low temperature exothermic reaction decreases, and heat release rate becomes small and later, which leads cylinder temperature decreasing. Heat release peak of high temperature exothermic reaction decreases and combustion phase is retarded. Peak pressure decreases and phase of peak pressure retards as RG increasing.

Figure 4 shows the influence of intake air temperature on cylinder pressure and heat release rate with fixed RG value. It can be seen that intake air temperature has a dominant influence on combustion. From the previous research, the threshold of intake air temperature for gasoline HCCI combustion is above 170 °C [11]. As intake air temperature decreases, the ratio of low temperature exothermic reaction decreases. This leads less heat release of high temperature exothermic reaction and later peak of heat release. Maximum heat release rate phase and peak pressure phase are also retarded as intake air temperature decreasing, meanwhile the combustion duration is prolonged. When intake air temperature is tuned to 55 °C, peak of heat release is too low and combustion duration is too long, which may leads deteriorate combustion or misfire.

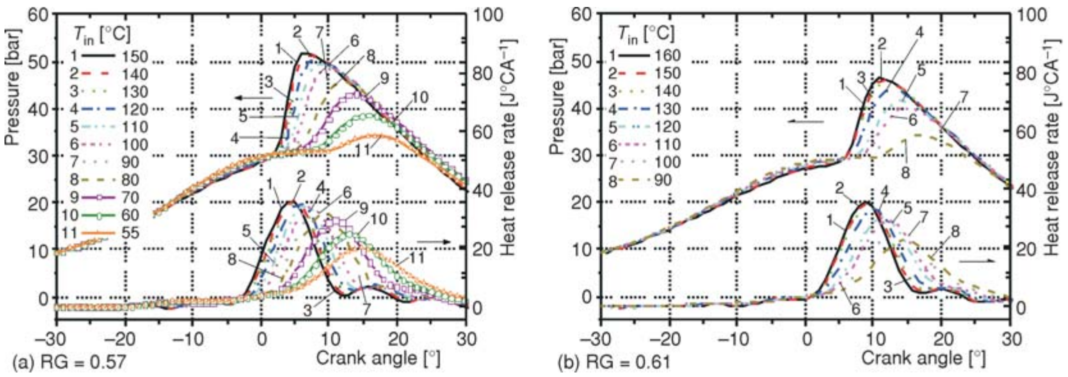

Figure 4. Effect of intake air temperature on pressure and heat release rate of dual-fuel HCCI engine

Intake air temperature has two factors to influence dual fuel HCCI combustion. First, intake air temperature has great effect on both low temperature exothermic reaction and high temperature exothermic reaction. The N-heptane has high cetane number with high low temperature exothermic reaction activity. As intake air temperature increases, heat release of low temperature exothermic reaction increases. Meanwhile, free radical quantity increases, which accelerates reaction and increases temperature. This leads high temperature exothermic reaction advanced. Secondly, intake air temperature also has effect on cylinder charge. As intake air temperature increases, cylinder charge decreases due to low air density. Air fuel mixture becomes rich when fuel injection is kept same. So mixture temperature increases more than low temperature intake air temperature, which accelerates exothermic reaction.

When RG is kept as 0.57, n-heptane content is high and low temperature exothermic reaction is accelerated, which leads relative early combustion phase. As intake air temperature falls from 150 °C to 80 °C, combustion start phase is retarded and low temperature exothermic reaction content is reduced slowly. As intake air temperature falls from 80 °C to 55 °C, combustion start phase is retarded significantly. When RG is kept as 0.61, n-heptane content is low and minimum intake air temperature for HCCI combustion is 90 °C due to less exothermic reaction from n-heptane. The threshold intake air temperature for HCCI combustion can be reduced with low RG value.

Figure 5 shows influences of intake air temperature on CA50 and combustion duration with different RG groups. It can be seen that CA50 is retarded and combustion duration is prolonged as intake air temperature decreases in fixed RG condition. As intake air temperature decreases, low temperature exothermic reaction and high temperature exothermic reaction are both suppressed, heat release rate becomes less, so combustion phase is retarded and combustion duration is prolonged. In fixed intake air temperature condition, CA50 is advanced as RG decreases due to less low temperature exothermic reaction. As RG increases, the intake air temperature range for HCCI combustion becomes narrow. When RG is 0.57, intake air temperature range is 150 °C to 55 °C. When RG is increased to 0.65, intake air temperature range becomes 174 °C to 150 °C. The reason is that low temperature exothermic reaction of n-heptane promotes combustion and releases heat for high temperature exothermic reaction. As RG increases, n-heptane content decreases. Heat release from low temperature exothermic reaction of gasoline is much less than n-heptane. So intake air temperature low limit should increase in high RG

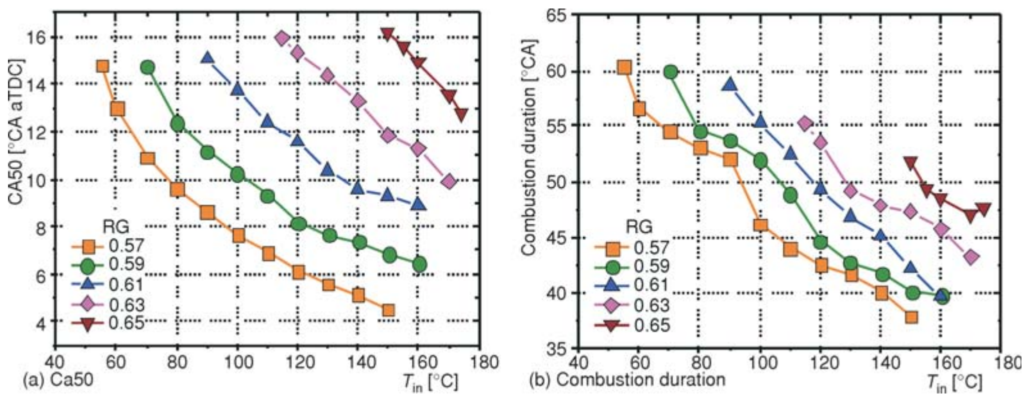

Figure 5. Effect of intake air temperature CA50 and combustion duration of dual-fuel HCCI engine

value condition. Intake air temperature range for stable HCCI combustion becomes narrow in high RG value condition. Misfire occurs in too low intake air temperature and knocking occurs in too high intake air temperature.

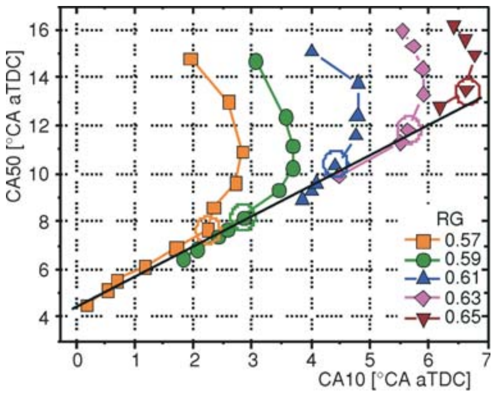

Figure 6. Effect of intake air temperature on the relation of CA10 and CA50 of dual-fuel HCCI engine

Figure 6 shows effect of intake air temperature on the relation of CA10 and CA50. In different RG value conditions, as intake air temperature decreases, CA10 and CA50 increases simultaneously. The CA10 has linear relation with CA50 in high intake air temperature area. When intake air temperature decreases to low level, CA50 is retarded much but CA10 is advanced. Firstly, when intake air temperature decreases too much, low temperature exothermic reaction and high temperature exothermic reaction are both suppressed, which retards CA10 and CA50 both. Secondly, air charge increases due to lower intake air temperature, air fuel ratio of mixture increases, which promotes low temperature exothermic reaction. So CA10 is advanced and CA50 is retarded slightly. With the combination these two influence facts, CA10 is advanced and CA50 is retarded. Meanwhile, cylinder temperature, peak pressure and peak heat release rate decrease. Combustion duration increases significantly. Combustion stability becomes worse with misfire.

In fig. 6, the points of maximum CA10 and CA50 in linear relation are marked with circle symbol. These points are intake air temperature low limits with HCCI stable combustion. In different RG value conditions, the marked points have large CA10 and CA50 value. The peak heat release rate and peak pressure are suppressed in high load and low intake air temperature area, which is beneficial for load expansion and NO_x emission. N-heptane is effective for duel fuel HCCI combustion to expand HCCI combustion range and suppress knocking tendency.

Figure 7 show the influences of intake air temperature on peak pressure (p_{peak}) and maximum pressure rising rate (PRR_{max}). Peak pressure decreases as RG increases with the same

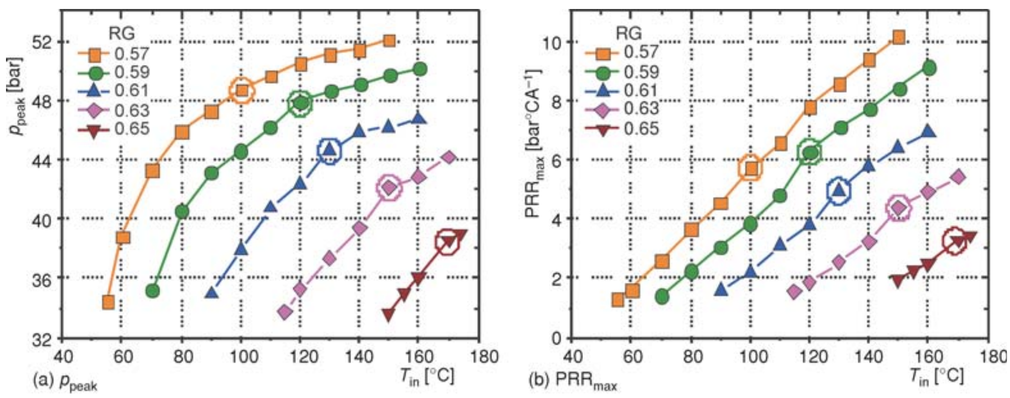

Figure 7. Effect of intake air temperature on p_{peak} and PRR_{max} of dual-fuel HCCI engine

intake air temperature. Peak pressure decreases as intake air temperature decreases with the same RG value. Peak pressure is mainly affected by combustion phasing and heat release rate. As intake air temperature increases, heat release rate increases. Peak pressure phasing becomes close to TDC and peak pressure increases. As intake air temperature increases, PRR_{max} increases simultaneously due to high heat release rate.

Figure 8 shows influences of intake air temperature on indicated mean effective pressure (IMEP) and COV of IMEP. As intake air temperature decreases, IMEP increases first and decreases later in the same RG value condition. Maximal IMEP happens in medium intake air temperature. The optimal intake air temperature decreases as RG decreases. The IMEP is mainly affected by p_{peak} and p_{peak} phasing. When p_{peak} phasing is close to TDC and p_{peak} changes little, IMEP is affected by p_{peak} phasing. When p_{peak} phasing is late and changes little, IMEP is mainly affected by p_{peak}. When intake air temperature is in relative high range, p_{peak} phasing is close to TDC. As intake air temperature decreases, IMEP increases due to longer combustion duration. When intake air temperature is in relative low range, p_{peak} phasing is late after TDC. As intake air temperature decreases, p_{peak} phasing changes little and combustion becomes worse. So p_{peak} decreases significantly, which leads IMEP decreasing.

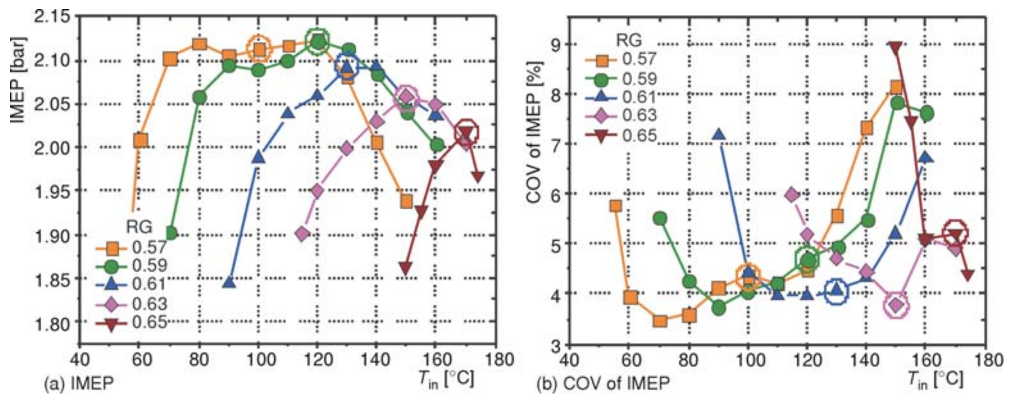

Figure 8. Effect of intake air temperature on IMEP and COV of IMEP of dual-fuel HCCI engine

As intake air temperature decreases, COV of IMEP first decreases and then increases, which shows that HCCI combustion has an optimal intake air temperature for stable combustion.

Figure 9 shows influences of intake air temperature on HC and CO emissions. In fixed intake air temperature condition, HC emission increases significantly as RG value increases. In fixed RG value condition, as intake air temperature decreases, HC emission increases. The reason is that cylinder temperature boundary layer becomes thicker as intake air temperature decreases. This leads unburned HC emission in cylinder temperature boundary layer and piston ring gap increases. Meanwhile, the unburned HC from expansion stroke and exhausting stroke also increases as intake air temperature decreases [12]. The optimal HC emission points stays in low range.

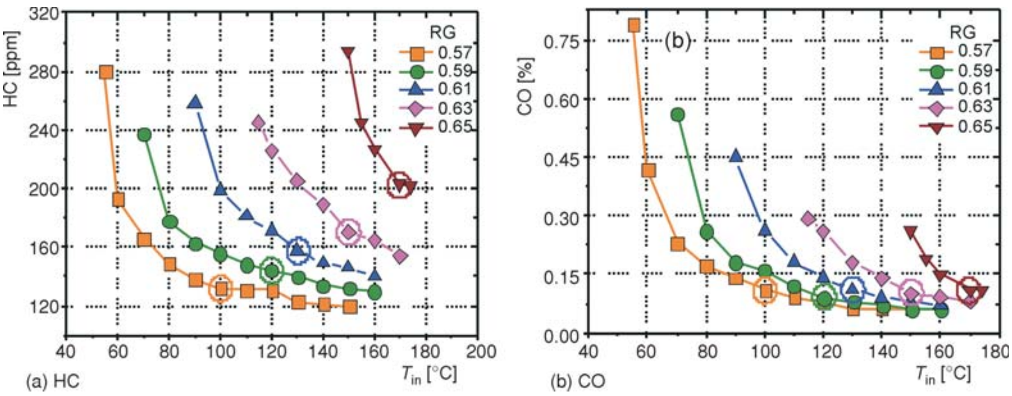

Figure 9. Effect of intake air temperature on HC and CO emissions of dual-fuel HCCI engine

In fixed intake air temperature condition, CO emission increases as RG increases. In fixed RG value condition, CO emission decreases as intake air temperature increases. The CO is intermediate product, which is mainly generated from low temperature combustion reaction and oxidized to CO_2 in high temperature combustion reaction. As intake air temperature decreases, low temperature exothermic reaction of n-heptane is suppressed. Combustion phasing is retarded and high temperature reaction time is shortened, which leads low cylinder temperature and high CO emission. The CO emission increases significantly in low intake air temperature due to insufficient combustion. The CO emission in optimal intake air temperature condition which is marked in figure is very low.

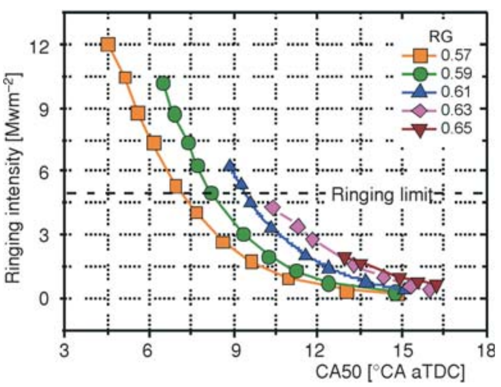

Figure 10. Relationship between RI and CA50

For duel fuel HCCI combustion, NO_x emission is always in a very low level, which is less than 10 ppm. So NO_x emission is not discussed in the paper.

Figure 10 shows the relationship between RI and CA50. As intake air temperature increases, combustion phasing is advanced. Pressure rising rate increases, which leads RI increasing. In fixed RG value condition, RI decreases as CA50 is retarded. Figure 11 shows the relationship between COV_{IMEP} and CA50. The COV_{IMEP} increases as CA50 is retarded. If COV_{IMEP} exceeds threshold limit, the combustion will consider as unstable combustion.

From previous research, RI limit is 5 MW/m^2 and COV_{IMEP} is 5% [13, 14]. Figure 12 show the CA50 range with RI and COV_{IMEP} limits for stable HCCI combustion. When RG is 0.59, CA50 range is 5 °CA. When RG is 0.57, CA50 range is 6.9 °CA. So it can be seen that CA50 range increases as RG decreasing, which is useful for HCCI operating range expansion. Dual-fuel injection with n-heptane and gasoline combined with intake air temperature control can expand HCCI operating range.

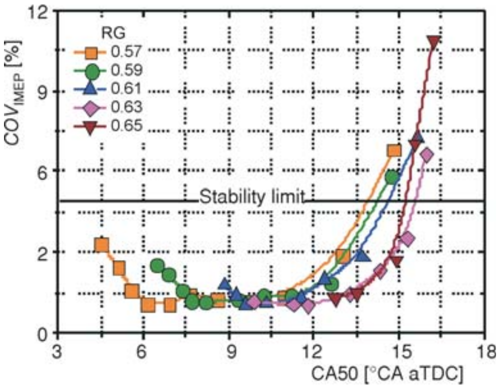

Figure 11. Relationship between COV_{IMEP} and CA50

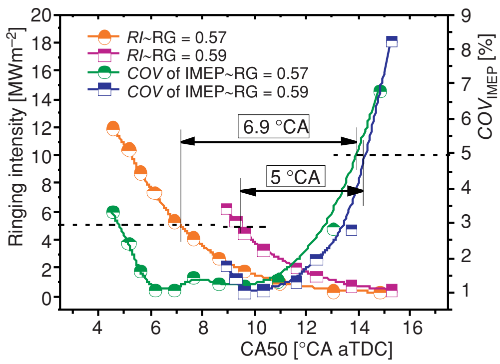

Figure 12. Effect of RI and *COV* on the region of CA50

Conclusions

In the study, HCCI combustion with n-heptane and gasoline in a 4-cylinder engine is investigated. The conclusions of this study are:

- As n-heptane contents decrease, cylinder temperature decreases, and combustion phasing is retarded. Peak pressure decreases and is also retarded.
- As intake air temperature decreases, heat release and peak pressure decreases. When intake air temperature is about 55 °C, HCCI combustion becomes worse and misfire happens.
- As intake air temperature decreases, IMEP first decreases and then increases. The optimal intake air temperature with maximal IMEP decreases as RG value decreases.
- In fixed intake air temperature condition, HC and CO emission increases as RG increases. In fixed RG value condition, HC and CO emission decreases as intake air temperature increases.
- Dual-fuel injection with n-heptane and gasoline combined with intake air temperature control can expand HCCI operating range.

Acknowledgment

The authors would like to thank Science and Technology Commission of Shanghai Municipality (Project No. 09DJ140030), Shanghai Jiao Tong University and Shanghai Automotive Industry Corporation (SAIC) for financial and technical support to this study.

Nomenclature

T_{in} – intake air temperature, [°C]
p_{peak} – peak pressure, [bar]

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Paper submitted: May 24, 2014
Paper revised: October 19, 2015
Paper accepted: November 19, 2015