Research Paper

Condition of SI-CI Operation with Lean Mixture of Primary Reference Fuel and Hydrogen

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Received on July 12, 2010

Presented at the JSAE Annual Congress on May, 20, 2010

ABSTRACT: In order to control the heat-release rate at homogeneous charge compression ignition (HCCI) operation, the feasibility of spark-assisted compression ignition (SI-CI) combustion was demonstrated with lean mixture of primary reference fuel (PRF) and hydrogen. In this study, the criteria at octane number and hydrogen ratio were investigated using a rapid compression/expansion machine for different equivalence ratios, compression ratios and spark timings. Experimental results of in-cylinder pressure and heat-release rate indicated possible advantageous characteristics of SI-CI operation with lower pressure-rise rate and higher engine output. Also, flame images were visualized to observe various combustion forms including HCCI, SI-CI and SI combustions.

KEY WORDS: Ignition Engine, Lean-Burn Engine/SI-CI, Primary Reference Fuels, Hydrogen [A1]

1. Introduction

Compared to conventional combustion systems, the homogeneous charge compression ignition (HCCI) combustion system is well known for its high thermal efficiency and low pollutant emissions, especially nitrogen oxides (NO_x) and particulate matter (PM) [1]. However, HCCI operations are restricted to a narrow range of engine output due to the knocking that occurs at high load and the misfiring that occurs at low load.

To solve the knocking problem, some researchers have attempted to control the ignition in HCCI combustion systems by using conventional gasoline [2]. As for the misfiring problem, control of intake temperature, equivalence ratio, and compression ratio has been investigated with fuels that have low octane numbers [3].

In more recent research, a new concept, which is based on spark-ignition/compression-ignition (SI-CI) combustion, has been proposed. In the new concept, SI-CI combustion is used to ensure ignitability and to prevent knocking by using SI combustion of a lean pre-mixture to trigger the CI combustion of the end gas [4].

Compared to other approaches, the SI-CI approach can ignite a lean mixture at lower intake temperatures and lower compression ratios. In this study, the results are divided into two parts which the first part examined the possibilities and the changes of combustion forms of SI-CI at fixed-spark timing $\theta_i = -20^\circ$ ATDC at various octane numbers, hydrogen ratio, compression ratios and equivalence ratios and the range of SI-CI region were exhibited [5-7]. The second part as being examined in this study, the effect of spark timings on the condition of the SI-CI operation was discussed to understand the possibilities to expand SI-CI range from the previous studies.

In this study, in order to clarify the conditions of the SI-CI operation, experiments were conducted using the rapid

compression/expansion machine (RCEM), which provides advantages compared to a conventional engine due to its completely homogeneous charge preparation and the simplicity associated with setting engine conditions. In order to enhance the understanding of the nature of flame development in various combustion forms, flame images were observed for various combustion forms, including HCCI, SI-CI and SI. Also, cylinder pressures and heat-release rates were measured at different equivalence ratios, compression ratios, and spark timings to investigate the criteria of SI-CI for a lean mixture of primary reference fuels (PRFs) with hydrogen addition. After this, combustion forms associated with various spark timings were observed. Tests under various conditions were conducted for each of the different spark timings. From the results of tests for various octane numbers of PRFs and hydrogen ratios, the criteria of SI-CI combustion were determined for different compression ratios, equivalence ratios, and spark timings. Also, based on the rate of pressure rise and the engine output, the conditions of the SI-CI operation were determined.

2. Experimental setup

In this experiment, a rapid compression/expansion machine (RCEM), shown in Fig. 1(a), was used, and its specifications are provided in Table 1. The RCEM consisted of a single-cylinder engine driven by a motor, which simulated combustion during piston reciprocation. The compression ratio ε was changed geometrically by adjusting the thickness of a spacer between the cylinder head and cylinder block. A mixing chamber with a volume of 1,650 cm³ was installed to produce fuel/air mixtures over a wide range of charge pressures and equivalence ratios.

The fuel/air mixture was introduced into the combustion chamber through an intake valve. The original head of the engine

Table 1: RCEM Specifications and test conditions

Bore × Stroke	110 × 106 mm
Compression ratio, ε	13, 15
Engine speed	600 rpm
Initial temperature, T_i	97 °C
Cylinder wall temperature, T_{cw}	56 °C
Spark timings, θ_i	-70 to 0 °ATDC
Valve close timing, θ_{vc}	-180 °ATDC
Fuel	PRF, H_2

(a)

(b)

Fig. 1 Schematic diagram (a) and cylinder head (b) of RCEM

was replaced by a specially-designed combustion chamber, as shown as in Fig. 1(b). A spark plug was mounted at the edge of the combustion space, and the window was installed for visualizing flame images at the opposed side. A Photron high-speed camera (FASTCAM SA1 675K-M1) with a CMOS sensor was used to record flame images at 20,000 fps without any filter.

The cylinder pressure was measured by a piezoelectric pressure transducer. For every experiment, the mixture of gaseous primary reference fuel PRF, hydrogen and air with the assigned equivalence ratio ϕ and hydrogen ratio r_H was prepared in the mixing chamber at the pressure $p_i = 0.2$ MPa. Then the RCEM was driven by a motor for at least one minute to ensure the homogeneous mixture. Combustion process started after the intake valve closed at bottom dead center BDC, when the initial temperature T_i of the mixture reached 97 °C, which was measured by a thermocouple in the inner mixing chamber. The initial pressure $p_i = 0.125$ MPa was measured at BDC by a strain gauge sensor mounted on the mixing chamber. In this study, experiments were made at a fixed speed of 600 rpm for PRF mixture with different octane numbers of PRF ON from 0 (n-heptane) to 100 (iso-octane).

3. Results and discussions

Previous works showed the results of three conditions, i.e., Case I for a compression ratio $\varepsilon = 13$ and equivalence ratio $\phi = 0.45$; Case II for $\varepsilon = 13$ and $\phi = 0.60$; and Case III for $\varepsilon = 15$ and $\phi = 0.45$ [5-7]. Also, in this research, the effects of compression ratio ε , equivalence ratio ϕ , hydrogen ratio r_H and octane number ON on the range of SI-CI operation were explained, and, in addition the research focused on determining the effect of spark timing on the expansion of range of the SI-CI combustion process.

The results of the experiment for each case were analyzed based on the pressure history p , the rate of heat release $dq/d\theta$, the average combustion temperature T_{ave} , the maximum rate of pressure rise $dp/d\theta_{max}$, the indicated mean effective pressure IMEP, the fraction of CI combustion in SI-CI r_{CI} and the start timing of CI combustion in SI-CI θ_{CI} for certain conditions of r_H and ON at various spark timings θ_i .

3.1. Various combustion forms

In this research, at first, various combustion forms were identified by the investigation of the rate of heat release. Figure 2(a) showed the courses of p and $dq/d\theta$ against the crank angle θ at ON = 0 and $\varepsilon = 15$ for different r_H . In $r_H = 0.35$, combustion was achieved in HCCI form without spark and was featured by two stage combustion, in which the first stage was low temperature reaction LTR and the second was high temperature reaction HTR. In $r_H = 0.5$, misfiring occurred in HCCI mode, and required a spark ignition. The combustion switched from HCCI to SI-CI mode by using the spark ignition. SI-CI also exhibited two stages of combustion, in which the first stage was SI and the second stage is CI. In $r_H = 0.7$, the combustion changed from SI-CI to SI mode due to high flammability of hydrogen. SI exhibited only single stage of heat-release rate with flame propagation. Such changes of combustion form reflected the flame images in Fig. 2(b). Developments of natural flame luminosity in three combustion forms of HCCI, SI-CI, and SI were exhibited, corresponding with the p and $dq/d\theta$ in Fig. 2(a). In $r_H = 0.35$, for the [A]: HCCI, ignition was started by multiple sources seen at $\theta = 0.5$ °ATDC, and combustion occurred very rapidly. Combustion almost completed at $\theta = 5.5$ °ATDC. In $r_H = 0.50$, for the [B]: SI-CI, the flame propagation of SI seen at $\theta = 3.5$ °ATDC, triggered CI seen at $\theta = 7.5, 8$, and 8.5 °ATDC. The CI flame continued to develop until combustion was complete. In $r_H = 0.70$, for [C]: SI, propagation flame was seen at $\theta = 3.5$ °ATDC. At $\theta = 13.5, 15.5, 17$, and 18.5 °ATDC, the two-part flame image that was observed was due to the flame stretch of SI. This flame stretch could be seen clearly at the $\theta = 28.5$ °ATDC. Among the three combustion forms, HCCI combustion was faster than either SI-CI or SI. SI combustion required a long time to complete the combustion process.

Fig. 2 Histories of pressure and heat-release rate at different r_H for in Case III (a), together with flame images of three combustion forms [A] : $r_H=0.35$ (HCCI), [B] : $r_H=0.50$ (SI-CI) and [C] : $r_H=0.70$ (SI) (b) at $ON = 0$ and $\theta_i = -20$ °ATDC in Case III

3.2. Combustion conditions by spark timings

Before the condition by spark timings was done, the experiments to clarify various combustion forms with various octane number ON , various hydrogen ratio r_H , compression ratio and equivalence ratio at a fixed spark timing $\theta_i = -20$ °ATDC were carried out and the regions of those combustion forms are shown in Fig 3, 5 and 7 without indicating by star plot [6-7]. At the present, the effects of spark timing on SI-CI combustion are focused:

3.2.1. Condition of $\varepsilon = 13$ and $\phi = 0.45$ (Case I)

In this case, the experiment was done to confirm the effect of spark timings on the SI-CI combustion by fixing the hydrogen ratio r_H with n-heptane fuel $ON = 0$. In previous researches [6-7], the regions associated with various ON and r_H for the different combustion forms of (A) HCCI, (B) SI-CI, (C) SI, and (D) Misfire/Partial combustion (when heat released in the combustion process is less than 70% of input heat) are shown at a fixed spark timing $\theta_i = -20$ °ATDC for Case I as shown in Fig. 3 was clarified. In this research, the experiments were conducted in condition of $r_H = 0.3$ and $ON = 0$ (indicated by star in Fig. 3) with various θ_i from 0 to -70 °ATDC to investigate the characteristics of SI-CI.

In Fig. 4, (a) combustion processes of p , $dq/d\theta$ and T_{ave} are shown against crank angle θ and (b) combustion characteristics of IMEP, $dq/d\theta_{max}$, θ_{CI} and r_{CI} shown at various θ_i . SI-CI form, which is represented by two stages of combustions in heat-release rate, occurs with various θ_i , ranging from -10 to -40 °ATDC. It is different from HCCI combustion that spark timing can control the ignition and combustion characteristics of SI-CI. Advancing the

Fig. 3 Region of combustion forms at ON and r_H in Case I at spark timing $\theta_i = -20$ °ATDC

(a) Combustion processes

(b) Combustion characteristics

Fig. 4 Change of combustion forms for $r_H = 0.30$, $ON = 0$ at various spark timings in Case I

spark timing further causes the combustion form change from SI-CI to SI which can be seen at $\theta_i = -50$ °ATDC as single stage combustion in heat-release rate. T_{ave} follows the trend of heat-release rate and is lower when spark timing is retarded. In Fig. 4(b), IMEP in SI-CI combustion is greater than that in the SI form. SI-CI combustion has greater IMEP compared to SI may be caused by the fact that the CI combustion in SI-CI combustion that increases the degree of constant volume. From the experimental result, it is clear that IMEP increases when the fraction of CI combustion in SI-CI combustion r_{CI} increases. Besides, the timing for giving maximum IMEP is about -5 °ATDC in this case. SI-CI gives a greater $dp/d\theta_{max}$ than SI due to the combustion that occurs during CI. No knocking occurs with SI-CI because there are no pressure oscillations during SI-CI form of combustion. Also, θ_{CI} is strongly correlated with θ_i and also affects r_{CI} , which is approximately 0.8 at $\theta_i = -15$ °ATDC in Case I.

3.2.2 Condition of $\varepsilon = 13$ and $\phi = 0.60$ (Case II)

Similar to Case I, the experiment was done to confirm the effect of θ_i in the region of combustion forms with a condition at

Fig. 5 Region of combustion forms at ON and r_H in Case II at spark timing $\theta_i = -20$ °ATDC

(a) Combustion processes

(b) Combustion characteristics

Fig. 6 Change of combustion forms for $r_H = 0.45$, $ON = 0$ at various spark timings in Case II

$ON = 0$ and $r_H = 0.45$ for $\varepsilon = 13$ and $\phi = 0.60$, the condition for which is indicated by star in Fig. 5. Figure 6 shows (a) combustion processes and (b) combustion characteristics with above condition at various θ_i . SI-CI occurs with $\theta_i = -10$ and -20

°ATDC, confirmed by investigating the rate of heat release of a two stage combustion. Outside of this range, the combustion takes place in SI form seen as a single stage. Based on the heat-release rate, it is apparent that the results of advancing or retarding spark timings advance or retard started timing of SI and CI of SI-CI. Also, retarded spark timing gives lower T_{ave} . Figure 6(b) shows that SI-CI gives a greater IMEP than SI, and timing for giving high IMEP is at $\theta_i = -10$ °ATDC when combustion is in SI-CI form. The value of $dp/d\theta_{max}$ for SI-CI is greater than that of SI and peak of heat-release rate of CI is also higher than that of SI. As θ_i is retarded, θ_{CI} is also retarded. The value of r_{CI} reaches its maximum at $\theta_i = -10$ °ATDC which corresponds to maximum IMEP timing.

3.2.3 Condition of $\varepsilon = 15$ and $\phi = 0.45$ (Case III)

In this case, experiments were done to investigate the effects of θ_i in the region of combustion forms with conditions at various ONs and r_H for $\varepsilon = 15$ and $\phi = 0.45$, that is, for the conditions indicated by stars in Fig. 7. At ON = 0 and $r_H = 0.55$, a boundary point between SI-CI and SI was selected, and at $\theta_i = -20$ °ATDC, the combustion was in SI form. Figure 8 shows (a) combustion processes and (b) combustion characteristics with above condition at various θ_i . Results explain that the combustion changes from SI to SI-CI when θ_i advances from -20 °ATDC to -30 °ATDC, which can be only seen in $dq/d\theta$, not in p graph. Out of this spark timing range, combustions turn to SI when spark timing is further advanced and retarded. In this case, it shows that there is a possibility for expanding the range of SI-CI by advancing the spark timing. From the results of combustion characteristics in Fig. 8(b), both IMEP and $dp/d\theta_{max}$ of SI-CI combustion are

comparable to those of SI combustions. Furthermore, T_{ave} increases when θ_i advances. The value of r_{CI} is around 0.3 at $\theta_i =$

(a) Combustion processes

(b) Combustion characteristics

Fig. 7 Region of combustion forms at ON and r_H in Case III at spark timing $\theta_i = -20$ °ATDC

Fig. 8 Change of combustion forms for $r_H = 0.45$, ON = 0 at various spark timings in Case III

Fig. 9 Combustion characteristics for ON = 0, ON = 20 and ON = 50 at various r_H , spark timings in Case III

-30 and -35 °ATDC.

In Fig. 9, the combustion characteristics of various ON and r_H at various θ_i are shown. With higher ON fuels, such as ON = 20 and ON = 50, range of SI-CI with the effect of θ_i are comparable compared to ON = 0 fuel. The similar range might have resulted from similar overall ON (PRF and H₂). IMEP slightly increases when ON increases and r_H decreases. $dp/d\theta_{max}$ of SI-CI are remarked to change with similar trend at ON=0, 20 and 50 with r_H = 0.50, 0.45 and 0.35 respectively. At first, $dp/d\theta_{max}$ increases when combustion form changes from SI to SI-CI and CI combustion of SI-CI is found to start before top dead center (TDC). Then, $dp/d\theta_{max}$ changes to decrease after the CI combustion of SI-CI starts after TDC. Next, $dp/d\theta_{max}$ starts to increase again as the ignition delay of CI in SI-CI is long. At last, $dp/d\theta_{max}$ changes to decrease again as CI combustion of SI-CI occurs late in expansion stroke. This trend of $dp/d\theta_{max}$ is found in all cases. Furthermore $dp/d\theta_{max}$ of SI-CI at ON = 0 is higher than that of ON= 20 and 50. This means that ON has strong influence on $dp/d\theta_{max}$ and CI. The results of θ_{CI} and r_{CI} show the same trend for ON = 0, 20 and 50 in Case III, which is similar to that of the previous cases (Cases I and II). Besides, the increase of r_{CI} correlates with the increase of IMEP.

4. Conclusions

In this study, the requirements for SI-CI combustion by various spark timings were experimentally investigated, and combustion forms were confirmed by analyzing flame images. Based on the results obtained, the following conclusions are made:

- Images of various combustions, such as HCCI, SI-CI, and SI, show the development of the natural flame. The auto-ignition of end gas to produce the CI of SI-CI combustion is clearly shown.
- SI-CI combustion can occur in a certain range of spark timings. Advanced or retarded spark timings change the combustion form from SI-CI to SI or vice versa.
- For PRF fuel with higher octane number, even the selection of advanced spark timing will not convert SI to SI-CI combustion.
- SI-CI combustion mostly provides greater cycle work when spark timing is adequately controlled. In the experiments, the addition of hydrogen totally eliminates knocking.
- For SI-CI combustion, when the start timing of CI is retarded as a result of retarded spark timing, the ratio of CI increases which results to the increase of engine output. Furthermore, range of SI-CI operation can be expanded by adjusting the spark timing.

The SI-CI combustion form has been investigated with various parameters, such as ε , ϕ , r_H , ON, and θ_i . However, the advancement of equivalence ratio to find the limitation including full load and stoichiometric condition because the advance of equivalence ratio to stoichiometric condition was not applied as high NO_x emission and possible knock occur. Furthermore, combustion stability and exhaust pollutant emissions are not included in this study due to the limited capabilities of RCEM. Also, the effect of unburned hydrocarbon, heat loss on ISFC and cycle efficiency will be investigated in the future works. Finally, It is our hope that this study will stimulate interest in additional engine tests in the future.

References

- (1) P. M. Najt, D. E. Foster, "Compression-Ignited Homogenous Charge Combustion", SAE Paper 830264 (1983)

- (2) K. Yoshiwa, A. Teraji, H. Miyakubo, K. Yamakuchi, T. Urushihara, "Study of High Load Operation Limit Expansion for Gasoline Compression Ignition Engines", Journal of Engineering for gas turbine and power, Vol.128, 2006.
- (3) H. Machrafi, S. Cavadiasa, "An Experimental and Numerical Analysis of the Influence of the Inlet Temperature, Equivalence Ratio and Compression Ratio on the HCCI Auto-Ignition Process of Primary Reference Fuels in an Engine", Fuel Processing Technology, vol. 89, Vol. 89, Nov. 2008, pp. 1218-1226.
- (4) T. Noda, S. Rey, M. Shioji, T. Itoh, S. Kimura, "A Study of SI-CI Hybrid Combustion with Low Octane Number Fuel and Hydrogen", Trans. JSAE (in Japanese), vol. 40, P. 20094164, Vol. 40, No. 2, p. 313-318 (2009).
- (5) S. Rey, H. Morishita, T. Noda, M. Shioji, "Investigation of SI-CI Combustion with Low Octane Number Fuels and Hydrogen using a Rapid Compression/Expansion Machine", Edited Book, Journal of Power and Energy, Springer, ISBN: 978-4-431-99778-8 (2010).
- (6) H. Morishita, S. Rey, T. Noda, M. Shioji, "Feasibility of SI-CI Combustion at Lean Mixture of Primary Reference Fuels with Hydrogen Addition", JSAE Proceeding (in Japanese), 30-20095704 (2009).
- (7) S. Rey, H. Morishita, T. Noda, M. Shioji, "Feasibility of SI-CI Combustion at Lean Mixture of Primary Reference Fuels with Hydrogen Addition", APAC15 Proceeding, vol. 2, APAC15-312 (2009).