The Experimental Comparison between Stratified Flame Ignition and Micro Flame Ignition in a Gasoline SI-CAI Hybrid Combustion Engine

Author, co-author (Do NOT enter this information. It will be pulled from participant tab in MyTechZone)

Affiliation (Do NOT enter this information. It will be pulled from participant tab in MyTechZone)

Abstract

Controlled Auto-Ignition (CAI), also known as Homogeneous charge compression ignition (HCCI), has been the subject of extensive research because of their ability to providing simultaneous reduction in fuel consumption and NOx emissions in a gasoline engine. However, due to its limited operation range, combustion mode switching between CAI and spark ignition (SI) combustion is essential to cover the overall operational range of a gasoline engine for passenger car applications. Previous research has shown that the SI-CAI hybrid combustion has the potential to control the ignition timing and heat release process during both steady state and transient operations. However, it was found that the SI-CAI hybrid combustion process is often characterized with large cycle-to-cycle variations, due to the flame instability at high dilution conditions.

In order to control the heat release process stably and expand the operating range of SI-CAI hybrid combustion, the stratified flame ignition (SFI) and micro flame ignition strategy (MFI) involved in the SI-CAI hybrid operation were analyzed respectively based on the engine experiments carried out on a single cylinder research engine equipped with both intake and exhaust mechanical variable valve actuation systems. The premixed homogenous dilution charge as main fuel was injected by intake port injector. Meanwhile, the stratified gasoline fuel (in SFI) or DME (in MFI) injected by direct injector in the cylinder was used as an enhanced flame kernel. The results show that both SFI and MFI strategy are useful to expand the dilution combustion range and adjust the combustion phase of SI-CAI hybrid combustion. But SFI strategy faced the high cyclic variation of heat release process in continuous cycles, while the key problem of MFI is knock and the worse caused by fast heat release. Both of these two strategies require optimization to be feasible to combustion control at different conditions.

Introduction

With both emissions standards and fuel consumption mandates becoming more stringent in the main market of the globe in the upcoming years, advanced combustion technology becomes more and more important when attempting to improve the gasoline engine efficiency. CAI (Controlled Auto-ignition), also named as HCCI (Homogeneous Charge Compression Ignition), proposed in the end of last century, is of considerable interest in gasoline engines because of its potential to achieve simultaneous reductions in fuel consumption and NO_X emission [1].

But the application of CAI or HCCI combustion to production engines is still confronted with several challenges, such as combustion process control and limited operating range [2]. In order to cover the overall range of operations, SI combustion is still needed beyond the range of CAI, which brought in the problem of mode switching between the two combustion modes. Many efforts had been paid on the smooth and reliable switching between SI and HCCI mode at the boundary of HCCI operating range. But the switching control was difficult and liable to cause another actual problem, such as combustion stability and responding speed. In the researches mentioned above, SI-CAI hybrid combustion (also named as spark-assisted HCCI combustion, SACI) had been found and gained wildly attraction, due to the fact that it can be an effective way to achieve the stable and high efficiency combustion in diluted circumstance.

The whole heat release process of SI-CAI hybrid combustion (SCHC) is divided into two stages, the first half of the process is dominated by flame propagation, the latter half is dominated by auto-ignition exothermic [3] [4]. Compared with HCCI combustion, there is some relatively reliable spark ignition process in SCHC, which is useful to improve the combustion stability and expand the operation limit of high dilution combustion [5][6].

In 2011, Chen et al. [7] achieved the continuous combustion mode transition with the adjustment of engine load. The SCHC has been used to bridge the temperature and residual gas fraction gap between HCCI combustion and SI combustion. In the same year, Manofsky et al [8] also use a similar method to achieve the simultaneous transition of the engine load and combustion mode. The above results indicated that the SCHC has a potential to extend the operating range of high efficiency and low temperature combustion. However, in these studies, a unique cyclic variation in SCHC has been found, which may be harmful to SCHC stability control. The phenomenon is a critical state of SCHC, it happens when the main heat release process of SCHC changed from CAI operation to SI operation under certain in-cylinder temperature and exhaust gas fraction conditions.

Similar results had been found in other researches [9] [10]. Recently, the diluted effect of EGR was thought as main reason of high cyclic variation. Wheeler et al pointed out cooled EGR can cause slower rates of flame propagation, decreased engine stability and even lead to misfire [11]. Due to the dilution effect of EGR, both the flame propagation speed and direction varied in continuous cycles at the condition of SI-CAI hybrid combustion, which is observed by Xu et al [12] through chemiluminescence flame imaging.

In SI-CAI hybrid combustion, the flame propagation in the initial stage plays a key role in the control of overall heat release. When the auto-ignition dominate the heat release process, the cyclic variation of initial flame kernel growth, whose main effect is inducing auto-ignition, has limited effect on the subsequent combustion process. In contrast, when the flame propagation is dominant in heat release process, the cyclic variation of initial flame causes the in-cylinder temperature and pressure fluctuation, which leads to high output variation. The homogeneous air-fuel charge in SI-CAI hybrid combustion was hard to settle the problem of the main heat release mode variation at certain in-cylinder conditions.

How to control the flame propagation process in high diluted condition is the main challenge to expand the operating range of SI-CAI hybrid combustion. In consideration of the confine of port fuel injection, the influence of gasoline direct injection has been investigated, due to its capable of controlling the in-cylinder charge stratification. Chang et al [5] proved that fuel injection during negative valve overlap was effective way to extend the dilution limit of spark ignition combustion. But Polovina et al [9] found the fuel injection during negative valve resulted in obvious increase in pumping loss. At some operating conditions, the fuel economy benefits from the combustion was less than the augment of pumping loss. In addition to NVO injection strategy, stratified flame proposed in lean burn GDI engine was also seen as an effective way to expand diluted limit [13]. The simulation results from Wang et al [14] show stratified flame could be used to assist controlling and stabilizing the gasoline high dilution SI-CAI hybrid combustion when whole charge in the cylinder remains stoichiometric. This method seems to avoid the pumping loss increase, but heavily dependent on the combustion chamber design. In this paper, above method was named as stratified flame ignition (SFI) SI- CAI hybrid combustion. Based on the fuel concentration stratification, the fuel reactivity stratification was thought as a further improvement method to expand the dilution boundary of SI-CAI hybrid. In these cases, dimethyl ether (DME) was injected directly into the cylinder as an assistance fuel, owing to its feature of easy evaporation, high octane number and oxygen-containing [15]. The flame propagation speed of dimethyl ether is fast than gasoline, and the auto-ignition of dimethyl ether would increase the igniting area, both of those characteristics are useful to stabilize heat release process. Using high ignitable fuel as the enhancer at the high dilution conditions have been described as micro flame ignition SI-CAI hybrid combustion (MFI) [16].

The goal of this paper is to compare the ability and characteristic of SFI and MFI on controlling the hybrid combustion heat release process and find out the key parameters in the control of SI-CAI hybrid combustion in the two methods.

Experimental Setup

Engine specification and test bench

In this research, experiments were carried out on a four-stroke single-cylinder engine and its specifications are given in Table 1. The engine comprises a Ricardo Hydra engine block and a specially designed cylinder head equipped with two sets of identical mechanically fully variable valve actuation systems on the intake and exhaust valves. Each system integrates a BMW VANOS variable valve timing device and a BMW Valvetronics continuously variable valve lift device. With the fully variable valve system, intake and exhaust valve lifts can be continuously adjusted from 0.3 mm to 9.5 mm and the valve timings are adjustable within 60 °CA. In order to achieve auto-ignition combustion through trapped residual gases, the intake and exhaust valve profiles were adjusted to achieve variable negative valve overlaps.

Table 1. Engine specifications

Engine type	4 stroke single cylinder
Bore	86 mm
Stroke	86 mm
Displacement	0.5 L
Compression ratio	12.5
Combustion chamber	Pent roof / 4 valves
Fuel injection	Port fuel injection & direct injection
Injection pressure	3 bar
Fuel	Gasoline 93 RON
Inlet pressure	Naturally aspirated
Coolant temperature	80 °C
Oil temperature	50 °C

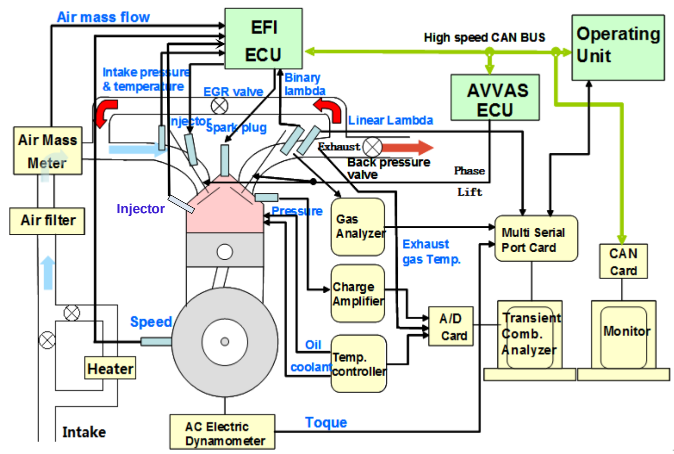


Figure 1. Schematic of the test setup

Figure 1 shows the schematic experimental setup with the control sub-system and the data acquisition sub-system developed at the authors' laboratory. The engine was connected directly to a 30 kW AC electric dynamometer. A linear oxygen sensor (with an accuracy of ±1.5%) was mounted in the exhaust pipe to ensure precise control of the air/fuel ratio. The exhaust gas temperature was measured by a K-type thermocouple installed in the exhaust pipe. At each experimental point, the in-cylinder pressure was measured with a Kistler 6125B piezoelectric transducer and a 5011B charge amplifier. The amount of airflow was measured with a laminar flow meter with an accuracy of ±1%. The residual gas fraction (RGF) was determined from the residual gas mass calculated from the exhaust gas temperature and the in-cylinder gas pressure at the exhaust valve closing time using the state equation of the ideal gas.

The gasoline in-cylinder direct injection system working as the actual engines drove by electronic motor. The direct injector located bellow the intake pipe at the cylinder wall. The piston has been redesigned considering with the requirements of wall-guide strategy. The piston had been designed again based on the purpose to reach the effective fuel distribution in the combustion chamber by numerical simulations [17]. On the basic of simulation results, a metal piston showed in Figure 2 had been manufactured and assembled in the experimental engine. The gasoline direct injection pressure remained 150 bar in SFI experiments.

Figure 2. The special designed piston to match the SFI strategy

Because of its ease of vaporization and flammable characteristics, the DME direct injection and supply system was designed and implemented carefully. A high pressure nitrogen gas is connected to the inlet valve of DME cylinder, which pressurizes DME to 50 bar, keeping it liquid in the entire supply pipe. A common rail injection system has been used for DME direct injection in order to keep the injection pressure constant at high pressure injections. In this study, the injection pressure of DME was set to 60 bar by the pressure relieve valve. Same solenoid direct injector was used in both SFI and MFI experiments.

Experimental method

To achieve the SI-CAI hybrid combustion with the residual gas trapping method, intake and exhaust valve profiles were configured to achieve a negative valve overlap. For analyzing the ability and feature of SFI and MFI, the intake valve parameters were kept constant in this study, to ensure that the effective compression ratio and the amount of air-gasoline charge remained unchanged in the experiments. And the exhaust valve parameters also stayed the same to keep the amount of residual gas ratio and effective expansion ratio as same as possible. The specific valve parameters were shown in table 2.

Table 2. Experiment specifications

Intake valve open timing	400 CA ATDC
Intake valve close timing	500 CA ATDC
Exhaust valve open timing	210 CA ATDC
Exhaust valve open timing	295 CA ATDC
Intake valve lift	3.64 mm
Exhaust valve lift	2.57 mm
Heat value of gasoline	44 kJ/g
Heat value of DME	21 kJ/g
Total heat value of fuel per cycle	484 J
Engine speed	1500 r/min

For evaluating the ability of SFI and MFI on control the combustion process at the high dilution conditions, relatively low speed small load operating point which was near the boundary of HCCI combustion without external exhaust recirculation. The total heat value of fuel per cycle was set at 484 J and engine speed was 1500 r/min was chosen as the reference point. In HCCI combustion the IMEP would reach about 3.6 bar. The co-operation of injection timing and spark timing on the combustion control was investigated to test the effectiveness of stratified flame on expanding the dilution limit of SI-CAI hybrid combustion.

Results and discussion

The Stratified flame ignition (SFI) at low loads

At low loads, though the of HCCI combustion could be achieved, the extent to dilution limit of SI-CAI hybrid combustion is still important because it may improve the combustion control and realize the smooth transition between HCCI and SI-CAI hybrid combustion [18]. When in-cylinder charge keeps stoichiometric at wide-open throttle, sufficient residual gas leads to HCCI combustion with unacceptable MPRR. Thus, for investigate the effect of SFI strategy on the SI-CAI hybrid combustion, the overall excess air coefficient (lambda) of in-cylinder charge reached to about 1.3 and exhaust valve close timing was later than that of HCCI operating point.

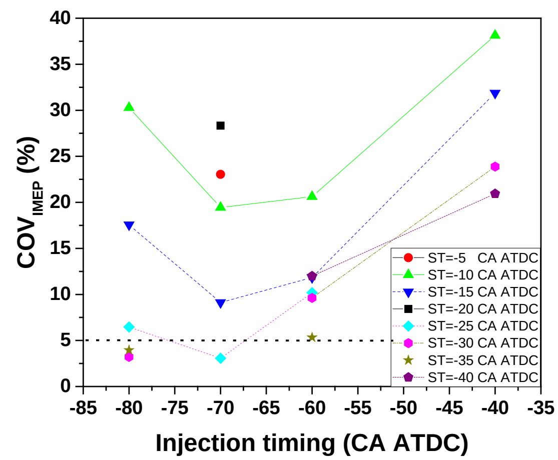


Figure 3. The influence of injection timing and spark timing on cyclic variation in SFI strategy

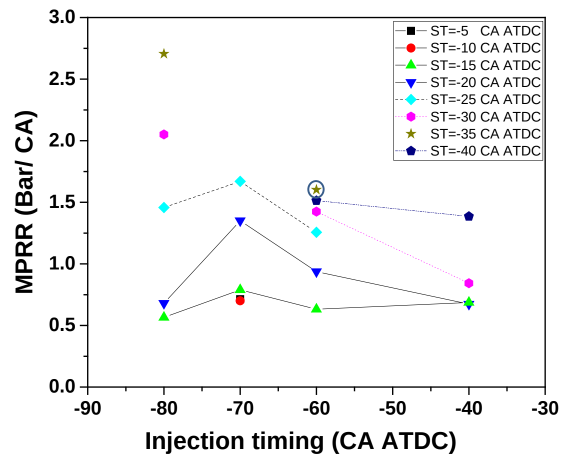
Figure 3 shows the influence of injection timing and spark timing on cyclic variation in SFI strategy. There was only a narrow window in which effective stratified flame could be established through fuel spray injection with piston wall guidance. With the acceptable coefficient of variation (COV) of IMEP below 5%, it can be found the injection window ranges from -80 CA ATDC to -60 CA ATDC with a proper spark timing. Contrary to simulation results of the same engine [17], when the fuel injected into the cylinder at -40 CA ATDC, spark ignition was not able to ignite the in-cylinder diluted charge effectively. It illustrated that the preparation time for stratified air-fuel charge need longer duration and the effective spark ignition window had narrowed down in actual practice. The -70 CA ATDC was the best injection timing at this condition, because the at the same spark timing the variation of the operating point with this injection timing have the lowest coefficient of variation. But the spark timing range when the fuel injected at -70 CA ATDC is limited to narrow range due to high cyclic variation and unacceptable knock. There is a special operating point that needed attention, which spark timing was -40 CA ATDC with -60 CA ATDC direct fuel injection. At this point, the tendency that early spark timing decreases the variation is broke. The result of this operating point had been confirmed by repeated experiments. The possible reason is that the stratified fuel distribution cannot be formed due to too short period between the injection timing and spark timing.

In this study, due to the constant engine speed, the maximum pressure rise ratio (MPRR) was still use to represent the knock level, as a relatively complicated standard, due to the fact that there may be obvious variation caused by auto-ignition strength in SI-CAI hybrid combustion. Referred to the previous researches [19] [20], the heat release proportions of auto-ignition show significant difference in continuous operating cycles. The cycles with high proportion of auto-ignition led to high MPRR, correspondingly, the MPRR of cycles with low proportion of auto-ignition was small. That phenomenon makes the mean value of 100 continuous cycles remain low, but actually severe knock that may damage the engine can be existing. Similarly, using ring intensity to represent knock has the same problem. without doubt mean value of MPRR still has the sense to evaluate the combustion degree. But for evaluate the actual strength of knock, some researchers [5] proposed that using the mean value of the top 50% of MPRR in continuous 100 cycles, which may diminish the influence of the cycles with low MPRR. Thus, Figure 4 plots the results of mean value of 100 continuous cycles and the mean values of top 50%.

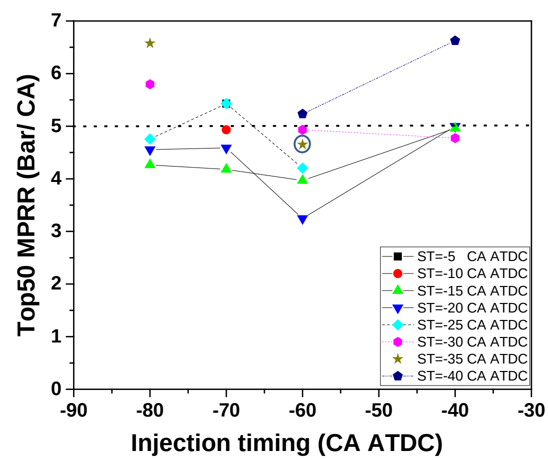
In Figure 4(a), when the spark timing is earlier the -25 CA ATDC at injection timing fixed at -70 CA ATDC, the engine would face the damage risk due to the high MPRR, which result in the failure of data acquisition. Though the engine cylinder head has been strengthened, the MPRR more than 10 bar/CA in some cycle is beyond the ultimate strength. Thus the data presented in this paper don't include any operating point whose MPRR higher than 10 bar/CA, even though the mean value of MPRR in continuous 100 cycles is less than 5 bar/CA. As a result, it is found that, within the injection window, the advance of spark timing is limited by high MPRR, which leads to narrow spark window at any injection timing. And as the SI-CAI Hybrid combustion gets stable, the MPRR increases rapidly. All value of MPRR in Figure 4(a) seems acceptable, but in actual practice, most of operating with small COV of IMEP faced the challenge of knock.

Figure 4(b) is used to illustrate the complexity of knock in hybrid combustion. With only the top 50% MPRR in the continuous cycles, the value increases obviously compared to the mean MPRR of the mean value of 100 continuous cycles. Specially, the top50 MPRR of some operating point whose MPRR are less than 1 bar/CA, such as spark timing of -5 CA ATDC, -10CA ATDC @ -70 CA ATDC injection timing, spark timing of -15 CA ATDC @ -70 CA ATDC injection timing, and so on, are more than 5 bar/CA. Furthermore, the trend the MPRR increases with early ignition timing is broken too. Due to the high heat release variation, knock cycle may occur in the unstable operating point in SI-CAI hybrid combustion, which leads to the judgement of knocking based on mean value wasn't sufficient and the standard based on frequency and amplitude may need be investigated in actual.

If the knock standard has been set up as both MPRR and Top50 MPRR should be less than 5 bar/CA and there is no cycle with more than 10 bar/CA MPRR, SFI strategy is a potential method to meet the requirements of COV of IMEP and knock standard, such as the operating point @ spark timing -35 CA ATDC & injection timing -60 CA ATDC in this group, which was marked in a circle in Figure 4. The acceptable operating range of spark and injection timing in SFI strategy was limited in a narrow window, which demands for a lot of work in control and calibration. Actually, if the spark timing adjusted carefully at -70 CA ATDC injection timing, there would be some acceptable operating points. In general, though the SFI strategy is effective to control SI-CAI hybrid combustion, the knock caused by unstable combustion is still a main challenge.



(a) MPRR of the mean value of 100 continuous cycles



(b) the mean value of top 50% MPRR in 100 continuous cycles

Figure 4. The influence of injection timing and spark timing on maximum pressure rise ratio in SFI strategy

The aim of SFI strategy is to control the SI-CAI hybrid combustion. Thus, the combustion phase - CA50 (crank angle at which 50% of the heat release has occurred) should be feasible and stable. As shown as Figure5, the CA50 of the mean value of continuous 100 cycles can be adjusted by spark timing linearly. At the same spark timing, the CA50 shows relatively small change with injection timing, which means that the fuel distribution is useful to adjust the previous flame propagation stably on some level in SI-CAI hybrid combustion. However, due to the existence of heat release cyclic variation, the standard deviation of CA50 (std CA50) show the similar change tend as the COV of IMEP from Figure 6, which means the small variation of CA50 can only be achieved by the operating point with high MPRR. The obvious variation of CA50 is caused by the variation of heat release proportion of Auto-ignition. Auto-ignition is useful to stabilize the heat release, but it is easy to cause high MPRR. Due to the coincident change of the variation of IMEP and CA50, the effective operation range of SFI strategy is also acceptable for the combustion control.

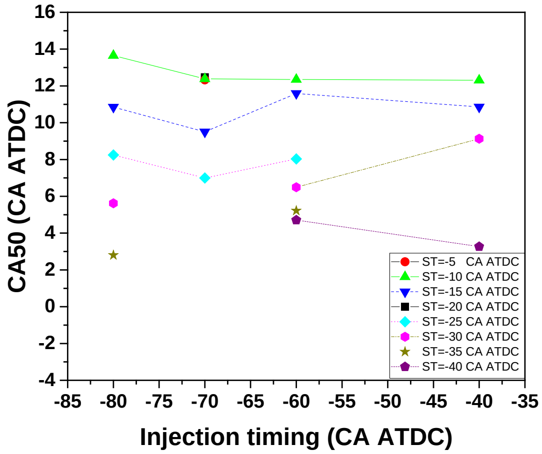


Figure 5. The influence of injection timing and spark timing on CA50 in SFI strategy

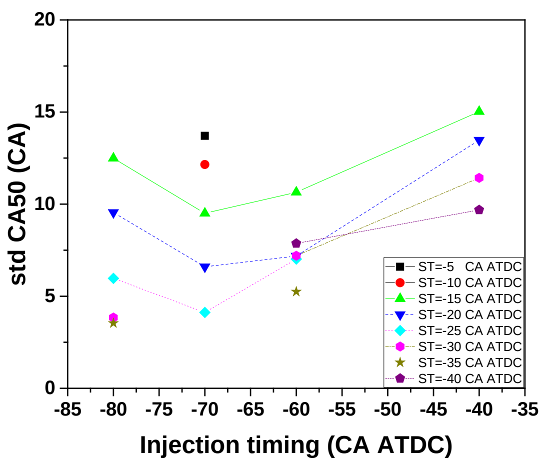


Figure 6. The influence of injection timing and spark timing on combustion duration in SFI strategy

Due to the fixed fuel heat value, better thermal efficiency means higher IMEP. As shown as in Figure 7, the maximum thermal efficiency is reached at the operating point whose injection timing is -70 CA ATDC and spark timing is -25 CA ATDC. Referring to the knock standard mentioned above, this operating point is above the acceptable limit slightly. The thermal efficiency of the operating point which meets all requirements reaches 36% and its IMEP is 3.5 bar. Both of those performance parameters at the acceptable operating point are only less than the operating point at maximum IMEP and got 26.5% improvement compared to traditional SI combustion. Though the heat release ratio of the operating point of SI-CAI hybrid combustion may be unstable, due to the existence of Auto-ignition in some cycles, the fuel consumption is better than SI combustion. SFI is an effective way to expand the dilution limit and control the heat release process, though its acceptable operation conditions are limited. The heat release instability is the main challenge in the application of SFI strategy.

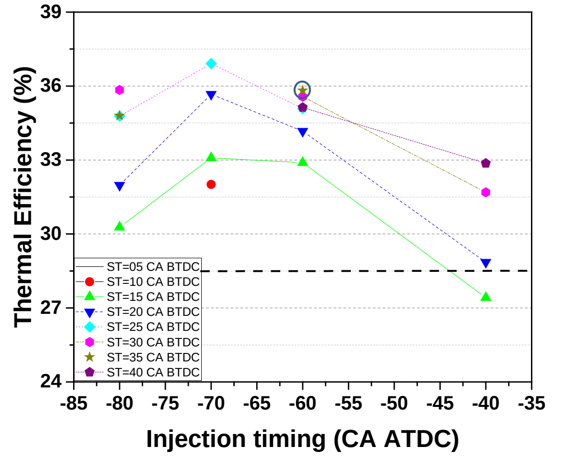


Figure 7. The influence of injection timing and spark timing on thermal efficiency in SFI strategy

The Micro flame ignition (MFI) at low loads

For the investigation on the improvement of combustion stability of SI-CAI hybrid combustion, the DME took the place of traditional gasoline injected into the cylinder directly to achieve the stratification of fuel reactivity. In order to compare the characteristics of SFI and MFI strategy, the valve parameters of MFI strategy are the same as SFI strategy. And the heat value of the DME injected into the cylinder remain the 30% of total fuel heat value, according to that the heat value of gasoline and DME were 44 J/mg and 28.8 J/mg. Because DME fuel contains the oxygen, the excessive air co-efficient of the in-cylinder charge rise to 1.5.

Due to high reactivity of DME fuel, at diluted conditions, the speed of flame propagation is increased and the initial flame stability can be improved. From Figure 8, it is found that the COV of IMEP is improved significantly compared to SFI strategy, and the value of all operating points are below 5%. Due to the fact that the in-cylinder temperature and pressure condition could meet the requirement of auto-ignition of DME near the top dead center, DME can play the role as an extensive ignitor to ignite the in-cylinder charge. it would benefit both the initial flame propagation process and subsequent auto-ignition process. But due to the existence of fuel stratification, the coupled effect of spark timing and injection timing on the combustion control is still important. At -40 CA ATDC spark timing, when the DME was injected into cylinder before -50 CA ATDC, COV of IMEP is amplified. It indicates that flame propagation triggered before the proper fuel-air mixture can lead to high COV due to the instability of heat release in initial flame propagation, though it has been improved in MFI strategy.

Due to the improvement of combustion stability, the heat release gets fast and the MPRR increases markedly in contrast to SFI strategy. As shown as in Figure 9(a), all MPRR of operating points with injection timing earlier than -40 CA ATDC almost exceeds the knock limit. And when the injection timing of DME is -80 CAATDC, the MPRR is too large to be controlled. Similarly, when DME injection timing is from -50 CA ATDC to -70 CA ATDC, the early spark timing also leads to over-limit MPRR. All the missing operating point in the Figure 9 is caused by same standard as SFI strategy. Only when the spark timing is -40 CA ATDC, the MPRR of the operating point with injection timing if -70 CA ATDC is lower than 5 bar/CA due to relative combustion instability.

As the result of the improvement of combustion stability, it can be found that the Top50 MPRR is very closed to MPRR in Figure 9(b) compared to SFI strategy. For similar reason, the relationship between the cyclic variation and MPRR in MFI strategy is obscure. According to the knock standard the Top50 MPRR is also below 5 bar/CA, the DME injection timing earlier than -40 CA ATDC is entirely unsuitable for use. Though the operating range of MFI strategy shown in this paper is also narrow, the increase of dilution charge can decrease the MPRR and expand the operating range effectively. In one word, due to the high reactivity of DME, the knock tendency of MFI gets strong and the heat release can be stabilized.

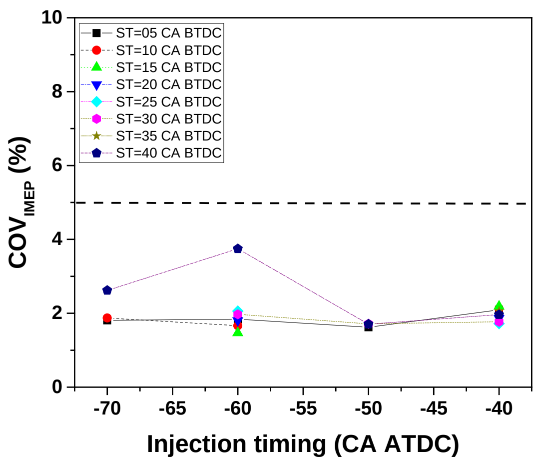
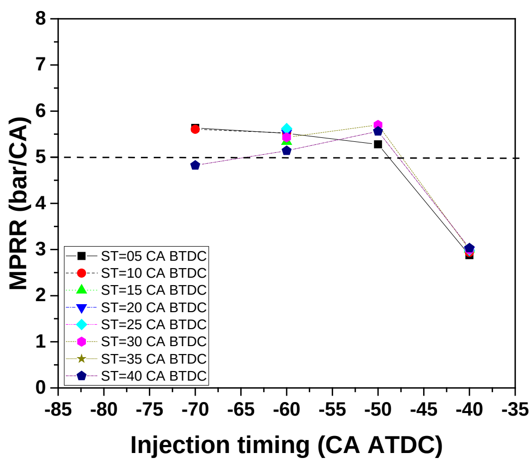
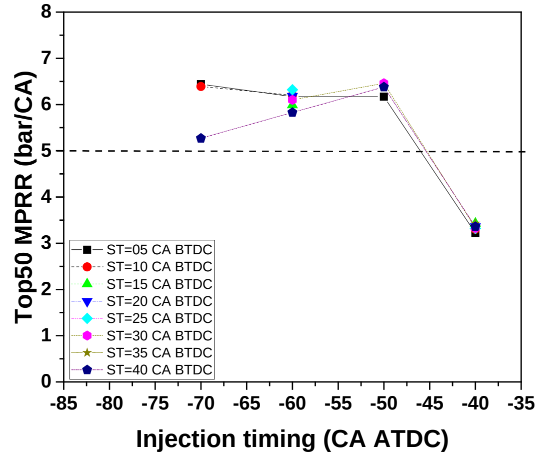


Figure 8. The influence of injection timing and spark timing on cyclic variation in MFI strategy



(a) MPRR of the mean value of 100 continuous cycles



(b) the mean value of top 50% MPRR in 100 continuous cycles

Figure 9. The influence of injection timing and spark timing on maximum pressure rise ratio in MFI strategy

The difference between MFI and SFI strategy on combustion control is that, the ignition of SFI are almost totally dependent on spark, but in MFI strategy the auto-ignition of DME could play the ignitor roles on combustion at some conditions. It can be found in Figure 10 that the effect of spark timing on CA50 shows a trend of weakness with the delay of injection timing. When the injection timing is -40 CA ATDC, the spark timing almost has no influence on CA50. It may be caused by the following reasons. The mixture with late injection timing need time to prepare ignitable stratified air-fuel charge. In this stage, spark is hard to initiate stable flame propagation. When the stratified charge could meet the requirements of ignition, due to the fact that the piston has reach to top dead center and in-cylinder temperature and pressure also meets the requirements of DME auto-ignition, the effect of spark has merged into the wide-ranging ignition of auto-ignition of DME. Thus, the early injection of DME leading to the early timing at which the stratified charge has been prepared well allowed the spark igniting the flammable charge in the cylinder and adjust the CA50.

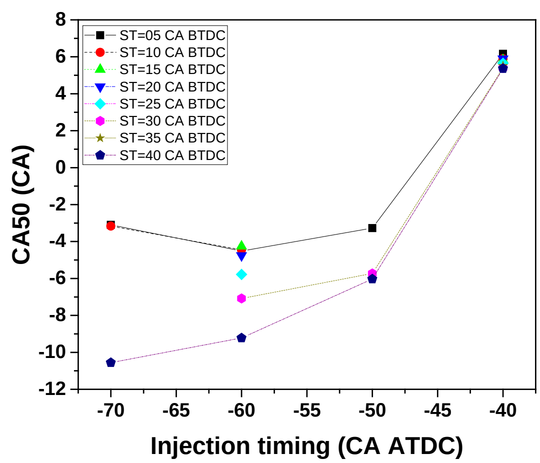


Figure 10. The influence of injection timing and spark timing on CA50 in MFI strategy

Early DME injection timings, such as -70 CA ATDC and -80 CA ATDC, except the high cyclic variation operating point, due to the wide distribution of DME in the cylinder, lead to wide spread combustion and the advance of CA50. The advance of CA50 would be harmful to the control of MPRR and thermal efficiency. So the drop of heat release ratio and delay of combustion phase is the direction of combustion control in MFI strategy at this operating point.

Due to the improvement of cyclic variation, the standard deviation CA50 improved too, which means the total heat release process has been controlled effectively and stabilized as illustrated in Figure 11. The value of std CA50 usually is less than 1 CA, which can be ignored compared to the value in SFI strategy. Corresponding to the COV of IMEP, the std of CA50 at -40 spark timing is relatively high than other operating points. In general, in MFI strategy, at these conditions in these paper, the cyclic variation of combustion is under effective control.

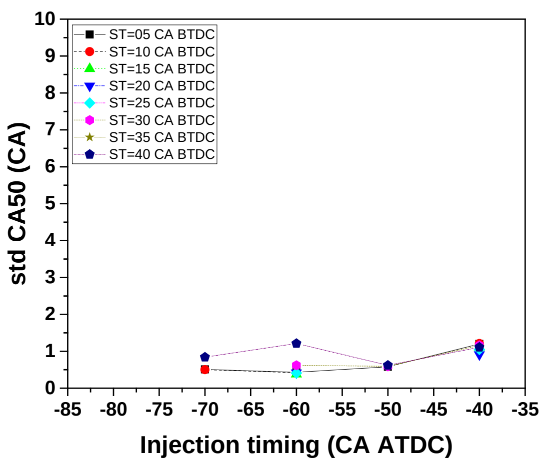


Figure 11. The influence of injection timing and spark timing on combustion duration in MFI strategy

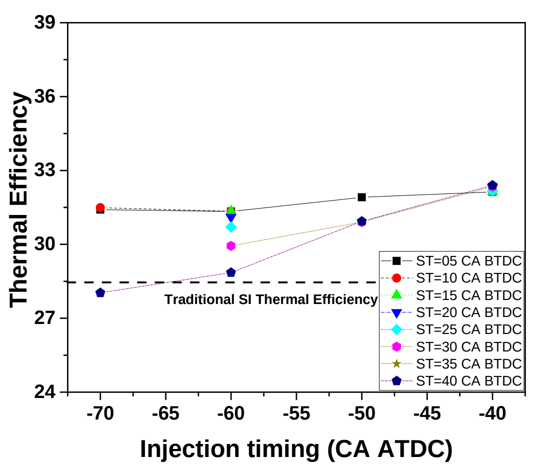


Figure 12. The influence of injection timing and spark timing on thermal efficiency in MFI strategy

Though the combustion stability has been improved in MFI strategy, the thermal efficiency gets worse compared to SFI strategy, due to too early heat release process and higher PMEP, as shown as Figure 12. Thus, at these conditions, late spark timing and DME injection timing are useful to improve the thermal efficiency. Even so, the value of thermal efficiency in MFI strategy is still better than traditional spark ignition combustion. The early combustion phase leads to the occurrence of knock, which limited the improvement of thermal efficiency and is the main challenge of MFI strategy. Decreasing the amount of DME and increasing the amount of dilution charge are both useful to improve the fuel economy of MFI strategy, which also need a lot of calibration work. From the perspective of combustion control, MFI strategy has the better ability on igniting the in-cylinder charge at the dilution conditions.

Discussion

Since the aim of this paper is to compare the combustion feature of SFI strategy and MFI strategy, the in-cylinder conditions was chosen to meet the operating requirements of both SFI and MFI strategy. According to the results presented above, the SFI strategy and MFI strategy face different challenges in the combustion control of SI-CAI hybrid combustion. So the combustion boundary conditions in this paper weren't the most suitable conditions for the two strategies. Thus, though the effective control range of SFI strategy is limited and the knock tendency of MFI is strong at the conditions in this paper, for both two strategies, there were more feasible conditions to show their advantages. In SI-CAI combustion, too fast heat release of initial flame propagation would result in knock. In contrast, too slow heat release of that would lead to high variation. At the conditions which are suit to the characteristic of the two strategies, the balance between the high MPRR and high variation could be achieved. Due to the same reason, the performance parameters, such as thermal efficiency, couldn't reflect the actual potential of SI-CAI hybrid combustion based on those two strategy, especially for MFI strategy.

Though the performance parameters were not optimized, it can be concluded that the fuel reactivity distribution is much easier to initial the flame propagation in the first stage of SI-CAI hybrid combustion compared to single fuel distribution. But the too fast heat release ratio in the initial stage easily causes the high MPRR and knock. So it cannot be judged that which strategy is better. Both two combustion control strategy need appropriate conditions and optimized.

Summary

In the current study, engine experiments were carried out on a single cylinder gasoline engine in attempt to compare the combustion feature of SFI strategy and MFI strategy to extend the dilution limit of gasoline SI-CAI hybrid combustion and obtain stable combustion process. The results show that stable SI-CAI hybrid combustion has been successfully achieved at low loads and high dilution conditions in a 4-stroke gasoline engine equipped with a production type mechanical variable valve lift and variable timing system. Preliminary analyses have been performed to understand the characteristic and the main challenge of SFI and MFI strategy. The results and conclusions can be summarized as follows:

The SFI strategy controls the combustion phase - CA50 effectively, however, the operating range based on injection timing and spark timing is limited to narrow range due to high cyclic variation and unacceptable knock. Due to the high heat release variation, knock cycle may occur in the unstable operating point in SI-CAI hybrid combustion, which leads to the judgement of knocking based on mean value insufficient. Based on the same reason, the standard deviation of CA50 show the similar change tend, but due to the rational combustion phase, the fuel consumption can be improved obviously compared to the traditional SI combustion. In general, the combustion stability is the main challenge in the application SFI strategy.

Compared to the combustion ignited by spark in SFI strategy, the MFI strategy where the auto-ignition of DME could play the ignitor roles on combustion at some conditions, weakens the effect of spark timing on CA50 and suppresses the cyclic variation significantly. However, the fast heat release process leads to high MPRR and knock, and the early combustion phase also results in the deterioration of fuel economy. MFI strategy is more easy to initial and stabilize the flame propagation of SI-CAI hybrid combustion compared to SFI strategy. But it's limited by knock and the increase of fuel consumption caused by the fast heat release ratio and early combustion phase.

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Contact Information

Tao Chen
State key laboratory of Engines
Tianjin University
Tianjin, China
Weijin Road 92, Nankai Distinct
tao.chen@tju.edu.cn

Prof, Hui Xie
State key laboratory of Engines
Tianjin University
Tianjin, China
Weijin Road 92, Nankai Distinct
xiehui@tju.edu.cn

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Definitions/Abbreviations

CA	Crank Angle
CA50	Crank angle at 50% burned mass
CAI	Controlled auto-ignition
COV	Coefficient of variation
DME	Dimethyl Ether
HCCI	Homogeneous charge compression ignition
IMEP	Indicated mean effective pressure
MFI	Micro flame ignition
MPRR	Maximum pressure rise ratio
NVO	Negative valve overlap
SACI	spark assisted compression ignition
SCHC	SI-CAI hybrid combustion
SFI	stratified flame ignition
SI	Spark ignition
std	standard deviation
TDC	Top dead center
Top50 MPRR	mean value of top 50% MPRR in 100 continuous cycles