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Research Article

Experimental Investigation of Injection Strategies on Low Temperature Combustion Fuelled with Gasoline in a Compression Ignition Engine

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The present study focuses on the experimental investigation on the effect of fuel injection strategies on LTC with gasoline on a single-cylinder CI engine. Firstly, the engine performance and emissions have been explored by sweeping SOI1 and split percentage for the load of 0.9 MPa IMEP at an engine speed of 1500 rpm. Then, the double-injection strategy has been tested for load expansion compared with single-injection. The results indicate that, with the fixed CA50, the peak HRR is reduced by advancing SOI1 and increasing split percentage gradually. Higher indicated thermal efficiency, as well as lower MPRR and COV, can be achieved simultaneously with later SOI1 and higher split percentage. As split percentage increases, NO_X emission decreases but soot emission increases. CO and THC emissions are increased by earlier SOI1, resulting in a slight decrease in combustion efficiency. Compared with single-injection, the double-injection strategy enables successful expansion of high-efficiency and clean combustion region, with increasing soot, CO, and THC emissions at high loads and slightly declining combustion efficiency and indicated thermal efficiency, however. MPRR and soot emission are considered to be the predominant constraints to the load expansion of gasoline LTC, and they are related to their trade-off relationship.

1. Introduction

With great concerns about engine emitted pollutant and global warming issues, alternative combustion concepts are drawing increasing attention worldwide. The concepts applied to compression ignition (CI) engines mainly consist of homogeneous charge compression ignition (HCCI) [1], premixed charge compression ignition (PCCI) [2], low temperature combustion (LTC) [3], and so forth. They all share the feature of achieving lower temperature combustion together with a lean mixture distribution by allowing extra time from end of the injection to start of the combustion (SOC), thereby yielding the simultaneous ultra-low nitrogen oxides (NO_X) and particle matter (PM) emissions, which are greatly challenged in conventional CI engines. Therefore, all these combustion concepts can be labeled under the term of LTC.

LTC concept is generally characterized by long ignition delay, high exhaust gas recirculation (EGR) rate, and premixed charge. With the further research, except the dominating role of chemical kinetics in LTC already been recognized, the importance of fuel and air mixing process has also been realized. However, as the conventional fuel in CI engines, diesel fuel has cetane number (CN) higher than 40 and poor volatility, which makes its ideal mixing with air before the onset of combustion unachievable at high engine loads even by the combination of a variety of technical means, for example, high pressure injection, cooled EGR, and decreased compression ratio [4]. As a result, the operation range of high-efficiency and clean LTC with diesel is still limited within low and medium loads.

Recently, the fuel properties of LTC have gained great scientific concerns, mainly because fuel properties control the time scales of both chemical kinetics and fuel-air mixing. Thus, it is suggested that a less reactive fuel is preferred for combustion control at high engine loads. In the former studies, mixture of gasoline and diesel termed as dieseline

by Turner et al. [5] is demonstrated as a promising fuel for simultaneous reduction of NO_X and soot emissions at a lower EGR level, owing to the improved premixture by the better volatility and lower CN. The relevant works have been conducted extensively during the past decade [5, 6], but it is challenging to further increase the engine load. Based on the deep insight into fuel properties of LTC, Johansson et al. proposed to inject gasoline directly into cylinder by common-rail system, which is referred to as partially premixed combustion (PPC) concept [7]. Under PPC conditions, autoignition can be made to occur after the fuel and air are well mixed, and soot emission can be reduced. The successful operation of PPC concept with gasoline has been estimated to reach 49-50% brake efficiency between 1.5 and 2.6 MPa gross indicated mean effective pressure (IMEP) while keeping low emissions [8]. Meanwhile, mixture concentration distribution can be well controlled by adjusting injection strategies, which is favorable for combustion phasing and burning rate control. Furthermore, the high-octane fuel PPC has the ability of reducing the heavy reliance on the EGR usage in diesel LTC, avoiding the consequent fuel economy penalty.

Nevertheless, a full separation between end of the injection and SOC results in unacceptable pressure oscillation which enhances heat transfer and leads to increased specific fuel consumption. Thus, the high pressure rise rate is a great concern for such premixed combustion. In an effort to solve the maximum pressure rise rate (MPRR) issue while maintaining stable combustion, low-octane gasoline has been used to avoid the overmixing of fuel and air [9]. The issue might also be alleviated via applying advanced injection strategies, for example, the double-injection strategy proposed by Kalghatgi et al. [10]. The research identifies that gasoline split injection early in the compression stroke helps reduce MPRR for a given load and enables heat release to occur later with low cyclic variation as compared with single-injection strategy. Because of that, higher IMEP can be reached with lower smoke and NO_X; for example, one of the operating points has mean IMEP of 1.595 MPa, as well as AVL smoke opacity of 0.33% and NO_X of 0.58 g/kWh. The research group from Wisconsin University has conducted some relevant works of comparing the single- and double-injection strategy at A50 (1300 rpm @ 1.3 MPa IMEP) condition [11]. Interestingly, the double-injection strategy produces higher MPRR and NO_X emission as compared to single-injection strategy, which demonstrates the engine performance and emissions are strongly influenced by injection parameters in multi-injection strategy. Ciatti and Subramanian from Argonne National Laboratory have proposed three injection strategies to struggle for meeting the current emission legislation [12]. For the medium and high loads, the partially premixed charge is obtained through an earlier injection and the rest of the fuel is injected around top dead center. As load increases, the first injection has to be well advanced to prepare sufficient premixing charge. The significance of mixture stratification resulting from the overlap of fuel spray and followed combustion in controlling combustion rate has been recognized by Yang et al. [13].

Based on the analysis of the existing problems, the authors intend to explore the effect of fuelling strategies on LTC with 93 research octane number (RON) gasoline. The study is driven in two steps. Firstly, a sweeping of start of the first injection (SOI1) and split percentage is experimented in detail to investigate the effect of these two factors on combustion and emission characteristics, as well as to seek for the key limiting factors of operation range expansion. Secondly, the double-injection strategy is tested at high load condition for load expansion, with a baseline experiment with single-injection. Therefore, the current research will be served as a theoretical evidence for the operation range expansion of high-efficiency and clean combustion in CI engines.

Table 1: Engine and injector specifications.

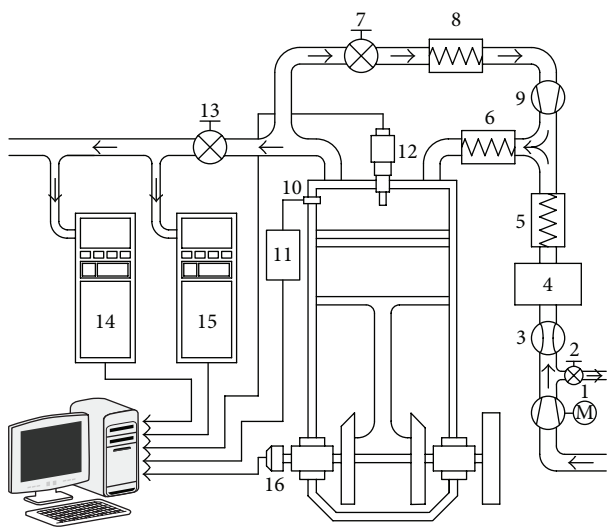
Bore (mm)	105
Stroke (mm)	125
Connecting rod length (mm)	210
Squish height (mm)	0.85
Displacement (L)	1.08
Compression ratio	16 : 1
Swirl ratio	1.5
IVO (°CA ATDC)	−377
IVC (°CA ATDC)	−133
EVO (°CA ATDC)	125
EVC (°CA ATDC)	−342

2. Experimental Apparatus

2.1. Engine. The experiments were all performed on a modified six-cylinder CI engine. The test cylinder with a displacement of 1.08 L was separated from other cylinders to avoid multicylinder interference and was equipped with independently adjustable intake/exhaust, exhaust gas recirculation (EGR), and common-rail injection system while other engine components remain intact. The engine specifications are listed in Table 1. The compression ratio was reduced from original 17.5 to 16 for prolonging ignition delay. Fresh air was externally compressed by an auxiliary compressor to simulate the boosted condition, whose pressure was adjusted by a by-pass valve close to the compressor outlet. Both the EGR valve and the back pressure valve were applied to control the amount of exhaust gas flow into the intake pipe and consequently the EGR rate. The schematic diagram of the engine setup is illustrated in Figure 1.

2.2. Instrumentation. In-cylinder pressure was measured with a pressure transducer (Kistler 6125A) in conjunction with a charge amplifier (Kistler 5011). The shaft encoder (Kistler 2614A4) had a resolution of 0.5° crank angle (CA). Combustion parameters discussed in this paper were calculated from averages of 100 consecutive cycles of cylinder pressure data. Both heat release rate (HRR) and MPRR were calculated by a combustion analysis software package from the averaged cylinder pressure.

The test cylinder was equipped with a second generation prototype common-rail system from Bosch, which is the same as the one on the original engine. The nozzle had an



(1) Compressor
(2) By-pass valve
(3) Air flow meter
(4) Surge tank
(5) Inlet heater
(6) Inlet cooler
(7) EGR valve
(8) Intercooler
(9) One-way valve
(10) Pressure transducer
(11) Charge amplifier
(12) Direct injector
(13) Back pressure valve
(14) Exhaust analyzer
(15) Smoke meter
(16) Encoder

Figure 1: Schematic of experimental setup.

umbrella angle of 150° and 8 orifices, whose diameter was 0.15 mm. The ECU for controlling the direct injection system was coordinated by software on a PC. The arrangement enabled flexible settings of common-rail pressure, injection timing, injection quantity, and multi-injection strategies. The fuel flow rate was measured by a fuel consumption meter (AVL 733S) with a gravity scale, and each operating point was sampled for at least 3 minutes.

The concentrations of gaseous emissions, for example, NO_X, total hydrocarbon (THC), carbon monoxide (CO), and carbon dioxide (CO_2), were measured using an exhaust analyzer (Horiba MEXA-7100DEGR), which measures NO_X by the chemiluminescent method, THC by the flame ionization method, and CO and CO_2 by the nondispersive infrared method. The EGR rate was determined via calculating the ratio of intake CO_2 to exhaust CO_2 concentration, as shown in (1). Consider

$$\mathrm{EGR} = \frac{[\mathrm{CO_2}]_{\mathrm{intake}}}{[\mathrm{CO_2}]_{\mathrm{exhaust}}} \cdot 100\%. \quad (1)$$

A filter smoke meter (AVL 415S) was utilized to measure soot levels in terms of filter smoke number (FSN) and changed into mass by the empirical formula provided by the instrument manual as follows:

$$\mathrm{soot} = \frac{5.32}{0.405} \times \mathrm{FSN} \times e^{0.3062\times\mathrm{FSN}} \times 0.001 \times \frac{(m_{\mathrm{air}} + m_{\mathrm{fuel}})}{1.2929}, \quad (2)$$

where m_{air} and m_{fuel} are the intake air flow and fuel consumption rate, respectively, kg/h.

During the combustion process, not all the chemical energy of fuel has been released. The analysis of the energy utilization that is represented by the combustion efficiency, namely, the fraction that is burned compared to that which is supplied, is calculated using the following [14]:

$$\eta_{\mathrm{comp}} = \left(1 - \frac{\sum_{i=1}^{n} x_i Q_{\mathrm{LHV}i}}{Q_{\mathrm{LHVfuel}}}\right) \cdot 100\%, \quad (3)$$

where x_i and $Q_{\mathrm{LHV}i}$ represent the mass fractions and lower heating values (LHV) of HC, CO, and hydrogen (H_2), respectively. For this study, Q_{LHVHC} has been treated equal to Q_{LHVfuel}.

Combustion stability was expressed by the coefficient of variability (COV) of IMEP, and a value of 5% was thought to be an acceptable limit for this type of engine. The COV of IMEP was defined by the following:

$$\mathrm{COV_{IMEP}} = \frac{1}{\mathrm{IMEP_{mean}}} \sqrt{\frac{\sum_{i=1}^{N} (\mathrm{IMEP}_i - \mathrm{IMEP_{mean}})^2}{N-1}}. \quad (4)$$

2.3. Fuel. Commercially available 93 RON gasoline was used for all engine tests. Since the high pressure pump and injector were originally designed to operate with diesel fuel, a lubricity agent (Afton H4140 [15]) of 1000 ppm was added to gasoline fuel to avoid failure of the common-rail injection system. The physical and chemical properties of H4140 lubricity agent were listed in Table 2.

Table 2: Physical and chemical properties of H4140 lubricity agent.

Physical form	Liquid
Color	Amber (shallow)
Density (kg/m^3)	0.91
Solubility	Insoluble in cold water only
Viscosity (cSt@40°C)	17
Flash point (°C)	100 (closed cup)

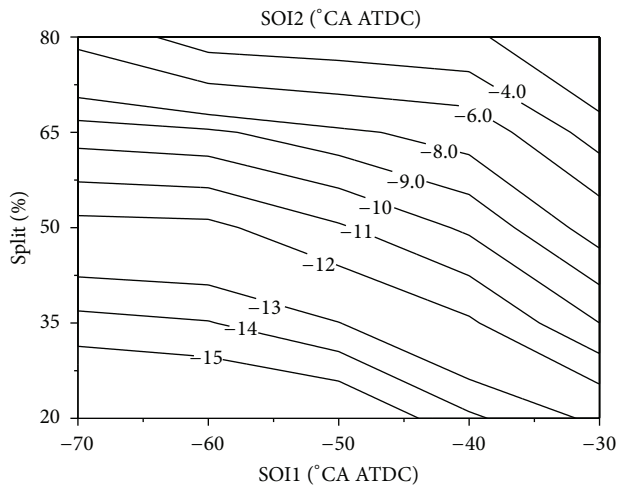


Figure 2: SOI2 as a function of SOI1 and split percentage; CA50 set at 10°CA ATDC.

3. Results

3.1. SOI1 and Split Percentage Sweeping. The major parameters affecting gasoline autoignition considered herein include SOI1 and split percentage. Thus, a sweep in SOI1 and split percentage had firstly been conducted to seek for optimized engine performance and emissions. In this section, the experiments were carried out for the load of 0.9 MPa IMEP (fuelling rate of 50 mg/cycle) at an engine speed of 1500 rpm. SOI1 was altered from −30 to −70°CA after top dead center (ATDC) with an interval of 15°CA and fuel split percentage from 20% to 80% in 10% intervals, where the remaining fuel was injected in the following injection event. Intake pressure and temperature were raised sufficiently to 220 kPa abs. and 323 K, respectively, for stable combustion. A baseline EGR level of 45% was used to avoid combustion reactions during the early stage of the compression stroke. Since the cone angle of the injector is as large as 150°, an appropriately lower injection pressure of 40 MPa was applied to reduce spray penetration, avoiding fuel wall-impingement and entering into the crevice volume. During the SOI1 and split percentage sweeping, the combustion phase of 50% accumulative heat release (CA50) was maintained at 10°CA ATDC, for the efficient combustion coupled with acceptable pressure rise rate. Since EGR rate was kept constant during the experiments, CA50 was mainly controlled by start of the second injection (SOI2).

The contour plot in Figure 2 clearly shows the SOI2 as a function of SOI1 and split percentage to keep CA50 fixed.

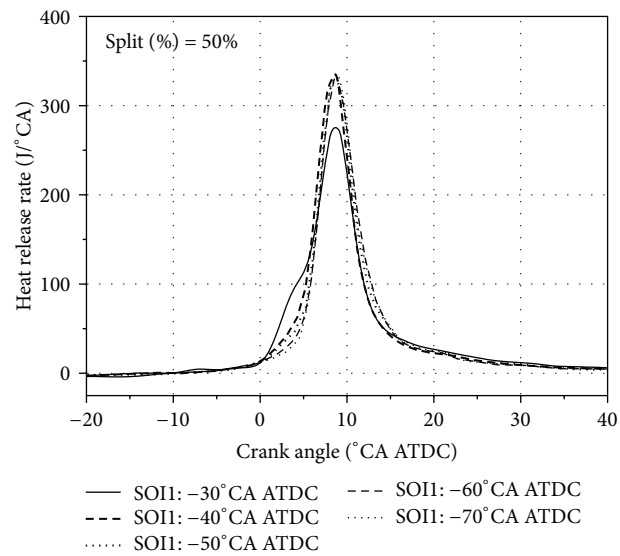


Figure 3: Heat release profile as a function of SOI1; split percentage set at 50%.

When SOI1 is advanced, the split fuel and air mixture get even leaner locally and its reactivity is weakened as a consequence, so SOI2 has to be put forward. With the increase of fuel amount in the first injection, the richer premixed charge with enhanced reaction activity has shown the potential to advance the combustion process, so SOI2 has to be delayed for the fixed CA50. It can therefore be concluded that SOI2 should be put forward along with the earlier SOI1 and lower split percentage and retarded closer to TDC otherwise.

Figure 3 presents the effect of SOI1 on heat release profiles while the split percentage is kept at 50%. In the multi-injection strategy in PCCI concept fuelled with diesel, the pilot fuel with good autoignition property generally occurs to combustion during the compression stroke, forming the heat release process of pilot fuel, which reduces the ignition delay and premixed combustion of the main injection, resulting in lower PRR and noise but higher soot level and fuel economy deterioration. Thus, on an energy basis, the pilot fuel is always kept to less than 25% of the total fuel [16]. Based on the points discussed above, for the double-injection strategy in gasoline LTC, large amount of EGR is necessary to prevent premature autoignition of the split fuel, and no obvious heat release process is observed before the total fuel is injected into cylinder as a consequence. The following injection event forms a significant stratification of the gasoline vapor and ignites the premixed charge by the split fuel and air mixing, so a single-peak heat release is observed. With SOI1 fixed at −30°CA ATDC, the combustion reaction occurs at an earlier stage, which leads to a slight decrease in peak HRR, as well as a longer combustion duration. The advancement of SOI1 renders better mixing and produces a more uniform mixture of the split fuel and air, whereas the heat release profiles are almost unchanged, which suggests that the effect of mixing time scale on premixed charge is weakened after a period of sufficient mixing.

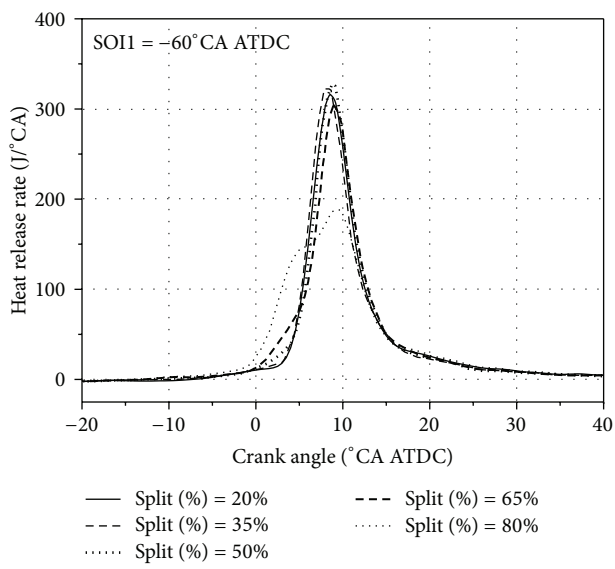


Figure 4: Heat release profile as a function of split percentage; SOI1 set at −60°CA ATDC.

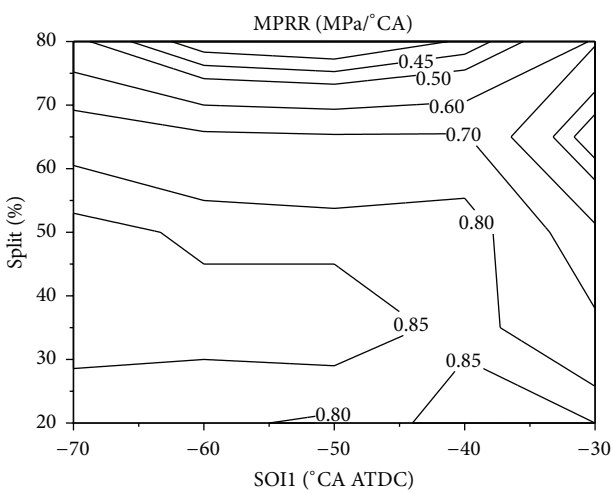


Figure 5: MPRR as a function of SOI1 and split percentage.

Figure 4 compares the heat release profiles of various split percentages with SOI1 fixed at −60°CA ATDC. A single-peak heat release process is observed and remains unaffected with the split percentage ranged from 20% to 50% for the reaction of the lean mixture from split fuel suppressed by EGR. As split percentage reaches 65%, the equivalence ratio of the premixed charge is up to 0.3, which is so reactive that some of the premixed charge occurs to be compressed-ignited before the main combustion process has happened; thereby significant changes are emerging in the heat release profiles. As the fuel split percentage is further increased to 80%, SOC is put forward obviously and a prominent double-peak heat release is noticed, while the equivalence ratio of premixed charge arrives at 0.37, so a smooth combustion process is achieved consequently.

MPRR for various SOI1s and split percentages are given in Figure 5. Under the single-injection case, fuel and air are

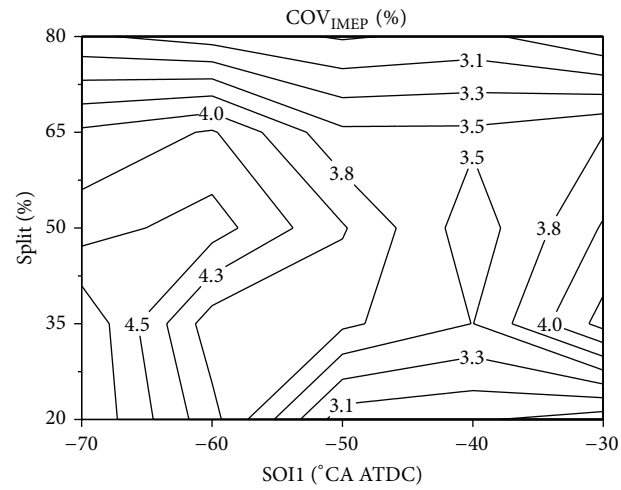


Figure 6: COV_{IMEP} as a function of SOI1 and split percentage.

well premixed prior to combustion, whereas there is less time interval between end of the second injection event and SOC with double-injection strategy, resulting in mixture stratification. For this reason, the burning rate is greatly alleviated and instantaneous HRR is reduced by the partial overlap of the second injection and combustion. So it is figured out that the region with MPRR below the threshold value of engine knock is pretty broad. Moreover, the increase in split percentage helps improve the fuel stratification. However, the earliness of the first injection provides more time interval for uniform mixing of fuel with air, which is supposed to play a more important role in MPRR as compared to SOI1. Nevertheless, the mixture stratification may also be weakened by excessively low fuel quantity in the second injection; namely, the split fuel accounts for most of the total fuel, resulting in higher MPRR as well.

The influence of SOI1 and split percentage on coefficient of variation of IMEP (COV_{IMEP}) is presented in Figure 6. Compared with single-injection strategy, the combustion stability of the double-injection strategy, indicated by COV_{IMEP}, declines apparently in terms of the lean mixture caused by the first injection but still within the stable combustion range. Clearly, the lower COV_{IMEP} is observed in the regions with higher split percentage and the combination of lower split percentage and later SOI1, which can be attributed to the following reasons: as split percentage exceeds 65%, the equivalence ratio of the premixed charge is sufficient to initiate combustion reaction before the following injection event as mentioned previously; COV_{IMEP} becomes less sensitive to SOI1. On the other hand, with split percentage less than 65%, the ignition delay period for the split fuel is so long that the lean mixture is more likely to be disturbed by the in-cylinder airflow with advanced SOI1, thereby increasing cycle-to-cycle variations. The maximum COV_{IMEP} appears at the regions with earlier SOI1 and lower split percentage, which delivers superior MPRR level accordingly. Therefore, from the view of combustion control, applying higher split percentage has the capability of achieving simultaneously

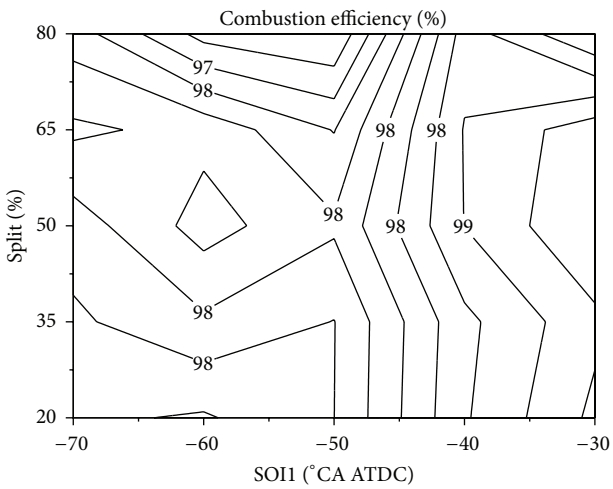


Figure 7: Combustion efficiency as a function of SOI1 and split percentage.

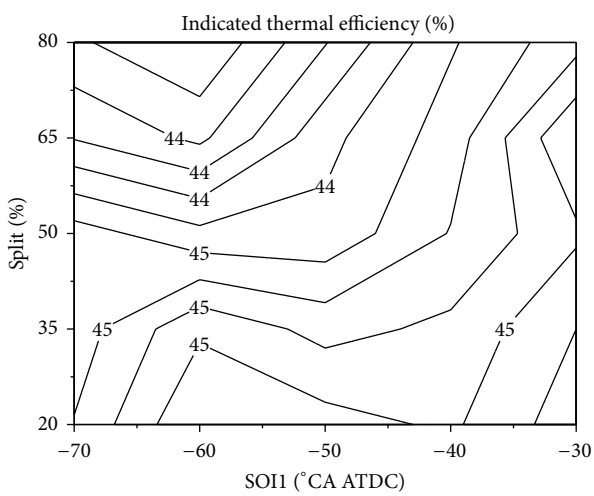


Figure 8: Indicated thermal efficiency as a function of SOI1 and split percentage.

lower MPRR and COV_{IMEP}, which are the indications of the successful operation range expansion of gasoline LTC.

Figure 7 shows the effects of SOI1 and split percentage on combustion efficiency. Overall, the flame quenching in lean premixed charge resulting from advancing SOI1 usually elevates the level of incomplete combustion products to a certain degree, which typically leads to a slight decrease in combustion efficiency. In addition, with the increase of split percentage, the combustion efficiency is reduced further. The detailed relationship between injection parameters and emissions will be discussed in the next section. Owing to the fixed CA50, approximately the same indicated thermal efficiencies under the operation condition are attained, basically between 44% and 45%, while suffering a little from the lower combustion efficiency in the region with earlier SOI1 and higher split percentage, as shown in Figure 8.

The normalized indicated specific NO_X, soot, CO, and THC emissions for various SOI1 and split percentage combinations using double-injection are given in Figures 9(a), 9(b), 9(c), and 9(d), respectively. From Figure 9(a), generally more fuel in the first injection means less NO_X emission, so it is clear that the regions with NO_X emission below 0.4 g/kWh are fairly board under the test condition. Based on the previous analysis, the reduction of NO_X is mainly due to the locally lower combustion temperature of the lean mixture resulting from the first fuel injection. On the other hand, SOI1 has a relatively small impact on NO_X emission, which exactly corresponds to the previous HRR results. Therefore, the amount of the first injection plays a key role in subduing NO_X emission.

As seen in Figure 9(b), with the advancement of the first injection, soot emission declines gradually due to the enhanced premixing of the split fuel with air, while an increase tendency is observed with more fuel in the first injection. This is mainly because the earliness of SOI1 leads to serious fuel wall-impingement, and the fuel may stick to the engine parts, for example, cylinder wall and piston head, forming an oil film, where more particulates are emitted from the combustion with extremely high equivalence ratio. Meanwhile, in order to keep CA50 fixed, SOI2 is closer to TDC with higher fuel split percentage, thereby mixing period of the second injection is not sufficient; thus the increased diffusion combustion delivers a higher local equivalence ratio, which also leads to soot decortication. Therefore, in order to obtain ideal soot level, the fuelling strategy with the combination of earlier SOI1 and lower split percentage should be employed. Nevertheless, considering the previous results, the regions emitting lower soot emission exactly correspond to those generating higher MPRR and COV_{IMEP}. Therefore, it is stated that the in-cylinder charge stratification to some extent is necessary for alleviating burning rate, while there could be a price to pay in terms of soot emission. Namely, there exists a trade-off relationship between MPRR and soot with double-injection strategy in the load expansion of gasoline LTC.

As pointed out in Figure 9(c), the relationship between SOI1 and CO emission is dramatically different divided by SOI1 of −50˚CA ATDC. If SOI1 is located after −50˚CA ATDC, the split fuel undergoes longer ignition delay period prior to SOC with SOI1 advancing, so the local mixture gets even leaner, resulting in lower combustion temperature that proved to be an obstacle for the convention of CO to CO_2. Therefore, CO emission is strongly influenced by SOI1 but largely unaffected by split percentage. On the other hand, the phenomena become much more complicated. With SOI1 advanced ahead of −50˚CA ATDC, the minimum value of CO emission is obtained with the split percentage of about 50%, while CO emission is increased whether the split percentage is higher or lower. As split percentage exceeds 50%, the locally leaner mixture cannot generate sufficient temperature for the oxidation of CO. Besides, the SOI2 has to be put forward to keep CA50 fixed as a result of the low split percentage, which also decreases the local equivalence ratio. These two factors combined together result in the special distribution of CO emission.

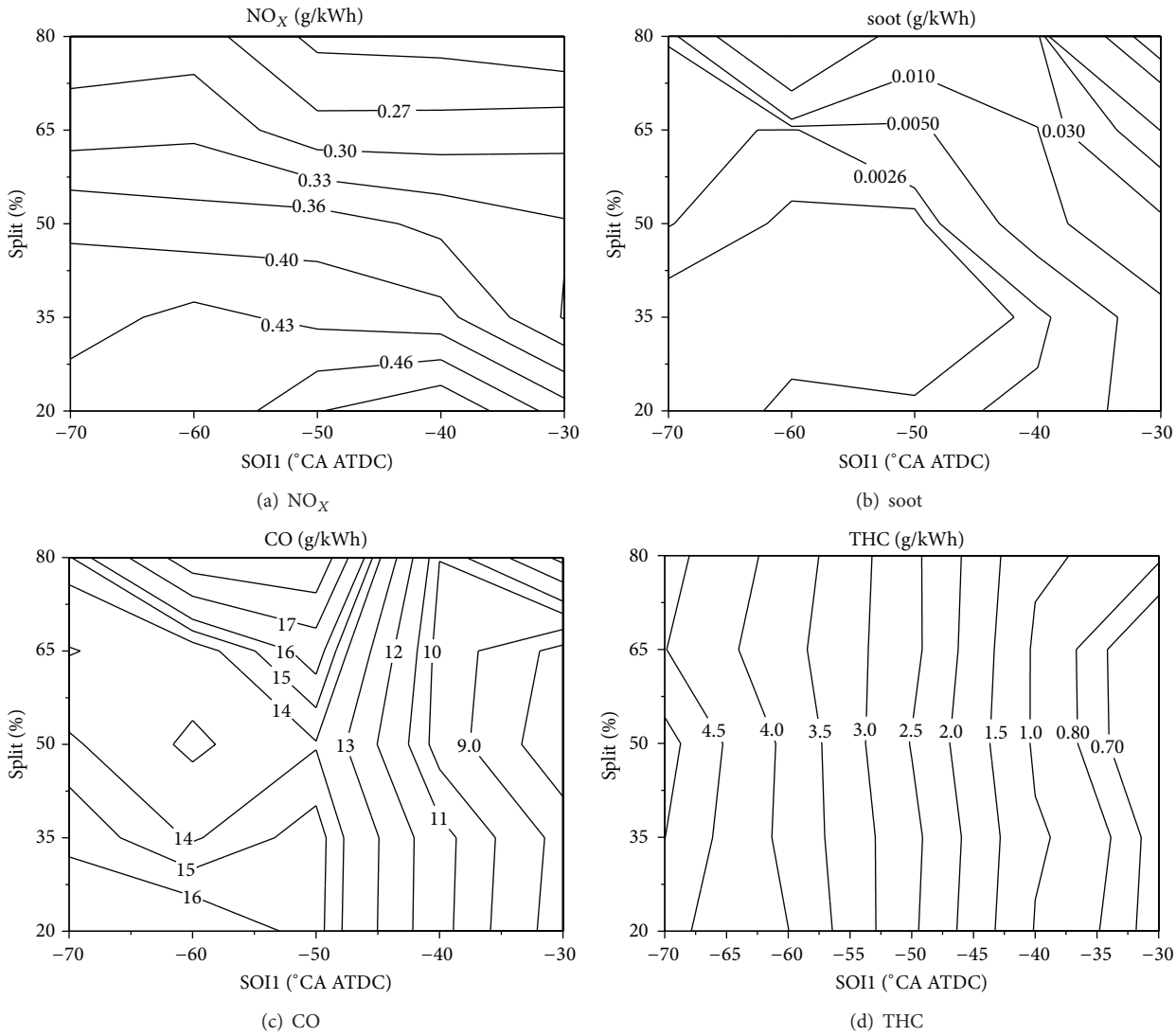


Figure 9: Emissions as a function of SOI1 and split percentage.

As Figure 9(d) shows, THC emitted from the double-injection strategy depends monotonically upon SOI1 in general. By applying earlier split injection under the running condition previously described, the spray penetration is increased due to the lower in-cylinder gas densities early in the compression stroke, so the split fuel is likely to cause serious spray impingement on combustion chamber wall surface, or enters into the crevice volume. Thus, gasoline LTC with double-injection strategy produces more THC with earlier SOI1 mainly due to partial flame quenching near cylinder wall, or unburned HC remains in the crevice volume and then is released during the exhaust stroke consequently. Meanwhile, the distributions of CO and THC emissions fully illustrate the change of combustion efficiency with SOI1 and split percentage as well.

3.2. The High Load Performance for Single- and Double-Injection Strategies. Based on the previous results, it was decided to investigate the capability of operating range expansion of the double-injection strategy, while the experiment performed with single-injection strategy had been added as a reference. Euro VI emission regulation and engine design were adequately considered to determine the criteria. The values of NO_X and soot emissions were both within the Euro VI regulation. The limits of MPRR and maximum cylinder pressure (P_{max}) were set to 1.2 MPa/°CA and 16 MPa, respectively, preventing mechanical damage to the test engine. In addition, the COV_{IMEP} of each test point should be less than 5% for stable combustion. During the experiments, the fuel mass was gradually increased until one or more of the following criteria were violated.

(i) $NO_X < 0.4$ g/kWh;

(ii) soot < 0.01 g/kWh;

(iii) MPRR < 1.2 MPa/°CA;

(iv) $COV_{IMEP} < 5\%$;

(v) $P_{max} < 16$ MPa.

Table 3: Parameters of maximum load for different injection strategies.

Injection strategies	Double	Single
SOI1 (°CA ATDC)	−43	—
SOI2 (°CA ATDC)	−23.5	−27.3
Split percentage	30%	—
CA50 (°CA ATDC)	10	10
EGR	45%	45%
Injection pressure (MPa)	50	50
Indicated thermal efficiency	44.1%	44.6%
Combustion efficiency	97.3%	98.4%
IMEP (MPa)	1.204	1.11
MPRR (MPa/°CA)	1.23	1.18
P_{max} (MPa)	12.84	12.66
NO_X (g/kWh)	0.17	0.32
soot (g/kWh)	0.98	0.76
CO (g/kWh)	1.80	1.10
THC (g/kWh)	1.16	0.40

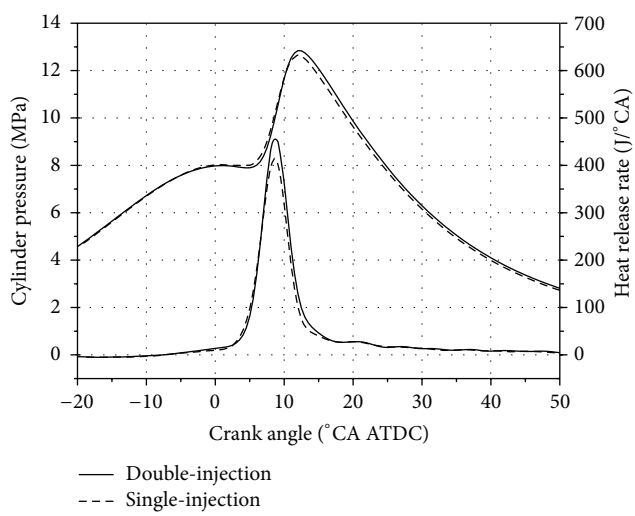


Figure 10: Cylinder pressure and heat release profiles of single- and double-injection strategies.

As mentioned in the previous section, the combination of advanced SOI1 and increased split percentage often generates unacceptable MPRR as well as soot deterioration. These two key factors had to be taken into account carefully during the load expansion, while maintaining relatively high combustion efficiency. Thus, the strategy with later SOI1 coupled with lower split percentage was applied for better comprehensive performance; the first injection was placed at −43°CA ATDC with a split percentage of 30%. During the process of operation range expansion, the combustion is configured to provide a CA50 of approximately 10°CA ATDC through adjusting injection timings. Further details of the test condition are documented in Table 3.

Figure 10 compares the cylinder pressure and heat release profiles of the single- and double-injection strategies. They both exhibit single-peak heat release pattern under the test condition. The original engine equipped with a selective catalytic reduction (SCR) exhaust catalyst is enough to approach Euro IV emission standard even at the full load with IMEP of 1.8 MPa. In the effort of optimizing injection parameters, the maximum IMEP of gasoline LTC is extended from 1.11 MPa to 1.204 MPa as figured in Table 3. This indicates that applying fuel double-injection strategy is totally feasible to extend operation range covering the low and medium load conditions commonly used, along with NO_X and soot levels below Euro VI emission standard without posttreatment system. But the combustion efficiency is slightly decreased because of split injection, and consequently the indicated thermal efficiency declines to some extent. Through the enhanced mixture stratification in the double-injection strategy, MPRR can be held within acceptable level and P_{max} is far below the engine design limit.

In the aspect of main emissions, NO_X emission of the double-injection strategy is further reduced by approximately 50% due to the leaner mixture from split fuel as compared to the single-injection case. It is suggested that NO_X emission could be well controlled by either the single- or double-injection strategy with sufficient boost and EGR. The fuel double-injection delivers slightly higher soot emission, which is mainly attributed to partial overlap between the second injection and combustion under the parameter settings. Furthermore, as shown clearly in Table 3, the increase of IMEP is limited due to the violation of soot criteria rather than others with increasing total fuel mass. Therefore, similar to MPRR, soot emission is also turned out to be a major factor determining the operation range, and they are related in a trade-off relationship as discussed previously in the double-injection strategy of gasoline LTC. Not surprisingly, the double-injection strategy emits more CO and THC emissions than the single-injection strategy mainly due to the lower in-cylinder combustion temperature and flame quenching near cylinder wall, respectively. The penalty of CO and THC is supposed to be one of the major reasons for the decreased combustion efficiency and indicated thermal efficiency.

4. Discussions

Overall, due to the trade-off relationship between MPRR and soot emission, it is difficult to accomplish high-efficiency and clean combustion with pure gasoline over the whole operation range of the original engine. During the optimization study on fuel properties in LTC, researchers have pained much emphasis on bio-fuels, for example, alcohol fuels. Applying alcohol fuels with excessively high oxygen content, and free from aromatic hydrocarbon and sulfur, has been identified to be an effective pathway for solving the issue existing in the load expansion of gasoline LTC due to the remarkable effect of innate oxygen on soot reduction. Butanol, as a competitive alternative fuel, has several advantages over the conventional alcohol alternative fuels for the engine applications [17]. In the four butanol isomers, n-butanol with the unique molecular structure and decomposition reaction shows the least potential to produce polycyclic aromatic hydrocarbons (PAHs), which is usually

considered to be the soot precursor [18]. Therefore, superior engine performance and emissions can be attained using either neat n-butanol [19, 20] or its blend with conventional fossil fuels [21]. However, how to achieve well-organized combustion with n-butanol needs much more studies in the future.

5. Conclusions

In the present work, experimental study has been conducted to investigate the effect of fuel injection strategies on the engine performance, emissions, and load expansion capability on a single-cylinder CI engine. The conclusions that can be withdrawn from this paper are as follows.

(1) With the fixed CA50, the peak HRR is reduced by advancing SOI1 and increasing split percentage.

(2) Higher indicated thermal efficiency, as well as lower MPRR and COV_{IMEP}, can be achieved simultaneously with later SOI1 and higher split percentage.

(3) As split percentage increases, NO_X emission decreases but soot emission increases. CO and THC emissions are increased by advancing SOI1, resulting in a slight decrease in combustion efficiency.

(4) Compared with the single-injection strategy, the double-injection strategy enables successful expansion of high-efficiency and clean combustion region, covering the commonly used engine loads. But soot, CO, and THC emissions are increased with the double-injection strategy at high loads, slightly declining the combustion efficiency and indicated thermal efficiency.

(5) MPRR and soot emission are thought to be the predominant constraints to the load expansion of gasoline LTC, while they are related to their trade-off relationship.

Nomenclature

ATDC: After top dead center
CA: Crank angle
CA50: The combustion phase of 50% accumulative heat release
CI: Compression ignition
CO: Carbon monoxide
CO_2: Carbon dioxide
COV: Coefficient of variability
EGR: Exhaust gas recirculation
FSN: Filter smoke meter
H_2: Hydrogen
HCCI: Homogenous charge compression ignition
HRR: Heat release rate
IMEP: Indicated mean effective pressure
LHV: Lower heating value
LTC: Low temperature combustion
MPRR: Maximum pressure rise rate
NO_X: Nitrogen oxides
PAHs: Polycyclic aromatic hydrocarbons
PCCI: Premixed charge compression ignition
PM: Particle matter
PPC: Partially premixed combustion
RON: Research octane number
rpm: Revolutions per minute
SCR: Selective catalytic reduction
SOC: Start of the combustion
SOI1: Start of the first injection
SOI2: Start of the second injection
THC: Total hydrocarbon.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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