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Enhancing combustion characteristics in a constant volume chamber using a novel multi-injection system for liquid fuel and propane-air stratified mixtures

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This study proposes a novel multi-injection strategy to enhance fuel atomization and combustion in a constant volume combustion chamber. By integrating a third injector into the conventional axis-opposed spray configuration and optimizing injection timing, the strategy significantly improves fuel–air mixing and ignition reliability, particularly under cold-start conditions. Two fuels with contrasting reactivity – n-hexadecane and iso-octane – were used to investigate spray and combustion characteristics. Laser diffraction analysis showed that the proposed strategy substantially reduced the Sauter Mean Diameter compared to single or impinging injection alone. Combustion experiments demonstrated improved ignition stability, advanced heat release phasing, and increased total heat release with the multi-injection approach. These effects were more pronounced for iso-octane, where ignition failure was frequent under baseline conditions. The results confirm that the proposed multi-injection strategy effectively stabilizes combustion and enhances thermal efficiency for both high- and low-reactivity fuels.

Key words: *multi-injection, axis-opposed spray, fuel atomization, low-reactivity fuel, combustion efficiency*

1. Introduction

Direct injection (DI) systems have been widely adopted in diesel engines to promote homogeneous fuel-air mixture formation and achieve higher thermal efficiency, particularly under high compression ratio conditions. In contrast, port fuel injection (PFI) remains a common strategy in gasoline engines due to its stability and low cost. Given that internal combustion engines contribute significantly to greenhouse gas (GHG) emissions [23], increasingly stringent emission regulations have prompted the automotive industry to develop more advanced engine technologies. In response to strict emission standards issued by the U.S. Environmental Protection Agency (EPA) and the National Highway Traffic Safety Administration (NHTSA) [5], manufacturers have accelerated the adoption of gasoline direct injection (GDI) systems. GDI offers superior fuel and thermal efficiency compared to PFI, largely owing to its enhanced injection precision [4, 29]. Kalwar et al. [13] highlighted the advantages of GDI in terms of power output and efficiency, emphasizing the importance of a well-mixed fuel-air mixture for stable combustion under homogeneous conditions. In addition, GDI engines also tend to emit fewer unburned hydrocarbons and show less combustion variability, particularly under medium-to-high load operating conditions. However, GDI engines still face challenges, notably elevated particulate matter (PM) and particle number (PN) emissions. These challenges necessitate further optimization of fuel injection strategies and combustion control to comply with upcoming emission standards.

PM and PN emissions are significantly elevated under cold-start conditions, where low cylinder wall temperatures and incomplete fuel vaporization promote the formation of liquid fuel films on the piston or liner surfaces. This leads to increased unburned hydrocarbon (UHC) and soot emissions [12, 22, 24]. Studies show that GDI engines generally emit more PM and PN than PFI counterparts, primarily due to the higher elemental carbon content present in the exhaust [2, 7, 25, 27]. Among various pollutants, organic gas emissions have been found to be the most sensitive to cold-start conditions. Moreover, cold-start contributes a disproportionately large fraction of total emissions over the unified driving cycle, especially in vehicles certified to stricter emission standards [3]. To mitigate wall-film-related emissions, several strategies have been investigated. For example, Rostampour et al. [24] reported that, under cold start conditions, the fuel film formation in PFI engines can reach up to 55% of total injected fuel, severely impacting fuel distribution and emissions. To address these issues, they adopted the advanced port fuel injection (APFI), and the maximum amount of fuel film formed on the walls is reduced by about 75%. Zhang et al. [28] proposed a dual-injection strategy combining GDI and PFI, which effectively reduced soot emissions at a 65:35 GDI/PFI ratio. In GDI engines, high-pressure injection, multi-pulse strategies, and split injection have been applied to enhance fuel atomization and minimize spray-wall impingement [14, 17, 26]. Lonari et al. [21] demonstrated that three-pulse injection at 35 MPa significantly reduced HC and NO_x emissions by up to 80% during cold-start catalyst light-off compared to conventional two-pulse injection at 25 MPa. Han et al. [11] experimentally investigated multiple injection strategies in a boosted single-cylinder DISI engine and found that increasing injection events significantly reduced PN emissions and knock intensity, while improving thermal efficiency and maintaining combustion stability. They further reported that multiple injections increased knock limits while maintaining torque and combustion stability, and reduced NO_x and UHC emissions by approximately 25%. A similar trend was reported by Guo et al. [10], proposed a novel direct-start strategy using multistage and split injection and experimentally demonstrated that three-stage injection and optimized split timing significantly improve combustion phasing and reduce UHC emissions under cold-start conditions. In addition, Fellner et al. [6] developed an algorithm-based calibration method for multiple injection pattern design in DISI engines, showing that optimized split strategies can prevent wall impingement and reduce particle formation while adapting to varying combustion conditions. Beyond injection strategies, further optimization has been explored by delay intake valve opening timing to enhance fuel atomization, thus achieve a 50–90% reduction in PN emissions [18], utilizing dual-fuel dual-direction injection strategy that successfully suppressed knock, improved thermal efficiency and expanded engine load [15], or employing dual spark plugs with multi-injection strategy to improve combustion stability and reduce CO emission [1], all of which have shown to improve combustion stability and reduce emissions.

Similar challenges are observed in GDI engines, diesel engines also suffer from comparable issues under certain operating conditions [8, 17, 22]. Kang et al. [16] evaluated multi-stage split injection with five injection events in a light-duty diesel engine and found that this strategy reduced fuel consumption and PM emissions by improving heat release smoothness, reducing flame penetration, and enhancing fuel-air utilization.

However, despite these advancements, the control of spray impingement and liquid fuel deposition remains a major challenge, especially under transient or low-temperature conditions. Recent studies also suggest that preheating or injection strategy adaptation can help mitigate these challenges [9]. Among various factors, fuel atomization plays a pivotal role in suppressing wall wetting and ensuring homogeneous mixture formation, which are essential for reducing PM and PN emissions. The core solution lies in enhancing fuel atomization quality, shortening the overall injection duration, and minimizing fuel impingement on the combustion chamber walls. To address these issues, our previous work proposed an impinging injection strategy, in which two injectors were installed axisymmetrically, directing sprays toward each other to induce droplet breakup through spray impingement interaction. The feasibility of this concept was demonstrated in earlier studies [19, 20], where improvements in atomization and combustion characteristics were observed. For fuels with varying viscosities, the Sauter mean diameter (SMD) of impinging injection was consistently reduced compared to conventional one-sided injection, indicating enhanced atomization performance. However, under low injection pressure conditions, the persistence of coherent liquid jets was observed in the impingement zone, leading to non-uniform droplet distribution and compromised fuel-air mixture homogeneity, ultimately hindering thermal efficiency. To overcome these limitations, the present study introduces a novel multi-injection strategy that integrates axis-opposed impinging injection with a one-sided injection. By employing three injectors and optimizing injection timing, this configuration aims to shorten the total injection duration and reduce the local SMD near the ignition zone, thereby enhancing mixture uniformity and promoting stable combustion under cold-start and low-load conditions.

In this study, a constant volume combustion chamber was employed to investigate the feasibility of a multi-injection strategy. The results showed that the proposed multi-injection strategy significantly improved atomization by reducing the Sauter Mean Diameter (SMD) compared to one-sided and conventional impinging injection. For fuel with low reactivity, the multi-injection strategy substantially enhanced ignition stability and improved combustion characteristics, particularly under pre-injection conditions. These improvements demonstrate that an appropriately timed pre-injection can promote ignition stability, faster flame propagation, and higher thermal efficiency, making it a promising strategy to improve combustion stability under cold-start and low-load conditions.

The work proceeds by introducing the experimental setup and test conditions, followed by an analysis of spray atomization and combustion characteristics using two representative fuels: n-hexadecane and iso-octane, which differ in ignition reactivity. Key combustion metrics such as maximum burning pressure, total burning time, and heat release rate are discussed. The study concludes with a summary of findings and their implications for improving engine performance under cold-start and low-load conditions.

2. Experiment apparatus and conditions

2.1. Experiment apparatus

Figure 1 shows the schematic diagram of the experimental apparatus, including a constant volume combustion

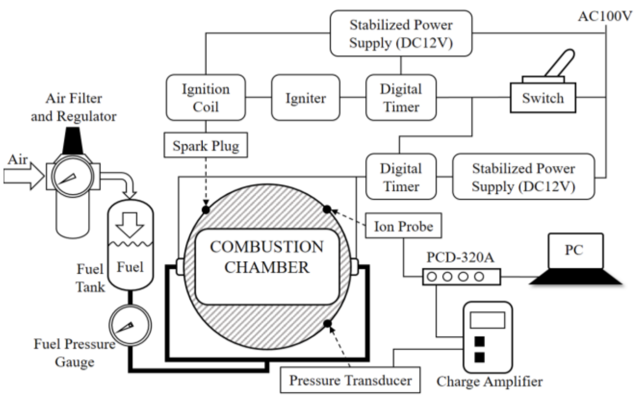

Fig. 1. Experiment apparatus

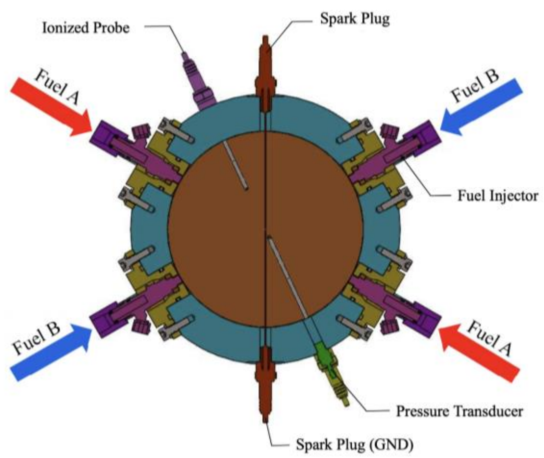

Fig. 2. Details of a constant volume combustion chamber

chamber, a propane-air mixture tank, a data sampling control system, a fuel injection system, and an ignition system. Details of the combustion chamber (volume 5600 cc, diameter 160 mm) are shown in Fig. 2. Two pairs of injectors (EAT321, 150 μm, 8 holes) were opposite and coaxially set on the chamber wall. The injection pressure was supplied by compressed air. The combustion pressure was recorded by a piezo-electric sensor (KISTLER 6041A, charge amplifier 5011B). The laser diffraction spray analyzer (LDSA-SPR1500, Microtract) and the analysis software Aerotrac ver.15 were used to observe droplet size distributions of different blend fuel types.

2.2. Experiment conditions

In this study, experiments were conducted at room temperature and atmospheric pressure. The injection pressure was 0.5 MPa. To investigate the influence of fuel properties on spray behavior and combustion, two pure fuels were used: n-hexadecane and iso-octane. These fuels differ significantly in physical properties, particularly viscosity, which directly affects the SMD of the spray. Table 1 lists the basic fuel properties. As shown in Table 1, n-hexadecane exhibits higher viscosity than iso-octane, resulting in larger SMD values.

Table 1. Fuel properties

Fuel type	n-hexadecane	iso-octane
Chemical formula	$C_{16}H_{24}$	C_8H_{16}
Density [g/ml]	0.774	0.68
Boiling point [K]	560	372
Viscosity [cP]	3.454	0.502
Cetane number	100	10
Octane number	–20	100
Low heat value [kJ/mol]	9953.3	5065.5
Vapor pressure	133.3 Pa (105°C)	5.1 kPa (20°C)

Spray characterization was performed using an LDSA. The system operated in trigger mode with a sampling window of 30 ms, and an SMD measurement range of 5–300 μm. To evaluate the atomization effect induced by spray impingement interaction, we compared the SMD of a one-sided injection, an impinging injection, and a multi-injection. Tests were carried out for both fuels under various injection durations.

For the combustion characteristics experiments, all test conditions were set to maintain the same overall equivalence ratio, $\Phi = 0.95$. To minimize the influence of injection duration on combustion results, the same injection duration was applied for both fuel types under all operating conditions. Since n-hexadecane and iso-octane have different densities and low heat values, the equivalence ratio of the propane-air mixture was adjusted accordingly to ensure a consistent overall equivalence ratio. Figure 3 illustrates the procedure for calculating the equivalence ratio of the propane-air mixture and the corresponding fuel quantity. Table 2 lists the specific equivalence ratios of the propane-air mixture used for the two fuels under multi-injection conditions.

To investigate the effect of injection timing, two types of injection conditions were defined: pre-injection and post-injection. In the pre-injection case, spark ignition was initiated after the spray tail had reached the central region of the chamber. In the post-injection case, ignition occurred before the start of fuel injection.

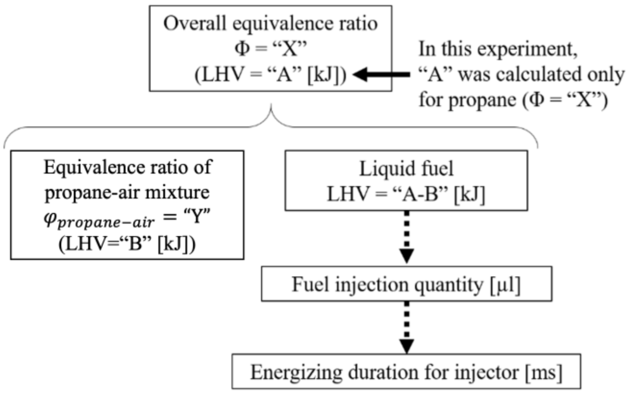

Fig. 3. Flow of calculating the equivalence ratio of propane and the liquid fuel injection quantity

Table 2. Equivalence ratio of propane-air mixture for multi-injection

Overall equivalence ratio Φ = 0.95		
Fuel type	$C_{16}H_{24}$	C_8H_{18}
Equivalence ratio of propane-air mixture	0.876	0.883

In our previous studies, a multi-impinging injection involving two injection stages was proposed. In contrast, the present study introduces a simplified multi-injection strategy with a single injection stage. Unlike conventional impinging injection or multi-impinging injection, which utilizes two axis-opposed injectors (injector BL and BR shown in Fig. 2) aimed toward each other, the multi-injection integrates a third centrally located injector (injector AR shown in Fig. 2), forming a three-spray system. This layout enables enhanced spray impingement interaction and mixture formation near the ignition zone, while simplifying the injection schedule.

This multi-injection aims to reduce SMD around the spark region, shorten the injection duration, and improve the spatial uniformity of the fuel-air mixture, thereby enhancing ignition reliability and combustion stability. For each experimental condition, ten repeated tests were conducted. The average values of combustion characteristics were calculated after excluding the maximum and minimum data points to reduce variability. In-cylinder pressure was recorded using a piezoelectric pressure sensor, and the heat release rate was calculated according to Equation (1).

$$\frac{dQ}{dt} = \frac{1}{\kappa - 1}\left(V \cdot \frac{dP}{dt}\right) \quad (1)$$

where: P = pressure of combustion chamber [Pa], t = time from ignition [s], V = combustion chamber volume [m^3], κ = 1.34 (specific heat ratio: constant value).

3. Results and discussions

3.1. Spray characteristics

As discussed in the introduction, the quality of fuel atomization has a significant effect on mixture preparation and combustion performance, particularly under cold-start or low-load conditions. In this study, the spray characteristics of different injection strategies were evaluated: one-sided injection, in which only a single injector (BR) was activated; impinging injection, where two axis-opposed injectors (BL, BR) were simultaneously operated; and multi-injection, in which three injectors (AR, BL, and BR) were simultaneously operated. The test fuels were n-hexadecane and iso-octane. The injection durations were set to 8 ms for the multi-injection and 10 ms for the conventional impinging injection. Although the overall fuel quantity and equivalence ratio were kept constant, the multi-injection configuration utilized three injectors operating simultaneously, allowing the required fuel to be delivered within a shorter duration compared to the conventional impinging injection setup. To investigate the effect of injection duration for each injection strategy, the conventional impinging injection was also tested with an 8 ms injection duration. From Table 1, n-hexadecane has high viscosity and low volatility, which generally results in larger droplet size. In contrast, iso-octane, with lower viscosity and higher vapor pressure, tends to facilitate finer atomization. The objective was to clarify how injection strategy and fuel properties affect the temporal evolution of droplet size.

Figure 4 and Fig. 5 show the temporal variation of SMD for n-hexadecane and iso-octane, respectively, under different injection conditions. Across both fuels, the impinging injection and multi-injection consistently resulted in significantly reduced SMD values than the one-sided injection under the same injection duration condition. Specifically, the SMD of n-hexadecane decreased by 33.3%, while iso-octane exhibited a higher SMD reduction of up to 70.0%. This reduction indicates that spray impingement interaction promotes enhanced atomization by inducing secondary breakup.

As shown in Fig. 4 and Fig. 5, n-hexadecane exhibits minimal differences in SMD between the impinging injection and multi-injection strategies under an 8 ms injection duration. However, when the injection duration is extended to 10 ms, the rate of SMD reduction decreases, indicating a saturation effect in fuel atomization improvement. Since the fuel mass was kept constant for all combustion experiments, the multi-injection achieves comparable atomization within a shorter injection duration. The time-saving effect is particularly advantageous under practical engine conditions where injection timing is limited. Therefore, the superiority of multi-injection lies in its ability to enhance fuel atomization efficiency while minimizing injection duration.

For iso-octane, its lower viscosity leads to overall reduced SMD values compared to n-hexadecane. However, even for this low-viscosity fuel, the impinging injection showed limited sensitivity to injection duration, as indicated by the minimal difference in SMD between the 8 ms and 10 ms injection duration conditions.

Compared to conventional impinging injection, the multi-injection strategy achieved a 37.5% reduction in SMD within the first 3 ms, highlighting its effectiveness in promoting atomization during the initial phase. The minimum SMD observed reached the 10 μm range, indicating highly effective atomization under this condition. This suggests that multi-injection is effective not only for high-viscosity fuels but also enhances atomization efficiency in favorable conditions, by accelerating droplet breakup and shortening the spray injection duration.

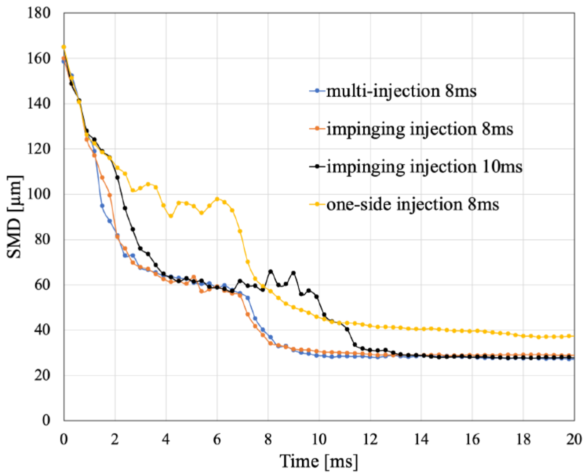

Fig. 4. SMD of n-hexadecane under different injection strategies

The enhanced atomization achieved by the newly proposed multi-injection method is expected to promote more homogeneous fuel-air mixture formation and enhance combustion stability, especially under challenging ignition conditions. The impact of this improved spray behavior on combustion characteristics is discussed in the following sections.

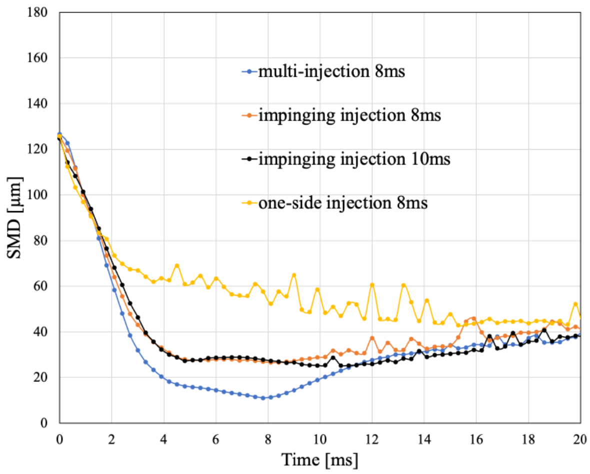

Fig. 5. SMD of iso-octane under different injection strategies

3.2. Combustion characteristics of n-hexadecane

Figure 6 presents the comparison of maximum burning pressure (MBP) and total burning time (TBT) for n-hexadecane under various injection strategies. The propane–air case ($\Phi = 0.95$) involved no liquid fuel injection and served as the baseline reference. It has the highest MBP (0.655 MPa) owing to less latent heat loss, but TBT is longer due to slow flame propagation speed.

In our previous study, the post30 injection timing with conventional impinging injection yielded the highest MBP, among the impinging injection cases, reaching 0.595 MPa. However, with the new multi-injection strategy, which featured a shorter injection duration, the same injection timing was no longer effective. In fact, the MBP of multi-injection with post30 injection timing is 0.577 MPa, representing a 3.0% decrease compared to conventional impinging injection with post30 injection timing. As the injection timing was advanced from post30 to post10, MBP increased to 0.601 MPa, showing an increase of 4.2% over the multi-post30 case. Notably, although pre-injection conditions were previously unsuitable for n-hexadecane with conventional impinging injection, the current results show that pre-injection is compatible with the newly proposed multi-injection strategy. The MBP reached 0.613 MPa at the multi-pre10 condition, marking a 3.0% increase relative to imp-post30.

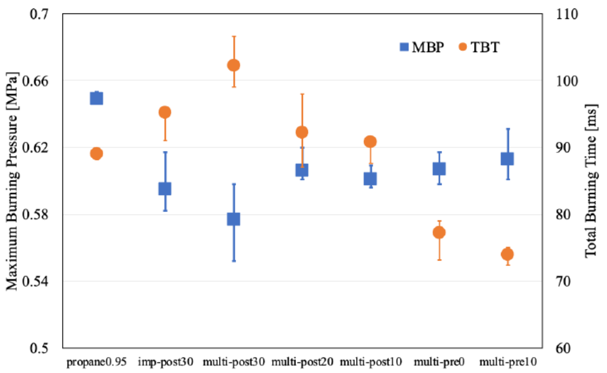

Fig. 6. Maximum burning pressure (MBP) and total burning time (TBT) under different injection strategies for n-hexadecane

Regarding combustion duration, the TBT of imp-post30 was 95.2 ms. TBT was gradually shortened as the injection timing advanced from post30 to post10. Under pre-injection conditions, TBT decreased to 74 ms at the multi-pre10 condition, which corresponds to a 22.3% reduction compared to imp-post30. Notably, multi-injection strategies with pre-injection showed reduced variability, as indicated by narrow error bars, suggesting improved combustion stability. These findings indicate that optimal injection timing is strongly dependent on the injection configurations. Multi-injection combined with pre-injection conditions enables faster flame propagation and shorter combustion durations.

Figure 7 illustrates the heat release rate (HRR) of n-hexadecane under various injection strategies. The graphs are divided into post-injection (Fig. 7a) and pre-injection (Fig. 7b) to highlight the effects of injection timing and configuration on combustion behavior.

In the post-injection conditions shown in Fig. 7a, the impinging injection post30 condition exhibits a relatively delayed and broadened HRR curve compared to the propane-air case, and it has an evident second stage combustion at the end of combustion, which indicates the heterogeneity of the fuel-air mixture. The introduction of the third injector in the multi-injection significantly altered the combustion characteristics. As the injection timing is advanced from 30 ms to 10 ms after ignition (multi-post30 → post20 → post10), the onset of heat release gradually shifts forward and the peak intensity becomes higher and more concentrated. Specifically, the maximum HRR increased from 112.9 J/ms at multi-post30 to 135.9 J/ms at multi-post10, corresponding to an increase of 20.4%. Compared to the impinging injection (112.2 J/ms), this represents an 18.9% maximum HRR increment. These results suggest that multi-injection promotes improved atomization and mixture formation near the spark location, thereby enhancing ignition quality and accelerating the flame propagation process.

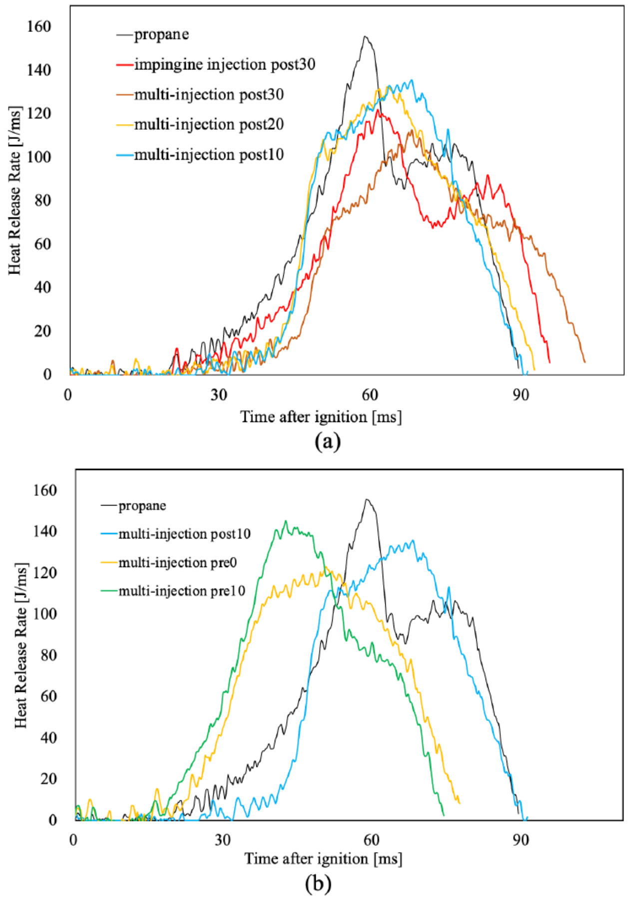

Fig. 7. Heat release rate (HRR) of n-hexadecane under different injection strategies: a) post-injection strategies (impinging and multi-injection); b) pre-injection strategies (multi-injection)

In the pre-injection conditions (Fig. 7b), this trend is even more pronounced. Both multi-pre0 and multi-pre10 demonstrate significantly earlier HRR initiation compared to post10 and propane cases. The combustion phase becomes more compact and the HRR curve steeper, indicating faster flame propagation speed and reduced ignition delay. In particular, the multi-pre10 condition achieved a maximum HRR of 145.3 J/ms, which is 28.7% higher than multi-post30 and 18.9% higher than impinging injection. These findings suggest that sufficient premixing prior to ignition plays a critical role in enhancing combustion phasing and thermal efficiency.

The mass fraction burned (MFB) is a key indicator used to characterize the combustion progress by quantifying the fraction of the total fuel mass that has been burned at a given time. Among its milestones, the time to reach 1% MFB (often termed MFB 1%) is commonly used as an approximation for ignition delay and combustion onset. A shorter MFB 1% value indicates faster ignition and finer mixture preparation near the spark plug.

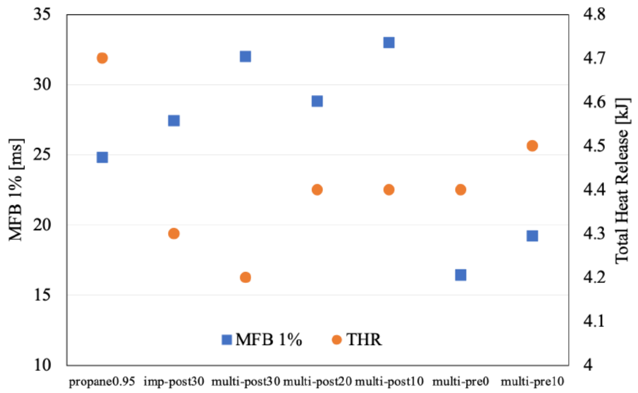

Fig. 8. Mass fraction burned duration (MFB 1%) and total heat release (THR) of n-hexadecane under various injection strategies

Figure 8 presents the combustion duration, represented by the time to reach 1% mass fraction burned (MFB 1%), and the total heat release (THR) for n-hexadecane under different injection strategies. MFB 1% duration increases significantly in the post-injection conditions. This indicates a slower combustion onset due to limited premixing time. In contrast, the pre-injection strategies result in the shortest MFB 1 value, suggesting accelerated early-stage combustion facilitated by improved mixture formation prior to spark timing. THR remains relatively stable across most conditions but shows a slight increase for the multi-pre10 case. This implies that early injection allows for more effective fuel utilization. Interestingly, even though MFB 1 is shorter for multi-pre cases, their THR does not drop, suggesting that faster initial combustion does not compromise total energy release.

Through these findings, while using n-hexadecane, the combination of pre-injection and multi-injection demonstrates a synergistic effect: it promotes more rapid and stable combustion. These findings confirm the superiority of the proposed multi-injection strategy over conventional impinging injection. The addition of a third spray source and optimized injection phasing significantly improves mixture preparation, resulting in faster combustion.

3.3. Combustion characteristics of iso-octane

Figure 9 shows the MBP and TBT of iso-octane under multi-injection with different injection timing conditions. Although iso-octane is inherently low reactivity, it still demonstrated strong combustion performance when appropriately injected. Among the tested conditions, the post10 condition resulted in the lowest MBP of 0.603 MPa, due to insufficient premixing. As the injection timing was progressively advanced into the pre-injection domain, both MBP and TBT showed substantial improvement. The multi-pre10 condition yielded the highest MBP of 0.674 MPa, representing an 11.8% increase compared to post10. Meanwhile, the TBT decreased from 89.9 ms (post10) to 73.6 ms (pre10) and further to 71.2 ms (pre20), corresponding to an 18.0% and 20.8% reduction, respectively.

Figure 10 presents the HRR of iso-octane under various injection conditions. Pre-injection strategies, particularly multi-pre10 and multi-pre20, demonstrate significantly earlier HRR onset and sharper peak shapes. The maximum HRR increased from 134.9 J/ms in the post10 case to 181.9 J/ms in pre10 and 168.7 J/ms in pre20, corresponding to an increase of 34.8 % and 25.1%, respectively. Additionally, the time to peak HRR advanced from 56.8 ms in post10 to 47.6 ms in pre10 and 42.8 ms in pre20, representing time reductions of 16.2% and 24.7%, respectively. These features reflect faster energy release and improved combustion phasing, enabled by better fuel-air mixture formation near the ignition site. The results highlight the critical role of pre-injection in promoting rapid and robust flame development under multi-injection strategies.

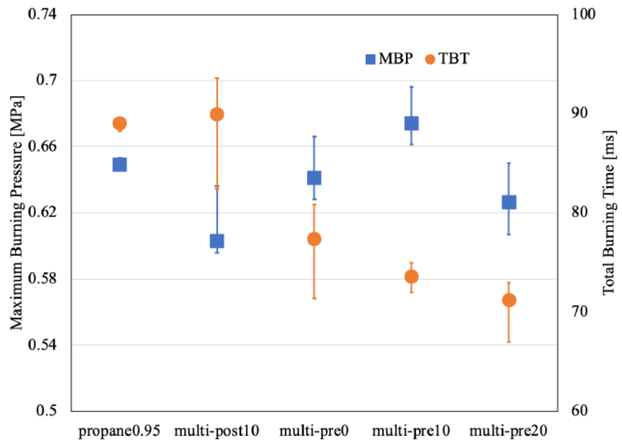

Fig. 9. Maximum burning pressure (MBP) and total burning time (TBT) of iso-octane under multi-injection with different injection timing conditions

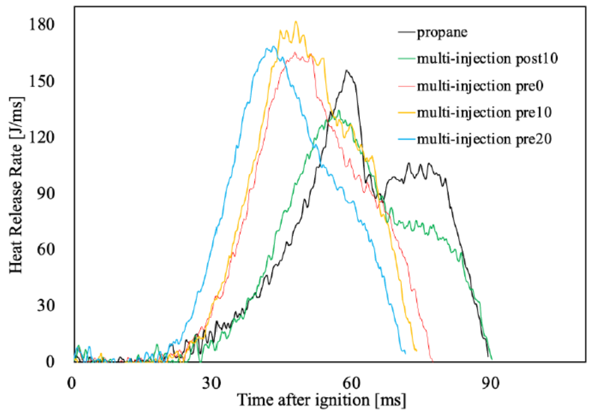

Fig. 10. Heat release rate (HRR) of iso-octane under multi-injection with different injection timing conditions

Figure 11 presents the MFB 1% duration and THR of iso-octane under various injection strategies. The shortest MFB 1% duration was observed under the multi-pre20 condition, indicating a more rapid combustion onset, which corresponds to previous results. Across all pre-injection strategies, THR values remained consistently above 4.5 kJ. Notably, the multi-pre10 case exhibited the highest THR of 4.9 kJ. The THR of the multi-pre10 condition slightly exceeds that of the propane baseline. While the total fuel-air equivalence ratio was maintained, this may be attributed to improved local fuel-air mixing near the ignition kernel, reduced wall heat loss, and more complete combustion under the multi-injection strategy.

These results highlight that the pre-injection strategy, when combined with multi-injection, is particularly effective for low-reactivity fuels. Compared to post-injection, it increased the maximum combustion pressure by up to 11.8% and reduced the total burning time by up to 20.8%, demonstrating substantial improvement in both combustion intensity and speed.

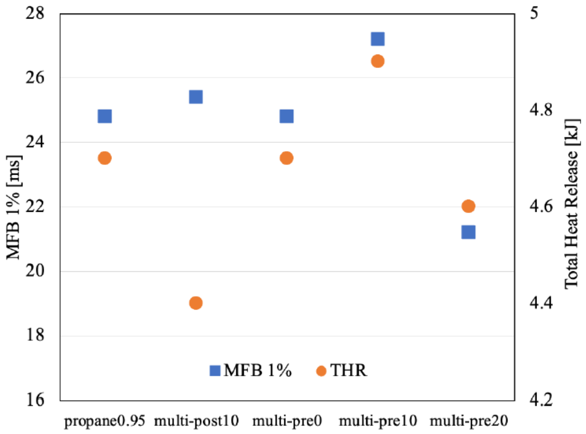

Fig. 11. Mass fraction burned duration (MFB 1%) and total heat release (THR) of iso-octane under multi-injection with different injection timing conditions

4. Conclusion

In this study, a novel multi-injection strategy was proposed and experimentally evaluated in a constant volume combustion chamber. By integrating a third, centrally located injector into a conventional impinging injection system, this approach aimed to enhance fuel atomization, improve mixture formation, and optimize combustion characteristics for fuels with varying reactivities. Two representative fuels, n-hexadecane and iso-octane, were selected to assess the effectiveness of the strategy under both high- and low-reactivity conditions. The key findings are summarized as follows:

1. Spray atomization was significantly improved with the multi-injection approach, leading to a 60.7% reduction in Sauter mean diameter (SMD) with low-viscosity fuel under identical total injection duration compared to the conventional impinging injection. In contrast, spray atomization of the high-viscosity fuel was barely affected by the multi-injection strategy. Nevertheless, when combined with optimal injection timing, a shortened total injection duration in multi-injection resulted in a shorter total burning time.
2. For high-reactivity fuel (n-hexadecane), compared to conventional impinging injection, the multi-injection strategy with pre-injection accelerated the start of combustion, as indicated by a 36% decrease in MFB 1% timing, and 18.9% increase in the maximum heat release rate. The total heat release was also increased by 4.7%, along with a 22.3% decrease in total burning time, suggesting that multi-injection with pre-injection conditions contributes to reducing the proportion of incomplete combustion and enhancing flame propagation.
3. For the low-reactivity fuel (iso-octane), the multi-injection strategy significantly improved combustion characteristics, particularly under the pre10 condition. Compared to the conventional propane case, multi-pre10 increased the maximum burning pressure by 3.9%, the maximum heat release rate by 16.8%, and the total heat release by 4.3%. In addition, the total burning time was shortened by 17.3%. These improvements suggest that pre-injection with multi-injection effectively promoted flame propagation and reduced heat losses, even for low-reactivity conditions.

Nomenclature

APFI	advanced port fuel injection
CO	carbon monoxide
DI	direct injection
DISI	direct injection spark ignition
EPA	Environmental Protection Agency
GDI	gasoline direct injection
GHG	greenhouse gas
HC	hydrocarbon
HRR	heat release rate
LDSA	laser diffraction spray analyzer
MBF	mass fraction burned
MBP	maximum burning pressure
NHTSA	National Highway Traffic Safety Administration
NOx	nitrogen oxides
PFI	port fuel injection
PM	particulate matter
PN	particle number
SMD	Sauter Mean Diameter
TBT	total burning time
THR	total heat release
UHC	unburned hydrocarbon

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