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Original Paper

Application of JP-5 in a CRDI diesel engine with various fuel injection distribution strategy

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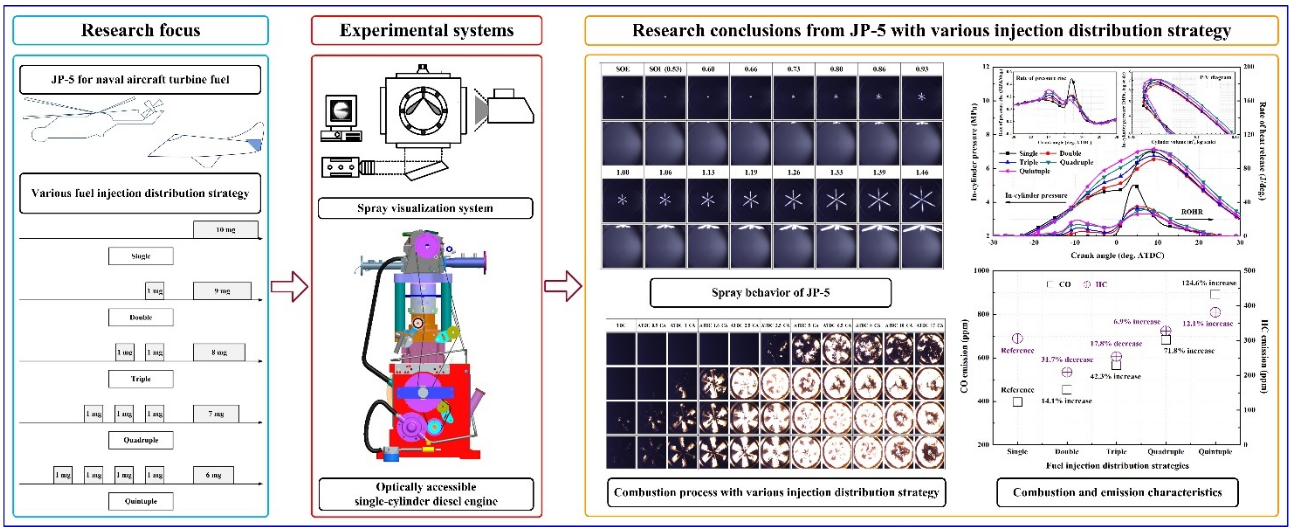
Graphical Abstract:



Abstract: An experimental investigation was performed on an optically accessible single-cylinder common rail direct injection (CRDI) diesel engine and constant volume chamber (CVC) to analyze the spray behavior, and combustion and emission characteristics of jet propellant (JP -5) for naval aircrafts. It was demonstrated that JP-5 had a symmetrical spray pattern in the sac-type injector. Additionally, multiple pre-injections shortened the ignition delay of the main injection, and improved the engine performance and combustion efficiency. The production of CO emission significantly increased with an increase in the fuel injection distribution. Furthermore, multiple fuel injection caused an increase in HC emission under excessively advanced condition. The production of NOx pollutant was the lowest in the double strategy. However, it increased with an increase in the number of injections. The combustion visualization images demonstrated that the single injection strategy had a typical premixed combustion flame and the diffusion combustion flame of the main injection was detected in the multiple injection strategy.

Keywords: Spray, Combustion, Emission, JP-5, Fuel injection distribution, Multiple injection

Abbreviations

CO	Carbon monoxide
CVC	Constant volume chamber
IMEP	Indicated mean effective pressure
CFPP	Cold flow plugging point
CRDI	Common rail direct injection
GMT	Gas mean temperature
HC	Hydrocarbon
JP	Jet propellant
NOx	Nitrogen oxides
P_{inj}	Injection pressure
ROHR	Rate of heat release
ROPR	Rate of pressure rise
SOE	Start of energizing
SOI	Start of injection
STP	Spray tip penetration

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1. Introduction

The most notable advantage of a diesel engine equipped with electronically controlled injectors and a common rail system is the diversification of fuel injection methods by controlling fuel injection timing, frequency, and pressure. In general, retardation of the fuel injection timing toward the top dead center (TDC) suppresses the rate of heat release (ROHR), resulting in reduction of nitrogen oxide (NOx) emission. In addition, the engine performance improves because the negative work is reduced in the compression stroke process. Lee **[1]** demonstrated that fuel injection distribution strategies such as multi-stage and split injection can enhance the engine performance and reduce harmful emissions such as NOx with the same fuel injection quantity compared with that of single injection strategies. In contrast to JP-8, which is used in land-based military aircraft, the kerosene-based jet propellant (JP-5) is used for naval aircraft turbine fuel. Bae *et al*. **[2]** highlighted that JP-8 as an alternative fuel for compression ignition diesel engines had a shorter spray tip penetration (STP), superior vaporization characteristic, and produced a homogeneous mixture inside the cylinder. A naval ship that

Table 1: Review results for JP-5 and military aviation fuel with various fuel injection distribution strategy

Authors **[#]**	Published year	Main contents
D.M. Korres *et al*. **[3]**	2008	· NOx characteristics from JP-5 and biodiesel blended fuels on single-cylinder diesel engine. · The addition of biodiesel to diesel fuel leads to increase NOx emission. · Reduction in NOx emission observed from JP-5 blended diesel fuel up to 40% by volume. · It was emphasized that NOx emission strongly depend on the engine type, experimental condition, and measurement technology in this paper.
K. Yehliu *et al*. **[4]**	2010	· Emission characteristics from biodiesel on turbocharged diesel engine under constant injection timing condition with single and split injection strategy. · Reduction of NOx emission was observed when the split injection strategy is applied instead of the single injection strategy.
J. Lee *et al.* **[5, 6]**	2011 2012	· Performance and emission characteristics from JP-8 in a heavy-duty diesel engine with valve covered orifice (VOC) nozzle. · JP-8 has abnormal asymmetric spray behavior from VOC nozzle unlike sac-type injector. · JP-8 show shorter spray tip penetration by superior evaporation rate and longer ignition period by lower cetane number compared to diesel fuel. · Remarkable increase in NOx and HC emission was observed from JP-8. · JP-8 has weaker flame luminosity intensity and shorter duration of flame than diesel fuel.
H. K. Suh *et al.* **[7]**	2011	· The improvement of combustion and emission characteristics from multiple injection strategies in a low compression diesel engine. · Peak in-cylinder pressure with multiple injection was increased to the level of single injection. · IMEP representing with combustion efficiency when multiple injection applied shows an increase compared to the single injection strategy. · More CO emission was produced from multiple injection strategies, however, significantly reduction of NOx emission is observed.
M. R. Herfatmanesh *et al*. **[8]**	2013	· Combustion and emission characteristics from two-stage injection in a diesel engine. · Significant interaction is founded between double injections from an electronically injector. · Multiple injection such as double strategy contributes to reduce the heat release rate, consequently suppresses NOx formation.
K. Cung *et al.* **[9]**	2015	· Spray-combustion interaction of multiple injection strategy on diesel engine condition. · Ignition delay of main combustion flame is increased as dwell period between multiple injection is extended.
J. Lee *et al.* **[10]**	2015	· Emission reduction potential from JP-8 in a light-duty diesel engine. · JP-8 has later combustion phase than diesel fuel under constant injection strategy condition. · More NOx emission is observed due to fuel conversion efficiency gradually recovers as injection timing moves to advanced region · NOx formation minimized by suppressed heat release rate when using multiple injection strategy.
K. Mathivanan et al. **[11]**	2016	· Performance and combustion characteristics with multiple injection strategies in a homogeneous charge compression ignition (HCCI) engine. · Thermal efficiency with multiple injection is higher than that of single injection mode. · Less HC was observed with multiple injection, NOx emission is slightly elevated in HCCI engine.
S. Park *et al*. **[12]**	2018	· Combustion and emission characteristics from various split injection strategies in a single-cylinder diesel engine. · Longer injection dwell time caused a decrease of the IMEP and an increase NOx formation including HC production. · Experimental investigation shows that shorter injection period between split injection strategies and not excessive high injection pressure conditions should be considered to improve combustion and emission characteristics.
H. Park *et al*. **[13]**	2019	· Application of multiple injection strategies to improve diesel combustion under cold-start conditions. · Pilot injection is powerful tool to vaporize following main injection at low temperature because of its small amount of heat release. · Multiple injection strategies such as double, triple, quadruple contributes to improve the combustion process at low temperature condition. · In addition, it was emphasized that triple injection strategy contributes to improve the combustion quality under diesel cold-start conditions.

carries naval aircrafts typically stores two types of fuels. The first type is a diesel fuel used for propulsion and power generation of naval vessels and the second type is JP-5, which is used in naval aircrafts. The physicochemical properties of JP-5 such as density, viscosity, and cetane number are inferior compared with that of diesel fuel. These characteristics prolong the ignition delay to ensure that the ROHR in the premixed combustion stage is rapidly increased. Cold flow plugging point (CFPP) of JP-5 is advantageous for an engine operating in an intense cold temperature environment. If a naval vessel storing diesel fuel and JP-5 were to perform a mission in an extremely low temperature field, using JP-5 as a single fuel might be a reasonable alternative. The utilization of JP-5 in a diesel engine equipped with a common rail system and electronically controlled injectors has not been extensively studied compared with that of JP-8. Therefore, to utilize JP-5 in diesel engines, various studies such as spray behavior, combustion and emission characteristics analysis are required.

Table 1 summarizes the review of the research results from the application of diesel engines and the diversification of injection methods with JP-5 and military aviation fuel. This study was conducted on an optically accessible common rail direct injection (CRDI) single-cylinder diesel engine and constant volume chamber (CVC) to analyze the spray behavior, combustion, and emission characteristics of JP-5. The fuel injection distribution strategy applied in this study was considered as a multiple injection strategy that combines pre-injection and main injection. The multiple injection strategies were divided into double, triple, quadruple and quintuple, and the experimental results were compared with that of the single injection strategy.

2. Experimental systems

Figure 1 shows the schematic diagram of the test apparatus used to conduct this study. The experimental system consisted of the following main components:

1) An optically accessible CRDI single-cylinder diesel engine (**Table 2**).
2) A 22-kW electric motor (HV2 induction motor, Hyosung) that precisely controls the engine speed.
3) A combustion analyzer (MT-7000S, Mobiltek) including piezoelectric pressure sensors (Type 6056A, Kistler), and an amplifier (Type 5018 Kistler).
4) Sensor-based portable emission analyzer (Testo-350K, Testo)
5) High-speed camera (Fastcam SA3, Photron) for spray and combustion flame visualization.

The fuel was supplied to the test engine for spray behavior visualization. The torque generated by the engine was measured with a torque meter (T8 ECO rotary) coupled with the test engine and the electric motor.

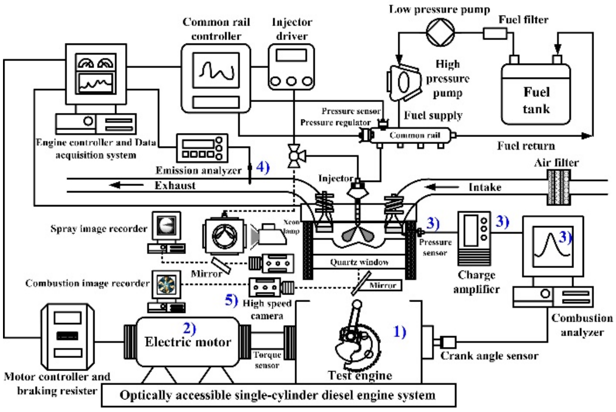

Figure 1: Schematic of the experimental system

Table 2: Specifications for test engine

Item	Descriptions
Engine Type	4-stroke, CRDI
Number of cylinder	1
Bore x Stroke	83 mm × 92 mm
Compression ratio	17.7 : 1
Displacement	498 cc

3. Injection strategy and experimental conditions

The test fuel selected to conduct this study was JP-5, which is used naval aircrafts. The main physiochemical properties of the test fuel are summarized and compared with that of diesel fuel in **Table 3**.

Table 3: Physiochemical properties of test fuel

Properties		Values	
		JP-5	Diesel
Carbon (wt %)		85.80	86.97
Hydrogen (wt %)		14.07	12.64
Density(kg/m^3,15 ^{o}C)		801.0	849.4
Kinematic viscosity (mm^2/s)		1.356	3.621
Cetane number		48.2	52.8
Flash point (^{o}C)		62.0	81.0
Cold flow plugging point (^{o}C)		-35.0 or less	-5
Lower heating value (kJ/kg)		42,950	42,710
Distillation temperature (^{o}C)	10%	190.5	227.5
	50%	205.5	296.4
	90%	233.9	352.8

The fuel injection method is an important strategy that determines the performance and emission levels of diesel engine. In a diesel engine equipped with an electronically controlled injector, the fuel injection distribution strategy considered as multiple injection is an important parameter that affects the diesel engine performance and pollutant levels with the same amount of fuel. The fuel injection distribution strategy used in this study is multiple injection strategy, which is a combination of main injection and per-injection.

Figure 2 shows the concept of the fuel injection distribution strategy used in this study.

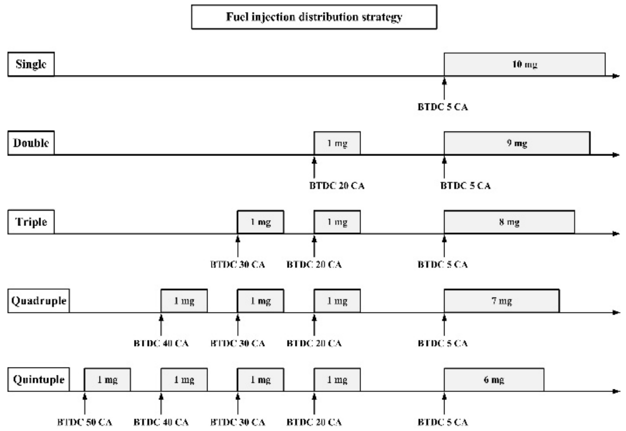

Figure 2: Concept of fuel injection distribution strategy

A high-performance optical lamp was selected to obtain a clear spray behavior image of JP-5. Detailed experimental conditions are shown in **Table 4**.

Table 4: Experimental conditions

Parameters	Descriptions
Spray visualization	
P_{inj}	40 MPa
Ambient pressure (P_{amb})	0.1 MPa
Fuel mass (m_f)	10 mg
Light source	High performance optical lamp
Image record	15,000 frame/second
Combustion visualization	
Image record	16,000 frame/second
Light source	Natural luminosity
Combustion and emission analysis with test engine	
Engine speed	1100 rpm
P_{inj}	40 MPa
Total fuel mass	10 mg
Coolant temperature	70 °C
Measurement of cycle	500
Fuel injection distribution strategy	
Single	Presented in Figure 2
Double	
Triple	
Quadruple	
Quintuple	

4. Results and discussions

4.1 Spray behavior characteristics

Figure 3 depicts the spray behavior of JP-5 using the high-speed camera in the CVC. The start of energizing (SOE) of the injector and the beginning of recording of the high-speed camera were synchronized to analyze the precise spray behavior. Fuel injection started at 0.53 ms after SOE and it showed a symmetrical characteristic as the spray developed. It has been reported to exhibit the characteristics of an asymmetrical spray pattern due to strong turbulence inside the nozzle when a jet fuel with low

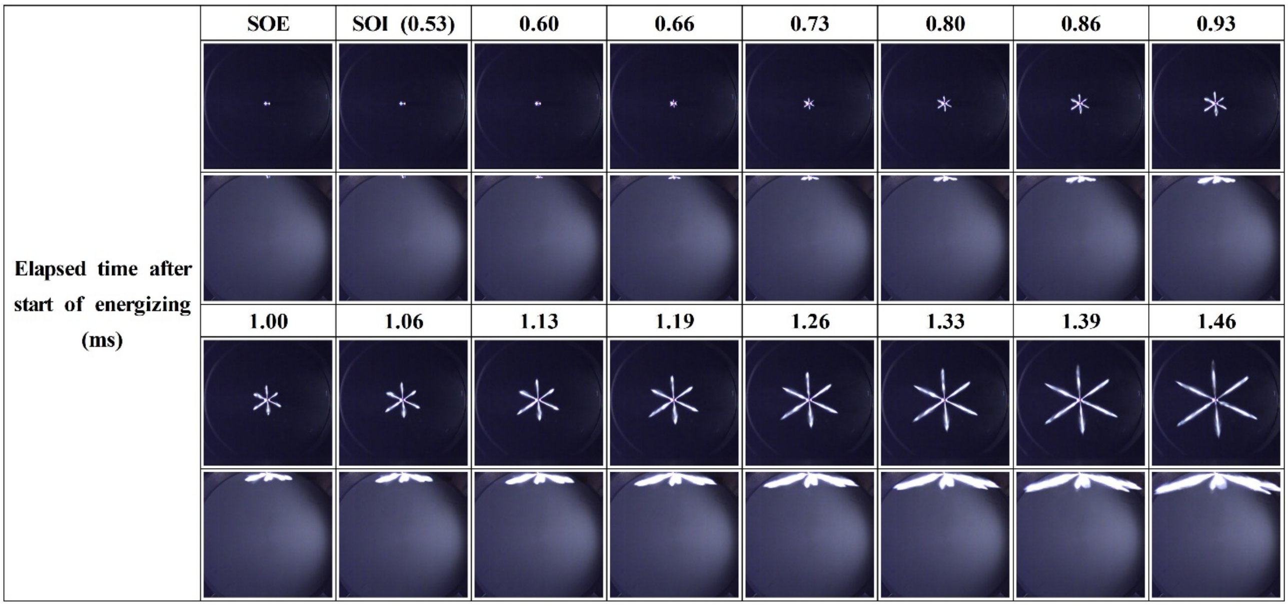

Figure 3: Spray behavior characteristic of JP-5

density, viscosity, and surface tension is used in a valve orifice covered (VOC) type injector. However, the sac-type injector is known to exhibit a symmetrical shape **[14][15]**. The spray droplets disperse with the development of the of JP-5 spray.

JP-5 has a lower density, viscosity, and distillation temperature as shown in **Table 3**. These properties of JP-5 lower the surface tension of the fuel, resulting in uncertainty inside the injector hole. It is hypothesized that the eddy current formed by uncertainty strengthens the spherical diffusion during spray development and results in a wider spray angle including a dispersion of spray droplets. In addition, the lower distillation temperature of JP-5 contributes to the excellent evaporation rate. The superior vaporization of JP-5 might disperse the spray and increase the mixing rate with ambient air **[5][16]**.

Figure 4 shows the results of STP based on images captured using a high-speed camera. The STP has a tendency to increase linearly with the development of the spray.

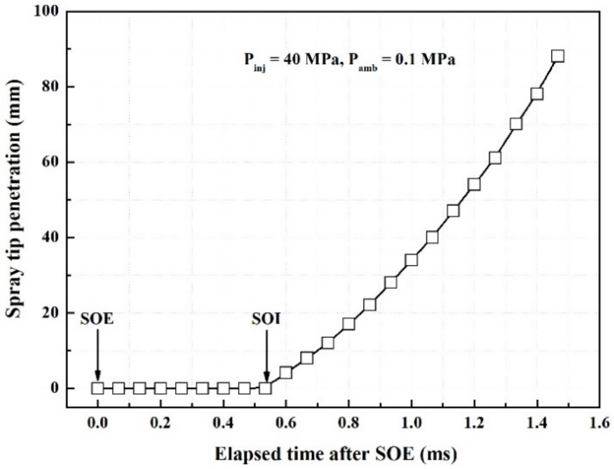

Figure 4: Spray tip penetration characteristic with various fuel distribution strategy

4.2 Combustion and emission characteristics

Figure 5 represents the effects of various fuel distribution strategies on in-cylinder pressure, ROHR, rate of pressure rise (ROPR), and P-V diagram.

It can be observed that the in-cylinder pressure, ROHR, and ROPR increase rapidly due to the strong premixed combustion intensity in the single injection strategy when only the main injection was applied. The in-cylinder pressure, ROHR, and ROPR rise gently in the multiple injection strategy as the fuel injection distribution was extended. Heat generation by a small amount of multiple pre-injection in the compression stroke process increased the in-cylinder pressure and temperature.

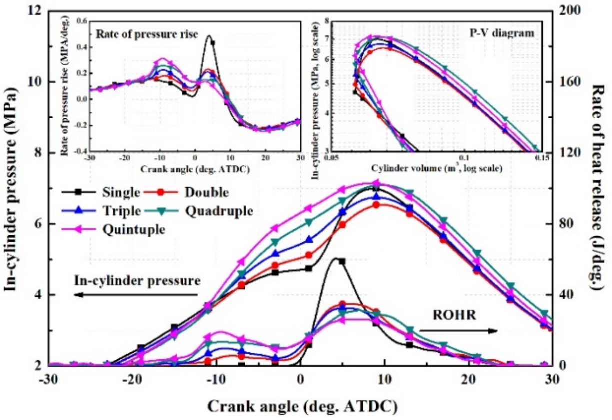

Figure 5: In-cylinder pressure, ROHR, ROPR, and P-V diagram characteristics with various fuel distribution strategy

Therefore, the mixture formed before the main injection transformed into a richer mixture. The premixed rich mixture shortened the ignition delay of the main injection, suppressed the ROHR of the main injection, and lowered the premixed combustion intensity.

Figure 6 shows the peak in-cylinder pressure and ROHR. The peak ROHR decreased because the amount of fuel in the main injection decreased and ROHR was suppressed.

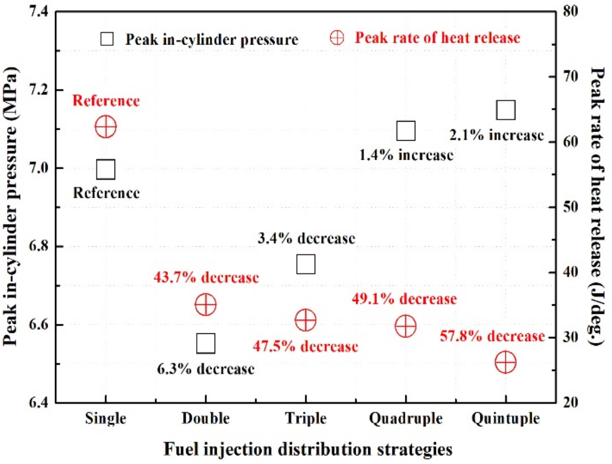

Figure 6: Peak in-cylinder pressure and ROHR characteristics with various fuel distribution strategy

A significant reduction of ROHR (by 57.8%) was observed in the quintuple strategy compared with that of single injection mode. In the double and triple injection strategy, the peak in-cylinder pressure was decreased by 6.3% and 3.4%, respectively. The quadruple and quintuple strategies showed an increase in the peak in-cylinder pressure. This can be explained from result of the continuous combustion of the rich mixture formed by the multiple pre-injection. IMEP used as a representative factor of combustion quality is closely related to combustion efficiency, which is defined as the ratio of fuel chemical energy and actual heat release.

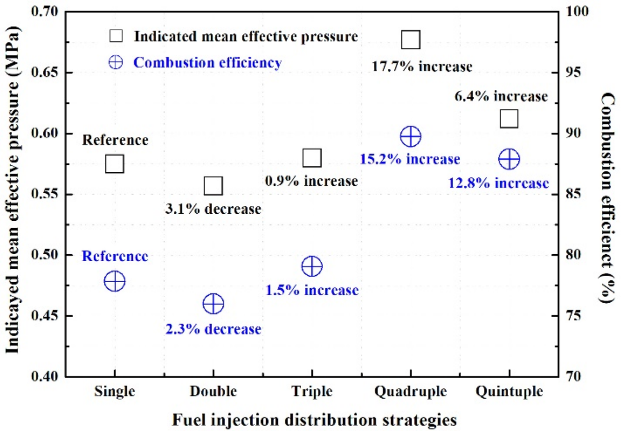

Figure 7: IMEP and combustion efficiency characteristics with various fuel distribution strategy

It can be observed in **Figure 7** that the IMEP decreased by 3.1% in the double strategy. However, it increased from the triple strategy. It can be observed from the P-V diagram in **Figure 5** that this is because the in-cylinder pressure slightly increased during the expansion stroke compared with that of the single injection strategy. Therefore, it can be concluded that the multiple injection strategy has a positive effect on the improvement of combustion efficiency.

Figure 8 shows the results that support this conclusion. An increase in the fuel injection distribution improved the fuel conversion efficiency, which is defined as the ratio of the fuel chemical energy and power, resulting in enhancement of engine performance.

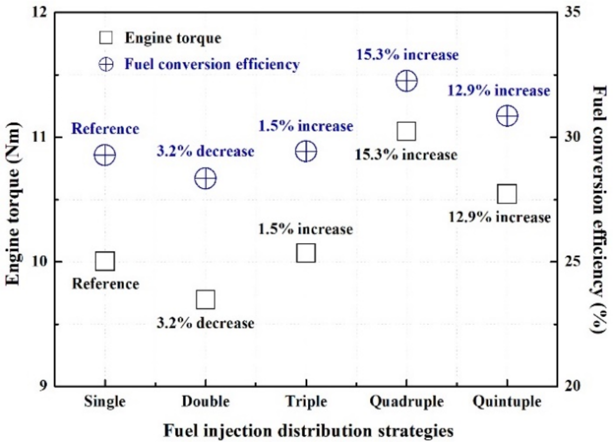

Figure 8: Engine torque and fuel conversion efficiency characteristics with various fuel distribution strategy

Figure 9 shows CO and HC emissions with the fuel injection distribution strategy. The heat released from the main injection decreased with an increase in the number of multiple pre-injections. In addition, low-temperature combustion such as incomplete combustion occurred resulting in lower CO oxidation rate. An increase in the number of pre-injections resulted in higher HC emission. A greater amount of HC was produced from the quadruple strategy than that of the single-injection strategy. Pre-injection improved the combustion quality of the main injection and reduced the amount of unburned HC. However, pre-injection in excessively advanced condition resulted in cylinder wall wetting and seeping of spray droplets into the crevice volume. These reasons were noted as a cause for increase in the unburned HC production.

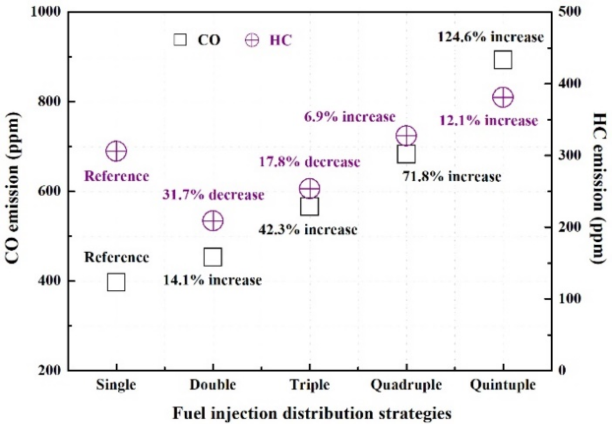

Figure 9: CO and HC emission characteristics with various fuel distribution strategy

Figure 10 shows NOx and peak gas mean temperature (GMT) results with various fuel injection distribution conditions.

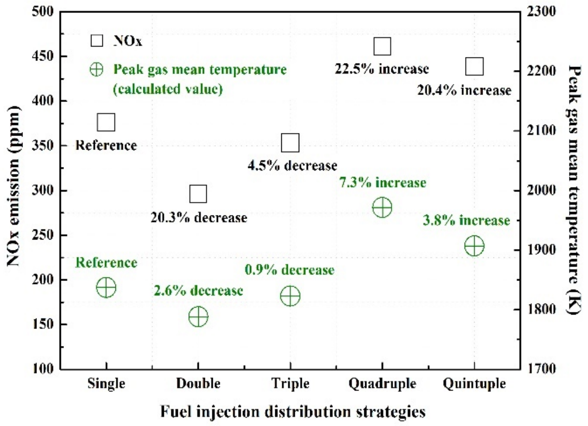

Figure 10: NOx and GMT characteristics with various fuel injection distribution strategy

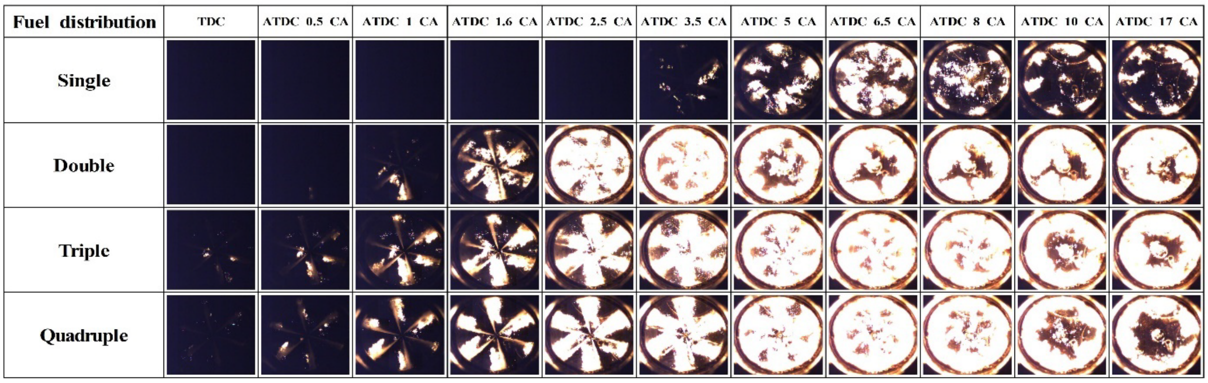

Figure 11: Combustion flame process with various fuel injection distribution strategy

In general, NOx is considered as thermal NOx, which is formed in the region where the combustion gas temperature is high. The following formula was applied to calculate the combustion gas temperature **[17][18]**.

$$T(\theta) = \frac{P(\theta)V(\theta)}{m_{intake}R} \tag{1}$$

$$m_{intake} = v_l \rho_{air} V_{IVC} \tag{2}$$

$$v_l = \frac{1}{2}\left\{sin\left[360\left(\frac{\theta}{\theta_{vod,intake}} - \frac{1}{\theta_{vod,\frac{intake}{exhaust}}\theta_{\frac{IVO}{EVO}}} - \frac{1}{4}\right)\right] + 1\right\} \tag{3}$$

Here, P(θ), V(θ), and T(θ) are the in-cylinder pressure, volume, and temperature at crank angle, respectively. m_{intake} is the mass of air inside the cylinder at intake valve closing, ρ_{air} is the air density, V_{IVC} is the cylinder volume at intake valve closing, v_l is the function of valve lift, $\theta_{vod,intake}$ is the intake valve opening duration, $\theta_{vod,exhaust}$ is the exhaust valve opening duration, θ_{IVO} and θ_{EVO} are the intake valve opening angle and exhaust valve opening angle, respectively. Although the peak ROHR of the multiple injection strategy was lower than that of the single injection strategy, it can be confirmed that peak in-cylinder pressure was similar or higher with an increase in the number of injections. Continuous combustion by pre-injection extension in the multiple injection strategy resulted in higher in-cylinder pressure and temperature. The production of NOx was decreased by 20.3% in the double injection strategy and was increased by 22.5% in the quintuple injection strategy.

4.3 Combustion visualization

Figure 11 shows combustion process images with various fuel injection distribution conditions. The ignition delay of the single injection strategy was longer than that of the multiple strategy based on the luminosity of the flame. The combustion pattern of the single injection strategy was similar to that of a typical premixed combustion. The ignition delay of the main injection became shorter and the flame spread in the form of diffusion combustion with an increase in the number of pre-injections in the multiple injection strategy. The ROHR of the single injection strategy rapidly dropped after ATDC 6.5 CA compared with that of the multiple injection strategy, and it can be observed that the combustion flame disappeared quickly during the expansion stroke.

5. Conclusions

An experimental investigation was conducted to analyze the combustion and emission characteristics including spray behavior visualization by applying various injection distribution strategies on an optically accessible CRDI single-cylinder diesel engine and constant volume chamber. The following conclusions were obtained from the experimental results:

1) The sac-type injector had a symmetrical spray behavior. The lower distillation temperature of JP-5 resulted in a higher evaporation rate and dispersed the spray droplets. The superior vaporization characteristic of JP-5 enhanced the air-fuel mixture formation.
2) Multiple pre-injection shortened the ignition delay of the main injection and suppressed the ROHR. As the fuel injection distribution extended, the peak in-cylinder pressure and engine performance were increased. Combustion efficiency, which is defined as the ratio of fuel chemical energy and actual heat release, and fuel conversion efficiency calculated as the ratio of the fuel chemical energy, and power were improved compared with that of single injection strategy.
3) A significant production of CO was observed by low-temperature combustion and lower oxidation rate with multiple injection. Greater unburned HC pollutants were

generated due to cylinder wall wetting and the seeping of spray droplets into the crevice volume under excessively advanced condition. The production of NOx was proportional to the peak combustion gas mean temperature. The amount of NOx produced was the lowest in the double strategy and it gradually increased with multiple injection.

4) It was confirmed from the luminosity combustion flame images that the ignition delay became shorter with an increase in the number of pre-injections. In the single injection strategy, a typical premixed combustion process by rapid ROHR was detected, and the combustion flame of the main injection exhibited a typical diffusion combustion process with a gently lasting ROHR in the multiple injection strategy.

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Author Contributions

This research presented in this paper was wholly contributed by the author.

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