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Original Paper

Effects of multiple uniformity split injection strategies on combustion and exhaust emission characteristics in a single-cylinder diesel engine

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Abstract: This study focuses on analyzing the effects of multiple uniformity split injection strategies on combustion and exhaust emission characteristics under idle conditions in a single-cylinder diesel engine. The multiple uniformity split injection strategies were divided into double, triple, quadruple, and quintuple injections. In addition, the combustion and exhaust emission characteristics were compared with a single injection strategy. Combustion characteristics, such as maximum in-cylinder pressure, maximum rate of heat release (ROHR), maximum rate of pressure rise (ROPR), and maximum in-cylinder temperature, were all shown to have decreased as the number of split injections increased, compared with those for a single injection strategy. The indicated mean effective pressure (IMEP) and engine torque representing the engine performance were lowest for double injection, compared to single injection. The coefficient of variation of the IMEP (COV_{IMEP}), which is the representative index of combustion stability, was lowest under quadruple injection conditions. In all multiple uniformity split injection conditions, NO_x emission levels were reduced by up to 83.9% owing to a suppression of the rate of heat release and low temperature combustion. The CO_2 emission levels were also lower, whereas the CO and HC emission levels were higher compared to the single injection strategy. However, the CO_2, CO, and HC levels all increased with increasing evenly divided injections.

Keywords: Multiple uniformity spilt injection, Exhaust emission, Combustion characteristic, Engine performance, Combustion stability

Abbreviations

ABDC	after bottom dead center
ATDC	after top dead center
BBDC	before bottom dead center
BTDC	before top dead center
CO	carbon monoxide
CO_2	carbon dioxide
COV_{IMEP}	Coefficient of variation of IMEP
CRDI	Common rail direct injection
EVC	exhaust valve closing
EVO	exhaust valve opening
IMEP	indicated mean effective pressure
HC	hydrocarbon
IVC	intake valve closing
IVO	intake valve opening
m_f	fuel injection mass
MFB	mass fraction burned
MPa	mega Pascal
NO_x	nitrogen oxides
O_2	oxygen
P_{inj}	Injection pressure
ROHR	rate of heat release
ROPR	rate of pressure rise
rpm	revolution per minute
SOE	start of energizing
vod	valve opening duration

1. Introduction

Diesel engines are widely used in automobiles, trucks, ships, and naval vessels because of their higher thermal efficiency, large power output, reliability, and fuel economy, as compared to other engines. In particular, diesel engines equipped with electronically controlled common rail fuel systems can be applied using different fuel injection strategies, depending on various engine operating conditions **[1]-[3]**.

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Despite these advantages, NO_x emissions generated from diesel engines have a negative impact on human health and the atmospheric environment. To minimize these negative effects, several studies have focused on injection strategies, such as fuel injection timing, split injection, and fuel injection pressure control, in diesel engines equipped with common rail fuel injection systems **[4]-[6]**.

The most obvious way to reduce NO_x in diesel engines is to lower the combustion temperature. To reduce the combustion temperature in diesel engines without exhaust gas recirculation (EGR), it is necessary to lower the intensity of premixed combustion by reducing the ignition delay period **[7]**.

As the fuel injection timing undergoes retardation towards the top dead center (TDC), the ignition delay reduces. This is because, during fuel injection, the in-cylinder temperature is increased. Thus, the premixed combustion intensity is reduced during initial combustion, and the combustion temperature is lowered, thereby reducing the amount of NO_x generation. However, the combustion noise is disadvantageous in the single injection condition. Therefore, to reduce NO_x emissions, a split injection strategy can be employed to offset the disadvantages arising from the single injection strategy **[8]-[9]**.

Split injection strategies are considered as a highly attractive method for the optimization of combustion and emissions in diesel engines using common rail fuel injection systems, because they do not require engine modifications or additional costs. Split injection extends the reaction region between air in the combustion chamber and the combustion flame by dividing the main injection quantity into two or more injections **[10]-[11]**.

Therefore, reducing the distribution of the fuel rich region in the combustion chamber and shortening the ignition delay reduces the rate of heat release and also lowers the overall combustion flame temperature. These parameters have a positive effect on the reduction of NO_x emissions **[12]-[13]**.

In this regard, this research applies various uniformity split injection strategies in the region where the highest NO_x emissions are generated, during a single injection timing experiment. In addition, the exhaust emissions of CO, HC, and CO_2 were analyzed. The multiple split injection strategies studied were double, triple, quadruple, and quintuple injections. The experiments were performed by evenly dividing the amount of fuel applied in the single injection test.

2. Experimental system and injection strategies

2.1 Experimental system

Figure 1 shows a schematic diagram of the experimental system for analyzing the effects of multiple uniformity split injection strategies on combustion and exhaust emissions in a common rail direct injection (CRDI) diesel engine.

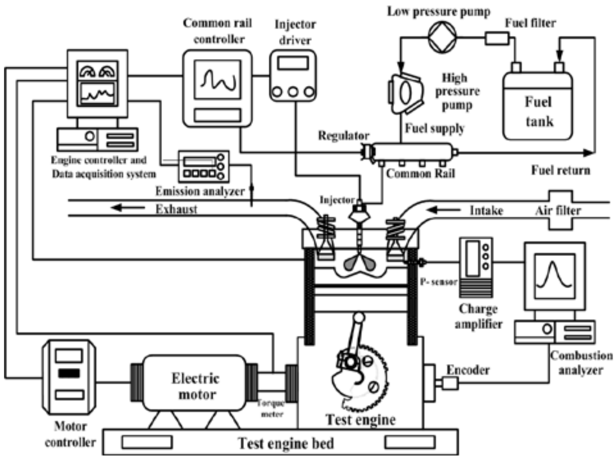

Figure 1: Experimental system for multiple uniformity split injection strategy system

The experimental system comprises a CRDI diesel engine, a 22-kW electric motor for controlling the test engine speed, a combustion analyzer, an exhaust gas analyzer, and a fuel injection control system. The swept volume of the single-cylinder diesel engine used in the experiment is 0.498 L. The CRDI diesel engine can control fuel injection electronically and also enable high pressure injection. The speed of the test engine is precisely controlled using a 22-kW electric motor; however, its torque is not controlled. The torque generated from the engine is measured using a torque meter mounted between the engine and the electric motor. The energy delivered to the electric motor via combustion is consumed by a braking resistor coupled with the electric motor controller. The in-cylinder pressure is continuously measured using a piezoelectric combustion pressure sensor (Kistler, 6056A) coupled with a charge amplifier (Kistler, Type 5018) for 500 consecutive engine cycles. A gas sensor-based emission analyzer (Testo-350K) equipped with a detachable control unit is used to measure NO_x, O_2, CO_2, CO, and HC in the exhaust gas. Fuel injection parameters such as injection pressure, injection timing, and injection energization time are controlled using a LabVIEWbased programmed injector driver (Zenobalti CO., ZB-5100).

Detailed test engine and exhaust gas analyzer specifications are listed in **Table 1**.

Table 1: Specifications for test engine and emission analyzer

Item		Descriptions
Single-cylinder diesel engine		
Engine Type		4-stroke, CRDI
Number of cylinder		1
Bore × Stroke		83 mm × 92 mm
Compression ratio		17.7 : 1
Displacement		498 cc
Number of valve		2-Intake, 2-Exhaust
Valve timing	IVO	BTDC 7°
	IVC	ABDC 43°
	EVO	BBDC 52°
	EVC	ATDC 6°
Emission analyzer		
Model		Testo-350K
Measuring range	O_2	~ 25 vol%
	CO_2	~ 50 vol%
	CO	~ 10,000 ppm
	HC	100 ~ 18,000 ppm
	NOx	~ 40,000 ppm

2.2 Multiple uniformity split injection strategies

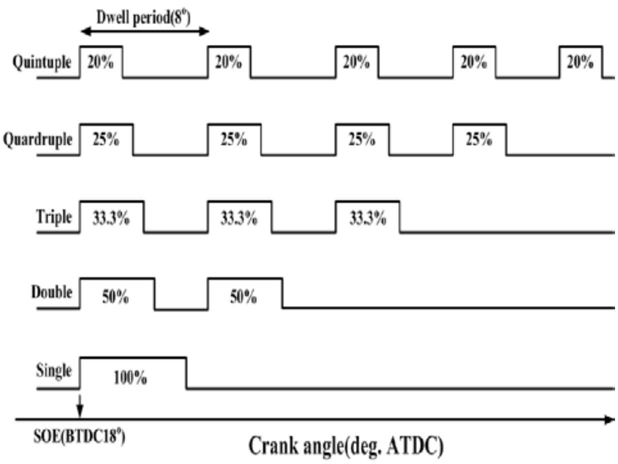

Figure 2: Concept of multiple uniformity split injection strategy

The multiple uniformity split injections applied in this study were double, triple, quadruple, and quintuple injections. In all the tests, the engine speed was precisely maintained at 1,000 rpm, fuel injection pressure was maintained at 40 MPa, and coolant temperature was maintained at 70 °C. In multiple uniformity split injections, the amount of fuel injection was determined by dividing the quantity of single injection fuel evenly between the number of injections being studied. **Figure 2** indicates the concept of multiple uniformity split injection strategies applied in this work, and **Figure 3** depicts the NO_x emission levels relative to fuel injection timing based on BTDC 18°, for the single injection timing test.

Table 2 lists the detailed test conditions. In all the tests, the first fuel injection timing was set to BTDC 18°, because the highest NO_x emission levels were generated here in the single injection timing test.

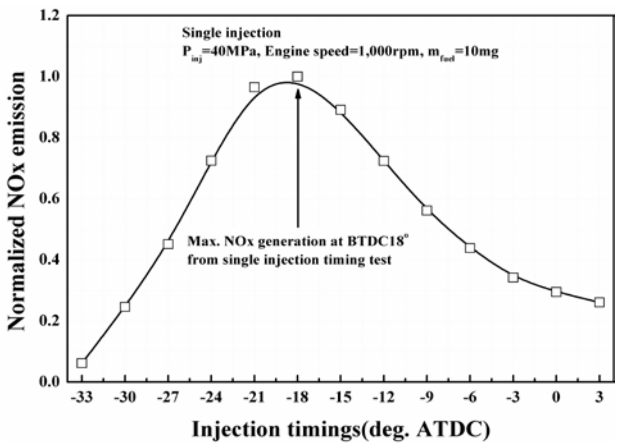

Figure 3: Normalized NOx emissions relative to single injection timings

Table 2: Experimental conditions

Parameters		Descriptions
Engine speed		1,000 rpm without load (Idle)
Fuel injection pressure		40 MPa
Coolant temperature		70 °C
Single injection		
Injection timing		BTDC 18°
Injection quantity		10 mg (100%)
Multiple uniformity split injection modes		
Double	Timing	BTDC 18°&10°
	Quantity	5 mg + 5 mg
Triple	Timing	BTDC 18°&10°&2°
	Quantity	3.33 mg + 3.33 mg + 3.33 mg
Quadruple	Timing	BTDC 18°&10°&2°&ATDC 6°
	Quantity	2.5 mg + 2.5 mg + 2.5 mg + 2.5 mg
Quintuple	Timing	BTDC 18°&10°&2°&ATDC 6°&14°
	Quantity	2.0 mg+2.0 mg+2.0 mg+2.0 mg+2.0 mg

In addition, a crank angle of 8° was chosen as the dwell time to eliminate the interaction between fuel injections. The fuel used for the test was high sulfur diesel, which is used for naval ship propulsion and power generation in diesel engines. The properties of this test fuel are summarized in **Table 3**.

Table 3: Properties of test fuel

Properties	Values
Fuel type	High sulfur diesel

Carbon (wt %)		86.97
Hydrogen (wt %)		12.64
Sulfur (wt %)		0.025
Density(kg/m^3,15°C)		849.5
Cetane number		52.8
Flash point (°C)		81.0
Pour point (°C)		-27.0
Water (wt%)		0.002
Lower heating value (kJ/kg)		42,710
Distillation temperature(°C)	10% recovery	227.5
	50% recovery	296.4
	90% recovery	352.8

3. Results and discussion

3.1 Combustion characteristics

Figure 4 delineates the results of in-cylinder pressure and rate of heat release (ROHR) under the single injection and multiple uniformity split injection conditions. Based on a comparison with multiple uniformity split injections, it is evident that the in-cylinder pressure and ROHR were highest under single injection conditions.

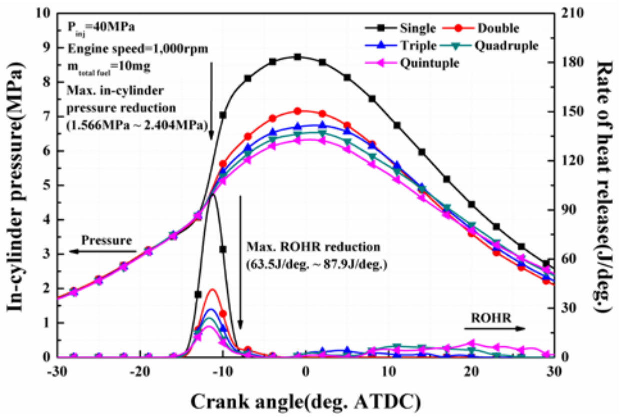

Figure 4: In-cylinder pressure and ROHR characteristics

This is because, under single injection conditions, the premixed combustion intensity was highest as injected fuel was not being ignited immediately, and the fuel accumulated in the compression stroke process was burning rapidly during the ignition delay period. In the case of multiple uniformity split injection conditions, the maximum in-cylinder pressure decreased as the number of evenly divided injections increased, but the in-cylinder pressure tended to increase slightly in the expansion stroke process. This is because a small amount of evenly divided fuel injection timing is retarded toward the TDC and fuel was injected after the TDC and combustion was continuously performed in the expansion stroke process. Compared with single injection conditions, the results showed a decrease in the maximum in-cylinder pressure by up to 2.404 MPa, and the maximum ROHR decreased by up to 87.9 J/deg, as the number of evenly divided injections increased. As the single injection amount was divided evenly, the quantity of fuel burning before TDC decreased and the ignition delay during combustion of the post injection fuel by the pre-injected fuel was shortened. Therefore, ROHR by premixed combustion was suppressed. The tendency for peak in-cylinder pressure and ROHR to decrease is confirmed in **Figure 5**.

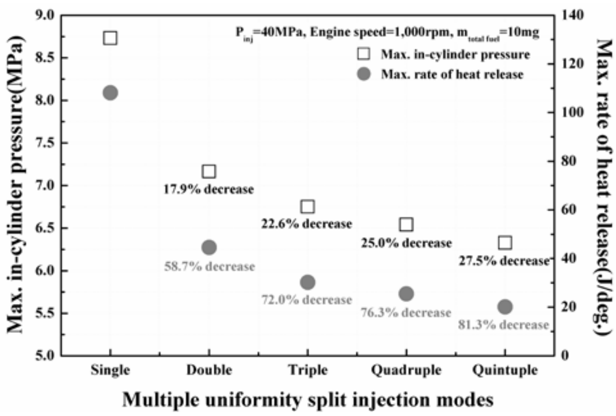

Figure 5: Max. in-cylinder pressure and ROHR characteristics

Figure 6 represents the results of the in-cylinder temperature history in the multiple uniformity split injection conditions. The following **Equation (1)-(3)** was applied to predict the profile of in-cylinder temperature **[14]-[16]**.

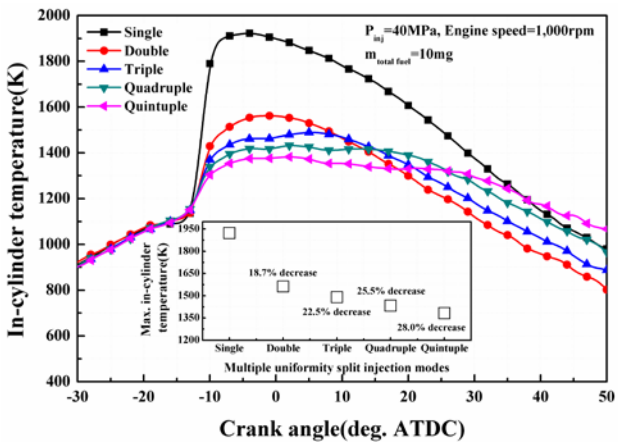

Figure 6: In-cylinder temperature characteristics

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

$$m_{intake} = v_l \rho_{air} V_{IVC} \quad (2)$$

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

Here, P, V, and T are in-cylinder pressure, volume, and in-cylinder temperature, respectively. m_{intake} is intake air mass at intake valve closing, ρ_{air} is air density, V_{IVC} is cylinder volume at intake valve closing, v_l is the function of valve lift, $\theta_{vod,intake}$ is intake valve opening duration, $\theta_{vod,exhaust}$ is exhaust valve opening duration, θ_{IVO} and θ_{EVO} are intake valve opening angle and exhaust valve opening angle, respectively.

The in-cylinder temperature was the highest under single injection conditions where the premixed combustion intensity was the greatest, and the maximum in-cylinder temperature tended to decrease as the number of evenly divided injections increased. However, it can be clearly seen that the in-cylinder temperature during the expansion stroke increases as the number of evenly divided injections increases, with the exception of single injection. This can be explained by the post-combustion of the fuel injected after the TDC, which causes in-cylinder pressure to increase. Increased in-cylinder pressure and temperature during the expansion stroke process resulted in increased IMEP and engine torque.

Figure 7 displays ROPR under multiple uniformity split injection conditions.

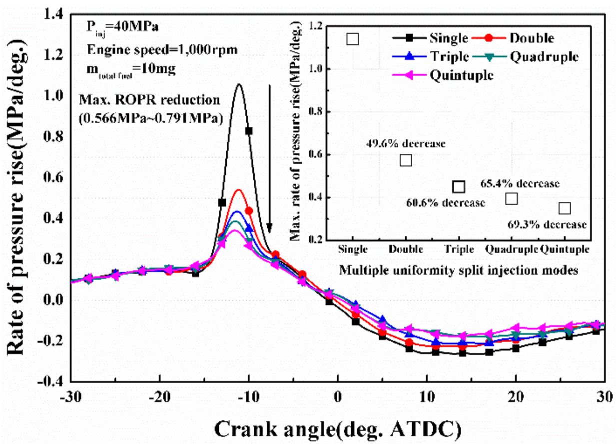

Figure 7: Rate of pressure rise characteristics

From the test results, it can be seen that the ROPR was highest in the single injection strategy with the greatest premixed combustion intensity, and as the evenly divided injections increased, the maximum ROPR dropped from 0.566 MPa to 0.791 MPa when compared to that of single injection. This means that the different premixed combustion intensities, due to the difference in the fuel quantity in the first injection, affected the increase in ROHR. This can be explained by the variation in fuel quantity due to the split injection. As the evenly divided injections were increased, the amount of fuel in the first injection decreased, resulting in a decrease of the premixed combustion intensity. As a result, the ignition delay period decreased, leading to slower ROPR and ROHR. Additionally, under multiple uniformity split injection conditions, as the number of injections was increased, the ROPR gradually declined because the first injection amount of fuel decreased.

Figure 8 indicates the accumulative ROHR and the mass fraction burned (MFB) under multiple uniformity split injection conditions.

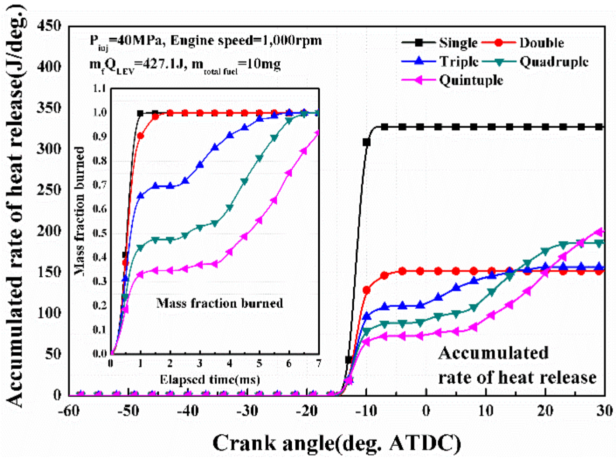

Figure 8: Accumulated ROHR and MFB characteristics

Compared to the single injection strategy, it can be confirmed that as the evenly divided injections increased, MFB occurred more slowly during the combustion period. This can be explained as the result of low temperature combustion because the injected fuel was divided into smaller amounts. The initial MFB decreased as the number of evenly divided injections increased under multiple uniformity split injection conditions, but the accumulative ROHR increase over the combustion period was extended.

3.2 Combustion stability, efficiency and engine performance

IMEP and COV_{IMEP} for multiple uniformity split injections are depicted in **Figure 9**. n all test results, IMEP tended to decrease compared to the single injection strategy. The IMEP decreased by 51.5% under double injection conditions, and IMEP increased as the amount of fuel per injection decreased with increasing injections. In the double injection tests, fuel was injected at BTDC 18° and BTDC 10°. The in-cylinder pressure was found to be lower than the single injection and higher than triple or more injection strategies. The greatest heat release from the first injection in multiple injection strategies was generated during the compression stroke. Thus, negative work occurred in the compression stroke.

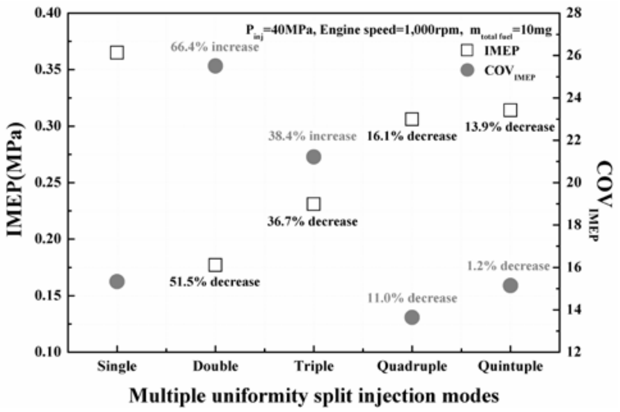

Figure 9: IMEP and COVIMEP characteristics

In addition, there was no further combustion during the expansion stroke under double injection conditions. From triple injection onwards, additional combustion occurred during the expansion stroke after the TDC. Small amounts of heat released by additional fuel injection and combustion promoted positive work after TDC, which caused an increase in IMEP. The higher IMEP, the higher the combustion efficiency, which is defined as the ratio of the fuel's chemical energy to the accumulated ROHR during combustion. The comparison of IMEP characteristics is also possible in a PV diagram. **Figure 10** displays a P-V diagram of the multiple uniformity injection conditions. IMEP is proportional to the area under the curve on the diagram. As the number of evenly split injections increased, the area during the expansion stroke also increased, which is consistent with the IMEP characteristic results in **Figure 9**.

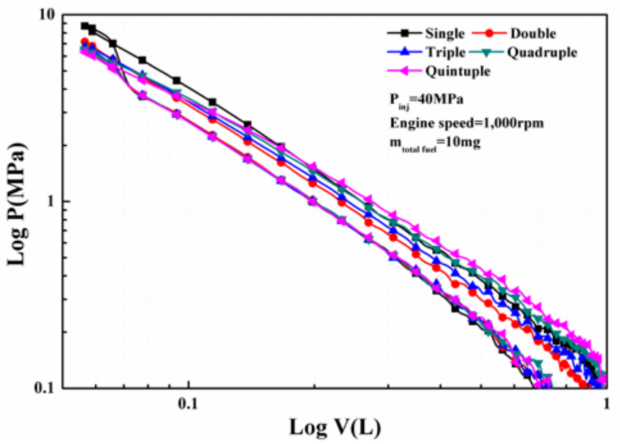

Figure 10: P-V diagram characteristics

The combustion efficiency characteristics under multiple uniformity split injection conditions were verified in **Figure 11**. Compared with the single injection strategy, the COV_{IMEP} increased by 66.4% under double injection conditions, and decreased from triple injection onwards. The low COV_{IMEP} indicates that engine operating conditions were stable. In the case of the quintuple injection condition, COV_{IMEP} was slightly increased. This results in sustained combustion during the expansion stroke, which had a positive effect on the IMEP, but resulted in a slight decrease in engine operation stability.

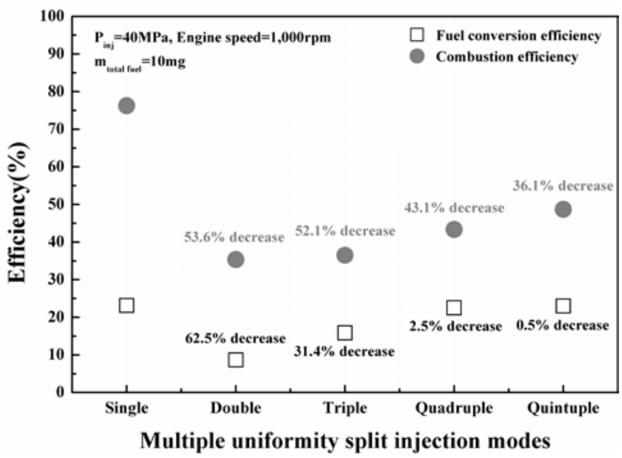

Figure 11: Efficiency characteristics

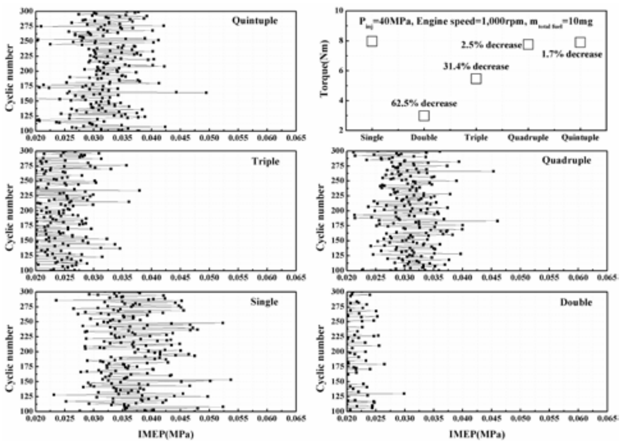

Figure 12: Cyclic IMEP and engine torque characteristics

Figure 12 shows the cyclic IMEP and engine torque characteristics under multiple uniformity split injection conditions. As described above, the combustion efficiency increased as the number of injections increased, likewise it can be seen that the cyclic IMEP increased. The IMEP is a very important variable that plays a decisive role in the change of engine torque, and the engine torque characteristics influenced by the size of the IMEP under the multiple uniformity split injection conditions can be confirmed in **Figure 9**.

3.3 Exhaust emission characteristics

Figure 13 indicates the results of exhaust emissions analyses under multiple uniformity split injection conditions.

In general, NO_x generated from an internal combustion engine is classified as thermal NO_x, and is formed in a region where the combustion gas temperature inside the cylinder is high. In the test results of NO_x emission characteristics for single injection timing in **Figure 3**, NO_x emission decreased as fuel injection timing was retarded based on BTDC 18º. This can be explained as follows. First, as the fuel injection timing was retarded, the ignition delay period was shortened, reducing the ROHR. The shorter ignition delay reduced the intensity of premixed combustion, which led to a decrease in ROHR and a drop in the cylinder temperature. Second, as the fuel injection timing was late, the time for which the high temperature combustion gas remained in the combustion chamber was reduced, and the combustion phase moved to after TDC. Since the intensity of premixed combustion was high under single injection conditions, ROHR also increased and in-cylinder temperature rapidly increased. In addition, since the rapid ROHR occurred during the compression stroke process, the time that the high temperature combustion gas remained in the combustion chamber also increased. As the number of injections increased under multiple uniformity split injection conditions, the intensity of premixed combustion decreased, which caused a lowering of the in-cylinder temperature by suppressing a rapid ROHR. As shown in **Figure 13**, the NO_x emission level tended to decrease as the number of evenly divided injections increased, especially in the quintuple injection test where the NO_x emission level was reduced by 83.9% compared to the single injection test. This is because homogenization of the mixture was facilitated by the split-injected fuel, and the maximum ROHR was reduced by low temperature combustion.

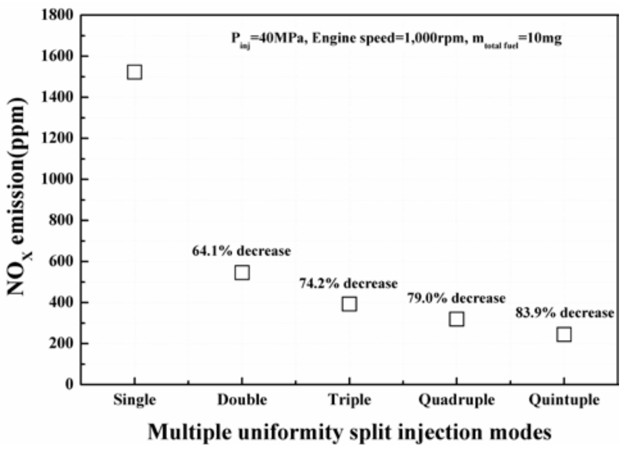

Figure 13: NOx emission characteristics

Figure 14 shows the results of O_2 concentration and CO_2 emission in the exhaust gas.

In the multiple uniformity split injection cases, the oxygen concentration was higher than under single injection conditions, and the oxygen concentration decreased as the number of split injections increased. Higher oxygen concentrations in the exhaust gas mean that there was not enough oxygen participating in the combustion process.

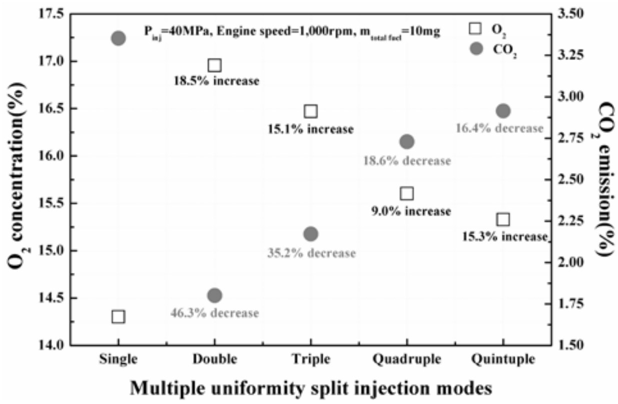

Figure 14: O2 concentration and CO2 emission characteristics

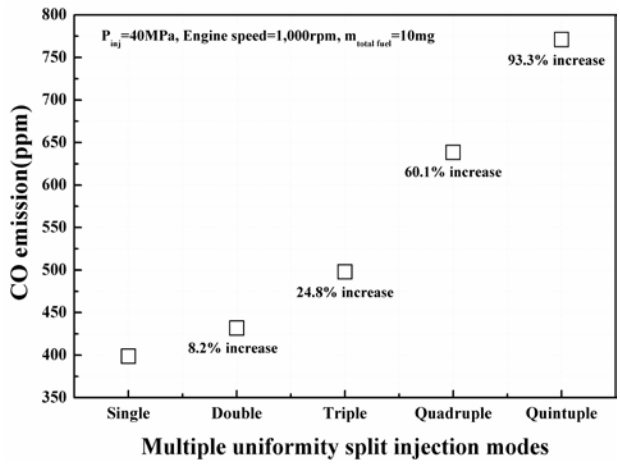

Figure 15: CO emission characteristics

Oxygen was largely consumed under single injection conditions where a great quantity of fuel was injected at one time. In double injection tests, 50% of the single injection quantity is injected twice, but the combustion of fuel from the second injection is not actively carried out by the first combustion. However, since a small amount of fuel was combusted after the TDC from the triple injection onwards, the oxygen concentration in the exhaust gas was reduced. In the case of CO_2 characteristics, the emission level tended to decrease compared to the single injection test, but as the number of evenly divided injections increased, the combustion period became longer and the oxidation reaction of the fuel continued. This caused an increase in CO_2 emissions.

Figure 15 shows the carbon monoxide (CO) emissions in multiple uniformity split injection modes. Compared with the single injection strategy, the CO emission level increased as the number of multiple evenly divided injections increased. As the number of injections increased, the combustion period became longer and the oxygen consumption rate increased, but the oxidation rate of CO decreased because the suppressed ROHR lowered the combustion temperature.

Figure 16 presents the results of hydrocarbon (HC) emissions for multiple uniformity split injection modes.

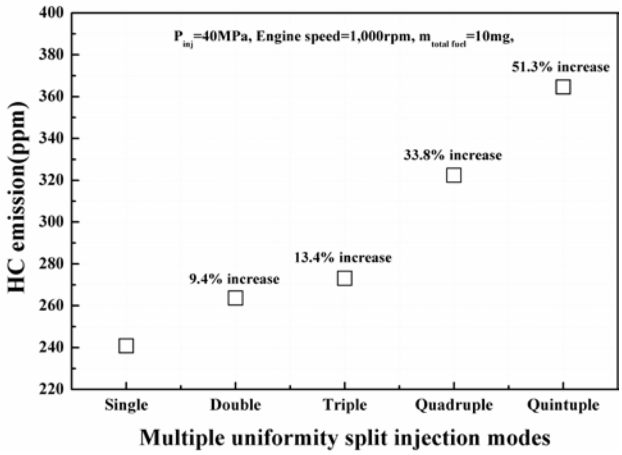

Figure 16: HC emission characteristics

As shown in the CO emission characteristics in **Figure 15**, HC emission levels tended to increase as the number of split injections increased. In multiple uniformity split injection modes, the first injected fuel formed a lean mixture, and premixed combustion was observed in this mixture; but from the second injection, diffusion combustion was more pronounced than premixed combustion. Thus, the leaner mixture remained as unburned hydrocarbons during the combustion process owing to the smaller fuel injection quantity, which caused greater HC emissions as the number of split injections increased.

4. Conclusion

As a result of analyzing the effects of multiple uniformity split injection strategies on combustion and exhaust emission characteristics under idle conditions of a CRDI diesel engine, the conclusions in this research are as follows:

1) As the number of divided injections increased, the maximum in-cylinder pressure, maximum ROHR, maximum ROPR, and maximum in-cylinder temperature decreased. Increasing the number of split injections reduced the intensity of premixed combustion to suppress the ROHR.

2) Compared with single injection, the IMEP was lowest in the double injection strategy, but it increased again as the number of injections increased. Engine torque tended to be in line with the IMEP. The COV_{IMEP}, indicating the combustion stability, was lowest for the quadruple injection strategy. The fuel energy conversion efficiency and combustion efficiency were highest under single injection conditions. In addition, the fuel energy conversion efficiency and combustion efficiency tended to increase as the number of split injections increased.

3) Compared with single injection conditions, NO_x emissions decreased as the number of evenly split injections increased, with the greatest decrease being 83.9% under quintuple injection conditions. This can be explained by the split injection suppressing the generation of NO_x emissions by reducing combustion temperature.

4) As the number of evenly split injections increased, CO and HC tended to increase. Low temperature combustion reduced the rate of CO oxidation. In addition, increasing the number of split injections promoted the production of unburned HC because it formed more lean mixture. Therefore, CO and HC emission levels increased under multiple uniformity split injection conditions when compared to single injection conditions.

Author Contributions

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

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