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Biodiesel, HSD, and JP-8 combustion process and emission characteristics in a dual-stage fuel injection condition

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Abstract: This research was focused on an investigation of the effect of injection dwell time in a dual-stage injection on the combustion and emission characteristics of biodiesel using an optically accessible single-piston diesel engine. In addition, the results from biodiesel combustion and emission characteristics were compared to those of fossil fuels such as HSD and JP-8 using combustion process visualization as well as emission analyzer. Regarding combustion characteristics, JP-8 showed the highest peak in-cylinder pressure and rate of heat release in comparison to biodiesel and HSD because the higher lower heating value and vaporization characteristics of JP-8 improved premixed combustion. However, the IMEP of JP-8 was lower than the corresponding pressure of HSD. From the viewpoint of emissions, biodiesel had reduced emissions of NOx, HC, CO, and CO_2 compared to fossil fuels regardless of the injection dwell time. The natural luminosity combustion images indicated that the biodiesel fuel had a shorter ignition delay, and the combustion progress of JP-8 was accelerated due to superior vaporization, although the initial combustion was slightly delayed in the second injection phase compared to biodiesel and HSD.

Keywords: Injection Dwell Time, Dual Stage Injection, Biodiesel, HSD, JP-8

1. Introduction

Diesel engines possessing high thermal efficiency, superior durability, robustness, and favorable reliability have been widely used to provide power in a variety of applications such as military combat vehicles, marine vessels including naval ships, on-road and off-road vehicles, locomotives, and industrial plants. In addition, injection control technologies, for example, high-pressure injection, multiple-injection strategies, and injection timing control have been applied in a state-of-the-art diesel engine and as a result, NOx and PM that are considered harmful emissions from diesel engines tend to be remarkably lower [1-3].

Biodiesel is an exceedingly attractive alternative fuel and can be used in current diesel engines without modification if blended in proper ratios with existing diesel fuel. The plentiful oxygen fraction of biodiesel compared to fossil fuels contributes to improving the initial combustion performance. From the view point of emissions, according to the majority of the literature, many authors have emphasized that biodiesel has merit in reducing HC and CO pollutants except for NOx; conversely, a few studies announced that HC and CO pollutants from biodiesel are slightly increased because of the lower vaporization, higher viscosity, and inferior atomization of biodiesel. However, biodiesel emissions are generally accepted to have reduced concentrations of HC, CO, and CO_2 because of the higher oxygen concentration and lower carbon ratio of this fuel [4-8].

JP-8 is a kerosene based jet fuel that is blended with particular additives and used in land-based military aircraft, military vehicles and various pieces of combat equipment. NATO nations have decided to use JP-8 in order to conduct effective military operations and to simplify the primary fuel used in the European battlefield. The vaporization characteristics and lower heating value of JP-8 are superior to diesel fuel, while JP-8 has inferior fuel density and cetane number. A few studies on the effect of JP-8 on the performance and emission characteristics in diesel engines have reported that JP-8 has a longer ignition delay characteristic and improves the premixed combustion intensity. In addition, the combustion process is accelerated because of the predominant evaporation rate compared to diesel fuel; however, engine performance is reduced when JP-8 is directly replaced with diesel fuel at the same injection pulse width. Considering the exhaust emissions of JP-8 in diesel engines, some authors have insisted that NOx and HC emissions are higher than the concentrations of these pollutants using diesel fuel, although these emissions could be less under various engine operation conditions. However, an increase in NOx emissions and a decrease in PM emissions using JP-8 compared to diesel fuel are commonly accepted [9-12].

In this context, this work focused on the investigation of the effect of injection dwell time on the combustion and emission characteristics of biodiesel in a single-piston diesel engine under dual-stage injection. In addition, the natural luminosity combustion process of biodiesel was visualized with an optically accessible system, and the results for biodiesel were compared to HSD and JP-8 fuels.

2. Experimental Configuration, Fuels and Procedures

2.1. Experimental Configuration

A schematic of the experimental configuration used to investigate the effect of fuel injection dwell time on the combustion and emission characteristics, including visualization of the combustion process, of biodiesel, HSD, and JP-8 fuels is shown in Fig. 1.

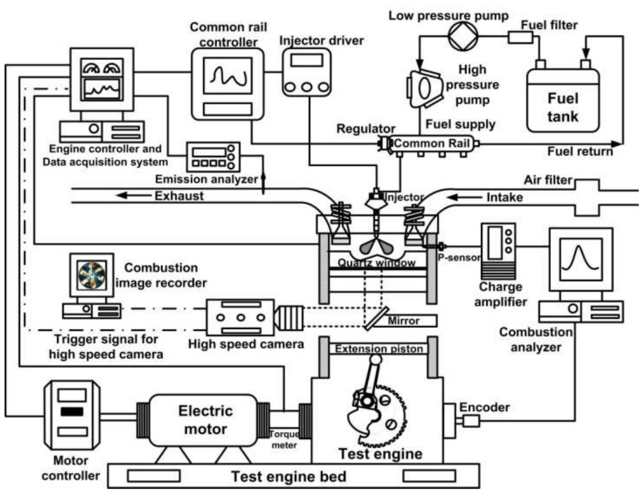


Figure 1. *Schematic diagram of the experimental configuration*

The experimental apparatus presented in Fig.1 consisted of a single-piston diesel engine, combustion and emission analyzer, an engine control system, and a 22kW electric motor to control the engine speed in detail. The test engine used for this work is based on a four-stroke, water-cooled, naturally aspirated, single-piston direct-injection diesel engine equipped with a common rail system. Detailed test engine specifications are depicted in Table 1.

In addition, the test engine was designed to include an optically accessible component that allows the visualization of the combustion process. The optical access system was composed of an extended piston with a quartz window, 45° mirror, and high speed digital camera (Photron, Fastcam SA3); this system measured the natural luminosity flames of the continuous combustion processes. Images of the combustion processes were recorded at 16,000 frames per second with a resolution of 256×256, and the shutter speed of the camera was fixed at 1/32,000 seconds to obtain sharp images. The in-cylinder pressure to analyze the combustion characteristics was continuously measured with a piezoelectric combustion pressure sensor (Kistler, 6025A) coupled to a charge amplifier (Kistler, type 5018) for 1,000 consecutive engine cycles. The rate of heat release was calculated based on the averaged in-cylinder pressure value and the application of the first law of thermodynamics [13] using a combustion analyzer (Mobiltek Eng CO., MT 7000S). A gas-sensor-based portable emission analyzer (Testo, 350K) was used to measure the NOx, HC, CO, CO_2, and O_2 concentrations in the engine-out gas. The fuel injection pressure, injection timing, and injection duration were operated by a Labview-based programmable injector driver (Zenobalti CO., ZB-5100) and engine control system. A rotary encoder (Koyo, TRD-J360) mounted on the crankshaft was used to acquire the crank angle.

Table 1. *Test engine specifications*

Parameters		Value
Engine type		4-stroke, single piston diesel engine
Bore × Stroke		83 mm × 92 mm
Compression ratio		17.7 : 1
Displacement		498cc
Fuel injection system		Common-rail direct injection system
Injector hole number		6
Valve timing	IVO	BTDC7°CA
	IVC	ABDC43°CA
	EVO	BBDC52°CA
	EVC	ATDC6°CA

2.2. Experimental Fuels and Procedures

In this work, three different test fuels, such as biodiesel, HSD for marine engines (i.e., diesel and gas turbine power plants of a naval vessel in the Korean navy), and JP-8 for land-based aircraft and battle equipment, were applied to an optically accessible single-piston diesel engine. The test fuel specifications are summarized in Table 2.

Table 2. *Test fuel specifications*

Properties		HSD	Biodiesel	JP-8
Carbon (wt%)		86.97	77.71	85.48
Hydrogen (wt%)		12.64	13.05	14.37
Distillation temperature (°C)	10%	227.5	330.5	194.0
	50%	296.4	334.3	212.0
	90%	352.8	343.0	237.1
Sulfur (ppm)		250	-	8
Density (kg/m^3, 15°C)		849.4	882.7	809.1
Cetane number		52.8	56.3	46.8
Kinematic viscosity (mm^2/s, 40°C)		3.621	4.341	1.451
Lower heating value (MJ/kg)		45.57	39.86	46.31
Flash point (°C)		81.0	154.0	65.0

All of the tests were conducted at a constant engine speed of 800rpm and fuel injection pressure of 30MPa without the EGR condition. The first injection timing was fixed at BTDC20°CA and the second injection timings varied from BTDC10°CA to TDC in intervals of 5°CA under the dual-stage fuel injection condition. Residual fuel in the fuel line and the common rail was removed by compressed air before each experiment began. The fuel injection signal was synchronized with starting to record the combustion process with the visualization system in order to change the combustion image frame number to the crank angle. The detailed experimental conditions are shown in Table 3.

***Table 3.** Experimental conditions*

Engine speed		**800rpm**
Fuel injection pressure (P_{inj})		30MPa
First fuel injection timing (FT_{inj})		BTDC20°CA
First fuel injection duration (FD_{inj})		0.85ms
Second fuel injection timing (ST_{inj})		BTDC10°CA ~ TDC
Second fuel injection duration (SD_{inj})		0.85ms
Coolant and oil temperature (°C)		60°C
High speed camera	Frame rate	16,000fps
	Shutter speed	1/32,000seconds

3. Experimental Results and Discussions

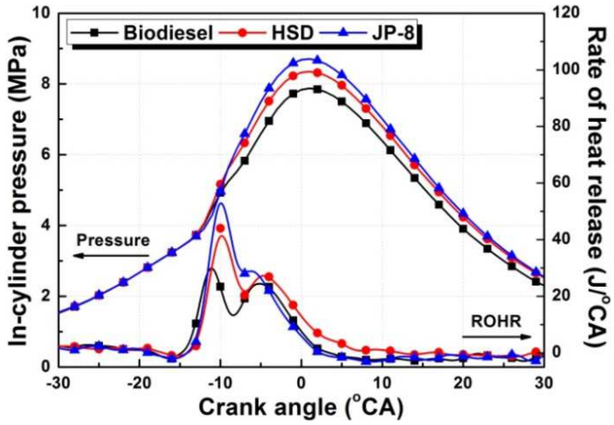
3.1. Combustion Characteristics of Biodiesel, HSD, and JP-8

In-cylinder pressure data have been used to analyze the engine combustion behavior such as the start of combustion and rate of heat release. The combustion characteristics of biodiesel, HSD, and JP-8 are displayed in Fig. 2.

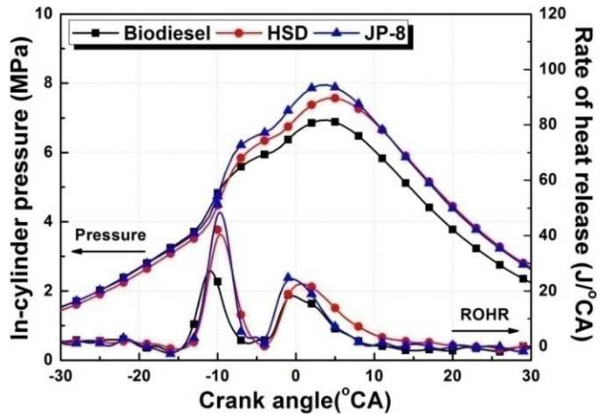
Biodiesel presents the lowest in-cylinder pressure and rate of heat release compared to the other fossil fuels regardless of the fuel injection dwell periods, however, the start of heat release of biodiesel was slightly faster than the values for HSD and JP-8 fuels due to the shortest ignition delay.

Biodiesel has the lowest lower heating value and highest kinematic viscosity, despite the highest cetane number, leading to poor values for the in-cylinder pressure and rate of heat release compared to the other test fuels. Considering the ignition delay, the higher oxygen concentration and cetane number of biodiesel, these parameters affect the superior burn in the first premixed combustion stage [14-16].

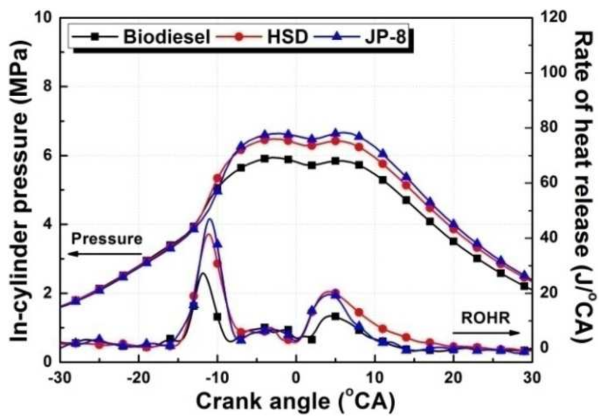
JP-8 exhibits a superior premixed combustion intensity and inferior diffusion flame intensity than HSD because of better evaporation and rapid mixing with air due to the lower cetane number in the combustion chamber. As illustrated in Fig. 2, the fuel injection dwell time produces the peak in-cylinder pressure value. The peak in-cylinder pressure gradually decreases as the fuel injection dwell time is prolonged and the second injection timing is retarded.



(a) Injection dwell time (10°CA : BTDC20°CA & BTDC10°CA)



(b) Injection dwell time (15°CA : BTDC20°CA & BTDC5°CA)



(c) Injection dwell time (20°CA : BTDC20°CA & TDC)

***Figure 2.** In-cylinder pressure and rate of pressure rise characteristics as a function of injection dwell time*

Fig. 3 represents the IMEP and maximum in-cylinder pressure value with fuel injection dwell time. IMEP is the most effective index of the combustion properties and the work per cycle. The JP-8 fuel is expected to have superior IMEP due to the higher in-cylinder pressure, as seen in Fig. 2. This result can be explained by combustion efficiency. Diesel combustion has a longer diffusion flame than JP-8; this characteristic provides plentiful work when the piston is descending in the expansion stroke condition. Another possible reason supporting this result is thermal loss external to the cylinder caused by high temperature because the rate of heat release of JP-8 in the premixed combustion stage is higher than the rate of diesel fuel [17, 18].

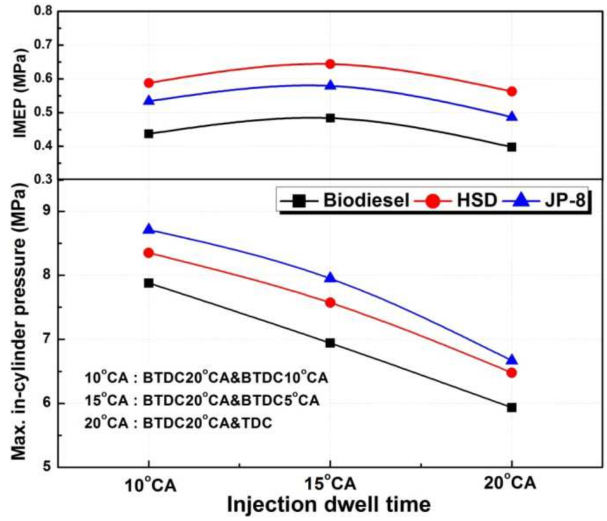


Figure 3. *IMEP and maximum in-cylinder pressure characteristics as a function of injection dwell time*

The heat loss generated by a high temperature in the cylinder during combustion of JP-8 produces the reduction of the exhaust gas temperature. This result can be confirmed in the exhaust gas temperature characteristics with injection dwell time, as shown in Fig. 4.

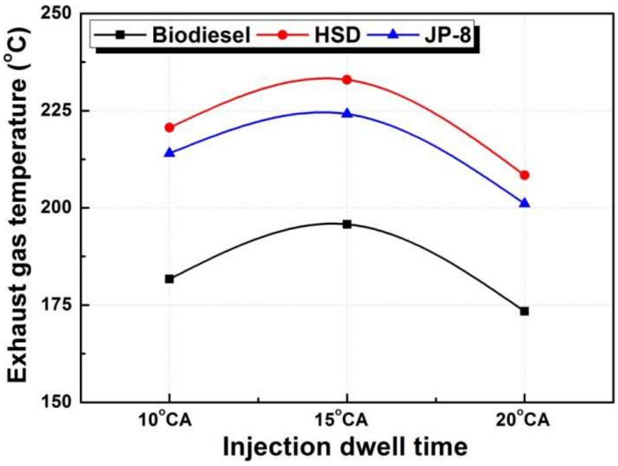


Figure 4. *Exhaust gas temperature characteristics as a function of injection dwell time*

In addition, the IMEP and exhaust gas temperature are at the best values in the fuel injection dwell time of 15°CA (BTDC20°CA&BTDC5°CA) irrespective of the test fuel. JP-8 has the highest peak in-cylinder pressure in comparison with HSD and biodiesel. At low idling condition, the main cause for lower exhaust temperature of biodiesel than fossil fuels may be the diminished rate of heat release because of the lower heating value of biodiesel, despite the highest cetane number and the faster combustion start by the oxygen-rich fuel. Prolonged injection dwell period and retarded second injection timing lead to the reduction of the maximum in-cylinder pressure value, IMEP, and exhaust gas temperature.

3.2. Emission Characteristics of Biodiesel, HSD, and JP-8

Engine-out emission characteristics such as NOx, HC, CO, and CO_2 including O_2 in the exhaust gas were measured for biodiesel, HSD, and JP-8 using a gas-sensor-based portable emission analyzer. Fig. 5 shows the results of the emission characteristics as a function of injection dwell period for the three different fuels.

As shown in Fig. 5, biodiesel has a reduction in the emissions of NOx, HC, and CO_2, and CO pollutants compared to the fossil fuels. In the case of NOx emissions, the majority of studies have announced that the use of biodiesel produces an increase in NOx emissions, whereas a few researchers have emphasized that biodiesel leads to a decrease in NOx emissions. The main reason for the increase in these emissions is the superior oxygen content and higher cetane number. Additionally, the higher engine power is expected to cause the higher NOx emissions [7, 9, 19, 20].

In the current investigation, biodiesel has a shorter ignition delay compared to the other fuels as explained in the combustion characteristics section. As a consequence, the lower premixed combustion intensity in the first reaction stage provides a lower rate of heat release. In addition, biodiesel has a poor peak in-cylinder temperature due to a lower heat release, contributing to a lower NOx emission in the no load operating condition.

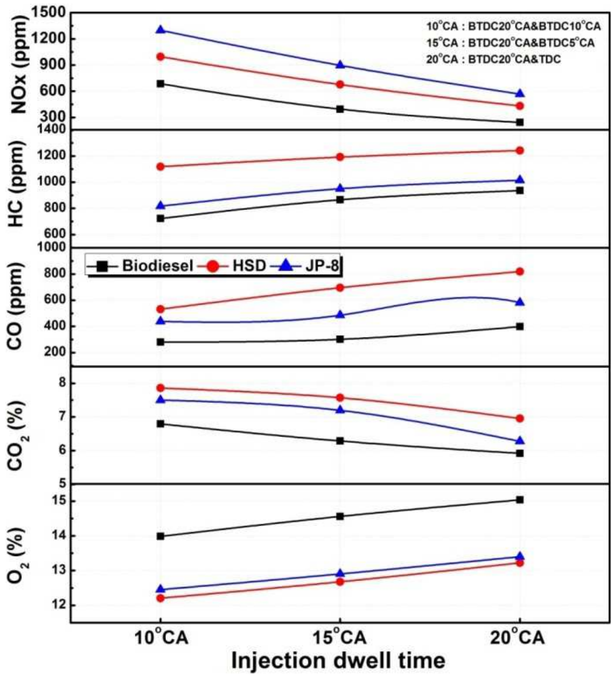


Figure 5. *Engine-out emission characteristics as a function of injection dwell time*

On the other hand, JP-8 exhibits higher NOx emissions compared to HSD and biodiesel as a function of injection dwell time. JP-8 has a superior volatility rate and lower heating value than the other fuels, so these fuel properties improve the air-fuel mixture in the combustion chamber, which is produced at a higher rate of heat release in the premixed combustion step. Therefore, numerous heat releases lead to the increase in the in-cylinder temperature, leading to the increase the NOx emission concentrations. Retarding the second injection of the three different fuels reduces the peak in-cylinder pressure due to the shorter ignition delay, which causes a lower peak in-cylinder temperature. As a result of the longer injection dwell time, the NOx emissions tend to decrease [21, 22].

Generally, HC emissions in a compression-ignition diesel engine are most influenced by incomplete combustion and unburned fuel deposited on the cylinder wall. Emissions of HCs are an especially severe problem at no load and low load conditions [23]. Biodiesel has various positive attributes such as the lowest carbon content, highest oxygen concentration in the fuel, and highest cetane number, excluding volatility, compared to the test fuels used in these experiments.

More HC pollutants are expected to be emitted from biodiesel due to lower volatility, higher viscosity because of fuel deposits, as well as incomplete combustion by poor atomization. As can be confirmed from the experimental result of Fig. 5, biodiesel produces lower HC emissions in comparison with the fossil fuels irrespective of injection dwell time. This result can be explained by the oxygen atoms in biodiesel that enhance the oxidation reaction.

JP-8 has less HC emissions compared to HSD at a comparable injection dwell time. This result can be attributed to the higher volatility of JP-8 that reduces the amount of fuel deposited onto the cylinder wall compared to HSD. Therefore, the higher volatility of JP-8 leads to more evaporation and mixing with air, providing better combustion performance with this fuel than HSD.

The concentration of CO emitted from biodiesel decreases compared to the fossil fuels. The emission characteristics of CO are similar for the three different fuels, and have a similar effect as HC. The most important factor for reducing the CO emissions of biodiesel is more oxygen atoms in the fuel and a lower ratio of carbon to hydrogen. This chemical composition can overcome poor atomization due to the higher viscosity, poor mixing with air, and poor combustion quality of biodiesel [24, 25].

HSD has higher CO emissions than JP-8 in all of the experimental conditions. Inferior air-fuel mixtures are formed by HSD because of the lower volatility of this fuel compared to JP-8, leading to the decline of the combustion rate in the premixed burn condition. Incomplete combustion product CO emissions are easily produced because diffusion combustion always occurs in the rich mixtures of this circumstance. In addition, retarding the second injection timing increases the CO emissions because the injected fuel is burned in a diffusion combustion phase [14, 25].

Biodiesel results in fewer CO_2 emissions compared to the fossil fuels in all of the experiments. Biodiesel is a low carbon alternative fuel and has a lower ratio of elemental carbon to hydrogen, which contributes to reducing the CO_2 emissions during the combustion process [8, 25, 26].

In addition, retarding the second injection timing leads to less CO_2 emissions for all of the tested fuels. In the dual-stage injection strategy, the first injection affects the premixed combustion, and in the second injection, diffusion combustion is actively occurred. The fraction of unused oxygen in the first combustion stage is used for the oxidation reaction in the second combustion.

As the second injection is retarded after the first injection, the oxidation reaction rate is decreased because the diffusion combustion after ignition mainly progresses during the expansion stroke. Therefore, unused O_2 in the engine exhaust gas increases as the injection dwell time is extended, as shown in Fig. 5, which is caused by the reduction in CO_2 emissions. Biodiesel shows the highest unused O_2 fraction in the exhaust gas. This result implies that the increased oxygen in biodiesel is used to accelerate the oxidation reaction for more efficient combustion compared to the fossil fuels.

3.3. Combustion Process Visualization of Biodiesel, HSD, and JP-8

The natural flame luminosity images to investigate the effect of injection dwell time on the combustion behaviors of biodiesel, HSD, and JP-8 fuels from TDC to ATDC50^{o}CA in the combustion chamber are represented in Fig. 6.

The high speed images from natural flame luminosity disclose that the second combustion is characterized as diffusion combustion and that the fuel during the second injection was injected into the high pressure and temperature region that occurred after the first premixed burn from the first fuel injection. As the injection interval period was extended, the images confirmed that the second combustion was gradually delayed for all of the test fuels.

The diffusion flame spreads out in the entire combustion chamber from ATDC2^{o}CA in 10^{o}CA of dwell time, ATDC4^{o}CA in 15^{o}CA dwell time, and ATDC8^{o}CA in 20^{o}CA dwell time. Biodiesel shows the best initial combustion in the second stage condition compared to the fossil fuels. The combustion of biodiesel might be enhanced by the superior cetane index and oxygen content of this fuel. Comparing biodiesel combustion with HSD and JP-8 combustion, the initial combustion point of JP-8 in the second injection stage is slightly delayed in all of the test conditions.

The diffusion flame luminosity intensity of JP-8 is at a lower level than biodiesel and HSD in 10^{o}CA of dwell time compared to the other test conditions. This result from the images signifies that the diffusion combustion and flame intensity of JP-8 in the second injection timing condition are inferior in comparison to biodiesel and HSD, however, combustion is accelerated because of the vaporization of JP-8 [27, 28].

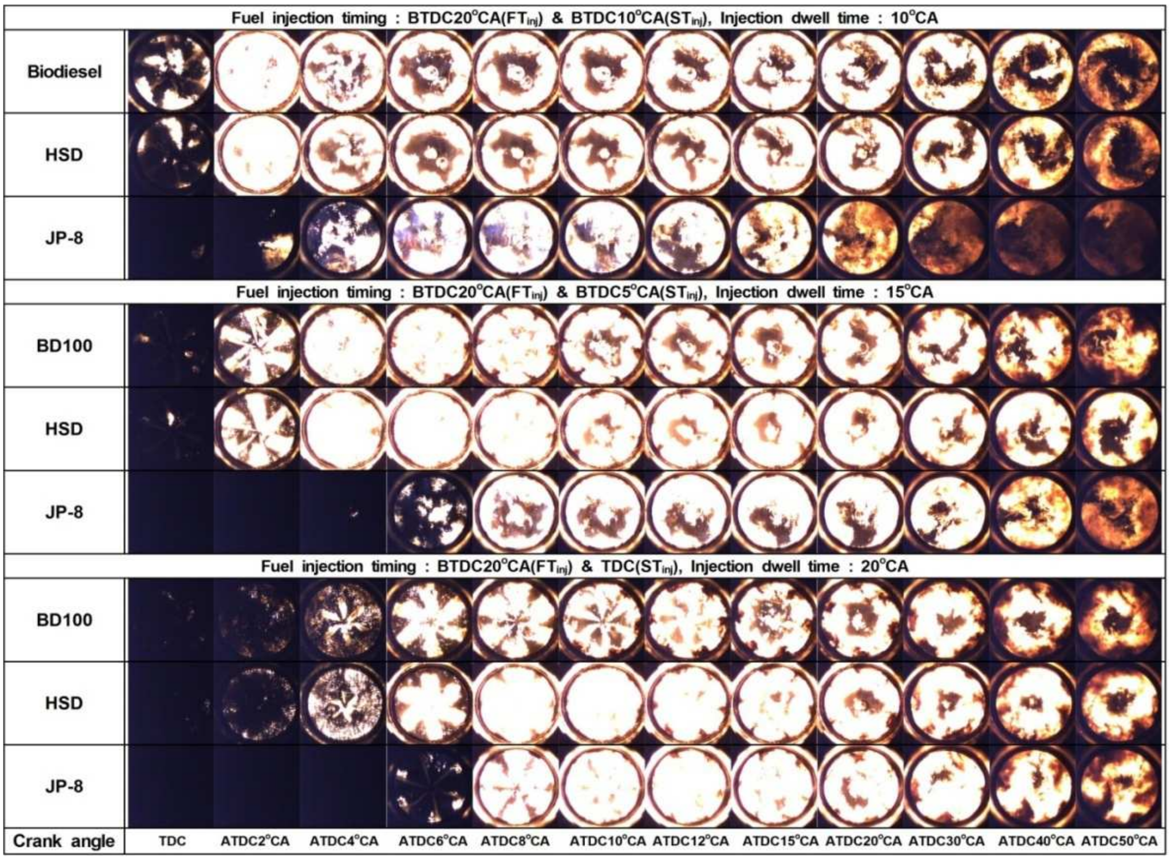


Figure 6. *Natural flame luminosity images with injection dwell time*

4. Conclusion

An investigation to determine the effect of the injection dwell time for a dual-stage injection condition on a biodiesel combustion process and the subsequent emission characteristics was performed using an optically accessible single-piston diesel engine system, a combustion analysis system, and an emission measurement system at a constant low engine speed and low injection fuel pressure. In addition, experimental results from biodiesel were compared with fossil fuels such as HSD and JP-8. From the results and discussions above, the main findings in this research are summarized as follows:

(1) An oxygenated biodiesel fuel showed a lower in-cylinder pressure and rate of heat release than the studied fossil fuels according to combustion characteristic analysis at all of the test conditions; however, biodiesel had a shorter ignition delay than the fossil fuels due to the higher cetane number and oxygen concentration of this fuel. IMEP, which can be represented by the combustion performance and the work per cycle, was highest for HSD in comparison with biodiesel and JP-8 due to the longer diffusion flame characteristic and lower heat loss of HSD. The lower heat energy loss of HSD than JP-8 can be explained by the exhaust temperature characteristics. Retarded second injection timing in the dual-stage injection condition reduced the peak in-cylinder pressure, rate of heat release, rate of pressure increase, IMEP, and exhaust gas temperature.

(2) Biodiesel had great benefits in reducing the emissions of NOx, HC, and CO_2, and CO compared to the emissions of fossil fuels for all of the experiments. JP-8 had higher NOx emissions than HSD; however, the results indicated that HC, CO, and CO_2 emissions from JP-8 were evidently decreased compared to HSD. In addition, the amount of unused O_2 in the exhaust gas from the biodiesel combustion process was higher than the amount of unused gas in the fossil fuels. As the injection dwell time was extended for all of the test fuels, the NOx and CO_2 emissions showed a tendency to be reduced; however, the emissions of HC and CO tended to be increased.

(3) From the combustion process images, biodiesel had a better initial combustion in the second injection phase compared to the fossil fuels, and JP-8 had the worst start of combustion among the tested fuels. The diffusion flame luminosity of JP-8 vanished earlier than HSD and biodiesel, implying that JP-8 has faster combustion due to its superior vaporization behavior compared to HSD and biodiesel, in spite of late burning after fuel injection.

Acknowledgements

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Nomenclature

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
EGR	Exhaust gas recirculation
EVC	Exhaust valve closing
EVO	Exhaust valve opening
FD_{inj}	First fuel injection duration
Fps	Frame per second
FT_{inj}	First fuel injection timing
HC	Hydrocarbon
HSD	High sulfur diesel
IMEP	Indicated mean effective pressure
IVC	Intake valve closing
IVO	Intake valve opening
JP	Jet propellant
NATO	North Atlantic Treaty Organization
NOx	Nitrogen oxides
O_2	Oxygen
P_{inj}	Fuel Injection pressure
PD_{inj}	Pre-injection duration
PT_{inj}	Pre-injection timing
Rpm	Revolutions per minute
SD_{inj}	Second fuel injection duration
ST_{inj}	Second fuel injection timing

References

[1] S.H. Park, I.M. Youn, and C.S. Lee, “Influence of two-stage injection and exhaust gas recirculation on the emissions reduction in an ethanol-blended diesel-fueled four-cylinder diesel engine,” Fuel Process. Technol. vol. 91, pp. 1753-1760, 2010.

[2] H.M. Lee, “Fuel-based estimation of exhaust emissions from a medium speed propulsive diesel engine for a naval vessel under ocean going conditions,” Nav. Eng. J. vol. 125, No. 4, pp. 113-118, 2013.

[3] H.M. Lee, and Y.H. Jung, “The effect of dynamic operating conditions on nano-particle emissions from a light-duty diesel engine applicable to prime and auxiliary machines on marine vessel,” Int. J. Nav. Archit. Ocean. Eng. Vol. 4, pp. 403-411, 2013.

[4] P.K. Sahoo, L.M. Das, M.K.G. Babu, P. Arora, V.P. Singh, and N.R. Kumar, “Comparative evaluation of performance and emission characteristics of jatropha, karanja and polanga based biodiesel as fuel in a tractor engine,” Fuel, vol. 88 pp. 1698-1707, 2008.

[5] G. Fontaras, G. Karavalakis, M. Kousoulidou, T. Tzamkiozis, L. Ntziachristos, and E. Bakeas, “Effects of biodiesel on passenger car fuel consumption, regulated and non-regulated pollutant emissions over legislated and real-world driving cycles,” Fuel, vol. 88, pp. 1608-1617, 2009.

[6] J.P. Szybist, J. Song, M. Alam, and A.L. Boehman, “Biodiesel combustion, emissions and emission control,” Fuel Process. Technol. vol. 88, pp. 679-691, 2007.

[7] S. Murillo, J.L. Mıguez, J. Porteiro, E. Granada, and J.C. Moran, “Performance and exhaust emissions in the use of biodiesel in outboard diesel engines,” Fuel, vol. 86, pp. 1765-1771, 2007.

[8] J. Xue, T.E. Grift, and A.C. Hansen, “Effect of biodiesel on engine performance and emissions,” Renewable and Sustainable Energy Rev. vol. 15, pp. 1098-1116, 2011.

[9] G. Fernades, J. Fuschetto, Z. Filipi, D. Assanis, and H. Mckee, “Impact of military JP-8 fuel on heavy- duty diesel engine performance and emissions,” Proc. Inst. Mech. Engrs. Part D: J. Automot. Eng. vol. 221, pp. 957-970, 2007.

[10] D. Korres, E. Lois, and D. Karnois, “Use of JP-8 aviation fuel and biodiesel on a diesel engine,” SAE Technical Paper 2004-01-3033, 2004.

[11] J.W. Lee, H.C. Oh, and C.S. Bae, “Combustion process of JP-8 and fossil diesel fuel in a heavy duty diesel engine using two-color thermometry,” Fuel, vol. 102, pp. 264-273,2012.

[12] C. Jayakumar, J. Nargunde, A. Sinha, N.A. Henein, and E. Sattler, “Effect of biodiesel, jet propellant (JP-8) and ultra low sulfur diesel fuel on auto-ignition, combustion, performance and emissions in a single cylinder diesel engine,” J. Eng. Gas Turbines Power, vol. 134, pp. 1-11, 2012.

[13] J.B. Heywood, Internal Combustion Engine Fundamentals, McGraw-Hill, New York, 1988.

[14] J.S. Hwang, D. Qi, Y.J Jung, and C.S Bae, “Effect of injection parameters on the combustion and emissions characteristics in a common-rail direct injection diesel engine fueled with waste cooking oil biodiesel,” Renewable Energy, vol. 63 pp. 9-17, 2014.

[15] B. Kegl, and A. Heribernik, “Experimental analysis of injection characteristics using biodiesel fuel,” Energy and Fuels, vol. 20, pp. 2239-2248, 2006.

[16] S.H. Park, S.H. Yoon, and C.S. Lee, “Effects of multiple-injection strategies on overall spray behavior, combustion, and emissions reduction characteristics of biodiesel fuel,” Appl. Energy, vol. 88, pp. 88-98, 2011.

[17] J.W. Lee, and C.S. Bae, “Apllication of JP-8 in a heavy duty diesel engine,” Fuel, vol. 90, pp. 1762-1770, 2011.

[18] J. Jang, and C.S. Bae, “Effects of valve events on the engine efficiency in a homogeneous charge compression ignition engine fueled by dimethyl ether,” Fuel, vol. 88, pp. 1228-1234, 2009.

[19] K. Verbiezen, A.J. Donkerbroek, R.J.H. Klein-Douwel, A.P. van Vliet, P.J.M. Frijters, X.L.J. Seykens, R.S.G. Baert, W.L. Meerts, N.J. Dam, and J.J. ter Meulen, “Diesel combustion: In-cylinder NO concentrations in relation to injection timing,” Combus. Flame, vol. 151, pp. 333-346, 2007.

[20] D. leung, Y. Luo, and T. Chan, "Optimization of exhaust emissions of a diesel engine fuelled with biodiesel/diesel blends, Energy and Fuels," vol. 20, pp. 1015-1023, 2006.

[21] G.R. Kannan, and R. Anand, "Experimental evaluation of DI diesel engine operating with diestrol at varing injection pressure and injection timing," Fuel Process. Technol. vol. 92, pp. 2252-2263, 2011.

[22] J. Jeon, J.T. Lee, Y.S. Lim, S.I. Kwon, Y.H. Park, J. Cha, K. Lee, and S. Park, "Flame temperature distributions of biodiesel fuel in a single-cylinder diesel engine," Fuel Process Technol. vol. 110, pp. 227-234, 2013.

[23] D.H. Qi, H. Chen, L. Chen, Y. Bian, and Z. Bian, "Experimental studies on the combustion characteristics and performance of a direct injection engine fueled with biodiesel/diesel blends," Energy Convers. Manage. vol. 50, pp. 2985-2992, 2010.

[24] H. Aydin, and C. İIkılıç, "Effect of ethanol blending with biodiesel on engine performance and exhaust emissions in a CI engine," Appl. Therm. Eng. vol. 30, pp. 1199-1204, 2010.

[25] M. Karabektas, "The effects of turbocharger on the performance and exhaust emissions of a diesel engine fuelled with biodiesel," Renewable Energy, vol. 34, pp. 989-993, 2009.

[26] Z. Utlu, and M.S. Koçak, "The effect of biodiesel fuel obtained from waste frying oil on direct injection diesel engine performance and exhaust emissions," Renewable Energy, vol. 33, pp. 1936-1941, 2008.

[27] J. Pan, W. Yang, S. Chou, D. Li, H. Xue, J. Zhao, and A. Tang, "Spray and combustion visualization of biodiesel in a direct injection diesel engine," Therm. Sci. vol. 17, pp. 279-289, 2013.

[28] L.M. Pickett, and L. Hoogterp, "Fundamental spray and combustion measurement of JP-8 at diesel conditions," SAE Technical Paper 2008-01-1083, 2008.