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Spray, Combustion, and Air Pollutant Characteristics of JP-5 for Naval Aircraft from Experimental Single-Cylinder CRDI Diesel Engine

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Abstract: This study was performed to analyze the spray, combustion, and air pollutant characteristic of JP-5 fuel for naval aircraft in a spray visualization system and a single-cylinder CRDI diesel engine that can be visualized. The analysis results of JP-5 fuel were compared with DF. The spray tip penetration of JP-5 showed diminished results as the spray developed. JP-5 had the highest ROHR and ROPR regardless of the fuel injection timings. The physicochemical characteristics of JP-5, such as its excellent vaporization and low cetane number, were analyzed to prolong the ignition delay. Overall, the longer combustion period and the lower heat loss of the DF raised the engine torque and the IMEP. JP-5 showed higher O\textsubscript{2} and lower CO\textsubscript{2} levels than the DF fuel. The CO emission level increased as the injection timing was advanced in two test fuels, and the CO emitted from the DF fuel, which has a longer combustion period than JP-5, turned out to be lower. NO\textsubscript{x} also reduced as the fuel injection timing was retarded, but it was discharged at a higher level in JP-5 due to the large heat release. The images from the combustion process visualization showed that the flame luminosity of DF is stronger, its ignition delay is shorter, and its combustion period is longer than that of JP-5.

Keywords: spray; combustion; air pollutant; JP-5; fuel injection timing; visualization

1. Introduction

Diesel fuel (DF) engines of compression ignition method are recognized as key propulsion engines of naval ships because of their excellent durability, fuel economy, robustness, and high power density [1–3]. Naval ships carrying naval aircraft use two types of fuel: DF and JP-5 fuel. DF is used for propulsion engines and power generation engines, and JP-5 fuel is used for naval aircraft. JP-5 fuel is classified as a kerosene-based aviation fuel with a great flash point and is used as a dedicated fuel for naval aircraft carried on naval ship, not for ground-based the fixed wing aircraft and rotor craft.

In the 1980s, the North Atlantic Treaty Organization (NATO) adopted utilizing JP-8 modified kerosene as a single fuel to effectively refuel all military aircraft based on the ground, combat, and operation vehicles that powered by on DF engines [4–6]. The United States (US) Navy proposed kerosene-based JP-5 fuel as the same fuel for naval ships operating with naval aircraft. Compared to JP-8, JP-5 has a narrow boiling range, so it requires much energy for ignition. The minimum flash point of JP-8 stored in a non-fluctuating onshore fuel tank is 38 °C. However, JP-5 stored in the fuel tank of a navigating ship has a flash point of at least 60 °C for storage stability [7,8]. Kerosene based JP-8 fuel for military shows very similar properties in characteristics to jet fuel used fuel for commonly commercial aviation. It is known that the aromatic content of JP-8 in the complex hydrocarbons is lower than that of DF, which results in a higher latent heat of evaporation and shorter spray tip penetration [9,10].

The results of various studies that applied JP-8 for the military and jet fuels for civilians to DF engines have been published. The jet fuel as well as JP-8 characteristics
such as superior vaporization and low kinematic viscosity including low density under constant fuel injection conditions have been reported as the main reasons for shorter spray tip penetration [11,12].

In particular, it has been reported that JP-8 fuel has a penalty in engine torque by its low density and asymmetric spray when using valve-orifice-covered (VOC) injector [6,13]. The excellent vaporization and long ignition delay of JP-8 increase heat release in the premixed combustion process, but its overall combustion period was reported to be short compared to DF [14,15].

JP-8 for military, as well as jet fuels for civilian aircraft, has an advantage in terms of carbon monoxide (CO) reduction due to the better acceleration of its oxidation rate caused by its higher rate of heat release (ROHR). Superior ROHR of jet fuels, however, leads to the formation of greater quantities of nitrogen oxide (NOx) [14,16].

Compared with the results of many studies that applied JP-8 fuel to DF engines, the reports of research that applied JP-5 fuel for naval aircraft to compression ignition DF engine are insignificant. An emergency situation can arise in which DF cannot be supplied to the engine during operations at sea. The maneuver of the naval ship must be guaranteed by immediately supplying to it another fuel (JP-5) stored for naval aircraft.

Given this scenario, it is necessary to investigate various characteristics of JP-5 fuel by applying it to a DF engine of compression ignition method. However, experimental research on DF engine onboard naval vessel is very limited. In order to overcome these limitations and achieve the study objectives, experiments were conducted on a single-cylinder DF engine equipped with a single-cylinder common rail direct (CRDI) system and an electronically controlled injector as well as visualization systems.

The purpose of this research was to focus on analyzing the spray, combustion, and air pollutants from exhaust gas characteristics of JP-5 fuel for naval aircraft by applying it to a single-cylinder CRDI DF engine. Spray visualization test was conducted to determine the spray tip penetration of JP-5 fuel. The combustion parameters such as the ROHR, the rate of pressure rise (ROPR), and the indicated mean effective pressure (IMEP) were analyzed with in-cylinder pressure. The overall combustion process was recorded through combustion visualization with a high-speed camera. In addition, the air pollutants from exhaust gas characteristics such as of carbon dioxide (CO\(_2\)), CO, and NOx were measured with a sensor-based mobile exhaust gas analyzer.

2. Experimental System and Procedure

2.1. Experimental Apparatus Configuration

Figure 1 shows a diagram of the experimental device configuration for analyzing the spray, combustion, and air pollutant characteristics of the DF and JP-5 fuels. The test equipment combined a single-cylinder DF engine capable of combustion visualization (MT-SDE100, Mobiltek), a fuel injection control system (ZB-5100 pick and hold injector driver, Zenobalti), a spray visualization system, an exhaust gas analysis system, a combustion analyzer, and an electric motor (HV2 induction motor, Hyosung) with a maximum power of 22 kW that constantly controlled the engine speed.

A single-cylinder CRDI DF engine was applied to analyze the combustion and air pollutant characteristics of the DF and JP-5 fuel. An extended piston and a 45° mirror with a quart window were installed to the test engine to acquire images of the combustion process. The main specifications of the engine for this study are given in Table 1. Fuel injection conditions such as the injection pressure, the injection timing, and the injection energizing time were adjusted by the engine control system and the LabVIEW-based programmed injector driver. An optical lamp (Xeon 1000, Optical system) was used as a light source to obtain a clear spray image. The test fuels for the spray visualization were supplied from the common rail of the test engine.

The O\(_2\), CO\(_2\), CO, and NOx in the exhaust gas were analyzed using a sensor-based mobile emission analyzer (Testo 350K, Testo). In-cylinder pressure was recorded using a piezoelectric pressure sensor (Type 6056A, Kistler) and an amplifier (Type 5018, Kistler).
Then in-cylinder pressure was averaged by continuously measuring 300 cycles to minimize the cycle-to-cycle variation. A combustion analyzer (MT-7000S, Mobiltek) was used to analyze various combustion parameters.

![Diagram of the experimental device configuration.](image)

**Figure 1.** Diagram of the experimental device configuration.

| Items                  | Descriptions                          |
|------------------------|---------------------------------------|
| Engine type            | Four-stroke, single-cylinder CRDI DF engine |
| Bore × Stroke          | 83 mm × 92 mm                          |
| Valve timing           | IVO BTDC 7 CA, IVC BTDC 43 CA, EVO BBDC 52 CA, EVC ATDC 6 CA |
| Compression ratio      | 17.7:1                                 |
| Displacement           | 498 cc                                 |

The revolution speed of test engine was precisely dominated by a 22 kW electric motor, and the torque value was checked with a torque meter (T8 ECO rotary torque transducer, Interface) that was coupled between the test engine and the electric motor.

### 2.2. Test Fuels and Experimental Conditions

Two fuels applied in this study were DF fuel for naval ships and JP-5 fuel for naval aircraft. These two fuels are stored in the fuel tank of naval ships carrying an aircraft. The main physicochemical peculiarities of DF and JP-5 fuels are presented in Table 2.

A powerful light was directly irradiated into the chamber for the spray visualization. The spray image was acquired by synchronizing the start of energizing (SOE) of the fuel injection equipment (injector) and the start of recording of the high-speed camera (Fastcam SA3, Photron).

Sac-type nozzle injector was applied to prevent combustion imbalance due to asymmetric spray. For the combustion visualization, an extended piston, a 45° mirror, and various devices that can be visualized were installed in a test engine, and combustion images were recorded with a high-speed camera. The experimental conditions of single-cylinder DF engine and the macroscopic visualization are summarized in Table 3.
Table 2. Important physicochemical peculiarities of the test fuels.

| Parameter                        | Unit   | DF    | JP-5  |
|----------------------------------|--------|-------|-------|
| Carbon content                   | %      | 86.97 | 85.80 |
| Hydrogen content                 | %      | 12.64 | 14.07 |
| Aromatic content [17]            | %      | 44    | 18    |
| Distillation temperature 10% recovery | °C   | 227.5 | 190.5 |
| Distillation temperature 50% recovery | °C   | 296.4 | 205.5 |
| Distillation temperature 90% recovery | °C   | 352.8 | 233.9 |
| Density (15 °C)                  | kg/m³  | 849.4 | 801.0 |
| Cetane number                    | -      | 52.8  | 48.2  |
| Kinematic viscosity (40 °C)      | mm²/s  | 3.621 | 1.356 |
| Low heating value                | MJ/kg  | 42.71 | 42.95 |
| Flash point                      | °C     | 81.0  | 62.0  |
| Cold flow plugging point         | °C     | −5    | below −35 |

Table 3. Experimental conditions.

| Contents                        | Conditions                                      |
|---------------------------------|-------------------------------------------------|
| Spray visualization             | Injection pressure 40 MPa                       |
|                                  | Injection energizing time 1.0 ms                 |
|                                  | Ambient pressure 0.1 MPa                        |
|                                  | Image record 15,000 frames/second with a 256 × 256 resolution |
|                                  | Shutter speed 1/25,000 s                         |
|                                  | Light source Xeon lamp                          |
|                                  | Atmosphere temperature Room temperature         |
| Engine operation                 | Engine speed 1100 rpm                           |
|                                  | Injection pressure 40 MPa                       |
|                                  | Injection energizing time 1.0 ms                 |
|                                  | Injection timing BTDC34 CA ~ BTDC 2 CA (4 CAD interval) |
|                                  | Coolant temperature 353 K                       |
| Combustion visualization        | Image record 16,000 frames/second with a 256 × 256 resolution |
|                                  | Shutter speed 1/60,000 s                         |
|                                  | Light source Natural luminosity                 |

3. Consideration of Results

3.1. Spray Visualization and Penetration Characteristics

Figure 2 displays the spray formation process of the DF and JP-5 fuels under conditions of Table 3. The SOE and the start of high-speed camera recording were synchronized to precisely analyze the spray development characteristics. When JP-8 for land-based military aircraft was applied to the DF engine with a valve-orifice-covered (VOC) nozzle injector, the spray behavior was reported as asymmetrical compared to DF [6].

However, it is generally accepted that the sac-type nozzle injector has a symmetrical spray pattern. These spray behavior characteristics are strongly connected with the nozzle shape, the fluid flow inside the nozzle, and the nozzle diameter. In addition, the turbulence strength of the fluid with a high Reynolds number in the internal nozzle increased. Therefore, the strong turbulence intensity can be said to be the cause of the asymmetric spray results when the fuel with low kinematic viscosity was injected from the VOC nozzle-type injector [18,19].

The injector applied in this experiment was the sac-type nozzle. In the spray visualization results in Figure 2, the spray shape shows a symmetrical development process. However, the spray tip penetration of JP-5 tended to be shorter as the spray formation developed. The length of spray tip penetration for the DF and JP-5 fuel based on images acquired with a high-speed camera is shown in Figure 3. Spray tip penetration is highly dependent on physical properties of fuel such as density and kinematic viscosity of the
fuel. These physical characteristics of JP-5 fuel are lower than DF. In addition, the lower aromatic component contained in the fuel, the greater latent heat of vaporization [9].

![Figure 2](image1.png)

**Figure 2.** Spray formation process of the DF and JP-5 fuel.

![Figure 3](image2.png)

**Figure 3.** Spray tip penetration of the DF and JP-5 fuel.

The physicochemical properties of JP-5 such as low density, kinematic viscosity, and aromatic content promote fuel atomization and increase the quantity of air introduced inside the spray. While these characteristics of JP-5 shorten the spray tip penetration, its better atomization and evaporation rate result in faster mixture than DF.
3.2. Combustion Parameter Characteristics

3.2.1. In-Cylinder Pressure, ROHR, and ROPR with Injection Timings

Figure 4 shows the in-cylinder pressure profile, ROHR, and ROPR of the DF and JP-5 fuels at the BTDC 30 CA and BTDC 6 CA, respectively. The in-cylinder curve of JP-5 did not significantly differ from that of DF in the early fuel injection (BTDC 30 CA) condition, but its ROHR showed a distinct difference.

![Figure 4. In-cylinder pressure, ROHR, and ROPR characteristics with the injection timings.](image)

The ignition delay of JP-5 is more retarded than DF, and its maximum ROHR is higher. The ignition delay phenomenon depends on chemical characteristics such as the cetane number that represents ignitability. The increased ignition delay duration provides time for the fuel and air to blend sufficiently, which leads to significant heat generation in the initial stage of combustion [20]. In-cylinder pressure of JP-5 was lower than that of DF during the expansion stroke in the late fuel injection (BTDC 6 CA) condition. This means that the diffusion combustion period of DF is longer than JP-5.

Figure 5 shows the maximum in-cylinder pressure, ROHR, and ROPR of the DF and JP-5 fuels with fuel injection timings.

![Figure 5. Max. in-cylinder pressure, ROHR, and ROPR characteristics with injection timings.](image)

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Figure 5 shows the maximum in-cylinder pressure, ROHR, and ROPR of the DF and JP-5 fuels with fuel injection timings.
It was predicted that the ignition delay period of JP-5 would be shorter due to its physical characteristics such as its excellent evaporation phenomenon, but the opposite happened—the ignition delay was longer with JP-5 than with DF. This result is mainly due to the cetane number representing the flammability. The premixed combustion intensity of JP-5 is greater than that of DF, so the maximum in-cylinder pressure, ROHR, and ROPR of JP-5 are superior to those of DF.

3.2.2. Ignition Delay and Engine Performance with Injection Timings

Figure 6 presents the ignition delay and engine performance characteristic of the JP-5 and DF fuels with the fuel injection timings. The ignition delay from DF engine has a significant effect on the combustion quality and performance. CA10 is used as a representative index of the ignition delay period [21]. In this paper, the ignition delay duration was expressed as CA10 and crank angle period between the SOE and the 10% mass fraction burned (MFB) was determined.

The characteristics of JP-5, such as atomization, evaporation, and rapid mixture formation, are superior to those of DF, but its cetane number that represents its flammability is believed to have the greatest influence on its ignition delay characteristics. As the fuel injection timing changes toward the TDC, the ignition delay period gradually shortens due to the increase of in-cylinder pressure and temperature.

The engine torque and the IMEP increase as the fuel injection timing shifts toward the TDC. Most of the heat release is formed during the compression stroke in an advanced fuel injection timing condition, so it acts as a negative work. However, the more retarded the fuel injection timing, the more work is required during the expansion stroke, which acts as a major cause of increasing positive work. In addition, the engine torque and the IMEP of JP-5 are lower than DF regardless of the fuel injection timing.

3.3. Air Pollutant Characteristics from Exhaust Gas

Figure 7 depicts the \( \text{O}_2 \) concentration and the \( \text{CO}_2 \) emission from exhaust gas. The \( \text{O}_2 \) concentration tended to decrease gradually as the fuel injection timing was retarded. As the fuel injection timing was varied to TDC, the in-cylinder pressure and temperature increased and the ignition delay duration tended to become shorter. This phenomenon is the main reason for prolonging the combustion period. Therefore, the \( \text{O}_2 \) concentration level from the exhaust gas reduces because the amount of the \( \text{O}_2 \) participating in combustion increases.

The \( \text{CO}_2 \) emission showed a trend opposite that of the \( \text{O}_2 \) concentration. As the fuel injection timing increased, the overall combustion duration decreased. This contributed to the reduction of the combustion efficiency and decreased the \( \text{CO}_2 \) emission, which is related to the combustion rate of the injected fuel into the combustion chamber. The \( \text{O}_2 \)
concentration of JP-5 is high, and CO\textsubscript{2} emission level is low compared to DF. Because the long diffusion combustion period of DF increases its overall combustion period, which increases the combustion time and combustion rate of the injected fuel, its O\textsubscript{2} concentration is lower than that of JP-5 and its CO\textsubscript{2} emission is greater.

![O\textsubscript{2} concentration](image1)

**Figure 7.** O\textsubscript{2} concentration and CO\textsubscript{2} emission characteristics with injection timings.

Figure 8 shows the CO and NOx characteristics of the JP-5 and DF with the fuel injection timings. CO is formed mainly by insufficient reaction with O\textsubscript{2} and incomplete combustion due to low temperature and pressure in the cylinder. As the fuel injection timing is retarded, the combustion becomes more complete because in-cylinder pressure and temperature have risen compared with the advanced condition, and some of the CO is converted to CO\textsubscript{2} when the oxidation intensity increases. In addition, spraying under the advanced fuel injection timing condition causes the cylinder-wall-wetting phenomenon, which leads to increase CO emission by incomplete combustion.

![CO emission](image2)

**Figure 8.** CO and NOx emission characteristics with injection timings.

It can be clearly confirmed from Figure 7a that the O\textsubscript{2} concentration increasingly decreased as the fuel injection timing was delayed from BTDC 34 CA to TDC. This means that the oxidation of the fuel was actively progressing, and the strong oxidation significantly affected the CO reduction. The CO emission level of JP-5 was higher than DF. This reduced the oxidation rate of CO because the combustion duration of JP-5 fuel by physical
characteristics such as low density and viscosity is no longer than DF. NOx reduced as the fuel injection timing was retarded. NOx reduction was consistent with the result of the ROHR analysis in Figure 5. This is because NOx forms thermal NOx, which is closely related to the combustion gas temperature. The NOx emitted from JP-5 was higher than DF. The superior evaporation rate and increased ignition delay of JP-5 releases much heat during the premixed combustion stage, and faster mixture formation of JP-5 reduces localized the fuel-rich areas unlike DF, which increases the combustion gas temperature by great ROHR. Therefore, more NOx depending on combustion gas temperature is formed to JP-5 than that of DF.

3.4. Combustion Visualization

Figure 9 shows real-time continuous combustion images of the DF and JP-5 fuel in a single-cylinder CRDI DF engine that can be visualized. The fuel injection pressure was fixed at 40 MPa, the fuel was injected at BTDC 6 CA, and the injection energizing time was kept at 1.0 ms. The start of the high-speed camera recording was synchronized with the SOE of fuel injector for accurate combustion process analysis. It was clearly confirmed that the ignition of DF fuel is faster than that of JP-5 considering their detected flame luminosities.

The diffusion flames of DF and JP-5 develop strongly after the initial ignition, but the flame of JP-5 does not spread throughout the combustion chamber. This shows that the diffusion flame intensity of DF fuel is stronger than that of JP-5. The results of the combustion visualization emphasized that the flame strength of JP-5 is inferior to DF after BTDC 40 CA. The rapid vaporization characteristics of JP-5 during the initial combustion accelerate the burning, which shortens the overall duration of the combustion.

Therefore, the excellent vaporization characteristics and long ignition delay of JP-5 enforce its premixed combustion intensity and increase ROHR; however, its diffusion flame during the overall combustion process is less dominant than that of DF because of its weak energetic oxidation reactions with the remaining air after the premixed combustion phase.
4. Conclusions

The spray, combustion, and air pollutant characteristics of DF and JP-5 fuels were analyzed in a spray visualization system and a single-cylinder CRDI DF engine. For the analysis and visualization of the spray characteristic, an optical diagnostic system connected directly to the common rail of the test engine and the high-pressure fuel line was used. The analysis of the combustion and air pollutant characteristics was carried out on a single-cylinder CRDI DF engine that could be visualized. The following significant conclusions were derived through this experimental research:

- In the sac-type nozzle, JP-5 has the same symmetrical spray pattern same as DF. The vaporization of JP-5 is better than DF because of the physicochemical characteristics of JP-5, such as poor kinematic viscosity and low aromatic content; however, the spray penetration gradually presents shorter characteristics as the spray developed.

- The low cetane value and superior vaporization of JP-5 prolong the ignition delay period regardless of the fuel injection timing. These characteristics are the main factors of the increase in the ROHR of JP-5. In addition, it makes engine torque and IMEP lower because the heat loss of JP-5 is greater than DF.

- As the fuel injection timing is advanced, the O\textsubscript{2} concentration from the exhaust gas increases and the CO\textsubscript{2} emission decreases. JP-5, which has a relatively short diffusion combustion intensity and overall combustion period, showed a higher O\textsubscript{2} concentration and a lower CO\textsubscript{2} emission than DF fuel. Retarding injection promotes the oxidation reaction and drops the in-cylinder temperature, which lowers the CO and NOx emissions. DF showed a lower CO emission than JP-5 due to its long combustion period. The high ROHR of JP-5 contributed to its higher NOx emission than that of DF.

- The direct imaging results of the combustion process showed a clear difference between the two fuels. The rapid vaporization and low cetane number of JP-5 results in a longer ignition delay than DF fuel, and the insufficient oxidation reaction of JP-5 lowers diffusion flame intensity.

It shows a symmetrical spray pattern when JP-5 fuel for naval aircraft is applied to a DF engine equipped with a SAC type injector. It is expected that a stable combustion can be occurred into the combustion chamber with this spray pattern. In a compression ignition engine, JP-5 has a long ignition delay and high ROHR. This lowers the engine torque and acts as a cause of increasing the NOx formation rate. It is believed that experiments applying various injection strategies such as multiple injection and split injection to JP-5 fuel are required in order to acquire more results in detail.

**Funding:** This research received no external funding.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** Data is contained within the article.

**Acknowledgments:** This study was performed by the 2021 Academic Research Project of the Naval Institute for Ocean Research of the Republic of Korea Naval Academy.

**Conflicts of Interest:** The author declares no conflict of interest.

**Nomenclature**

| Abbreviation | Description |
|--------------|-------------|
| ATDC         | After Top Dead Center |
| BBDC         | Before Bottom Dead Center |
| BTDC         | Before Top Dead Center |
| CA           | Crank Angle |
| CAD          | Crank Angle Degree |
| CA10         | Crank Angle corresponding to 10% MFB |
CO Carbon Monoxide
CO₂ Carbon Dioxide
CRDI Common Rail Direct Injection
DF DF Fuel
EVC Exhaust Valve Closing
EVO Exhaust Valve Opening
IMEP Indicated Mean Effective Pressure
IVC Intake Valve Closing
IVO Intake Valve Opening
JP Jet Propellant
MFB Mass Fraction Burned
MPa Mega Pascal
ms Millisecond
NATO North Atlantic Treaty Organization
NOx Nitrogen Oxides
O₂ Oxygen
P_inj Injection Pressure
ROHR Rate of Heat Release
ROP PRate of Pressure Rise
rpm Revolution Per Minutes
SFC Single-Fuel Concept
SOE Start of Energizing
TDC Top Dead Center
T_inj Injection Timing
US United State
VOC Valve-Orifice-Covered

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