



Ignition and combustion characteristics of various biodiesel fuels (BDFs)



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HIGHLIGHTS

- Ignition and combustion characteristics strongly depend on the properties of fuel.
- We examine ignition delays under different ambient pressure conditions.
- Lower viscosity fuel CME indicated the faster evaporation and ignited well.
- Significant longer ignition delay was found under lower ambient pressure condition.

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ABSTRACT

The fundamental data of ignition and combustion characteristics of various biodiesel fuels (BDFs) are exhibited for finding the optimal condition in diesel engines. The experimental research has been conducted in a constant-volume vessel with the pre-burn system under diesel-engine conditions. The ignition delays and heat release rates were investigated under different ambient temperatures and pressures. This study used diesel oil and various BDFs such as jatropha methyl ester (JME), coconut methyl ester (CME), soybean methyl ester (SME) and palm methyl ester (PME). The experimental results on fuel-spray development and combustion characteristics were affected by the properties of biodiesel fuels (BDFs), which may support potentially the optimal design of diesel engine fueled with BDFs. Evaporation and mixing are promoted at the tip of fuel jet with lower distillation temperature and lower viscosity, resulting in a shorter length dense region in the spray. These properties may disturb the mixture formation of BDFs at spray tip although the penetration lengths are almost same. The ambient temperature (T_i) and ambient pressure (p_i) strongly influenced the ignition and combustion processes of BDF and diesel oil. Though ignition delays of all BDFs are shorter than that of diesel oil in the whole temperature range from 600 K to 1200 K, CME exhibits the significant shortest delay, suggesting a dominant effect of physical properties of mixing process. At the ambient temperature 800 K and 4 MPa, all of BDFs and diesel oil predict the similar histories of heat release rate. The pre-mixture combustion with longer ignition delay dominates the combustion process at 700 K, but its period is almost constant irrespective of BDF. Ignition delay becomes longer than the injection period for high density and viscosity tested fuels, resulting in a very slow combustion.

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1. Introduction

Diesel from petroleum is the main energy source for internal combustion engines. Biodiesel has been considered to be an alternative fuel to diesel in order to reduce the use of petroleum fuels. Researchers have tried to use vegetable oils to produce biodiesel fuel (BDF). BDF offers a lot of advantages such as it is renewable, biodegradable and carbon neutral [1,2]. Soybean oil is one of the

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popular vegetable oils in United States, whereas, some others are found in Asian countries such as palm oil in Malaysia and coconut oil in the Philippines. The used cooking oils from general households, restaurants, and cafeterias have been collected and extensively used to produce biodiesel in Japan [3]. The use of biodiesel fuel (BDF) has many advantages like the regular diesel that are mostly used for transportation and power generation [4]. Biodiesel is composed of alkyl esters of fatty acids produced from vegetable oils, animal fats and used cooking oil. It can be produced by the transesterification process [5–11]. The direct use of vegetable oil and its blend in diesel engine has caused many difficult situations because of high viscosity and high phosphorus content. The transesterification reaction can successfully convert the straight vegetable oils into vegetable oil esters called Fatty Acid Methyl Esters (FAME) or biodiesel fuel (BDF). Biodiesel fuels (BDFs) have been directly used in the conventional diesel engine without modification [8–13]. Many researchers have started to develop the methods to investigate diesel combustion mechanisms in order to provide information to engine manufacturers. Diesel engines primarily operate on the principle of compression ignition.

The combustion phenomenon is generally composed of two combustion phases namely a premixed phase and a diffusion phase. The emission of diesel engine related with combustion processes of BDF has been described to have lower emissions of smoke, particulate matter (PM), carbon monoxide (CO) and hydrocarbon (HC) as compared using diesel oil, while the engine performance is almost unchanged or improved [14–17]. The targets of numerous researchers are extensively using BDFs to reduce CO₂ emission and the pollutant emissions to the environment and also to overcome the problem of NO_x emission [2–10,13–18]. However, very few researches have the fundamental data of ignition and combustion characteristics of BDF which are strongly affected by the properties of fuel. In particular, ignition delay and heat release rate are the important fundamental parameters in the investigation of the ignition and combustion characteristics in compression-ignition engines. Shahabuddin et al. [14] investigated the combustion characteristics of biodiesel based on the different varying conditions such as fuel injection timing, injection pressure, engine loads and compression ratio. The results showed that the potential of shorter ignition delay and lower heat-release rate is obtained by using higher cetane number and lower volatile fuels. The higher cetane number fuels generally depicted the shorter ignition delay and better fuel–air mixing [18]. Biodiesel intends to give better ignition quality though it has slightly lower cetane number than diesel oil. On the other hand, the high injection pressure and small nozzle-hole size provide smaller fuel droplets and faster fuel evaporation in the spray combustion process of liquid fuel, which corresponds to optimize the engine design [18,19]. The present study demonstrates the fuel spray development that is related with the ignition and combustion characteristics. The lower distillation temperature fuels exhibited the faster evaporation and easily mixed with air in the chamber [18]. The high speed fuel spray can capture both of the fuel combustion processes and the fuel injection system which are the important parts of fuel spray combustion. Combined with spray evaporation, the temporal evolution of the autoignition process determine the duration of the ignition delay.

The main purpose of this work is to exhibit the fundamental data of ignition and combustion characteristics of various BDFs and then simultaneously compare with the standard diesel oil data. This study investigated the ignition and combustion data of various biodiesel fuels (BDFs) by using constant-volume vessel at different temperature and pressure condition. Two types of conditions are considered depending on the properties of fuels. The base condition in the chamber is set at ambient pressure of 4 MPa and ambient temperature of 750 K, whereas the pressure is reduced

to 2 MPa in the final condition. The high-speed shadowgraph photos were applied to analyze the spray penetration and flame development during the combustion phenomena of these fuels. Based on the results, the authors have investigated the mechanism of ignition and combustion for these fuels to emphasize on the formation of fuel–air mixture and heat release rate.

2. Experimental setup

The injection system of pressure-storage type is setup to inject BDF into the combustion chamber as shown in Fig. 1. A common rail system has been applied to introduce BDF to the combustion chamber [18,20]. A modified version of common-rail injection system of Denso was used to operate and manage the injected fuel in this work. The fuel was injected at pressure of 80 MPa. A piezoelectric pressure-transducer (Kistler 6052A) was used to trace the pressure in the constant-volume combustion chamber and this enable us to determine the ignition delay. Pressure pick-up was connected to a charge-amp and an A/D converter and they were channeled to a computer for recording all experimental data. Fuel-spray penetration and flame developments were visualized and recorded with high-speed shadowgraph using digital camera with a speed of 10,000 fps.

2.1. Constant-volume vessel

The combustion characteristics of fuels are investigated using the pre-burn system with a constant-volume combustion vessel. An intake and exhaust valve, an injector, a spark plug, a stirrer and a pressure transducer are the important parts in this constant-volume vessel for diesel engine combustion conditions. A circular combustion chamber with volume approximately 150 cm³ has a dimension of 80 mm in diameter and 30 mm in depth. The quartz windows are equipped in this chamber to facilitate full optical access. The initial combustible premixed gases are charged and manually adjusted by the intake valve while an exhaust valve is mounted to eliminate the exhaust gases. A conventional spark ignition system is used to burn the premixed gas, meanwhile the temperature distribution before fuel injection is controlled by the stirrer which is kept constant over 8000 rpm. At the top of the vessel, there is a single shot injector which is 0.22 mm in diameter to inject the fuel. Like diesel-engine combustion, this chamber has been used to produce a high temperature and high pressure condition [18].

2.2. Optical diagnostics

The technique of shadowgraph is used to visualize the liquid spray penetration and development of flame. Shadowgraph is

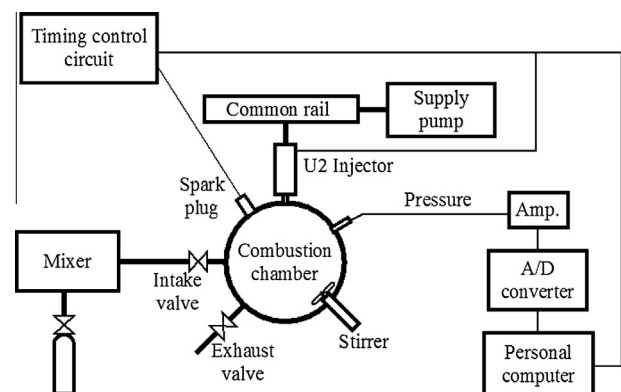


Fig. 1. Schematic diagram of experimental setup.

generally applied to analyze the density changes in a translucent system. These are shown by the displacement of rays resulting from being deflected. It is necessary to use the uniform intensity of light through the system in order to allow the differences in density visible. The setup is essentially following the Z-type schlieren setup. The light source, which is a 1 kW Xenon lamp (Katou light LS-1000) with 0.3 mm in diameter pinhole, supports the intense prediction throughout the system. The pinpoint light is then reflected by a flat folding mirror and is caught via a concave mirror (focus length 1910 mm). A concave mirror again reproduces the rays to flat folding mirrors and then targets to a pinpoint and entering high-speed CMOS camera (Phantom v7.1 or Fastcam SA1). The shuttered speed of camera was optimized based on the igniting rate of fuel–air mixture and the flame brightness. The image in this shadowgraph system is highly dependent on the density of fuel. In this study, photographs were captured at a speed of 10,000 fps and an exposure duration of 30 μ s.

2.3. Test fuels

There are four kinds of BDFs used in this study: jatropha methyl ester (JME), coconut methyl ester (CME), soybean methyl ester (SME) and palm methyl ester (PME). The properties of BDFs were determined prior to the study of ignition and combustion characteristics of fuels. These properties are very important to provide the ignition data of the fuels. The analysis of fuel properties was done by Shimadzu Techno Research Inc. ASTM D 613/05 and ASTM D 1160 were used to determine the cetane number and distillation temperature of the fuel, respectively. In general, biodiesel fuels have higher density and viscosity than the standard diesel oil at room temperature [11,12]. It can be clearly seen in Table 1 that the tested BDFs have particularly higher density, viscosity, and distillation temperature than the standard diesel oil although the cetane number of diesel oil is almost same as BDFs.

3. Operating condition

The high temperature and pressure environment was generated in the beginning when the liquid fuel was injected in the chamber [18]. Fig. 2 presents an example of the pressure history of the constant-volume vessel. The oxygen concentration was set to 21% after pre-combustion process while the ambient pressure (p_i) was controlled at 4 MPa as a base condition. Then, the effect of pressure was also investigated by reducing the ambient pressure p_i to 2 MPa. Based on the ideal gas law, the ambient gas temperature was calculated as a thermodynamically average temperature from the known pressure at the time of fuel injection and the mass of gas composition within the chamber. The reaction was normalized to produce combustion products by assuming the complete combustion. The premixed gases of oxygen, nitrogen, hydrogen and ethylene with a certain designated percentage were allowed to be introduced into the combustion chamber via the intake valve, and then ignited by spark plug to produce high temperature and

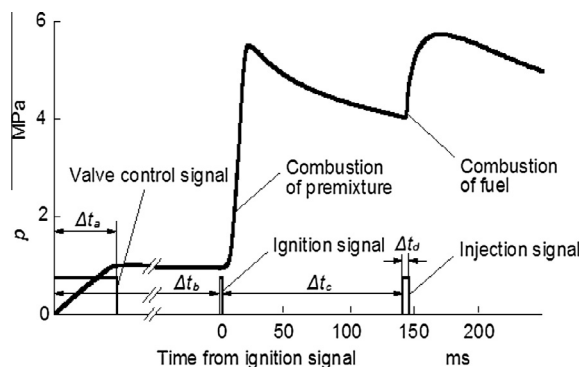


Fig. 2. Pressure history of the simulated fuel combustion process.

pressure through combustion. The stirrer was required to run 20 s before spark-ignition for uniform temperature distribution in the chamber. In the case of Fig. 2, the ignition of the premixed gas ended at 24.5 ms at a pressure of 5.7 MPa and the burnt gases began to cool down because of the heat transfer. The autoignition of the injected fuel causes the second pressure rise as shown in the figure.

The fuels were supplied using the common-rail system and injected into the vessel at a pressure of 80 MPa. The temperature was controlled in the range of 600–1200 K to study the effect of ambient temperature (T_i) on ignition delay and combustion characteristics. This temperature range covers the temperature from the start of the cooling process to the last warming-up condition for compression ignition engines. The quantity of fuel was maintained by the injection duration to reach an equivalence ratio of 0.22 at $T_i = 800$ K and $p_i = 4$ MPa. The shadowgraph images were taken at several conditions to visually study the liquid fuel spray combustion. These images were taken at $T_i = 750$ K and $p_i = 2$ and 4 MPa to investigate the spray penetration, flame development and mixture formation for BDF fuels and diesel oil.

4. Ignition delay

The ignition delay in this study was defined as the time between the start of injection and the rapid increase of pressure in the vessel. During the delay period, both the physical and chemical changes occurred at the same time [18,21]. The fuel was atomized, vaporized and well mixed with air during the physical ignition delay period while the ambient temperature, ambient pressure, fuel properties and oxygen concentration were related to the chemical process. In general, higher cetane number shows shorter ignition delay time. On the side of the physical properties, the higher density and viscosity of the biodiesel cause the longer ignition delay. On the other hand from the chemical properties, oxygenated fuel of biodiesel may promote the reaction to induce a shorter delay. If the delay time is too long, the accumulated mixture available for simultaneous explosion is large and thus it

Table 1
Properties of biodiesel fuels and diesel oil.

Properties	BDF fuels				Diesel oil		
	JME	CME	SME	PME			
Density (15 °C)	g/cm ³	JIS K 2249	0.8820	0.8751	0.8863	0.8767	0.825
Viscosity (40 °C)	mm ² /s	JIS K 2283	4.480	2.735	4.188	4.558	3.281
Cetane Number		ASTM D 613/05	56.4	52.2	55.6	56.8	54.4–56.5
Distillation Temperature							
T_{10}	°C	ASTM D 1160	350.0	248.5	351.0	344.0	201.8
T_{50}	°C		351.5	287.5	353.0	347.0	270.5
T_{90}	°C		354.5	342.5	356.0	352.0	334.9

causes rapid combustion with high pressure and temperature, contributing to NO_x emissions and combustion noise [22].

5. Results and discussions

Prior to describe the ignition and combustion characteristics of fuel, the spray penetrations and flame development for these fuels were discussed by utilizing the visualization data. The ignition delay time is plotted as Arrhenius form and reflects the important of chemical kinetics. The ignition delay times were investigated corresponding to heat-release rate which is based on the pressure history. Finally the combustion processes of fuels were analyzed under base condition.

5.1. Spray penetration and flame development

The spray penetration, the fuel–air mixture formation and the flame development were analyzed by using shadowgraph images. The experiments were conducted at $T_i = 750$ K, $p_i = 2$ MPa, 4 MPa, injection pressure (p_j) = 80 MPa, nozzle diameter (d_N) = 0.22 mm and oxygen concentration (r_{O_2}) = 21%.

The shadowgraph images show the spray penetration and flame development to provide further explanations for the effects of the properties of fuel on mixture formation and combustion process. For the liquid fuels, the injected spray normally consists of a cold, liquid phase core surrounded by a mixture which contains fuel droplets and vaporized fuel. The differences in spray penetration, spray configuration and flame region were recorded and illustrated on the shadowgraph images using OriginPro 8 (OriginLab Inc.). These shadowgraph images display the density difference of fuel sprays consisting of liquid and vapor phases, which facilitate us to easily determine the spray length. In Figs. 3 and 4, each row corresponds to an individual fuel and demonstrates the spray penetration from the start until the end of injection time. The observation result shows a slightly different profile of shade density and flame luminosity for different BDF sprays photographs at each column. To provide more explanation of the effect of combustion processes for BDFs, the flame development, which is discussed in the combustion process, taken by the shadowgraph photos are also depicted in this study. These figures described the differences of various BDFs showing the combustion luminosity superimposed onto the shadowgraph images. The rows correspond to a certain fuel with an image time interval of 0.08 ms.

There are slight differences of flame luminosity and spray behavior in these fuels. In particular, CME has a faster evaporation process at $p_i = 4$ MPa as compared to JME, SME and PME and it can be seen in Fig. 3. It means that the fuel contained in the spray tips

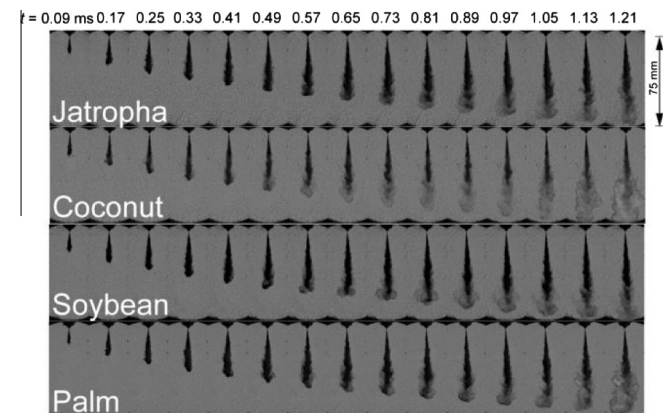


Fig. 3. Shadowgraph images of spray development of various BDF at $p_i = 4$ MPa and $T_i = 750$ K.

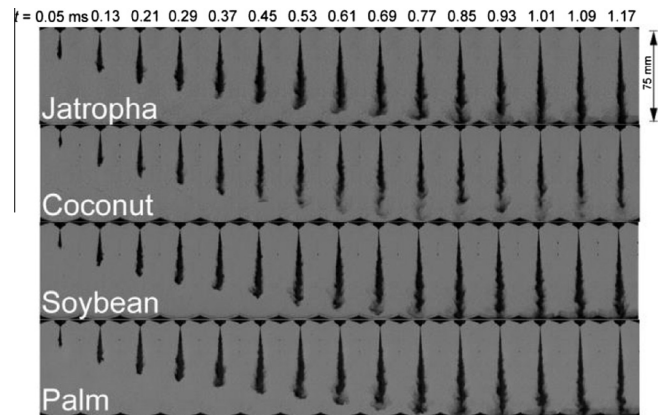


Fig. 4. Shadowgraph images of spray development of various BDF at $p_i = 2$ MPa and $T_i = 750$ K.

has been completely evaporated and easily penetrated to the chamber wall. The sprays of all fuels are evident to be similar and present the liquid dark phase from the beginning of fuel injection until $t = 0.41$ ms. The fuels were ready to evaporate at $t = 0.65$ ms. All fuel sprays were developed and reached the vessel wall at the time between 0.73 ms and 1.05 ms. The various evaporation and mixing processes can be easily distinguished for the liquid sprays. CME spray mixed with surrounding air at spray tip region prepared to ignite at $t = 0.73$ ms. The liquid phase was vaporized and auto-ignited during the time from 0.81 ms to 1.21 ms. However, the autoignition time happens around 1.13 ms for JME, SME and PME due to their higher density and viscosity than CME. Fig. 4 reveals that various biodiesel fuels have slow evaporation rates at $p_i = 2$ MPa which are shown as darker color in sprays core. High density and high viscosity of fuels showed slow evaporation with very dark spray-cores [21,17]. At 2 MPa, all fuel sprays have developed and reached the vessel wall at $t = 0.77$ ms. The mixing area for JME, SME and PME is just around the spray tip attached to the vessel at 0.69 ms, while the evaporation and well-mixed fuel slightly penetrates to the downstream of the sprays for CME. Because CME has the lowest viscosity, density and T_{10} distillation temperature in comparison with other BDFs, faster evaporation has occurred together with the shorter liquid phase length and longer vapor phase penetration. In general, all of the tested fuels represented longer liquid phase length under lower ambient pressure of 2 MPa. The narrow range of distillation temperatures of JME, SME and PME as shown in Table 1 may also retard the fuel evaporation at lower temperature.

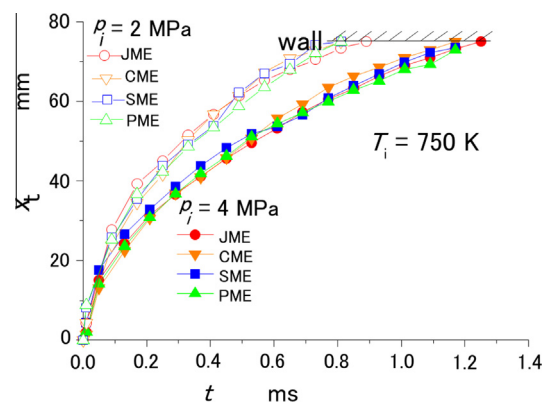


Fig. 5. Effect of ambient pressure on the penetration lengths of BDFs at $T_i = 750$ K.

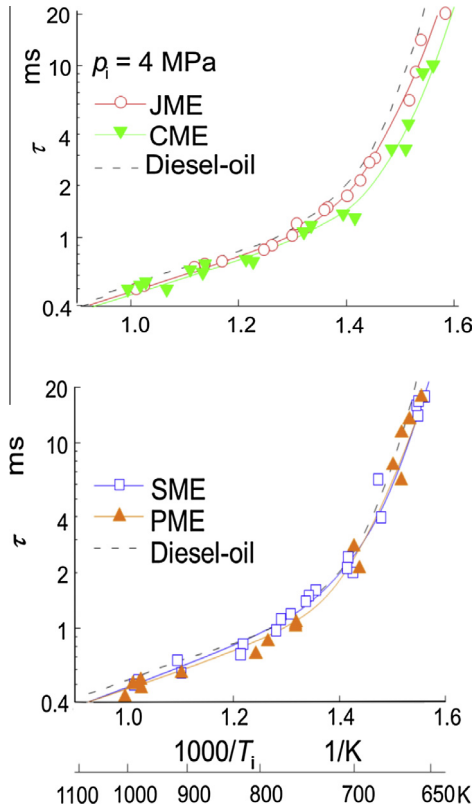


Fig. 6. Effects of T_i on τ for BDFs and diesel oil at $p_i = 4$ MPa.

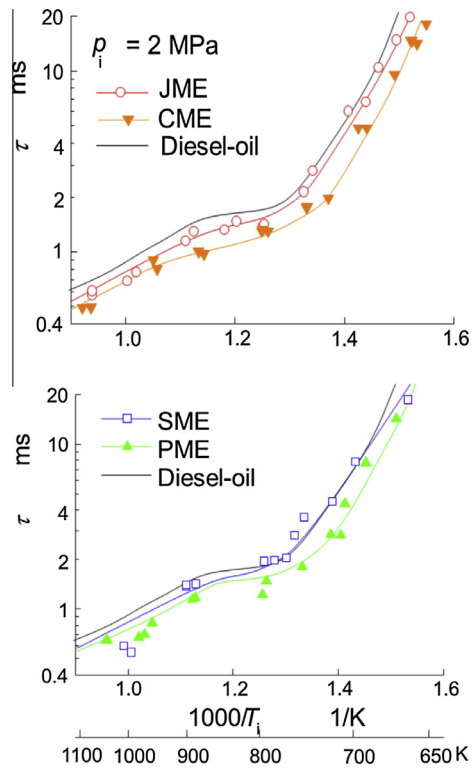


Fig. 7. Effects of T_i on τ for BDFs and diesel oil at $p_i = 2$ MPa.

The penetration lengths of various BDF sprays (x_t) versus the time from the injection start (t) at ambient pressures of 2 and 4 MPa are shown in Fig. 5. The start of injection or $t = 0$ is

determined by observing sequence shadowgraph images prior to the injection start until the fuel was injected into the chamber. Based on Fig. 5, the high viscosity and high density biodiesel fuels (BDFs) showed slightly shorter x_t value. The penetration lengths of JME, SME and PME sprays are almost the same to reach the vessel wall at 4 MPa. CME indicated a slightly longer penetration length than that the other BDF fuels. The spray penetration length is longer due to faster evaporation and better atomization [23]. In more detail, JME and PME sprays indicated shorter x_t at $p_i = 2$ MPa and $0.2 \text{ ms} < t < 0.6 \text{ ms}$ owing to their high density and viscosity properties than SME and CME as given in Table 1.

5.2. Ignition and combustion characteristics

In the diesel-combustion conditions, it is found that the great effect of ambient temperature rely on the ignition delay. This

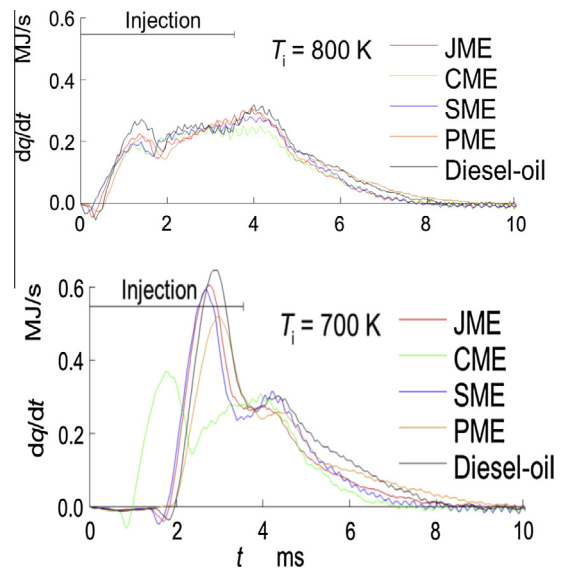


Fig. 8. Effects of T_i on dq/dt for BDFs and diesel oil at $p_i = 4$ MPa.

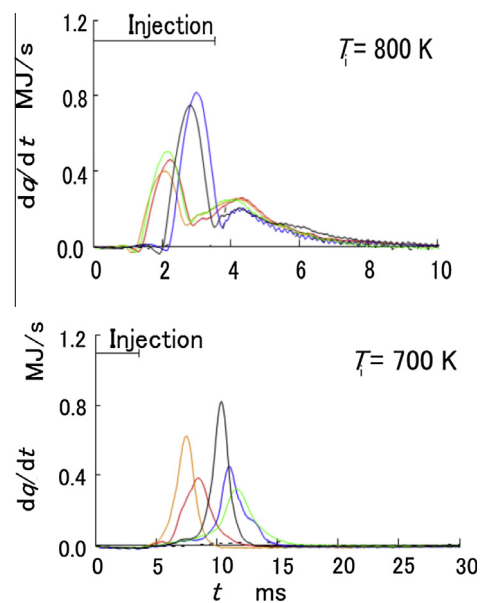


Fig. 9. Effects of T_i on dq/dt for BDFs and diesel oil at $p_i = 2$ MPa.

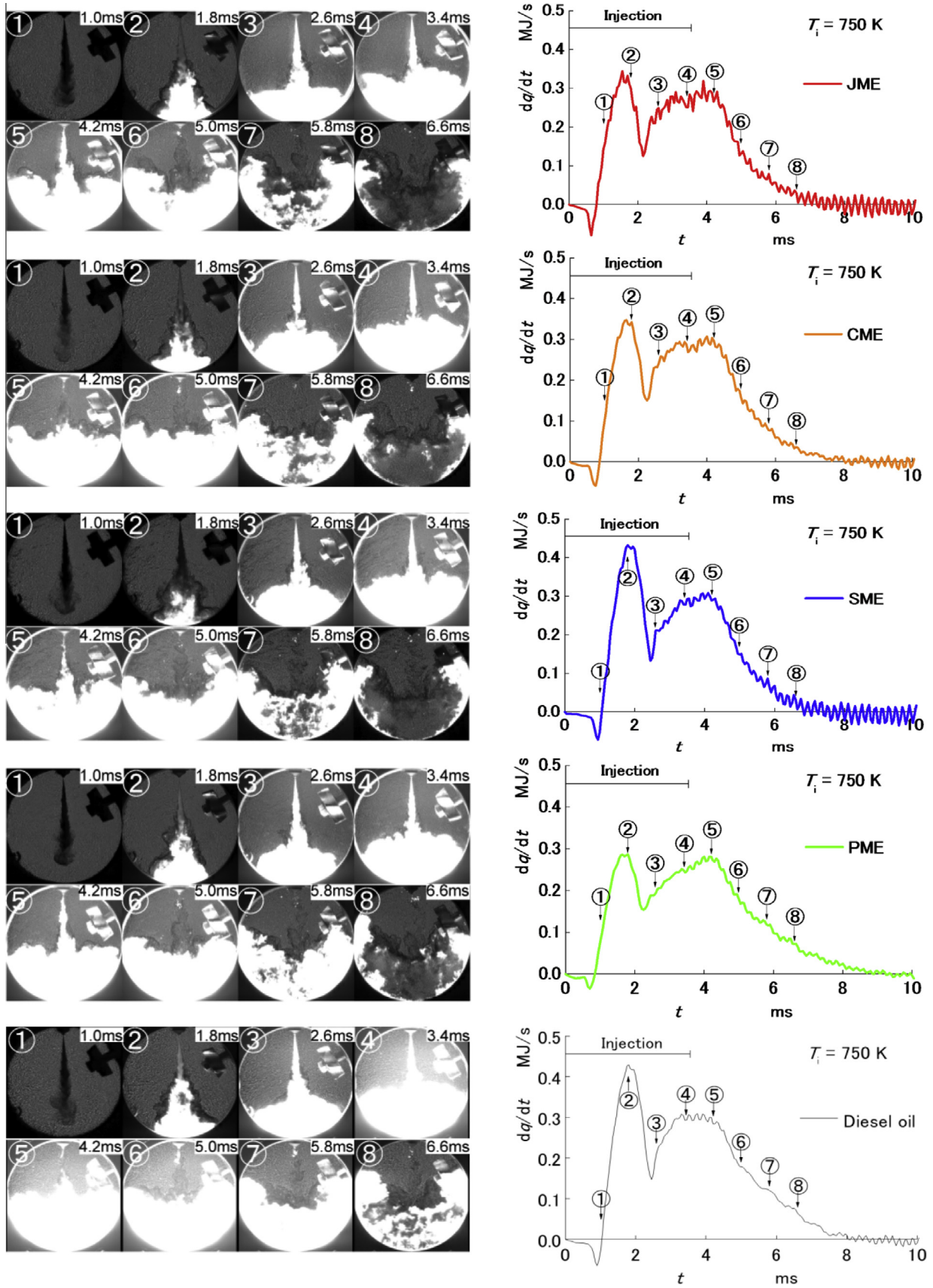


Fig. 10. Flame development and heat release rate of BDFs and diesel oil at $p_i = 4$ MPa and $T_i = 750$ K.

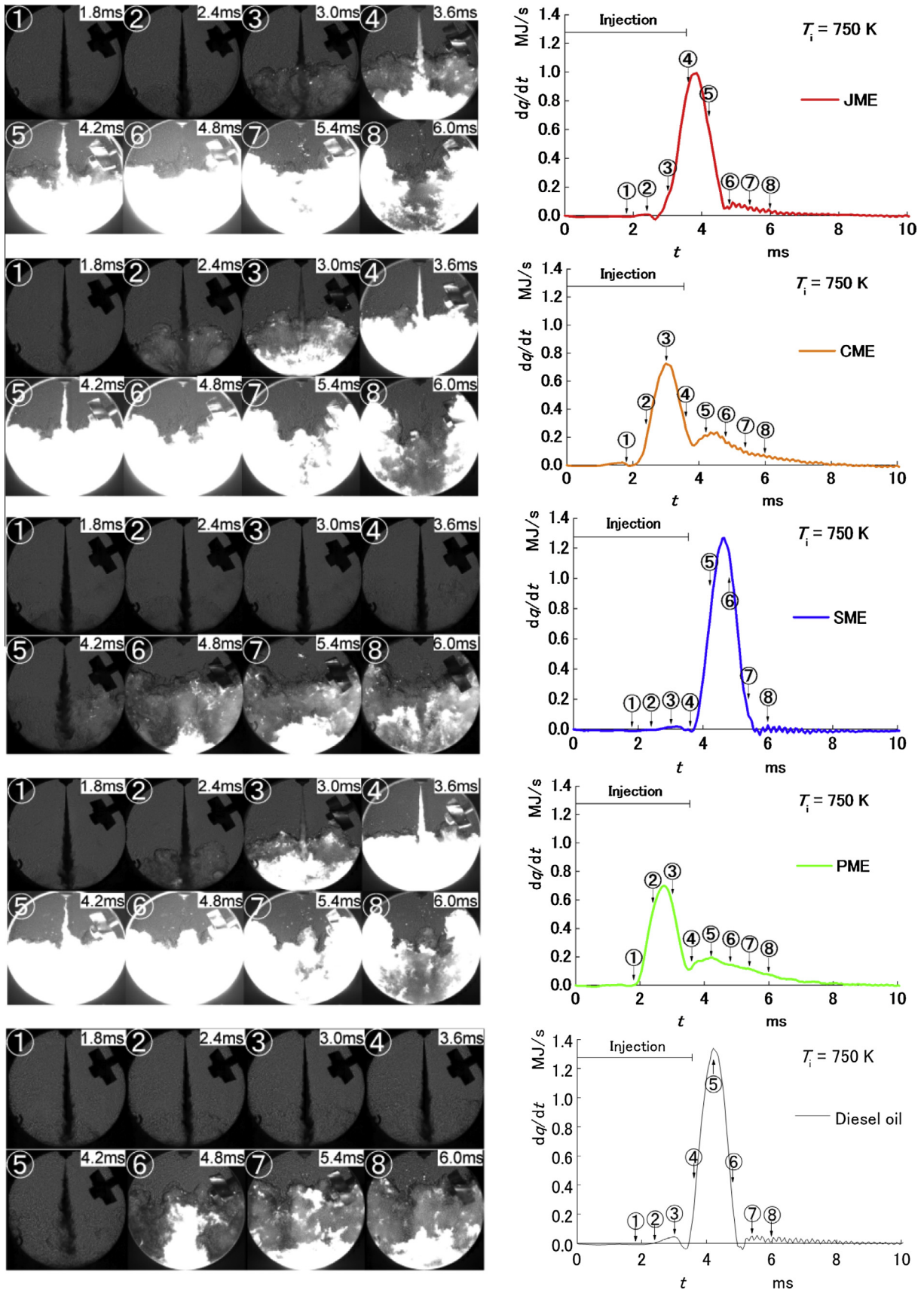


Fig. 11. Flame development and heat release rate of BDFs and diesel oil at $p_i = 2 \text{ MPa}$ and $T_i = 750 \text{ K}$.

dependence is associated with the chemical kinetics during auto-ignition of fuels. The turbulent mixing and chemical kinetics depend on the temperature and pressure. The differences in fuel properties namely density, viscosity and distillation temperature affect the evaporation, mixture formation and ignitability of fuels. In particular, lower density and lower distillation temperature fuels easily evaporate and mix with surrounding air in the chamber to form a more burnable mixture which tends to shorten ignition delay and subsequently increase the ignition at the low temperature. The longer ignition delay and the longer spray penetration correspond to higher dq/dt level and larger flame region.

5.2.1. Heat release rate (dq/dt)

It is necessary to calculate heat release rate (dq/dt) to illustrate the combustion characteristics of fuel. It depends on the ignition delay and the properties of fuel. This study calculated dq/dt in the constant volume vessel combustion based on the first law of thermodynamics [18]. Fig. 6 shows the effect of ambient temperature T_i on ignition delay (τ) for BDFs and diesel oil as an Arrhenius form at 4 MPa. The difference in ignition-delay trends in the entire low temperature region is believed to be caused by a difference of fuel properties. It is noted that fuel with high density and viscosity gives the longer ignition with slow evaporation. All of BDFs and diesel oil generally exhibit similar trend of ignition delay (τ). τ slightly decreases at higher T_i but largely increases at lower T_i . The amount of evaporated fuel and the chemical reaction rate in the combustion vessel decrease as ambient temperature decreases. JME, SME and diesel oil exhibited longer ignition delays at lower ambient temperature T_i at 750 K. The slight difference in the ignition-delay time can be distinguished by comparing the increase in the dq/dt curves during the initial combustion. The slower increasing in dq/dt rates corresponded to longer ignition-delay times [18,24].

BDF fuels hold different in ignition delay (τ) at $T_i > 750$ K. It is clearly seen in Fig. 7 that the reasonable shorter ignition delays were obtained at the temperature range from 700 K to 900 K. That temperature range covers top dead center (TDC) temperatures in the compression ignition engine with direct-injection [25–27]. It indicates that acceptable ignition characteristics may be obtained at normal engine conditions. The high temperature in the chamber at $T_i > 1000$ K indicates rapid evaporation to the injected fuels and shortens τ as shown in Fig. 7. The formation of more combustible gases creates shorter τ and promotes the ignition at higher temperature. Based on the results, shorter Arrhenius ignition-delay trends were observed at $p_i = 2$ MPa as compared to $p_i = 4$ MPa. The difference of τ at $p_i = 4$ MPa became smaller at high temperature and at the negative temperature coefficient regimes. The negative temperature coefficient regime affects the bend in these curves. The CME and PME showed slightly shorter ignition delays than the others.

Fig. 8 represents the combustion process of BDFs that shows the rate of heat release dq/dt at $p_i = 4$ MPa at different ambient temperatures. The longer ignition delays of JME, SME and diesel oil exhibited an rapid increased in dq/dt . At $T_i = 800$ K, all of test fuels have the same dq/dt curve after the premixed combustion has occurred at a higher rate. The combustion with the second peak of dq/dt rate for each fuel was observed at this time. After premixed combustion, the diffusive combustion is followed by a peak when fuel injection ends. At this temperature region, dq/dt curve exhibits a typical combustion process of direct injection (DI) compression ignition engines. At lower ambient temperature $T_i = 700$ K, the drastic change in ignition delay of CME is at around 1–2 ms. Similar trends of dq/dt of SME and diesel oil were observed at different ambient temperature. Meanwhile, two-stage combustion processes of all tested fuels are found at 800 K in Fig. 9. Particularly in CME, shorter ignition delay led to shorten the

premixed combustion and lengthen the period of diffusive combustion. However, at $T_i = 700$ K, the injected fuels were mixed well with air during longer ignition delay and thus showed only premixed combustion. The prolonged ignition delay slightly slower dq/dt increase for JME, SME and diesel oil, while rapid increase in dq/dt of CME and PME was observed due to the slow reaction rate. Therefore, the slow chemical reaction rate at $p_i = 2$ MPa can be found by a somewhat smaller increase in dq/dt during the premixed combustion and longer diffusion period compared with $p_i = 4$ MPa.

5.2.2. Combustion processes in standard condition

The variation in ignition delay can cause drastic changes in the combustion processes of BDFs and diesel oil. The combustion processes of BDFs and diesel oil, shown in Fig. 10, are explained in detail by the flame development with shadowgraph images at 750 K under base condition. The heat release rates (dq/dt) are separately predicted for each fuel. The photos at every condition show the flame development at the time just before and after ignition and also illustrate the combustion process in the flame region. In comparing the burning time of BDF and diesel oil, BDFs are completely burned at 5.8 ms. It was noted that the good fuel–air mixing reveals the rapid increase in dq/dt [24]. CME predicted shorter liquid phase than JME, SME, PME and diesel oil due to its lower viscosity and lower distillation temperature. It tends to completely evaporate and gives the better fuel–air mixing which causes a brighter flame with rapid increase in heat release rate. The diesel oil ignited until 6.6 ms, therefore, its combustion period is slightly longer than biodiesel (BDFs). The fast fuel evaporation and better mixture formation corresponded to the shorter spray length with brighter flame region. The combustion process of SME seemed to be quite similar with that of diesel oil during premixed combustion at 2 MPa as illustrated in Fig. 11 while similar trends are observed in both CME and PME. The very dark flame regions were still found at 4.2 ms in the diesel oil and SME. The mixture formation of JME, CME and PME may occur earlier than that of diesel oil and SME. Owing to low evaporation characteristics, the fuel sprays are heated by the burned fuels and more contact between the liquid phase and flame is observed. Lastly, significant differences can be found in dq/dt at same ambient temperature 750 K for two different pressures 4 MPa and 2 MPa.

6. Conclusions

The ignition and combustion characteristics of BDFs were fundamentally studied in this research under direct-injection compression-ignition engine conditions. Ambient temperature and pressure greatly affect the ignition delays of BDFs, especially at a lower temperature with longer ignition delay. CME shows slightly shorter ignition delay and better ignition at higher temperature than JME, SME and PME because of its significant lower viscosity and distillation temperature. Ignition delay decreases when temperature and pressure increase. The constant nozzle-hole diameter exhibits small effect to ignition delay and heat-release rate. The shorter ignition delay and rapid increase in heat-release rate can be obtained under high pressure and high temperature condition. Moreover, the ambient pressure 2 MPa case demonstrated the simulated condition of PCCI (premixed charge compression ignition) engine as well.

On the other hand, it is evidently seen that the evaporation and mixing process of every tested fuel is affected by physical properties of fuel such as density, viscosity and distillation temperature. The slow evaporation and mixing processes are predicted by high viscosity and high density BDFs. CME exhibited faster evaporation and ignited well during the short period than the other tested BDF

fuels. JME, SME and PME represented the slow evaporation and chemical reaction in comparison with the diesel oil. The shorter liquid phase suggests that BDF is easy to vaporize and mix with surrounding air, forming a more combustible charge during the autoignition period. Using high speed shadowgraph images successfully enables to explanations in spray penetration and flame development with time. These findings provide the information for the optimal design of diesel engines fueled with biodiesel fuels.

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