

A Study on Improvement of Diesel Spray Characteristics Fueled by Rape-seed Oil

Azwan Sapit, Sho Nagayasu, Yasunori Tsuboi, Yuzuru Nada, Yoshiyuki Kidoguchi

The University of Tokushima

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ABSTRACT

It is widely known that direct application of biomass fuels oil to DI diesel engines increases the carbon deposit in the engine. To minimize this effect, biomass fuel is subjected to transesterification process. Nevertheless, it is still desirable to use biomass fuel without transesterification. As diesel engine combustion and emissions are strongly dependent on spray characteristics and mixture formation, this study tries to clarify the spray characteristics of rape-seed oil (SVO) including spray structure, spray development, fuel evaporation, and droplets atomization.

Optical observation reveals that rape-seed oil (SVO) spray forms a stick-like structure without branching structure at spray boundary and has heterogeneous density distribution in a liquid column at spray centerline. SVO spray hardly penetrates at exceedingly initial stage of injection, in particular at low injection pressure. Combination of high injection pressure and high ambient temperature lengthens spray penetration and produces branching structure and fine droplets. Macro-scale characteristics of SVO spray can be improved by applying reduction of nozzle sac-volume and scaling of nozzle hole-diameter accompanied with high injection pressure. However, it is hard to improve stick-like structure and heterogeneous density distribution of SVO spray under low injection pressure and low ambient temperature.

INTRODUCTION

After the 1973 oil embargo, the non-renewable nature and limited resources of petroleum fuels become a matter of great concern. The present source of fuels used in internal combustion engines is expected to be depleted in the near future, especially if the consumption rate increases yearly. It has become very important to study the alternative sources of fuel because of the concern over the availability and the price of petroleum based fuels.

Furthermore, 1997 Kyoto World Climatic Changes Conference directives have been issued with the aim of reducing by 5% by 2010 of the emission in the atmosphere of "greenhouse" gases from 1990 levels. This is important because, in considering the actual tendencies of growth, the real reduction corresponds to more than 25%. Thus, to make sure that the target is achieved, further reduction of CO₂ emission from automobile is required. Diesel engines are

advantages for CO₂ emission and fuel diversity. All these aspects have drawn the attention to conserve and stretch the oil reserve, and at the same time, to reduce the emission level from current engine, by the way of alternative fuel research.

Biomass fuel are mainly derived from biomass or bio waste such as a vegetable oil or animal fat-based diesel fuel. Besides being renewable and biodegradable, they have characteristics quite similar to those of a common diesel fuel. They contain no sulphur elements and are regarded as no contribution to the accumulation of CO₂ in the atmosphere. However, actual practice in the biomass as fuel for diesel engines is subjected to transesterification process. This is because carbon deposit, for instance, are produced by direct use of biomass fuel in DI diesel engines. The carbon deposit causes harmful damage to engines and unfavorable effects on engine durability. Blending biomass with practical fuel can partly solve the problem. On the other hand, it is still desirable to use neat biomass fuel to DI diesel engine without transesterification or blending.

As for fuel characteristics, it is widely known that biomass fuel has high level of kinematic viscosity and high distillation temperature, and it is oxygenated fuel. Previous works [1-8] proved that biomass fuel increases NO_x emissions in many diesel engines. Particulate emissions decreases at heavy load due to oxygenated nature; in contrast, SOF (Soluble organic fraction) emissions increases at light load operation. High viscosity of biomass fuel results in resistance of fuel flow during fuel injection, affecting the spray development and, in the end, affects the atomization process. SOF emissions is caused partly by poor atomization and SOF emissions is supposed to be one of source of carbon deposit. Other problems concerning biomass fuel include limited oxidation and storage stability, a tendency to form deposits, corrosion issues, cold flow problems and questionable stability from diverse feed stocks.

One of the important strategies for low emission diesel engine is to control the combustion process. Precise control of the fuel injection, spray atomization and fuel-air mixing are among the fundamental factors that control the combustion and emission formation. It is reported that application of high-pressure injection and high ambient temperature could promote better spray atomization and fuel-air mixing [9-13]. These strategies should be also applied to direct use of biomass fuel.

In this study, the spray characteristics of rape-seed oil as a biomass fuel including microscopic spray structure and spray development, fuel evaporation, and droplets atomization is studied by optical technique. The technique reveals macro-scale and micro-scale spray structures. This study first examines source of carbon deposit on the view point of spray characteristics, then tries to improve spray characteristics of rape-seed oil. For this purpose, effect of nozzle sac-volume and scaling of nozzle hole-diameter on spray structure and atomization is investigated by photography technique.

EXPERIMENTAL SETUP

CONSTITUENT SYSTEM AND OPTICAL SETTING

Figure 1 shows the experimental setup. The outline of the setting is almost same as previous work [14]. The experimental system is composed of spray chamber, rapid compression machine, fuel injection device and optical system. A rapid compression machine [15] was used to create diesel atmosphere in the spray chamber. The spray chamber has a diameter of 60mm and a width of 20mm. A single-shot common rail fuel injection system was used to inject the fuel into the spray chamber. Two kinds of optical system, namely shadowgraph photography and direct photography, were used.

Arrangement of shadowgraph photography method is shown in Fig.1(a). The spray chamber has upper access for the fuel injector unit and two opening windows sized 60mm in diameter. For shadowgraph photography, both opening were sealed with quartz windows. One side of window was used for the nano-spark light [16] access and the other side was used for the still camera photography access. The nano-spark unit includes a nano-second spark light sources operated by high-voltage power supply. High-intensity light can be produced by electric discharge between electrodes located inside the spark head. The shadowgraph photography was performed in the complete dark room. The camera shutter of the still camera (Pentax, 6x7) was let open to enable the access of nano-spark light at short duration of

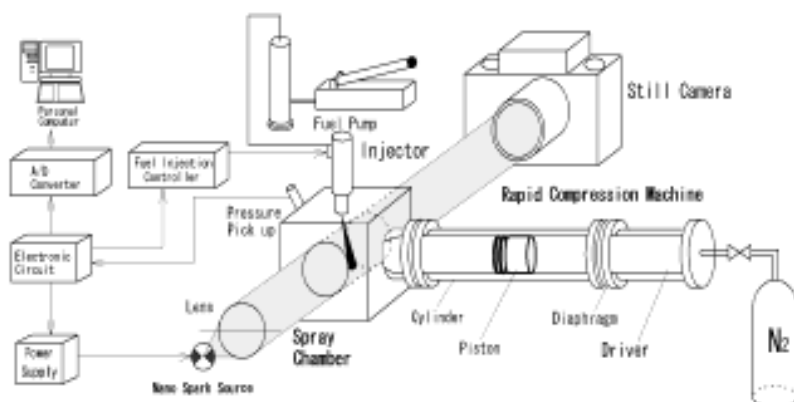
30ns into the camera. A prime lens (Nikkor 50mm f/1.4) was mounted on the camera. A Nikon DSLR D60 digital camera was also used interchangeably. Using this system, spray images were captured with still images on normal photographic black and white film (Fuji Neopan ASA400) by a magnification factor of 3.5.

In addition, this experiment also employed high speed video camera to capture dynamic behavior of spray by direct photography method. Figure 1(b) shows optical arrangement of this method. The high speed video camera (Nac MEMRECAM GX1, lens: AIAF DC-Nikkor 135mm f2D, frame speed: 20000fps) was set to capture the multiple-hole nozzle spray development from the bottom view. For direct photography method, only one opening window was sealed with the quartz window while the other was used to mount the fuel injector. The injector unit was installed on the side wall of the spray chamber. Light source used in this setting was metal halide lamp. The light reflection from two flat mirrors was used to illuminate the entire spray chamber.

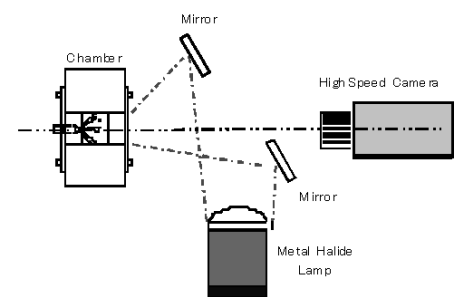
EXPERIMENTAL PROCEDURE AND EXPERIMENTAL CONDITION

The spray chamber was filled with mixture gas of nitrogen and argon. The inert gas was supplied to prevent spray ignition. This study concentrated on spray characteristics at initial stage of injection before ignition. This is because initial stage of mixture formation accompanied with spray atomization greatly affects combustion and emissions. Further, this study pays attention to spray behavior at light load condition of engine operation because SOF emissions which may be source of carbon deposit are mostly produced at light load condition and, at light load, injection terminates before ignition.

The ambient temperature T_i in the spray chamber was set at $T_i=298\text{K}$ or $T_i=700\text{K}$ with keeping ambient density at 15kg/m^3 corresponding to the density in ordinary DI diesel engine cylinder at start of fuel injection. Accordingly, ambient pressure was 1.0MPa for $T_i=298\text{K}$ and 2.4MPa for $T_i=700\text{K}$, respectively. High temperature atmosphere was



(a) Spray observation system and arrangement of shadowgraph photography



(b) Optical arrangement of direct photography

Fig.1 Schematic diagram of experimental setup

created using the rapid compression machine. When ambient temperature reaches designated temperature after termination of rapid compression, fuel was injected into the spray chamber and spray behavior was taken by above mentioned optical system. The injection pressure P_{inj} was $P_{inj}=40\text{MPa}$ or 70MPa and injection duration was kept for 2ms.

The images taken by films were scanned and changed to digital pictures, then the droplets captured in the images were analyzed using technical computing software (WaveMetrics IGOR pro6.0). The diameter of each droplets and the number of droplets were analyzed by previously developed image analysis technique [17].

TEST FUEL AND INJECTION NOZZLE

Rape-seed oil (SVO) was used representative as biomass fuel. JIS#2 diesel fuel (GO) was also used as reference fuel. Table 1 shows the fuel properties and Fig.2 shows the distillation characteristic of the test fuel reported by Yoshimoto et al.[18]. SVO has characteristics of high viscosity and high distillation temperature. Density and kinematic viscosity at room temperature of SVO is 911 kg/m^3 and 62cSt , respectively, and GO 836 kg/m^3 and 3.2cSt . SVO starts distillation at over 700K while GO reaches 90% distillation mass at about 600K [18].

Table 1 Fuel Properties

Fuel and Notation	GO	SVO
Density 15°C g/cm^3	0.827	0.911
Kinematic viscosity $\text{mm}^2/\text{s}@303\text{K}$	3.30	47.78
Carbon wt-%	0.86	0.78
Hydrogen wt-%	0.14	0.11
Oxygen wt-%	0	0.11
Lower heating value kJ/kg	42.70	38.14
Cetane index	58.2	unknown

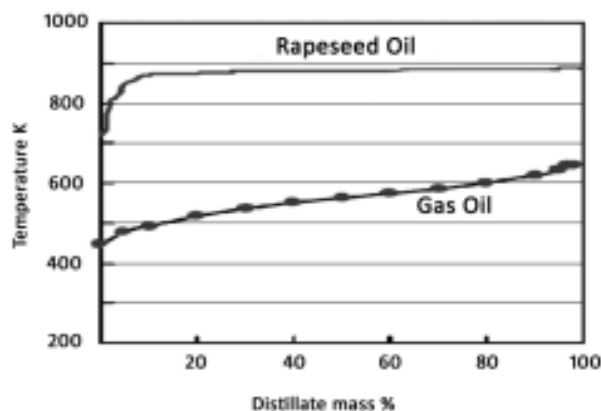


Fig.2 Distillation characteristic of test fuel[18]

Specification of fuel injection nozzle is one of important parameters that affect spray characteristics. This study changes nozzle sac-volume and nozzle hole-diameter scaling. These characteristics are known to improve spray atomization, leading to better emissions from diesel engines using diesel fuel. This study tries to investigate effect of sac-volume and nozzle scaling on SVO spray characteristics,

aiming to find measures to improve emissions using SVO in DI diesel engines. Table 2 summarizes nozzle specification used in this study. Nozzle P0 is a single-hole nozzle with hole-diameter of 0.18mm . This nozzle was used to compare spray characteristics between SVO and GO sprays. Nozzle P57 and P28 are four-hole nozzle with same hole-diameter of 0.25mm and different sac-volume.

The sac-volume of P57 is 0.57mm^3 . P28 is a mini-sac nozzle with sac-volume of 0.28mm^3 . P57 and P28 were used to investigate effect of sac-volume on SVO spray development. Nozzle PS, PE and PN are five-hole nozzles with same inlet hole-diameter and different outlet hole-diameter. PS has straight hole of 0.25mm in diameter. PE is enlarging hole with inlet diameter of 0.25mm and outlet diameter of 0.27mm . PN is narrowing hole with inlet diameter of 0.25mm and outlet diameter of 0.23mm . The three nozzles are mini-sac nozzles with sac-volume of 0.28mm^3 and flow rate is identical. Comparing SVO spray characteristics injected by these nozzles can reveal effect of scaling of nozzle hole on SVO spray development.

Table 2 Nozzle specification

Nozzle	Symbol	Number of holes	Nozzle hole inlet dia. mm	Nozzle hole outlet dia. mm	Sac volume mm^3	Flow rate g/min
Single hole	P0	1	0.18	-	-	1360
Larger sac vol.	P57	4	0.25	-	0.57	
Smaller sac vol.	P28			-	0.28	
Straight hole	PS	5	0.25	0.25	0.28	
Enlarging hole	PE			0.27	0.28	
Narrowing hole	PN			0.23	0.28	

RESULTS AND DISCUSSION

CHARACTERISTICS OF SPRAY STRUCTURE AND ATOMIZATION OF RAPE-SEED OIL

Spray structure was first compared between rape-seed oil (SVO) and JIS#2 diesel fuel (GO) to make clear spray characteristics of rape-seed oil. The still images of spray were taken by shadowgraph technique. Fuels were injected using nozzle P0 that is a single-hole nozzle with hole-diameter of $d_n=0.18\text{mm}$ at an orientation angle of 15° from the injector centerline.

Figure 3 compares spray images taken at time $t=0.5\text{ms}$ after start of injection (aSOI) under condition of ambient temperature $T_i=298\text{K}$ and injection pressure $P_{inj}=40\text{MPa}$. As seen from the macro-scale structure of the two sprays, SVO spray forms a stick-like structure. The so-called branching structure that derives from mainstream can be little observed at spray boundary as compared with GO spray. This is because SVO has high viscosity nature. Furthermore, the penetration of SVO spray is shorter than GO spray at this case. This is because SVO is hard to emit a jet at start of injection, which will be further discussed later. As seen from the enlarged images at spray boundary, the droplets size formed by SVO spray is bigger than that of GO spray.

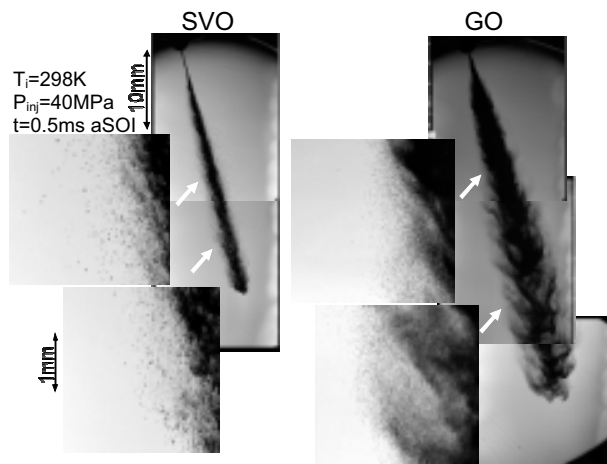


Fig.3 Comparison of spray structure and droplets between rape-seed oil and gas oil sprays ($T_i=298\text{K}$, $P_{inj}=40\text{MPa}$)

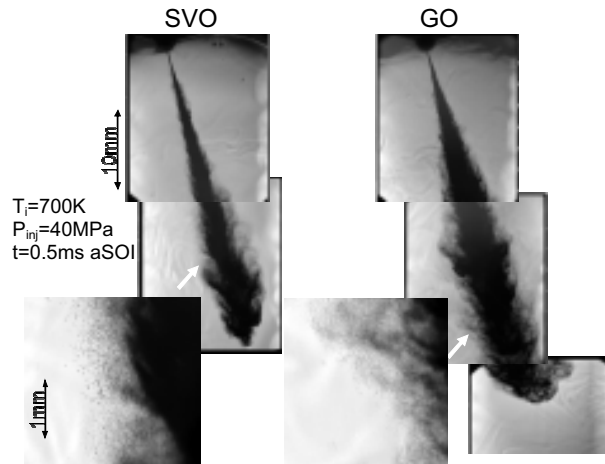


Fig.5 Comparison of spray structure and droplets between rape-seed oil and gas oil sprays ($T_i=700\text{K}$, $P_{inj}=40\text{MPa}$)

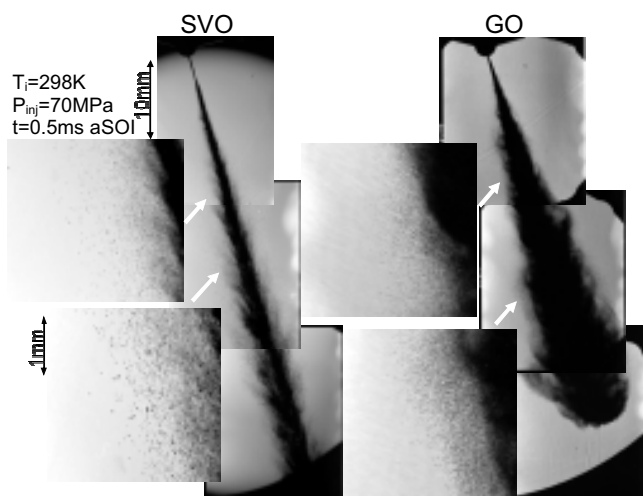


Fig.4 Comparison of spray structure and droplets between rape-seed oil and gas oil sprays ($T_i=298\text{K}$, $P_{inj}=70\text{MPa}$)

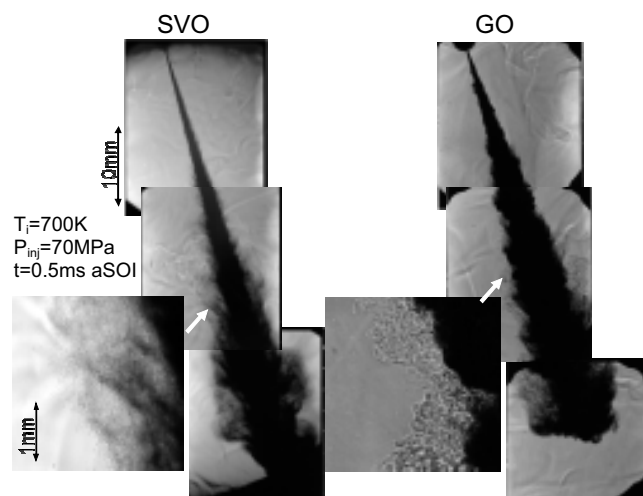


Fig.6 Comparison of spray structure and droplets between rape-seed oil and gas oil sprays ($T_i=700\text{K}$, $P_{inj}=70\text{MPa}$)

the number of droplets with SVO spray is less than GO spray. The droplets size and their distribution as well as the stick-like spray structure indicate that the atomization of SVO spray is worse than that of GO spray.

Figure 4 show same comparison as Fig.3 at higher injection pressure of $P_{inj}=70\text{MPa}$. High injection pressure produces great spray momentum and large injection rate that cause aerodynamic force. As seen from the macro-scale structures, spray penetration of SVO fuel gets longer as compared with GO spray when injection pressure increases. High viscosity characteristics of SVO produce high density and great momentum spray, which lengthens penetration. Branching structure that cannot be observed at $P_{inj}=40\text{MPa}$ can be detected along the SVO spray boundary at $P_{inj}=70\text{MPa}$. However, spray cone of SVO spray has still narrow-angle. Micro-scale images at spray boundary show that high injection pressure produces fine droplets even in SVO spray, especially at downstream of the spray.

Figure 5 compares SVO and GO sprays at ambient temperature of $T_i=700\text{K}$ higher than $T_i=298\text{K}$ in Fig.3. Injection pressure is $P_{inj}=40\text{MPa}$ same as Fig.3. When SVO

is injected into high temperature atmosphere, although spray penetration length changes little, spray cone angle gets greater especially at downstream of the spray and branching structure is clearly visible at spray boundary. In addition, the droplets of SVO spray seem to be smaller size and more consistence diameter as compared with Fig.3. This is due to decrease of kinematic viscosity caused by higher ambient temperature. High ambient temperature is required to support atomization of SVO spray.

Figure 6 shows sprays under condition of high injection pressure $P_{inj}=70\text{MPa}$ and high ambient temperature $T_i=700\text{K}$. SVO spray expands further from the center line especially at downstream of the spray forming a spray tip. In comparison with GO spray, spray cone angle of SVO spray is small at upper stream of the spray. Magnified images at spray boundary indicate that vapor phase can be clearly observed in GO spray; in contrast with GO spray, SVO spray seems to be difficult to form vapor phase. It is hard to improve droplets evaporation for SVO spray. SVO has difficulty in evaporation due to extremely high distillation temperature. When SVO is used in DI diesel engine, atomization can be improved by high injection pressure with high ambient