Comparative study of high-speed imaging of the initial phase of vegetable oil spray formation in a diesel injector

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Abstract

Straight Vegetable Oils (SVOs) combustible properties supported the research of its combustion in compression ignition engines in substitution for Diesel. The analysis of the initial stage of spray formation is essential to understand better and predict the processes involved in fuel atomisation. This work presents a comparative study of the initial phase of spray formation of Soybean oil to those obtained for the injection of Diesel at an In-Cylinder Pressure (ICP) of 2.5 MPa at room temperature. With a High-Speed Photographic Camera (HSFC) through a non-intrusive measurement technique. Experiments for Soybean oil show a long intact solid-liquid core until the primary breakup at 200 µs Fuel Injection Time (FIT) and poorly spray formation development until 300 µs FIT a fast penetration distance at the same FIT analysis with diesel. This low atomisation behaviour inside the engine combustion chamber results in incomplete combustion, low efficiency, carbon products deposition, and increased fuel consumption. These results emphasise the necessity of engine compression rate calibrations to achieve long-term running reliability using SVOs exclusively.

Keywords

Spray formation; Breakup; Soy vegetable oil.

Introduction

The spray characteristics are essential in designing a high-quality Compression Ignition (CI) engine. The spray firmly controls the combustion into the chamber, and the physical-chemical properties of the fuel have a significant effect on engine performance. The Straight Vegetable Oils (SVOs) is a widely available and renewable energy fuel source that minimises atmospheric pollutant. The high viscosity and surface tension are the main problems in their application (see **Table 1**). Still, practical engine running tests show an increase in torque and power compared to a Diesel with increased specific consumption and a slightly lower engine efficiency [1]. The drawback of SVOs is that spray experiments show poor atomisation and a liquid core near the nozzle hole [2, 3]. The poor spray atomisation reduces the CI engine lifetime, increasing lubricant oil degradation and the unburnt particles conduct to piston rings stuck [4].

Table 1. Physical-chemical property of Diesel and Soybean Oil.

Fuel property	Diesel	Soybean oil
ν at 40°C	2,814	30,354
ρ_f at 20°C	839,5	919,3
σ at 20°C	0,02824	0,03272

Have a lot of information about the complete spray development studies, such as the effects of using SVOs in CI engines, but over the initial stage of the spray formation necessity more research. The correct understanding of it is essential due to the large number of parameters that influence it, including the physical-chemical properties of both liquid and gas phases, velocities and temperatures of the fluids, and the nozzle geometry [5]. Therefore, this study aims to conduct a comparative analysis of the initial jet formation and primary breakup developed by Soybean oil to those obtained for the injection of Diesel, throw a commercial diesel injector nozzle in a high-pressure environment.

Material and Methods

The experimental apparatus setup consisted of a Constant Volume Chamber (CVC), diesel injector nozzle, High-Speed Photographic Camera (HSPC) and a light source (see **Figure 1**).

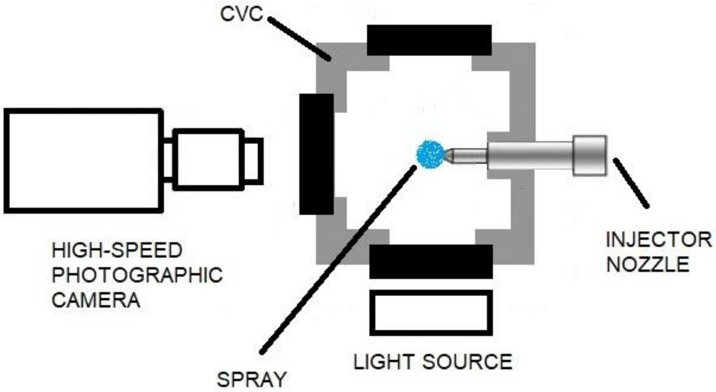

Figure 1. Top view of the experimental apparatus setup.

The tests were conducted in a CVC designed and manufactured specifically for imaging the tests at In-Cylinder Pressure (ICP) of 2.5 MPa with pure nitrogen (ρ_g= 23.24). Fuels and the nitrogen are tested at room temperature (25°C) provided a non-reactive background. A diesel injector nozzle SAC type developed the fuel injection with four diameter holes (280 µm each) with a work injection pressure of 18 MPa. The position of the injector nozzle on the CVC allowed the fuel injection from one hole to lie in a single plane perpendicular to the HSPC. The focal depth is set at the centre of the flow, allowing a sharp image of the evolving spray. To capture the raw data, and HSPC Phanton V411 model with a high-performance microlens AF-S VR Micro-Nikkor 105mm f/2.8G IF-ED was used with a 100W led lamp as a light source. The HSPC setup recorded a frame rate of 79 kfps with a resolution of 128 × 200 px^2 (6 × 9 mm^2), providing an image scale of 46.6 µm/px. The test sequences were Diesel and Soybean oil, respectively. The data acquisition system collects the images sequence from the HSFC, and the tip velocity and penetration raw data are analysed by software assistance (PCC version 2.3).

Results and Discussion

The application of the experimental apparatus as treated in the previous section allowed the capture of the injection event. The development behaviour of the first 300 µs of Fuel Injection Time (FIT) of Diesel and Soybean oil compared despising the injection delay between the fuels. The time between images to comparative analysis is 25 µs. The images were rotated so that the nozzle orifice being observed lies horizontally (see **Figure 2**).

Initial Jet formation

The comparative image study identifies that the Diesel fuel flow like a solid-liquid core from the injector hole up to 50 µs FIT with a core diameter identical to the nozzle injector. Between 50 µs and 100 µs FIT can identify a transverse expansion on the tip with an increase of the core diameter. For Soybean oil, the solid-liquid core remains up to 100 µs FIT, and the same solid-liquid core observation from Diesel is identified at 175 µs FIT but with a higher tip penetration instead. Interestingly, the Soybean oil keep the solid-liquid core tip penetration

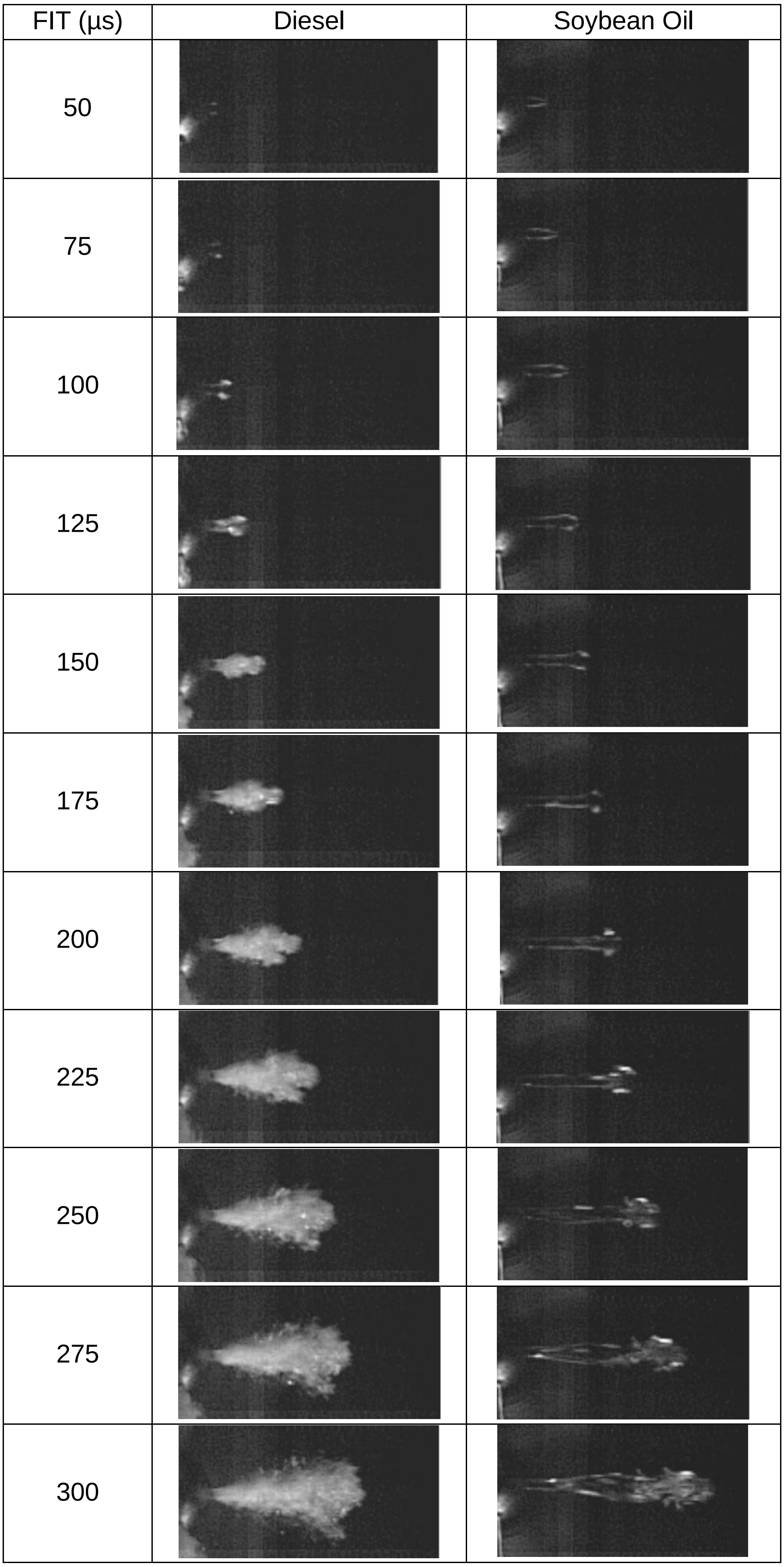

Figure 2. Comparative study of fuel injection formation for Diesel and Soybean oil at the exact FIT.

even in an atmosphere pressurised at 2.5 MPa (see **Figure 2, Figure 3**). The transverse expansion can be explained by the surface tension, the inertial velocities of the flow, the initial acceleration of the injected fuel during the needle lift and the laminar flow condition observed at the nozzle exit. The surface tension of the fuel is high enough to suppress the inertial rates of the flow injected at a high-density surround avoiding the jet break and generate a solid-liquid cap [6]. The inflation by the residual fuel present on the injector nozzle at the start of injection creates the undisrupted oblate spheroid drop [6]. For the diesel nozzle SAC type used, the residual fuel value is the sum of the dead volume between the injector needle and hole (divide by four holes) and the hole volume.

Primary Breakup

The Diesel solid-liquid core broke at 125 µs FIT. At 150 µs FIT, it is possible to note that separate liquid particles are thrown off and form a cone-shaped mantle, and the entire liquid core length stabilised with a size little larger than the injector hole diameter. At this point, the tip penetration and tip velocity still increase constantly until 175 µs FIT. From 200 µs FIT, the tip lost velocity but the tip penetration still growing constantly with the spray development until 300 µs FIT. For the Soybean oil, the instabilities on the solid-liquid core start at 200 µs FIT, and the cap broke at 225 µs FIT; after the break, the instability on the liquid core increase between the tip cap and the medium of the jet. The tip velocity increase constantly up to 300 µs FIT. The droplet formation is no longer well-defined like Diesel, and it is not possible to identify a spray formation. At 250 µs FIT, a stable, intact liquid core length is observed and stabilised with a height higher than the injector hole diameter. The velocity decrease between the 50 µs FIT and 75 µs FIT, showing an unstable behaviour until 175 µs FIT (see **Figure 2**, **Figure 3**). This process occurs under the combined action of surface tension, inertia, viscous forces, and the ambient gas dynamic effects. The ambient gas density significantly affects spray penetration and a negligible impact on spray dispersion [7]. In the present study, the ambient gas significantly impacts the spray dispersion over the two fuels' different physical-chemical properties. The comparative was made without injection delay. The tip velocity shows a different shape for Soybean oil, where even in a pressurised ambient, it acts as a non-Newtonian fluid, and the breakup appears after a long distance from the top of the nozzle.

The primary breakup length identified for both situations indicates that the fuel's development is not fully atomised. This behaviour is due to the low injection pressure and both fuels developed a low initial jet velocity even if the fluid is injected over a hole of 280 µm (see **Figure 3**). The Weber number defines the balance of inertial and surface tension forces and is calculated for gas and fuels densities (1, 2), and the Reynolds number is achieved by the kinematic viscosity (3). To properly located the flows at the jet breakup regime boundaries, the Ohnesorge number is calculated as well (4).

$$We_g = \frac{\rho_g \times u^2 \times d}{\sigma} \tag{1}$$

$$We_f = \frac{\rho_f \times u^2 \times d}{\sigma} \tag{2}$$

$$Re = \frac{u \times d}{v} \tag{3}$$

$$Oh = \frac{\sqrt{We_f}}{Re} \tag{4}$$

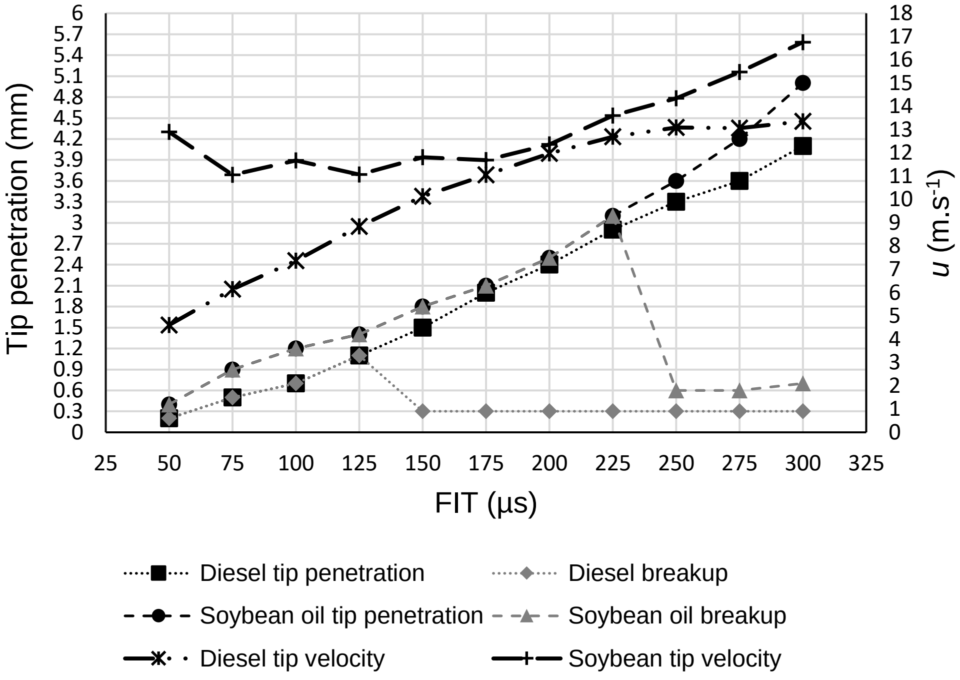

Figure 3. Tip penetration and breakup x time - Diesel and Soybean oil at 2.5 MPa ICP.

The value achieved for Reynolds number at 50 µs FIT supports that the fuel flow is laminar and is not inclined to break (see **Table 2**). The values achieved for Diesel identify that it is at the Second Wind Induced regime, and the Soybean oil is at the Rayleight regime (see **Figure 4**).

Table 2. The non-dimensional number for the jet breakup.

Fuel	We_g	We_f	Re	Oh
Diesel	5.77	208.40	497	0.029
Soybean oil	33.63	833.54	120	0.30

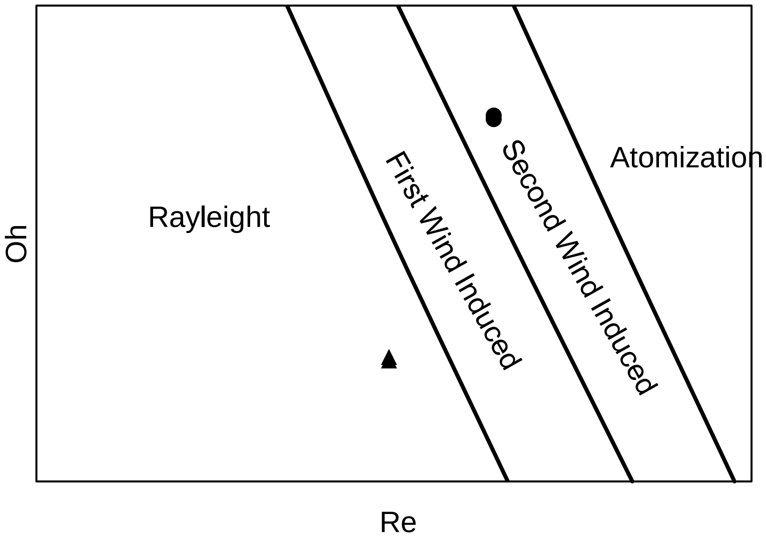

Figure 4. Comparative study of the breakup regime boundaries for Diesel (●) and Soybean oil (▲).

After this, the image analyses and the mathematical observation corroborate the observation that fuels studied are out of the atomisation regime [5]. The initial jet velocity (50 µs FIT) is low and indicates that the injection pressure is insufficient to flow to the atomisation regime. However, the dispersion observed at 225 µs for Soybean oil is not expected. Still, it can be explained by the aerodynamic interaction with the gas, potentially inducing a deceleration of the tip of the liquid fuel.

Conclusions

The present study highlights how the physical-chemical properties of two different fuel influence the initial spray formation over the standard parameter conditions. The ambient gas pressure and the fluid and gas temperature of the injector nozzle are kept constant for this analysis. The results achieved represent the fluid flow properties' variation over the mechanical injection mechanism and how it comports over a high-pressure atmosphere. They indicate that even at low pressure and injection velocity, the environment significantly impacts the spray formation. For fuel with low densities and surface tension, the spray formation increases and develop faster. With the test, it was possible to highlight the difficulties that the CI engines face when SVO is used to substitute the original Diesel fuel. So the compression ignition ratio is an important parameter to adjust when Diesel fuel is substitute by SVO's. Future studies recommend simulating more high-pressure environment conditions for pressures higher than 2.5 MPa and adjusting the fuel injection system to achieve high pressures and act with more accuracy the engine initial jet velocities.

Acknowledgements

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Nomenclature

We_g	Weber number gas
We_f	Weber number fuel
Re	Reynolds number
Oh	Ohnesorge number
ρ_g	Density gas [kg.m^{-3}]
ρ_f	Density fuel [kg.m^{-3}]
v	Viscosity [mm^2.s^{-1}]
d	Hole diameter [µm]
σ	Surface tension [Kg.s^{-2}]
u	Velocity [m.s^{-1}]

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