

# Spray characterization of Straight Vegetable Oils at High Injection Pressures

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## Abstract

We present results of high pressure spray characterization of Straight Vegetable Oils (SVOs) which are potential Diesel fuel substitutes. SVO sprays are visualized at high injection pressures (up to 1600 bar) to study their atomization characteristics. Spray structure studies are reported for the first time for Jatropha and Pongamia vegetable oils, under atmospheric conditions. Jatropha and Pongamia SVO sprays are found to be poorly atomized and intact liquid cores are observed even at an injection pressure of 1600 bar. Non-Newtonian behaviour of Jatropha and Pongamia oil is shown to be the reason for observed spray structure.

*Keywords:*

SVO; Non-Newtonian; Atomization

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## 1. Introduction

This work is motivated by the need to find renewable alternatives to diesel fuel for use in automotive engines. In particular, the current work examines the characteristics of unprocessed Straight Vegetable Oils (SVOs) as diesel fuel substitutes. SVOs are also called as Pure Plant Oils (PPO) in European countries. Jatropha and Pongamia oils are being considered to be most suitable diesel substitutes in Asia and many other parts of the world.

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The Jatropha oil is extracted from seeds of the Jatropha curcas tree. Jatropha curcas is mostly found in tropical and subtropical regions around the world (American tropics, Africa and Asian countries). Pongamia pinnata is a wild growing, seed bearing tree found in Asia and Australia. Jatropha and Pongamia plants can be grown on any type of soil and adapt well to varying climate conditions. Hence, these plants are being cultivated extensively as a source of biofuel. However, there is no data in the literature on spray characteristics of these oils at high injection pressures, typical of those found in modern common rail injection systems.

Spray atomization is the process of breaking the fluid jet coming out of nozzle into fine droplets. Good atomization ensures complete evaporation of liquid fuel and prepares a combustible mixture for complete combustion. Hence, spray atomization is an important process governing diesel engine performance. Physical properties of the fuel have a significant effect on the atomization process. High viscosity and surface tension of SVO have adverse effect on spray atomization, as they increase the SMD (Sauter Mean Diameter) of the spray compared to that of diesel under similar conditions [1, 2]. Hence, to adapt various SVOs and their blends to diesel engines, it is necessary to study their spray characteristics. This is the first reported study, to the best of our knowledge, on spray structure measurements of Jatropha and Pongamia SVOs.

As mentioned earlier, viscosity and surface tension are important properties affecting the atomization of the liquid. Typical properties of different SVOs are presented in Table 1 along with those of diesel for comparison. It is observed that the dynamic viscosities of SVOs are typically 7-8 times

Table 1: Physical properties of diesel and SVOs

Common name	Calorific value (kJ/kg)	Density [3] (kg/m <sup>3</sup> )	Dynamic Viscosity (cP)		Surface tension at 30°C (mN/m)
			40°C	100°C	
Diesel	43,350	815	4	-	23
Jatropha	39,774	908	30	6.5	32
Pongamia	34,000	923	37	6.8	33

higher than that of diesel at 40°C. At 100°C, SVO viscosities are lower than at 40°C but are still about 60% higher than that of diesel. Viscosity of SVO

can be reduced to the level of diesel by preheating oil to above 120°C [3, 4]. Alternatively, blending SVO (upto 30%) with diesel, can lead to a blend with a viscosity similar to that of diesel. Similar to the trend in viscosity values, surface tension values of SVOs are around 30% higher compared to that of diesel.

## 2. Experimental Setup

In the present study, a high pressure spray injection facility which utilises a common rail diesel injection system, is developed to study SVO sprays. The injection pressure can be varied from 200 to 1700 bar. The injection duration of the solenoid injector is varied (from 200 to 5000  $\mu s$ ) using a stand-alone injector driver. The spray structure is visualized using shadowgraphy technique. The optical setup consists of a pulsed Nd:YAG laser (Quanta-Ray, 10 Hz, 10 ns pulse, 450 mJ@532 nm), a fluorescent diffuser (Rhodamine dye plates), a collecting lens (focal length 100 mm), and a CCD camera with a resolution of 1600 X 1200 pixels (LaVision Imager pro X 2M). The camera was placed at 500 mm from the liquid jet for spray structure visualization. A long distance microscope (Questar, QM-1) was placed at 200 mm from the spray to obtain magnified images of the spray structure. The spray structure at different injection pressures and at different time instants after the start of injection, is visualized.

## 3. Results and Discussion

Spray characterization was undertaken for Pongamia and Jatropha SVOs, and diesel, at different injection pressures and injection durations. A single-hole solenoid injector with a hole diameter of 180  $\mu m$  was used. Oil temperature was maintained constant using a temperature controlled oil bath. SVOs are very viscous compared to diesel. Due to this, injection characteristics are found to be different compared to those of diesel. SVOs are difficult to inject at low injection pressures and small injection durations. It was observed that both Jatropha and Pongamia SVOs could not be injected below an injection pressure of 500 bar injection and an injection duration below 0.7  $ms$ , even at oil temperatures of 60°C. Hence, for spray characterization of SVOs, an injection duration of 1  $ms$  was used, with an oil temperature of 60°C. Diesel spray was also studied with an injection duration of 1  $ms$  though the temperature was maintained at 30°C. Injection delays for these

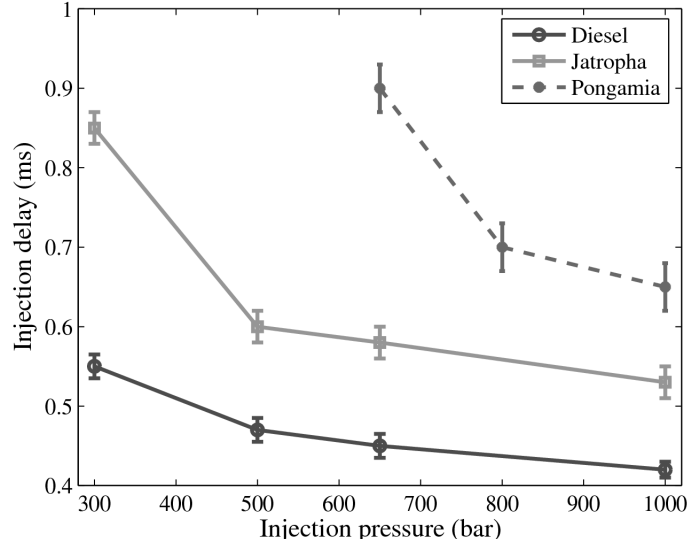


Figure 1: Injection delays at different injection pressures

oils are shown in Fig. 1. Injection delay is the delay between the start of the electronic pulse which is given to solenoid injector, and the time when the spray is observed at the injector tip. It indicates the resistance offered by the fuel to injector needle movement. It is an important control parameter for combustion pressure rise rate and  $\text{NO}_x$  formation in engines. The high viscosities of the SVOs give high resistance to injector needle movement at the start of injection causing higher injection delays. Injection delay for Pongamia SVO is 0.9 ms even at 700 bar injection pressure while diesel has a maximum injection delay of 0.55 ms at a lower pressure of 300 bar. The viscosity of the Jatropha oil is 20% lower than that of the Pongamia oil which has given 30% lower injection delay at an injection pressure of 650 bar. The injection delay is 20% lower for Jatropha oil at an injection pressure of 1000 bar. Thus, the higher injection delay observed for Pongamia oil as compared to Jatropha oil can be attributed to the higher viscosity of the Pongamia oil. This trend is observed at both the injection pressures. The variation in the injection delay from one spray event to another was high in case of Pongamia oil as compared to that of Jatropha oil.

Spray tip penetration as a function of time is shown in Fig. 2, for an injection pressure of 650 bar. It is an important parameter governing fuel-air mixture preparation before combustion. Low spray tip penetration is

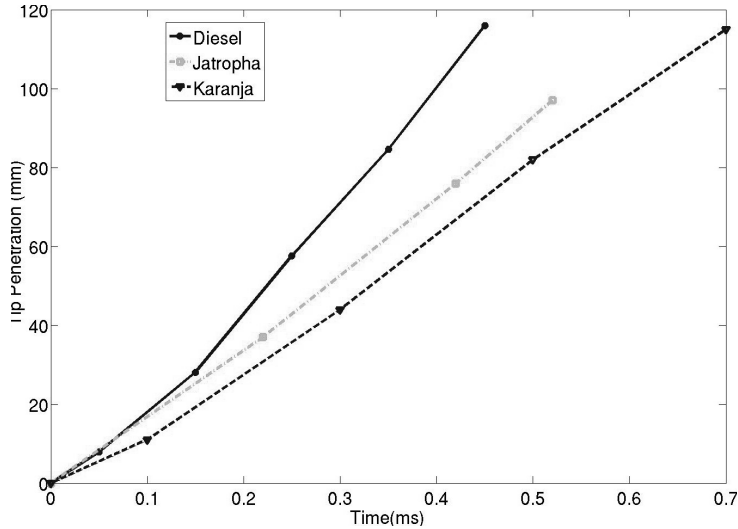


Figure 2: Spray Tip Penetration

not desired as it will not allow fuel to mix uniformly inside the chamber, while high tip penetration means the spray may impinge on the combustion chamber walls. SVO tip penetration is 30% lower compared to that of diesel. This may be due to momentum lost during injection due to high viscosity of oils. Pongamia oil spray has lower tip penetration and tip velocity as compared to that of Jatropha oil.

Figure 3 shows instantaneous spray structure images for diesel, and Jatropha and Pongamia SVOs at an injection pressure of 650 bar, at 0.3 ms after start of the injection. It is interesting to observe the presence of a liquid core for Jatropha and Pongamia SVOs (Fig. 3b, 3c). The spray structure of diesel (Fig. 3a), however, shows a dense atomized spray. A magnified view of the near-nozzle structure of the Pongamia and Jatropha sprays reveals that there is an intact liquid core present, which remains unbroken even at high injection pressures of up to 1600 bar. Figure 4 shows the liquid core for Pongamia oil at various injection pressures, at 20 mm below the nozzle tip, after 1.2 ms from the start of the injection pulse. The diameter of the liquid core increases with increase in the injection pressure. This is due to the increase in the mass flow. The liquid core diameter was observed to be around 0.12 mm at an injection pressure of 1200 bar. The presence of an intact liquid core indicates that the viscous and surface tension forces in SVO sprays are high enough to suppress disintegration of the liquid core. The presence of an in-

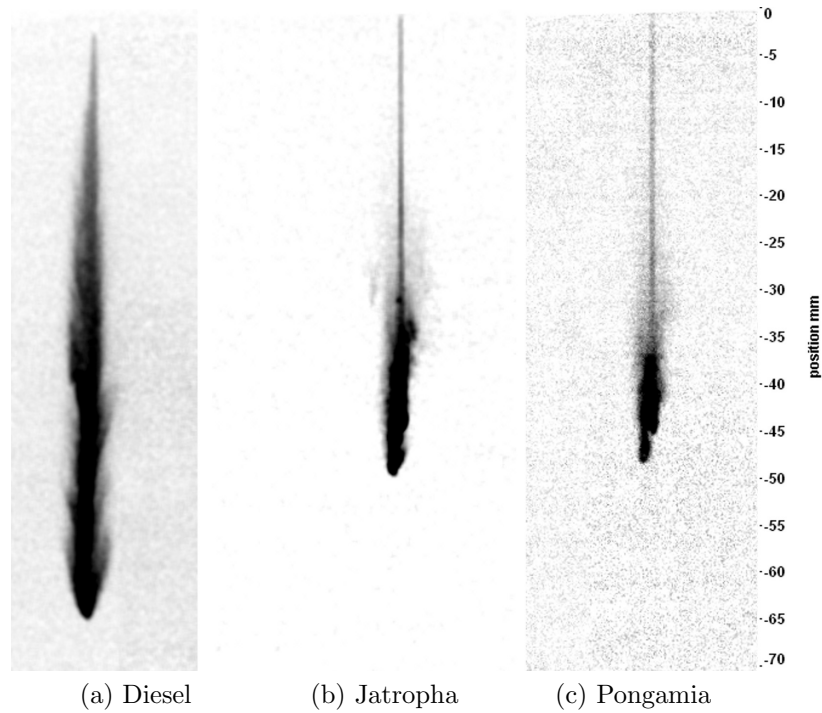


Figure 3: Spray structure of SVOs and diesel at an injection pressure of 650 bar and at 0.3 ms after start of the injection.

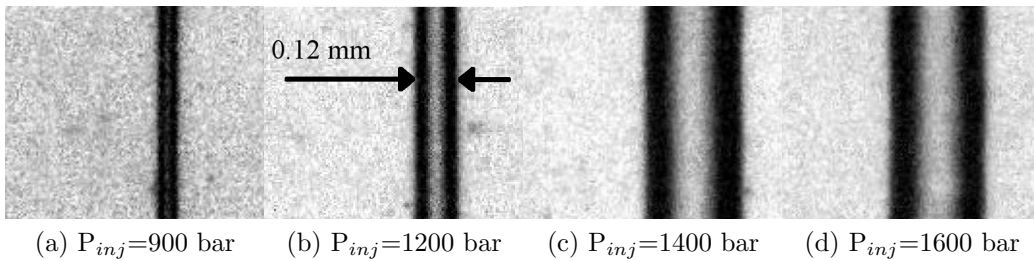


Figure 4: Liquid Core at 20 mm below injector tip for Pongamia spray at 2 ms after the start of the injection pulse

tact liquid core is not expected at such high injection pressures even with the high viscosity values measured for SVOs. Depending on the relative velocity of the jet, and the properties of the liquid and surrounding gas, the liquid jet breakup is governed by different breakup mechanisms. These breakup mech-

Table 2: Non-dimensional numbers for jet breakup

Fuel	V (m/s)	Re	We <sub>l</sub>	Oh
Diesel	250	8335	366750	0.0727
Jatropha	175	1140	156400	0.345
Pongamia	166	840	129600	0.428

anisms are distinguished on the Ohnesorge diagram (Fig. 5). Dimensionless numbers which are relevant for liquid jet breakup are the Reynolds number (Re), liquid Weber number (We<sub>l</sub>) and Ohnesorge number (Oh). The Weber number and Ohnesorge numbers are expressed as :

$$We_l = \frac{V^2 D \rho}{\sigma}; Oh = \frac{\sqrt{We}}{Re} = \frac{\mu}{\sqrt{\sigma \rho D}} \quad (1)$$

where  $\rho$  is the liquid density,  $V$  is the jet velocity,  $D$  is the nozzle diameter,  $\mu$  is the liquid dynamic viscosity, and  $\sigma$  is the liquid surface tension. Representative values for the diesel and SVOs are presented in Table 2. The jet velocity is calculated based on spray tip penetration. Representing these values on the Ohnesorge diagram (Fig. 5) shows that the jet breakup regime for diesel, under the given conditions, is in the atomization regime [5] (the liquid jet breaks into droplets much smaller than the nozzle diameter immediately after coming out of the nozzle). This is also observed from the experiments (Fig. 3a). For SVOs, Jatropha and Pongamia oil, jet breakup as per the Ohnesorge diagram is expected to be in the second wind-induced regime [5] (finite jet breakup length decreasing with increasing Reynolds number and droplet sizes smaller than the nozzle diameter). However, actual image visualization (Fig. 3b, 3c & Fig. 4) shows no jet breakup. From the SVO spray images it appears to be in the Rayleigh regime - characterized by unbroken jet length and jet breakup occurring due to the growth of axis-symmetric oscillations. These oscillations are initiated by jet inertia and surface tension forces. Droplets of diameter greater than nozzle diameter are pinched off from the jet. This indicates that Jatropha and Pongamia oil spray do not follow the mechanism outlined in the Ohnesorge diagram. In the current study, we did not observe jet breakup even up to 140 mm from the nozzle tip.

To investigate this behaviour, the chemical composition of SVOs was measured. Chemical compositions of Pongamia and Jatropha, measured using a gas chromatograph, are listed in Table 3. From the table, it is clear that both

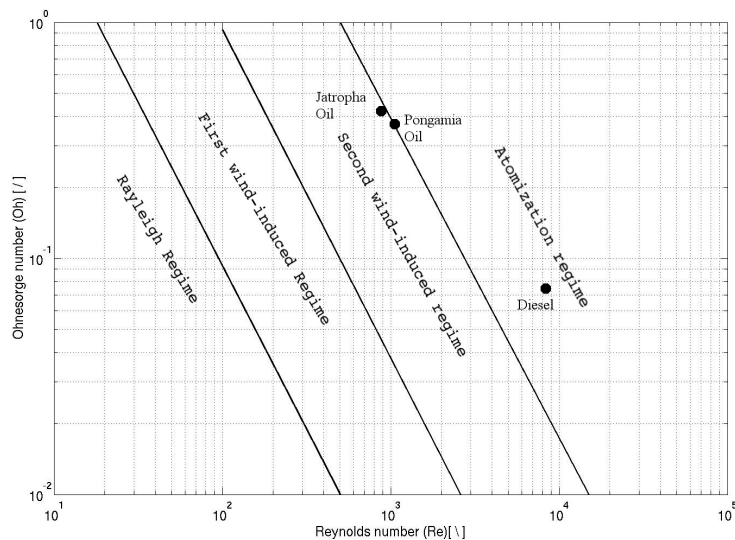


Figure 5: Ohnesorge diagram

Table 3: Fatty acid composition of vegetable oil (% mass)

	Pongamia	Jatropha
Palmitic C16:0	10.1	13.5
Stearic C18:0	4.3	0.5
Oleic C18:1	59.1	44.9
Linoleic C18:2	20.9	41.1
Linolenic C18:3	3.5	-

SVOs have nearly the same composition of fatty acids. These fatty acids, present in the form of triglycerides in SVOs, are responsible for their high viscosity [6]. Increasing the number of carbon atoms in the triglycerides increases the viscosity. More importantly, these triglycerides are also known for their non-Newtonian behaviour [6]. To confirm the non-Newtonian behaviour of these SVOs, the dynamic viscosity of Pongamia oil for different shear rates was measured. The results shown in Fig. 6, confirm that Pongamia oil is a non-Newtonian fluid and is a shear-thinning liquid. Diesel on the other hand shows a constant viscosity for different shear rates conforming to Newtonian behaviour.

Vegetable oils have been found to show a very high increase in dynamic viscosity when compressed to high pressures [7, 8]. It has been reported that



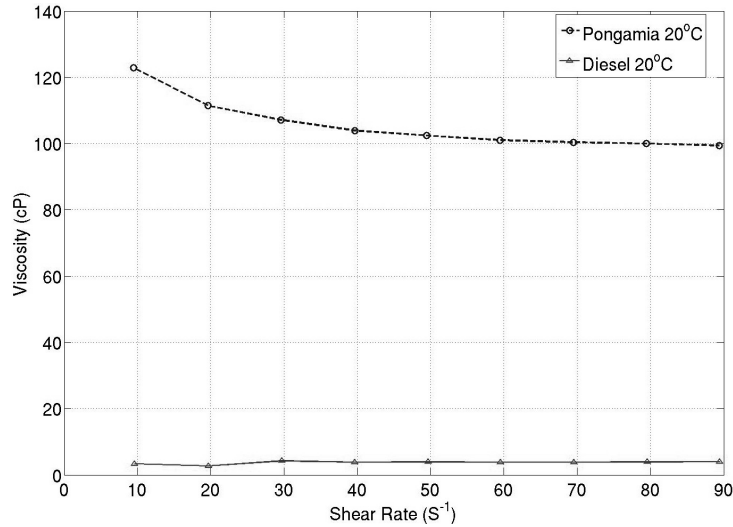


Figure 6: Dynamic viscosity of Pongamia oil as function of shear rate

for olive oil, the increase in viscosity is as high as 6 times from atmospheric to a pressure of 1800 bar [7]. Under extremely high pressures (above 4000 bar), these oils are known to undergo phase transition resulting in an exponential rise in viscosity. It is possible that these SVOs show some hysteresis when decompressed back to the atmospheric pressure, showing higher viscosity than initial values for a long time after decompression.

For both the oils studied here, it is felt that there may be a time dependent variation due to shear and compression in the high pressure pump used in this study. In the high pressure spray atomization process, as the liquid comes out of the nozzle, it experiences a sudden drop in pressure. Though the pressure drops to atmospheric pressure no jet breakup is observed. It is possible that the the oil viscosity is still high due to time dependent viscosity of these oil, and molecular relaxation time may be higher compared to the time scale of the atomization process. These properties of Jatropha and Pongamia SVOs, however, need to be further studied.

#### 4. Conclusion

In summary, the high pressure spray characterization of Jatropha and Pongamia SVOs are reported for the first time to the best of our knowledge. Due to the high viscosity of these oils, injection delays were observed to be much higher than those for diesel fuel. Pongamia oil shows high injection

delays at low injection pressures compared to Jatropha and this attributed to its higher viscosity. Pongamia oil exhibits a higher variation in the injection delay from one spray event to the other as compared to that of Jatropha oil. The spray tip penetration for Pongamia and Jatropha oils is less than that of diesel. The Pongamia oil spray gives a lower tip penetration and tip velocity compared to that of Jatropha oil. A very interesting and counter-intuitive observation concerns the presence of an intact liquid core even at injection pressures as high as 1600 bar. This observation concerning the absence of atomization is explained on the basis of preliminary chemical composition and rheology measurements. However, it is important to note that the presence of an intact liquid core is observed at low gas density corresponding to atmospheric pressure; improved atomization is expected at higher gas densities. Further studies on rheological properties are required to understand the spray structure of these SVOs.

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