



Spray characterization of an air-assist pressure-swirl atomizer injecting high-viscosity Jatropha oils



Yong Fan*, Nozomu Hashimoto, Hiroyuki Nishida, Yasushi Ozawa

Energy Engineering Research Laboratory, Central Research Institute of Electric Power Industry, 2-6-1 Nagatsuta, Yokosuka, Kanagawa 240-0196, Japan

HIGHLIGHTS

- We examined the spray characteristics of crude Jatropha oil and Jatropha methyl ester.
- Smaller Sauter mean diameter (SMD) was obtained using a pressure-swirl atomizer with assist air.
- Spray cone evolving from a twisted jet to a hollow cone with decreasing viscosity was observed.
- A local minimum and a local maximum in the SMD vs. viscosity curve were observed.
- SMD has a strong correlation with the radiation intensity by soot in the flame.

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ABSTRACT

The effect of the kinematic viscosity on liquid sprays injected by an air-assist pressure-swirl atomizer has been investigated in a series of experiments employing pulse-laser backlight imaging and laser diffraction droplet size distribution measurements. Sprays of crude Jatropha oil, Jatropha methyl ester, diesel fuel and propylene glycol brine were examined, and the liquid viscosity was controlled by changing the liquid temperature. It was found that atomization of the liquids was improved by introducing the assist air. Instantaneous images of the sprays taken using pulse-laser backlight illumination show that the 'spray cone' inside the nozzle cap evolves into the following five phases as the Reynolds number increases (i.e., liquid viscosity decreases): (1) a twisted liquid jet, (2) a folded liquid film, (3) a hollow spray cone with a smooth spray cone surface, (4) an unstable spray cone with periodic fluctuation, (5) a spray cone with many wrinkles on the cone surface. It was found that the droplet size in terms of the Sauter mean diameter (SMD) is small when the spray width is large. The SMD did not monotonically increase with the liquid viscosity. A local maximum of the SMD in the SMD vs. liquid viscosity curve was observed in the unstable transitional region where the transition from laminar flow to turbulent flow occurred. A local minimum of the SMD was observed at a higher liquid viscosity, where the 'spray cone' inside the nozzle cap changed from a twisted liquid jet to a folded liquid film. The change in the SMD as a function of liquid viscosity has a strong correlation with that in the flame radiation intensity as a function of liquid viscosity observed in a combustion test employing the same fuel atomizer (Hashimoto et al. submitted for publication). This indicates that the flame radiation intensity can be decreased by improving atomization characteristics.

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1. Introduction

Biofuels have great potential in power generation and transportation applications for the reduction of net CO₂ emissions [1]. Jatropha oil, a branched-triglyceride-type vegetable oil derived from the seeds of the Jatropha curcas tree, is a competitive fuel among the various biofuel alternatives mainly because of the high oil yield from Jatropha curcas seeds. In addition, Jatropha curcas is a drought-resistant perennial plant that can grow well even in marginal soil.

Another merit of Jatropha oil is that it is inedible. Thus, there is no conflict with its use as a food supply, unlike many other edible bio-fuels such as soybean oil, sunflower oil and rapeseed oil.

Jatropha oil can be esterified to produce Jatropha methyl ester (JME), a biodiesel fuel that is mainly of interest for use in diesel engines for transportation applications. On the other hand, the direct use of crude Jatropha oil (CJO) in oil-fired boilers and gas turbines is preferable to reduce the cost and CO₂ emission by avoiding the esterification process used in JME production. Since CJO has much higher viscosity than the diesel fuel, providing a good atomization performance for clean and efficient combustion is an important issue. Deshmukh et al. [2] conducted a spray experiment on straight

* Corresponding author. Tel.: +81 46 856 2121; fax: +81 46 856 3346.
E-mail address: fan@criepi.denken.or.jp (Y. Fan).

Jatropha oil using a diesel injection system. They reported that the atomization of straight Jatropha oil is poor. Straight Jatropha oil has a much larger injection delay and shorter penetration length than diesel fuel. An intact liquid core was observed even at an injection pressure of 1600 bar.

There are many types of fuel atomizers that produce a fuel spray for combustion from the energy of liquid pressure, air pressure, mechanical rotation and vibration, acoustics and electric field. Systematic discussions on the various atomizers and a theoretical basis of their atomization process have been given by Lefebvre [3] and Bayvel and Orzechowski [4]. Atomization is the process in which a liquid is disintegrated into droplets. Thin jets or sheets of liquid are often formed at the first stage of the atomization process because their high surface energy and instability make them more susceptible to further disintegration into droplets. The droplet size, as one of the important spray characteristics affecting the combustion, is dependent on the jet/sheet disintegration in the atomization process. Predication of the droplet size for practical atomizers requires understanding of the complex liquid disintegration mechanisms. However, even for the simplest case of round jet disintegration, four different disintegration modes exist depending on the Weber number (We) and Reynolds number (Re), i.e., Rayleigh capillary disintegration, first/s wind-induced wave disintegration and secondary atomization by aerodynamic forces. Senecal et al. [5] presented a linear stability analysis of sheet disintegration for droplet size modeling. Their model was based on an inviscid dispersion relation between long-wave and short-wave disintegration mechanisms obtained for jet disintegration. Recently, Sirignano and Mehring [6] reviewed the linear and nonlinear theory of the instabilities and distortion of liquid jets and sheets. Because of the complexity in modeling, empirical correlations of experimental results and modifications based on dimensional analysis are often used to describe the droplet size of specific atomizers [7–12]. Various droplet-sizing methods such as the mechanical spray patternator (droplet trapping and count) [8] and optical spray analyzers based on imaging, laser diffraction [9–12] or a phase Doppler anemometer [7] have been employed to measure the droplet size in experiments.

Among the various types of atomizers, pressure atomizers rely on the hydrodynamic energy converted from the liquid pressure to inject a high-velocity liquid stream into the surrounding air. The pressure-swirl atomizer is a widely used pressure atomizer because of its simplicity, good atomization performance and high combustion stability. The atomizer has a swirl chamber, in which a centrifugal force is imparted to the fuel entering with high tangential velocity to form a hollow liquid cone with an air core from the discharge orifice. In the atomization process, a large volume of liquid develops into a thin conical liquid sheet and then breaks into numerous tiny droplets. The atomization performance depends on the quality of the liquid cone, which is greatly affected by the physical properties of the liquid (viscosity, density and surface tension), the flow parameters (liquid pressure and flow rate) and the design of the atomizer. In an experiment of pressure-swirl atomization reported by Dorfner et al. [7], the mean droplet size increased with the liquid viscosity. Recently, Wimmer and Brenn [13] conducted a theoretical analysis of the viscous flow in a pressure-swirl atomizer to examine the effect of viscosity on the flow rate. By employing a fiber-sensor technique, Musemic et al. [14] measured the oscillation frequency of a liquid sheet on a hollow liquid cone produced by a pressure-swirl atomizer. They found that the viscosity has a strong effect on the dominant frequency. Using water-glycerol mixture at different mixing ratios, Yao et al. [15] investigated the atomization process of high-viscosity liquid spray from a pressure-swirl atomizer. It was claimed that the high viscosity prevents the fluid from forming a large cone, and thus the liquid breakup is difficult.

On the other hand, air-assist atomizers and similarly structured airblast atomizers [3,4] use both the aerodynamic energy of air and the hydrodynamic energy of the liquid for atomization. For air-assist and airblast atomizers, a relatively low velocity liquid stream is injected into a high-velocity air stream. When the liquid stream is injected into the air stream in the form of a liquid jet, the atomizer is called a 'plain-jet' airblast atomizer. An early study on the plain-jet airblast atomizer by Nukiyama and Tanasawa showed that the mean droplet size decreases as the liquid viscosity decreases [8]. When a liquid stream is injected into an air stream in the form of liquid film, the atomizer is called a 'prefilming' airblast atomizer. Lefebvre reported that the wave-sheet disintegration is suppressed when the air stream impinges on the liquid stream at an appreciable angle [9]. The so-called 'prompt atomization' mode dominates the liquid sheet disintegration. The mean droplet size is controlled mainly by the kinetic energy of the air. Nukiyama and Tanasawa [8] and Lorenzetto and Lefebvre [10] developed empirical formulas for the mean droplet size for the plain-jet airblast atomizer, and formulas were developed in a similar way for the prefilming airblast atomizer by Rizkalla and Lefebvre [11] and Rizk [12]. It was claimed that the liquid viscosity and air velocity have separate and distinct effects on the mean droplet size. Jakobs et al. [16] conducted a spray experiment using an air-assist atomizer to inject glycol with a viscosity of 21 mm²/s. It was found that increasing the air velocity up to 120 m/s has a great effect on decreasing the droplet size. Further increase of air velocity has only small influence on the droplet size. Avulapati and Venkata [17] developed an air-assist atomizer in which an air jet was directed onto the impinging point of two liquid jets. It was found in their experiment on the atomization of water-glycerol mixtures that the non-dimensional droplet size is almost constant over a liquid viscosity range over 1–39 mm²/s and a surface tension range of 22–72 dyn/cm when the air-to-liquid ratio exceeds a critical ratio of 0.05. It was claimed that this is attributed to the change in atomization mode from classical to prompt. Padwal and Mishra [18] studied the liquid atomization of non-Newtonian gel propellant which has high viscosity at low shear rates. It was found that the normally un-atomized gel propellant jet with the conventional air-assist atomizer could be fully atomized by employing air injection at the converging section of the fuel nozzle due to a decreased viscosity at the converging section.

Studies on the spray combustion characteristics of palm methyl ester (PME) and diesel fuel have been conducted using the laboratory-scale spray combustion test facilities at the Central Research Institute of Electric Power Industry (CRIEPI) [19]. First, the fuel spray for combustion was produced using a simple pressure-swirl atomizer. Unfortunately, the accumulation of soot (the deposition of carbonaceous materials) on the nozzle was found in the case of diesel fuel combustion [20]. A common practical method used to solve this problem is to introduce an air stream into the outer circumferential passage of the pressure-swirl atomizer and to discharge the air at its downstream end, where it flows radially inward across the nozzle face [21]. Although the original purpose of the air was to prevent the deposition of coke, the mean droplet size of a spray can be reduced by the air stream [19]. Because of this effect of the air stream on enhancing fuel atomization, air-assist pressure-swirl atomizers have been used in many oil-fired industrial gas turbines and boilers to improve the atomization at low injection pressures [22]. Therefore, the design of the fuel atomizer at CRIEPI was revised in a similar way so that approximately 10% of the combustion air was introduced to the nozzle face. It was found in a combustion experiment on diesel fuel and PME [20] with the new fuel atomizer that the air introduced to the nozzle face is effective in preventing the aforementioned problem of soot accumulation. Recently, combustion experiments of Jatropha oil and JME employing this new fuel atomizer were conducted by

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