BIODIESEL DROPLET COMBUSTION

S.C. Anthony Lam and Andrzej Sobiesiak*

**Mechanical, Automotive, and Materials Engineering, University of Windsor*
401 Sunset Avenue, Windsor, Ontario, Canada N9B 3P4
asobie@uwindsor.ca

Abstract

An experimental setup was assembled to test droplets of biodiesel as well as ultra-low sulfur diesel, and ethanol for their adherence to the diameter-squared linear relationship. The droplets' burning rate constants and temperature histories are reported. Apparatus for determining droplet diameter, thermocouple arrangement for droplet temperature history acquisition, illustrates a series of frames from a high-speed movie capturing the entire biodiesel burning sequence, changes of droplet diameter-squared over time and temperature history for biodiesel, ultra-low sulfur diesel and, ethanol biodiesel droplet, ethanol are introduced in the paper.

Results comprise three stages warm-up and combustion, combustion of the droplet with the liquid phase boiling and burn-off of vaporized fuel. For larger diameter droplets, that period could occupy significant fraction of the droplet's lifetime. The second stage is where the droplet has reached its boiling temperature and in general, all the fuels tested adhere to the D2 relationship. The biodiesel and diesel deviated slightly as a result of their multi-component nature.

Keywords: *biodiesel, droplet combustion, emissions reduction*

1. Introduction

Biodiesel is part of the solution in alleviating the world's dependence on fossil fuels due to the rapid depletion of non-renewable petroleum resources. Biodiesel is an alternative fuel produced from renewable resources with the potential to substantially reduce emissions associated with petroleum diesel usage. With properties exceeding conventional diesel fuel, biodiesel can be seen as a viable substitute. Impending regulatory changes will mandate low sulfur diesel fuel. Higher production costs will result as these changes will require additional treatment in order for diesel fuel to regain its former lubricity. Biodiesel has high lubricity and can be used in existing diesel engines with very few minor modifications depending on the blend of biodiesel used. Therefore, biodiesel offers an immediate and seamless way to fuel existing diesel vehicles. Biodiesel can also be used for fueling aircraft and has a potential for disaster remediation. There are four methods to produce biodiesel: transesterification, blending, microemulsion, and pyrolysis (thermal cracking). Transesterification is the most commonly used method in producing biodiesel.

In mobility engineering applications, understanding the atomization and subsequent combustion of liquid fuels is critical for the development of propulsion devices.

The overall objective of this research is to provide insight into the viability of biodiesel as a transportation fuel. There are two areas of interest in spray combustion. First, is the combustion of a single droplet. The second addresses the issue of droplet interaction within the spray that features randomly spaced droplets of various sizes. At this stage, single droplet biodiesel fuel combustion is investigated. A literature investigation has concluded that very little work has been done to characterize experimentally, in terms of the droplet burning rate constant, how biodiesel fuels burn.

An apparatus for studying single droplet combustion was assembled. A single droplet of biodiesel fuel was placed on quartz filaments. An optical system allows for visualization of the burning droplet and for the capturing of image sequences. From the individual frames of the sequences, the droplet diameter is measured. The droplet lifetimes and their burning rate constants were determined from plots of droplet diameter-squared as a function of time.

2. Experimental Methodology

Each fuel was subjected to droplet combustion testing during which their diameter changes and liquid temperature histories were recorded. For droplet testing, the fuels were suspended at the end of a 1 mm diameter quartz filament. Figure 1 illustrates the apparatus used in determining droplet diameter.

A macro lens with a magnification ratio of 1:1 was coupled with a CCD camera at a resolution of 512×240 pixels capturing at 125 fps was used to acquire the images as the droplets were burning. The time history of the droplet diameter over its burning lifetime was used to calculate the burning rate constants.

Temperature histories of the liquid phase were obtained by placing a single droplet of fuel on a K-type thermocouple connected to a data acquisition system as shown in Fig. . The temperature histories during combustion were recorded and used to evaluate the boiling temperatures of the various fuels.

To prevent contamination, new filaments and thermocouples were used for each fuel.

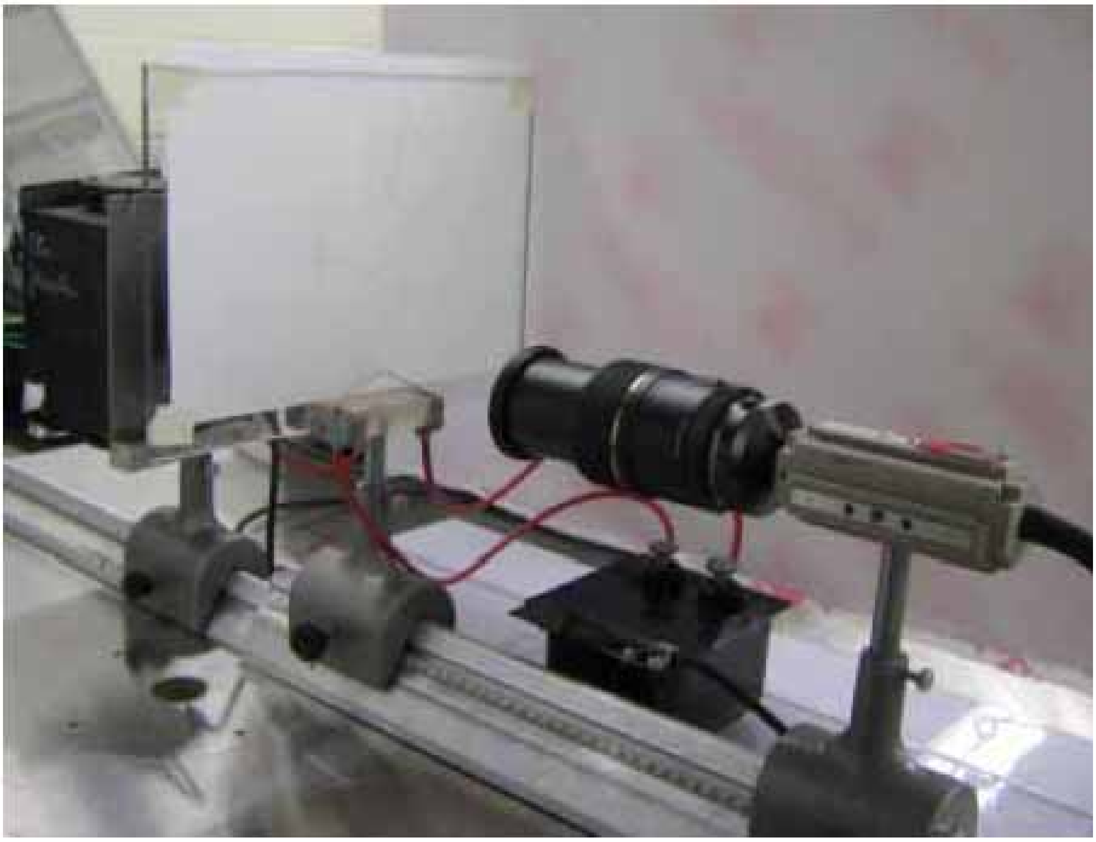


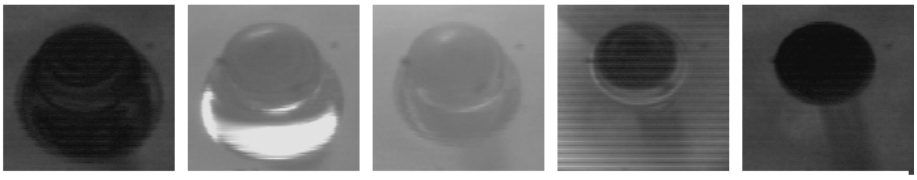
Fig. 1. Optical Apparatus for Determining Droplet Diameter

3. Results and Discussion

Droplet Burning Constant

Figure 3 illustrates a series of frames from a high-speed movie capturing the entire biodiesel burning sequence. Both the droplet and filament can be seen at time = 0.0 s as the droplet rests on the filament. The droplet completes burning at time = 2.931 s, where only the filament remains. Droplet diameters were subsequently measured from a sequence of images, such as those shown in Fig. 3

Fig. 2. Thermocouple Arrangement for Droplet



$t_0 = 0.0$ s $t_1 = 1.034$ s $t_2 = 1.551$ s $t_3 = 2.586$ s $t_4 = 2.931$ s

Fig. 3 Biodiesel Droplet Burning Sequence

It was conjectured that biodiesel will adhere to a diameter-squared linear relationship similar to other fuels such as diesel and ethanol. Experiments have shown biodiesel closely follows a droplet diameter-squared relationship during a certain period in its lifetime.

All D^2 graphs exhibited two characteristic stages as described in Table 1.

Table 1 - Definition of the Diameter^2 Characteristic Stages

Stage	Point	Observation
1	A → B	Warm-up (heating of the droplet to its boiling temperature) and combustion.
2	B → C	Combustion at boiling temperature.

In Figures 4 to 7, it can be noted that the duration of Stage 1 is longer for larger diameter droplets.

For biodiesel and diesel, the D^2 data points (not the trendline) for Stage 2 are slightly curved due to the multi-component properties of these fuels while ethanol is linear. A trendline was fitted to the points at Stage 2 to obtain the burning rate constant.

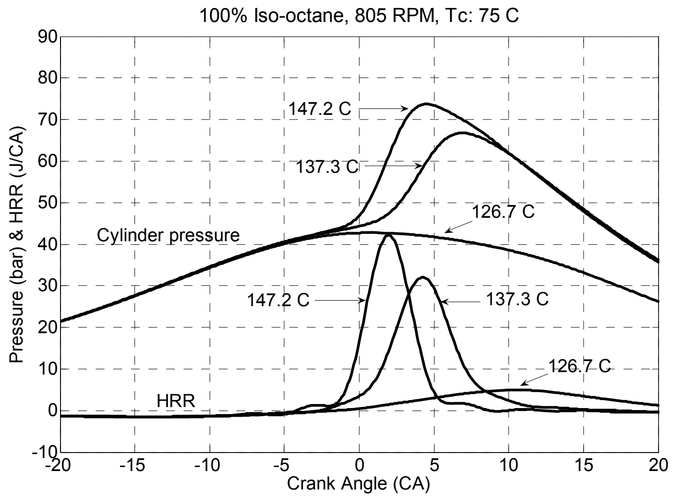


Fig. 4. Cylinder pressure and rate of heat release at different intake charge temperatures (805 RPM, 100% Iso-octane)

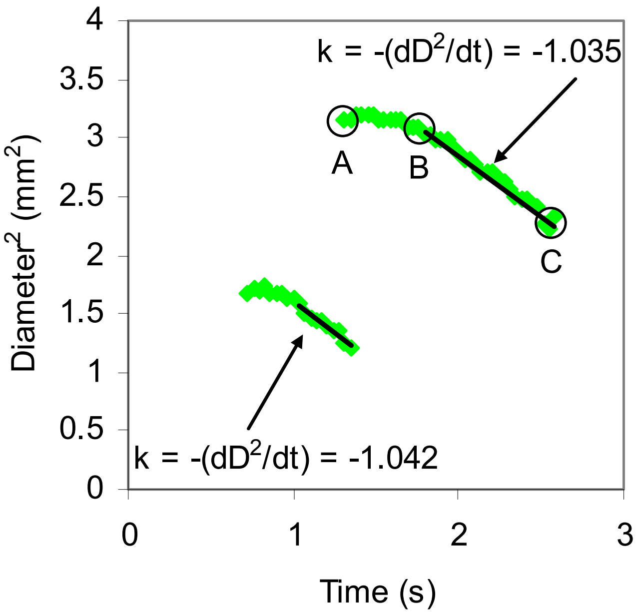


Fig. 5. Changes of Biodiesel Droplet Diameter-Squared Over Time (Points A, B, C are Illustrated)

Table 2 summarizes the obtained burning rate constants for the fuels tested. The burning rate constants for biodiesel and diesel were 1.038 mm^2/s and 0.901 mm^2/s respectively. For cetane (a diesel reference fuel), Chomiak [3] reported $k = 0.818$ mm^2/s. The burning rate constants obtained for ethanol was 0.668 mm^2/s. In Chomiak [3} the burning rate constant for ethanol (ethyl alcohol) was listed to be 0.889 mm^2/s.

Table 2 - Calculated Burning Constants

Fuel	Burning Rate Constant, k (mm^2/s)	
	Individual	Averaged
Biodiesel	1.035	1.038
	1.042	
Ultra-Low Sulfur Diesel	0.901	0.901
Ethanol	0.711	0.668
	0.624	

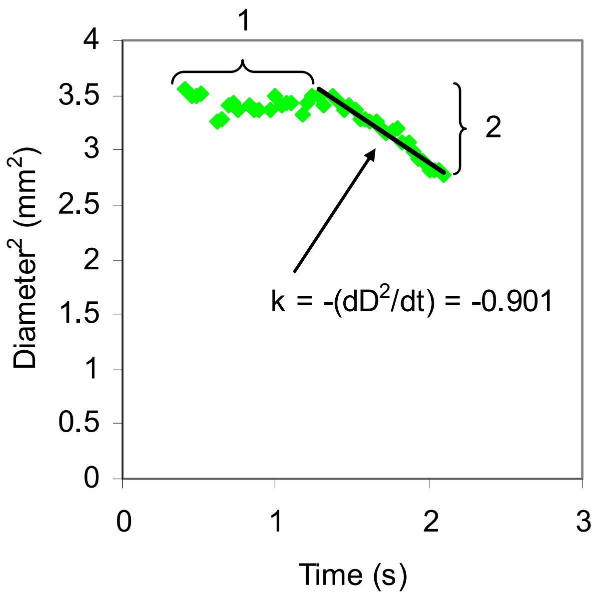


Fig. 6. Changes of Ultra-Low Sulfur Diesel Droplet Diameter-Squared Over Time (Stages 1, 2 are Illustrated)

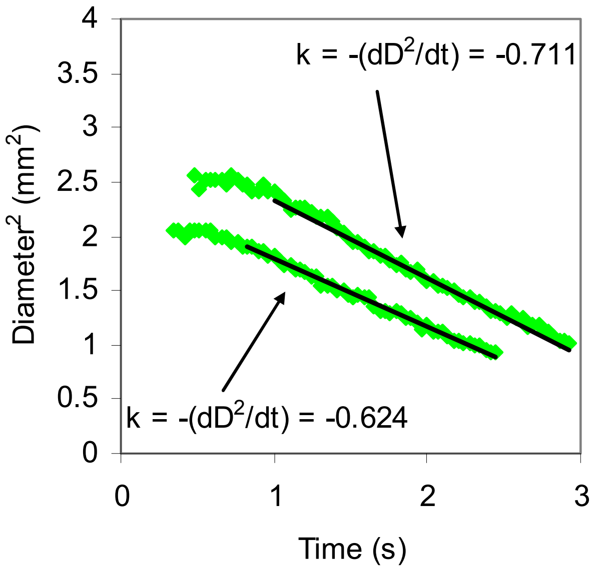


Fig. 7. Changes of Ethanol Droplet Diameter-Squared Over Time

Droplet Temperature History

Illustrated in Figs. 8 and 9, the liquid phase temperature histories for biodiesel and diesel were similar, while ethanol's temperature history was different. All temperature profiles exhibited four characteristic stages as described Table 3.

Table 3 - Definition of the Temperature Characteristic Stages

Stage	Point	Observation
1	A → B	Warm-up (heating of the droplet to its boiling temperature) and combustion.
2	B → C	Combustion of the droplet with the liquid phase boiling.
3	C → D	Burn-off of vaporized fuel.
4	D → E	Thermocouple cool down.

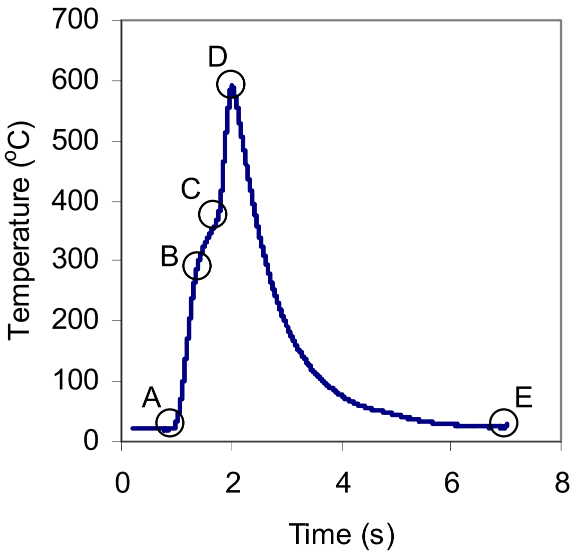


Fig. 8. Biodiesel Droplet Temperature History
(Points A, B, C, D, E are illustrated)

Point A on the temperature histories signifies droplet ignition, while Point C denotes completion of the droplet vaporization process. Within Points B and C (Stage 2), the liquid phase continues to boil. In Fig. 10 ethanol exhibits a plateau at Stage 2 compared to biodiesel and diesel. This is due to ethanol being a single component fuel. It was suspected that the period between Points C and D (Stage 3), signifies combustion of the remainder of the vaporized fuel.

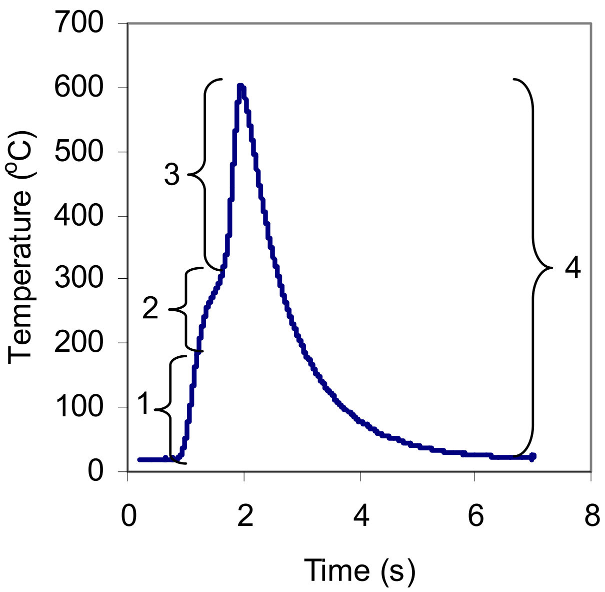


Fig. 9. Ultra-Low Sulfur Diesel Droplet Temperature History
(Stages 1, 2, 3, 4 are illustrated)

Table 4 summarizes the measured boiling temperatures. The boiling temperatures for the fuels tend to situate on the upper bounds of the referenced boiling temperature ranges. This is a result of the conduction along the thermocouple wires from the flame.

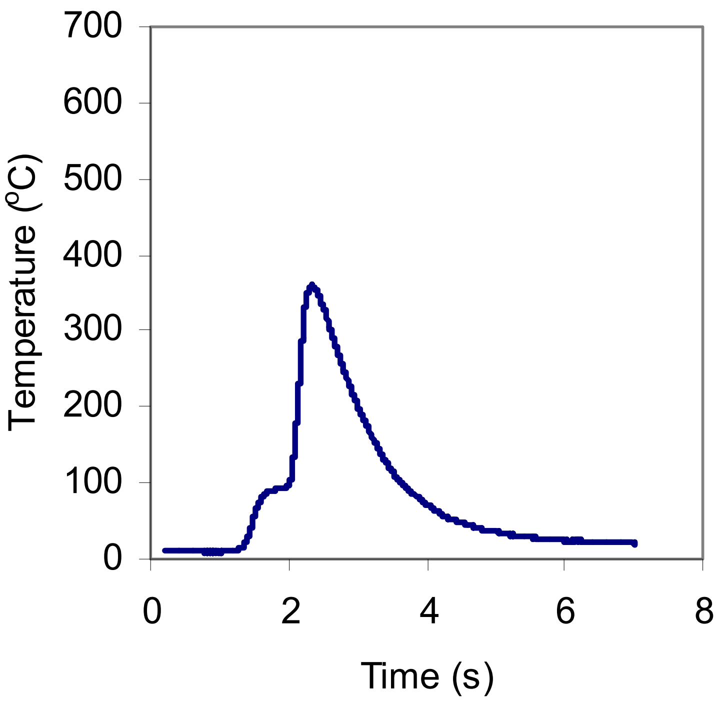


Fig. 10. Ethanol Droplet Temperature History

Table 4 - Boiling Temperatures of the Fuels Used

Fuel	Boiling Temperature (°C)	
	Measured	Referenced
Biodiesel	300 to 385	182 to 338 [10]
Ultra-Low Sulfur Diesel	250 to 315	186 to 337 [9]
Ethanol	90	78.3 [11]

4. Conclusion and Future Work

Results have revealed that there are three stages in droplet combustion. First, is the warm-up stage where the droplet is heated to its boiling temperature. For larger diameter droplets, that period could occupy significant fraction of the droplet's lifetime. The second stage is where the droplet has reached its boiling temperature and in general, all the fuels tested adhere to the D^2 relationship. The biodiesel and diesel deviated slightly as a result of their multi-component nature. Biodiesel had the highest burning rate constant.

Further work will include other feedstocks of biodiesel and their blends with petroleum diesel and ethanol. In addition, numerical simulations to model biodiesel droplet combustion will be completed.

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