THE INVESTIGATION OF DROPLET COMBUSTION CHARACTERISTICS OF BIODIESEL–DIESEL BLENDS USING HIGH SPEED CAMERA

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ABSTRACT

Biofuels are playing more and more important roles worldwide. While it will reduce the overall emission of greenhouse gases, it may damage the combustion system through corrosion and poor lubrication, and generates more local air pollution than fossil fuels if the biofuel burning properties are not well understood and controlled. This work investigates the effect of blending diesel fuel by biodiesel on the combustion of a single fuel droplet. Biodiesel blends substituting diesel oil in different concentrations on volumetric basis, in addition to pure diesel and purer biodiesel were studied. Schlieren and bbacklighting imaging techniques have been used to track the droplet combustion throughout its complete lifetime using a high speed camera. The results showed that partial substitution of diesel oil by biodiesel at the test conditions led to increasing secondary atomization from the droplet, compared to pure diesel or biodiesel fuel droplets. This in turn enhances evaporation, mixing, and then combustion. Additionally, the results showed a slight decrease in droplet burning rate of the blend compared to the pure fuel droplets. Nucleation has also been traced to take place inside the droplets of the blends. Moreover, flame size (height and width) has been reduced by increasing biodiesel concentration in the blend.

NOMENCLATURE

D	[mm]	Droplet Diameter
K	[m^2/s]	Burning rate constant
t	[s]	Time

Subscripts

i	[-]	Instantaneous
^{o}	[-]	Initial
total	[-]	Total time

Fuels

B100	Pure Biodiesel
BD07	93%Diesel+7% Biodiesel
BD10	90%Diesel+10% Biodiesel
BD20	80%Diesel+20% Biodiesel
BD30	70%Diesel+30% Biodiesel
D100	Pure Diesel

INTRODUCTION

Diesel fuels constitute the main source of pollutant emissions. Studies have shown that the formation of these pollutants can be reduced by including oxygenated fuels on diesel blends [1-3].

Biofuels are playing more and more important roles worldwide. While it will reduce the overall emission of greenhouse gases, it may damage the combustion system through corrosion and lubrication, and generates more local air pollution than fossil fuels if the biofuel burning properties are not well understood and controlled. Biodiesels are derived from animal fats or vegetable oils and are used in compression ignition engines. Biodiesel production by vegetable oils usually comes from soybean oil, castor oil or frying oil [1, 4].

Biodiesel are usually mixed with pure diesel in different proportions and are used in diesel engines without substantial modifications. One of the reasons for using biodiesel is its property to reduce the pollutant emissions because the oxygen in biodiesel fuel promotes combustion [5, 6].

Compared to conventional hydrocarbon-based diesel, biodiesel can be used to reduce emissions of pollutants, especially sulphur and soot. Another characteristic of this fuel is that as it has a higher flash point than diesel as shown in table (1), it is safer to be stored and managed.

When used as a vehicle fuel, biodiesel offers some tailpipe and considerable greenhouse gas (GHG) emission benefits over conventional gasoline and diesel fuels. The GHG emission benefits of biodiesel are especially significant, because carbon dioxide (CO_2) released during fuel combustion is offset by the CO_2 captured by the plants from which biodiesel is produced [1, 7].

Oxygen content in biodiesel contributes to better oxidation process within the combustion chamber. This reduces CO emissions, but promotes higher NOx emission. Additionally, the advanced start of injection, caused by biodiesel usage, also contributes to a higher production of NOx emissions.

The biodiesel-blended fuels generally can be investigated by using imaging techniques, such as Schlieren, shadwography, PIV, and Doppler [6, 8-10].

Table 1 Diesel and biodiesel properties [1]

Fuel Property	Unit	Diesel	Biodiesel
Fuel Standard	---	ASTM D975	ASTM D6751
Higher Heating Value	MJ/kg	32.6	30.12
Lower Heating Value	MJ/kg	30.6	29.02
Kinematic Viscosity @ 40ºC	mm^2/s	1.3–4.1	4.0–6.0
Specific Gravity	---	0.85	0.88
Density @ 15.5	kg/m^3	850.77	874.73
Boiling Point	ºC	180–340	315–350
Flash Point	ºC	60–80	100–170
Cloud Point	ºC	-35 to 5	-3 to 15
Pour Point	ºC	-35 to -15	-5 to 10
Cetane Number	---	40–55	48–65

The atomization characteristics of biodiesel-blended fuels were investigated in terms of spray tip penetration, sauter mean diameter, and mean velocity distributions using spray visualization system and phase Doppler particle analyser [5]. The effect of mixing ratio on the combustion characteristics was studied on the basis of the results of the combustion pressure obtained from the single-cylinder engine at various experimental conditions. The results indicated that the mean size of the droplets increases in accordance with the mixing ratio of the biodiesel because the viscosity and surface tension of the biodiesel are higher than those of the conventional diesel fuel.

On the other hand, liquid fuel spray is an integral of small size droplets. Therefore, understanding droplet combustion gives a good insight towards the understanding of the combustion characteristics of the liquid fuel spray. Droplet combustion has been studied extensively throughout different aspects [11-16]. Blending diesel by biodiesel is one of these aspects [17-20]. In the majority of the conducted work on droplet combustion, droplet size evolution, burning rate, and flame to droplet stand-off ratio represent the basic investigated parameters. However, there are some other factors that are as important as the aforementioned ones. Secondary atomization is one of these parameters that are of practical importance in spray combustion systems due to its role in enhancing fuel-air mixing and then improving combustion efficiency. Secondary atomization is the disintegration of the droplet into smaller size sub-droplets.

The main objective of the current work is to give an insight full scale exploration of the combustion characteristics of the biodiesel-blended diesel fuel droplet using high speed imaging. This exploration is carried out using backlit imaging for droplet and flame size investigations, in addition to tracking secondary atomization using Schlieren imaging. Schlieren imaging gives the capability of differentiating between different objects by temperature gradient. Therefore, it is useful for tracking the small size sub-droplets emitted from the original droplet.

EXPERIMENTAL WORK

Biodiesel blends substituting diesel oil in concentrations of 7%, 10%, 20% and 30% on volumetric basis, in addition to pure diesel and pure biodiesel have been studied. For simplicity, the blends will be symbolized as BD07, BD10, BD20, and BD30 respectively, while diesel and biodiesel will be given the symbols D100 and B100 respectively. The diesel-biodiesel blends are prepared in lab prior to experiments. Fuel droplets are generated and suspended on a 75 µm cross-shaped silicon carbide (SiC) fibre mesh using a micro-fine syringe with hypodermic (0.33*12.7mm) needle. A Photron-SA4 high speed colour camera has been used for tracking droplet lifetime during combustion with two different techniques. The former is backlighting imaging which is used for tracking droplet and flame size evolution. In this technique, two 6-volt LED lights with white light diffuser have been used behind the droplet and opposite to the camera lens as shown in figure 1. A Nikon AF Micro NIKKOR 60mm f/2.8D lens with a 55mm macro extension tube set is attached to the camera for obtaining a detailed focused image of the droplet and the corresponding flame.

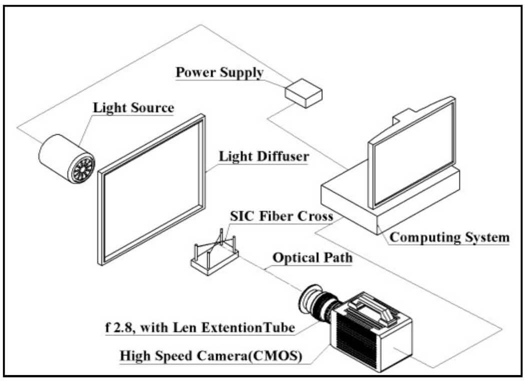

Figure 1 Backlit imaging setup.

Camera framing rate is set to 1000 frame per second. In the other technique, which is the 2-mirror Schlieren imaging, a Nikon AF NIKKOR 50mm f/1.8D lens is attached to the camera for tracking droplet secondary atomization during combustion. Hence, the camera has been set to 10000 frames per second to provide sufficient time for tracking. Figure 2 shows the Schlieren imaging setup. A pilot butane flame has been used for igniting the droplet. Sideway heating of the SiC fibre is found to produce the most reliable and repeatable ignitions.

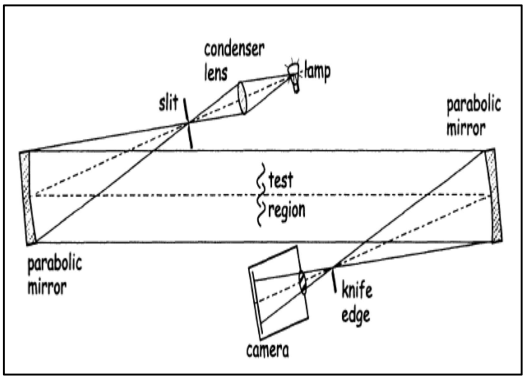

Figure 2 Schlieren imaging setup [21].

At the same time, the impact of the pilot flame has also been kept to the minimum. The images are recorded for the time between droplet ignition and flame extinction. Each test has been repeated four times, with the droplet initial diameter being fixed at 1.2±0.15 mm. The acquired images have been stored in (TIFF) format and processed by specifically written algorithms using Matlab.

RESULTS AND DISCUSSION

Backlighting Imaging

Backlighting imaging has been used for studying droplet size evolution and the corresponding visible flame dimensions. Droplet combustion characteristics have been investigated for the diesel/biodiesel blends (BD07, BD10, BD20, and BD30) as also those of pure diesel (D100) and pure biodiesel (B100).

Figure 3 shows the sequence of events of BD07 droplet combustion captured by backlighting imaging.

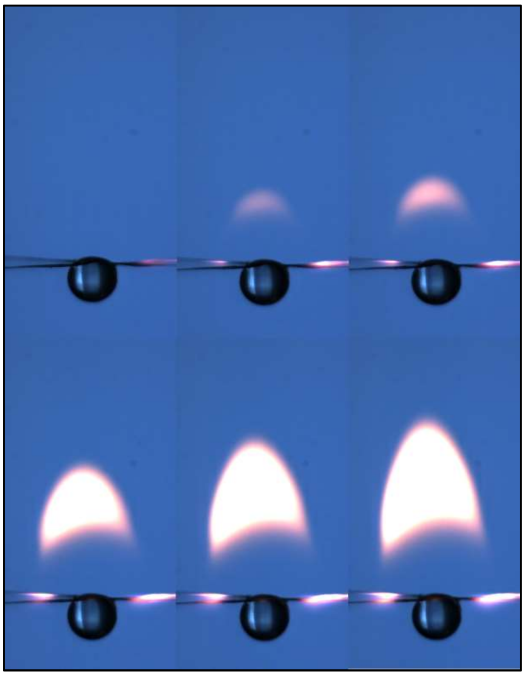

Figure 3 BD07 droplet combustion images.

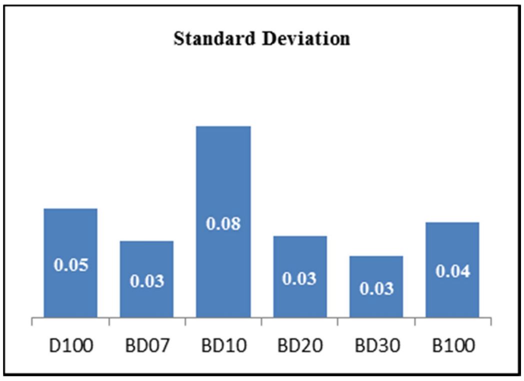

Figure 4 Standard deviation of droplet burning rate for the studied fuels.

As mentioned before, the tests have been repeated four times for every fuel. The repeatability of droplet burning rate has been evaluated by the standard deviation of the resulting droplet burning rate for each test as shown in figure 4.

Figure 5 shows the normalized evolution of the droplet squared diameter for diesel, biodiesel, and diesel/biodiesel blends respectively with time. Droplet size evolution has been estimated using the equivalent circular area of the droplet projected area evaluated by image processing using Matlab. Droplet size evolution has been expressed in terms of burning time divided by initial droplet size according to the D2-law of droplet combustion which states that $(D/D_0)^2=1-K(t/D_0)^2$ [22]. From the figure it can be seen that the burning rates of diesel and biodiesel droplets are almost less than those of their blends. This suggests that blending diesel by biodiesel leads to less fuel consumption for the same interval of time. Additionally, it can be seen that BD07 and BD20 blends are lasting for much longer time than other droplets. These fuels have been tested four times and for all the tests this burning rate has been noticed. Moreover, droplet expansion in the later stages of combustion has been noticed to occur for the diesel/biodiesel blends compared to the base fuels. This expansion is attributed to the evaporation of the less volatile component in the multicomponent mixtures [13].

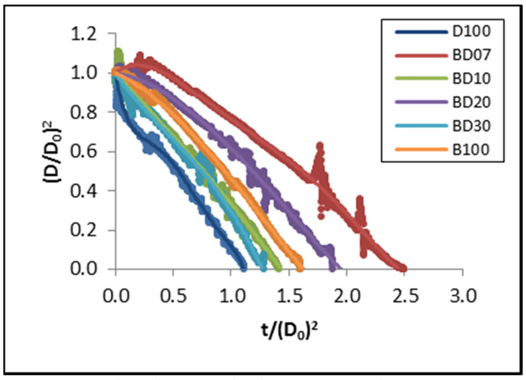

Figure 5 Droplet size evolution versus time.

The expansion onset time and occurrence intervals have been evaluated for all the blends and shown in figure 6. It can be inferred that the higher the biodiesel content in the mixture the earlier the droplet expansion to occur. However, the overall expansion interval is decreased by increasing biodiesel in the blend. This could be related to the combustion behaviour of both diesel and biodiesel droplets shown in figure 6. In which biodiesel shows a more stable and non-fluctuating size change compared to diesel droplet whose fluctuation is more obvious.

Figure 7 shows the normalized rate of change of droplet size with time for all the investigated fuels. The negative values illustrate the droplet size reduction, while droplet expansion is shown by the positive values. The figure shows that droplet size fluctuation is higher for the blends when compared to pure diesel and pure biodiesel droplets. Furthermore, it can be seen from the figure all the droplets show a slight increase in size in the first 10-20% of the overall combustion time. This is the transient heating period of droplet combustion.

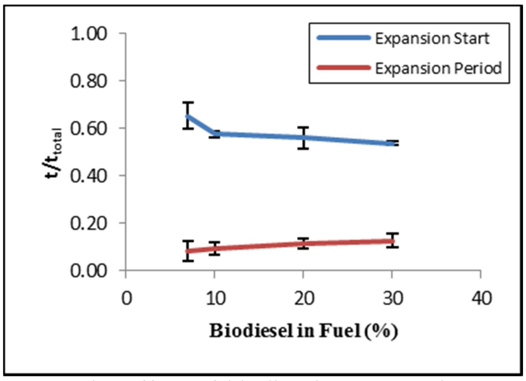

Figure 6 The effect of biodiesel concentration on the droplet expansion starting time and occurrence interval.

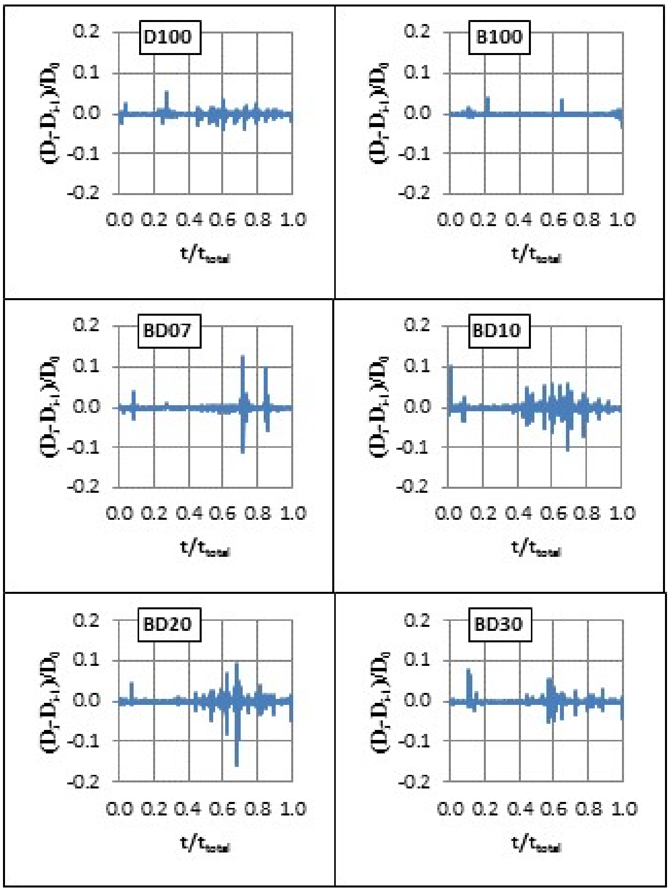

Figure 7 Normalized droplet size fluctuation versus time for the fuels under investigation.

Figure 8 shows the variation of flame height with time for diesel, biodiesel, diesel/biodiesel blends at 7, 10, 20, and 30% of biodiesel content in the blend. Flame height has been normalized according to the droplet size for each of the fuels. Time as well has been normalized in accordance to the total time required for complete combustion of the droplet. From the figure it can be seen that diesel droplet has the highest flame while biodiesel has the lowest, and in between are the flames of the diesel/biodiesel blends. This is attributed to the sooting tendency of the fuels, where biodiesel has a lower sooting tendency compared to diesel that is classified as a sooting fuel.

This in fact is the idea behind adding biodiesel to diesel. It can be seen from the figure as well that at the early 20% of the overall droplet combustion, there is a dramatic increase in flame height of almost all the fuels except biodiesel. This is due to the combustion of the fuel vapour that is generated by droplet heating and evaporation before ignition. After the vapour is consumed by combustion, flame height decreases to a certain level that is defined by fuel evaporation from the droplet surface and the tendency of this fuel to generate soot during combustion. However, this sudden increase in flame height has not been seen for biodiesel droplet, which could be attributed to the flash point of biodiesel that is much higher than that of diesel. This means that biodiesel needs a higher temperature for evaporation and ignition, in addition to the aforementioned low sooting tendency of biodiesel. All these factors led to biodiesel flame height being less than that of diesel and diesel/biodiesel blends.

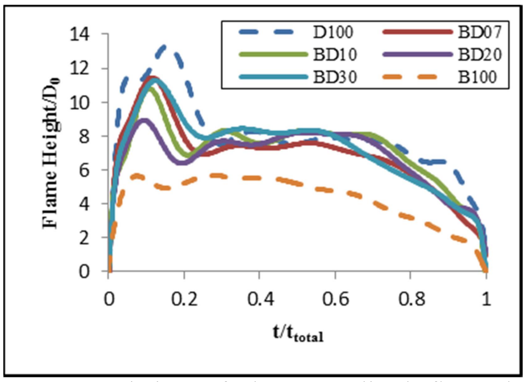

Figure 8 Variation of the normalized flame height with combustion time.

Figure 9 shows the normalized flame width versus normalized combustion time for the droplet combustion of the fuels under investigation. It can be seen from the figure that the diesel flame is the widest among all, followed by the blends, and then it comes the biodiesel flame.

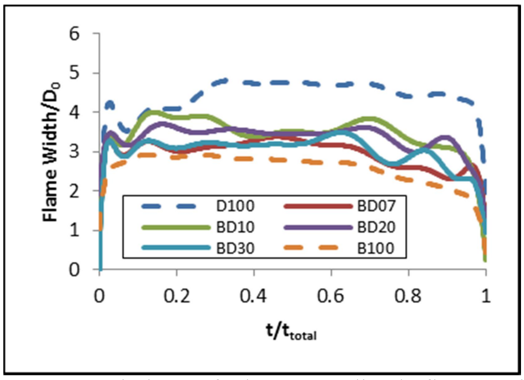

Figure 9 Variation of the normalized flame width with combustion time.

Generally, the arrangement is similar to that of figure 8, except that sudden rise in flame height which is not seen in the width, since vapour is flowing upward. Another parameter that can be found by comparing both figure 8 and figure 9, is the ratio between flame height and its width, which is found to be equals or slightly higher than two.

Figure 10 shows the average droplet burning rate and average flaming period of diesel, biodiesel and diesel/biodiesel blends per droplet size expressed in initial diameter squared. Flame lifetime represents the interval of time from the start of droplet ignition to the instant when flame extinction takes place. This time is slightly different from the droplet lifetime; since there is a very small period of time where the droplet evaporates completely whiles the flame still existing due to the combustion of the remaining fuel vapour. From the figure it can be seen that diesel and biodiesel burning rates are slightly higher than those of the blends, causing the flame period to be exactly the inverse. This may give an indication of the spray burning rate, which in turn indicates the fuel consumption.

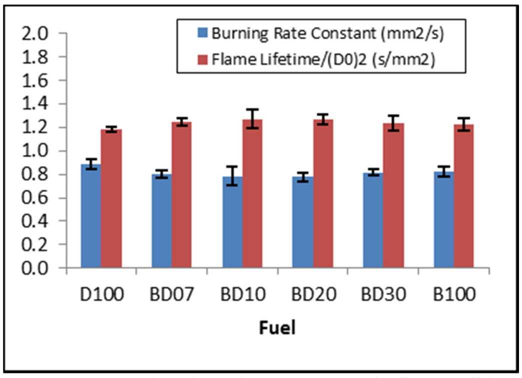

Figure 10 Droplet burning rate and flame lifetime of the investigated fuels.

Schlieren Imaging

Schlieren imaging has been used for tracking the micro-droplets emitted from the original droplet by secondary atomization. Three tests have been carried out for investigating each of diesel, biodiesel, 7%, 10%, 20%, and 30% diesel/biodiesel blends.

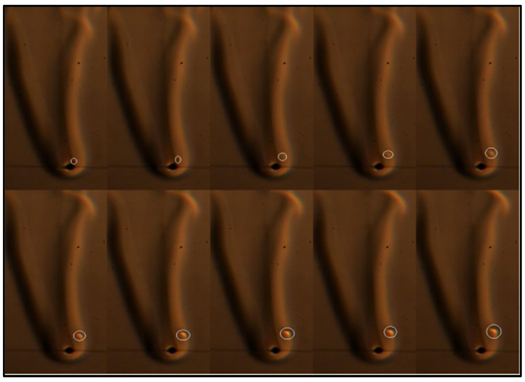

Figure 11 Schlieren images of secondary atomization from a BD07 droplet.

Figure 11 shows the sequence of events for sub-droplet emission from the BD07 droplet. The sub-droplet had its own flame surrounding it, therefore its detection by Schlieren imaging was easily conceivable.

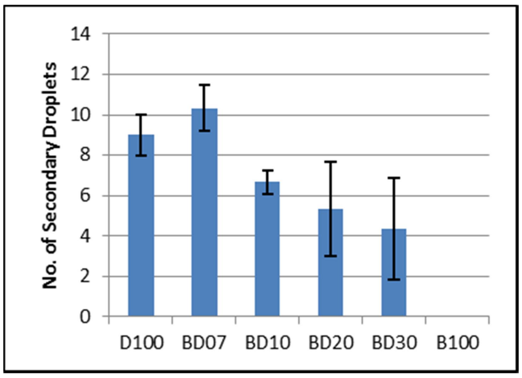

Figure 12 Averaged number of sub-droplets emitted from the original droplet.

Figure 12 shows the average number of sub-droplets emitted from the burning droplet of diesel, biodiesel, and diesel/biodiesel blends. It can be seen from the figure that biodiesel fuel droplet did not experience any secondary atomization at all the tests carried out. Diesel droplet, conversely, has had secondary atomization in a relatively high rate. Accordingly, the diesel/biodiesel blends have experienced secondary atomization in a rate lower than that of diesel. This rate is inversely proportional with biodiesel concentration in the blend.

CONCLUSIONS

In the present work an experimental investigation for the droplet combustion of diesel, biodiesel, and their blends has been carried out, and the followings have been found:

- The burning rates of diesel and biodiesel droplets are less than those of their blends. This suggests that blending diesel by biodiesel leads to less fuel consumption for the same interval of time.
- The droplet expansion in the later stages of combustion has been noticed to occur for the diesel/biodiesel blends compared to the base fuels. This expansion is attributed to the evaporation of the less volatile component in the multicomponent mixtures.
- The higher the biodiesel content in the mixture, the earlier the droplet expansion to occur. However, the overall expansion interval is decreased by increasing biodiesel in the blend. This is related to the combustion behaviour of both diesel and biodiesel droplets. Since biodiesel showed a more stable and non-fluctuating size change compared to diesel droplet whose fluctuation is more obvious.
- Diesel droplet has the highest visible flame while biodiesel has the lowest, and in between are the flames of the diesel/biodiesel blends. This is attributed to the sooting tendency of the fuels, where biodiesel has a lower sooting tendency compared to diesel that is classified as a sooting fuel.

- Diesel and biodiesel burning rates are slightly higher than those of the blends, causing the flame period to be exactly the inverse.
- Schlieren imaging is found to be a useful tool for investigating droplet secondary atomization, due to its capability of differentiating temperature gradient between objects.
- Biodiesel fuel droplet did not experience any secondary atomization at all the tests carried out. While, in contrast diesel droplet has had secondary atomization in a relatively high rate. Accordingly, the diesel/biodiesel blends have experienced secondary atomization in a rate lower than that of diesel except for the low biodiesel case (BD07). This rate is inversely proportional with biodiesel concentration in the blend.

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