Single droplet ignition and combustion of jet-A1, hydroprocessed vegetable oil and their blends in a drop tube furnace

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Abstract

The aeronautical sector needs to introduce alternative fuels in order to achieve a reduction in greenhouse gas emissions. A possible solution in the near future might be the blending of biofuels with jet fuel, which would allow the use of a greener fuel without significant changes in the existing fleets of the companies, which means the development of a "drop in" fuel. The present work aims to study the ignition and combustion characteristics of single droplets of jet-A1 (JF), hydroprocessed vegetable oil (NExBTL) and their mixtures in a drop tube furnace (DTF). The droplets were injected into the DTF using a droplet generator. Experiments were conducted in air for three DTF wall temperatures (900, 1000 and 1100 ºC). The ignition and combustion of the droplets were evaluated through the images obtained with a high-speed camera coupled with a high magnification lens. The images allowed for the observation of the burning phenomena, and data are reported for temporal evolution of droplet sizes and burning rates. The results revealed that the mixtures followed the D^2 law, except the mixture with 75% JF for a DTF wall temperature of 1100 ºC. This was due to the occurrence of puffing, which enhanced the burning rates. In addition, it was observed that the mixtures with higher content of JF present brighter flames, and higher burning rates.

Keywords: Single droplet, jet fuel, hydroprocessed vegetable oil, mixtures, ignition, combustion, puffing, micro-explosion

Introduction

Commercial aviation has become a global business of around 21450 aircraft currently operating on a single fossil fuel product. This sector is responsible for 2-3% of the global CO_2 emissions and its fleet will grow to almost 47990 aircraft by 2037 [1,2]. This rapid growth, coupled with the continuous increase in fuel prices and growing in CO_2 emissions from this sector (which are expected to grow up to 80% [3]), have inspired intense research on alternative fuels that could supply the sector and reduce the environmental costs. Biofuels are interesting candidates essentially because of their low greenhouse gas emissions. Any new aviation fuel must be fully interchangeable with the current jet fuel to avoid the logistic problems of airports handling multiple fuels of diverse quality and the commercial limitations this would impose. For these reasons, the main research drive has been around the development of "drop-in" fuels, which can be used in the existing fleet since industry keeps its assets in use for around 40 years [1] due to the high investment costs. A possible new fuel is the hydroprocessed vegetable oil HVO) called NExBTL. This is a very promising fuel since it has been already approved for blending with conventional jet fuel in ratios 50/50. In this context, the main goal of this work is to evaluate the effect of blending HVO with jet fuel on the ignition and combustion characteristics of the resulting mixtures.

Materials and Methods

Figure 1 shows the experimental setup used in this study. The drop tube furnace (DTF) comprises an electrically heated coil and a vertical quartz tube with an inner diameter of 6.6 cm and a length of 82.6 cm. It can achieve wall temperatures up to 1200 ºC that are monitored by two type-S thermocouples. The DTF has two opposed rectangular windows with 2 cm width and 20 cm height. The heating zone, where the coils are placed, is 30 cm long. The image acquisition system (IAS) is positioned perpendicularly to the quartz tube, in front of one of the rectangular windows, with a diffusive light placed on the opposite side of the IAS, as shown in Fig. 1.

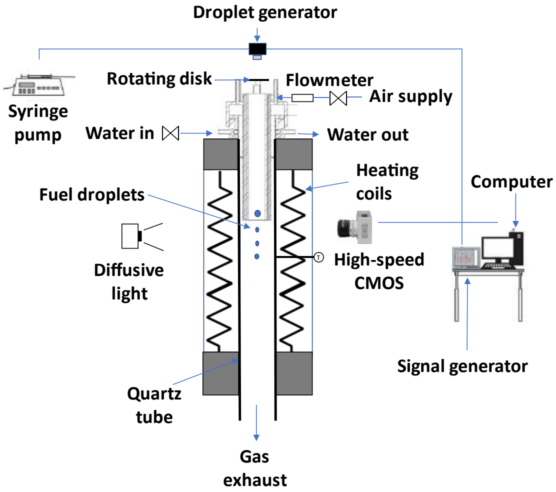

Figure 1: Experimental set-up.

The droplets were generated by a TSI device (MDG100), which produces monosize droplets with the help of a piezoelectric device. Droplets were produced with an initial diameter of 155 ± 5 µm, which is an acceptable compromise between actual sizes in practical applications and experimental constraints to obtain measurements with good accuracy. A rotating disk with a slot was placed between the droplet generator and the entrance of the injector in order to increase the space/time between consecutive droplets. The IAS consists of a high-speed CMOS camera connected to a computer, which allows for the control of the camera and stores images for further image data processing. The camera used was a CR600x2 from Optronics. A frame rate of 1000 fps was used, coupled with a resolution of 1280x500 pixels. A high magnification lens (Zoom 6000® Lens System) was attached to the high-speed camera to increase the spatial resolution of the image up to 8.2 µm/pixel. The set-up required background homogeneous illumination to intensify the contrast and to improve the quality of the images. Calibration of the IAS was done before each set of measurements. Subsequently, the scale pixel/mm was determined to allow the treatment of the data. To obtain data on burning rates the droplet diameters were automatically calculated by means of an edge detection algorithm. For each experimental condition, a minimum of 30 single droplets were analyzed.

Fuels characterization

Jet-A1, NExBTL and their blends were used in this study. Fuel mixtures were made with the aid of a volumetric pipette. The pipette has a volumetric capacity of 50 ml ± 0,05 ml. Subsequently, the mixtures were stored in closed glass recipients to preserve their properties.Table 1 shows the main properties of the fuels used [4].

Table 1: Fuel properties.

Parameter	100% JF	75% JF	50% JF	25% JF	No JF
Density (kg/m^3)	785.8	783.9	782.0	779.9	778.2
Viscosity (mm^2/s)	1.4	-	2.3	-	4.4
Aromatics (wt.%)	13.8	10.4	7.0	3.5	0.2
Boiling point (ºC)	< 300	-	-	-	< 330
LHV (MJ/kg)	43.4	-	43.6	-	43.9
HHV (MJ/kg)	46.0	-	46.5	-	47.0

Results and discussion

Ignition and combustion behavior of the single droplets

Figure 2 shows sequences of instantaneous images of burning droplets at different temperatures. After injection into the quartz tube, the droplets ignite due to the high air temperature and a flame is established at the wake of each droplet, as seen in Fig. 2. The figure also reveals that the flame intensity (luminosity) decreases and the droplet lifetime increases as the ambient air temperature decreases from 1100 ºC (Fig. 2a) to 900 ºC (Fig. 2c), regardless of the composition of the fuel mixture.

The composition of the fuel mixture also affects the burning characteristics mainly due to the different content of aromatics in the different fuel mixtures. In particular, the flame intensity increases, and the flame root moves closer to the droplet as the percentage of jet-A1 in the fuel mixture increases.

Interestingly, it was observed the occurrence of disruptive burning for the fuel mixture with 75% of jet-A1 (cf. Fig. 2a). At *t* = 16 ms (Fig. 2a) a sudden increase in the flame size and intensity occurs. This phenomenon, often called puffing, is characterized by the release of volatiles due to the breakup of an expanding gas bubble formed inside the fuel droplet. This event is followed by a rapid decrease in the diameter of the droplet, as seen at *t* = 24 ms. These observations are consistent with other studies [5]. The occurrence of puffing precedes the occurrence of micro-explosions, as observed at *t* = 40 ms, with the establishment of a spherical flame, and no visible droplet. Obviously, the occurrence of micro-explosions reduces significantly the droplet lifetime.

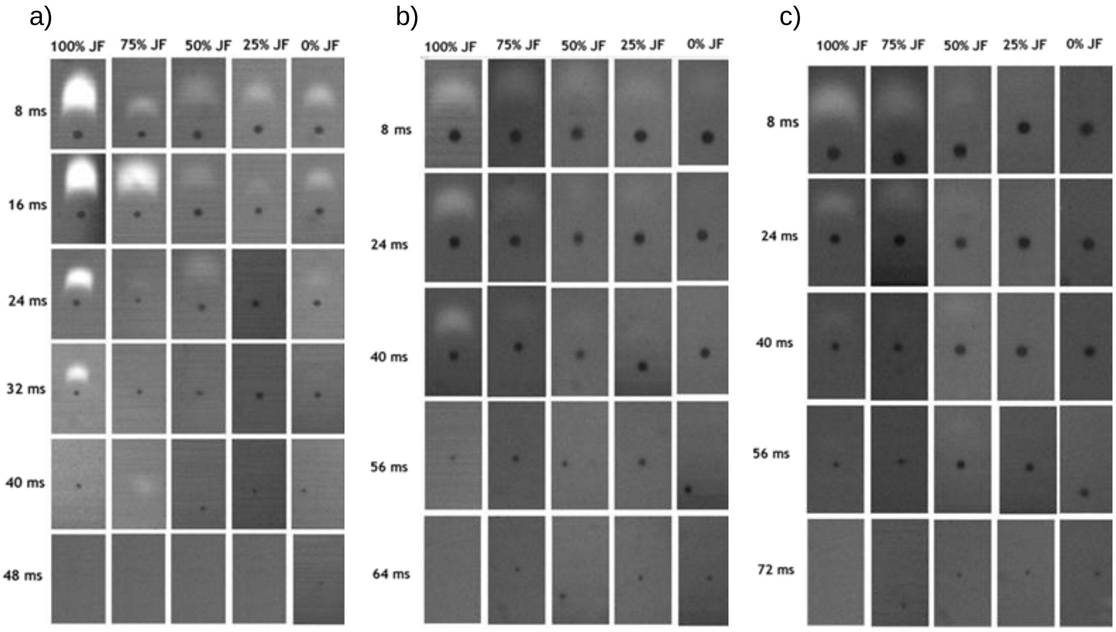

Figure 2: Sequences of instantaneous images of burning droplets at different temperatures. a) 1100 ºC; b) 1000 ºC; c) 900 ºC.

Figure 3 characterizes the micro-explosions regarding their frequency and the droplet diameters when they occurred. It is seen that micro-explosions occurred for 71% of the droplets for the fuel mixture with 75% of jet-A1 at 1100 ºC. In addition, the droplet diameter that favors disruptive burning for this test condition is 62.5-66.3 µm. It should be pointed out that disruptive burning enhances the secondary atomization and reduces the droplet lifetime and thereby improves the droplet burning properties [6].

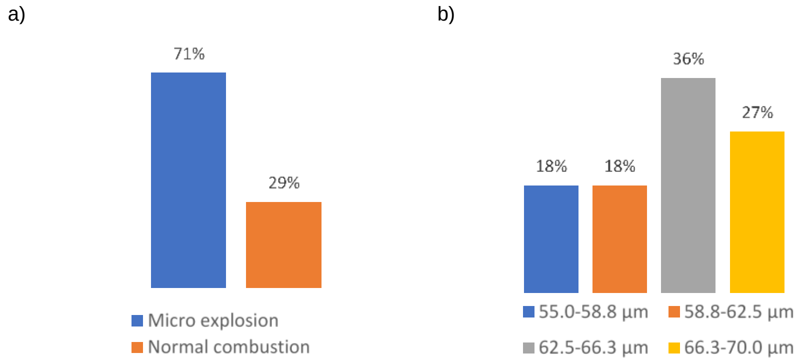

Figure 3: Characterization of the micro-explosions for the fuel mixture with 75% of jet-A1 at 1100 ºC. a) Frequency of micro-explosions; b) droplet diameter at the micro-explosion instant.

Droplet size evolution and burning rate

The analysis below is based on the well known D^2 law. Fig. 4 shows the normalized droplet diameter as a function of the normalized time for the three different temperatures studied. It is seen that the results are in good agreement with the D^2 law, which predicts that the normalized square diameter decreases linearly with the time with a nearly constant slope – the so called burning rate, K_b. Moreover, the evolution of the normalized droplet diameter is quite similar for all conditions, except for the fuel mixture with 75% of jet-A1 at 1100 ºC (Fig. 4a). The droplets of pure HVO present the longest burning time and the droplets of pure jet-A1 the shortest one. The evolution of the droplets of the fuel mixture with 75% of jet-A1 present the most distinctive behavior because of the occurrence of puffing and micro-explosions, as discussed earlier. Finally, Figs. 4a-c reveal that the droplet burning time increases as the air temperature decreases.

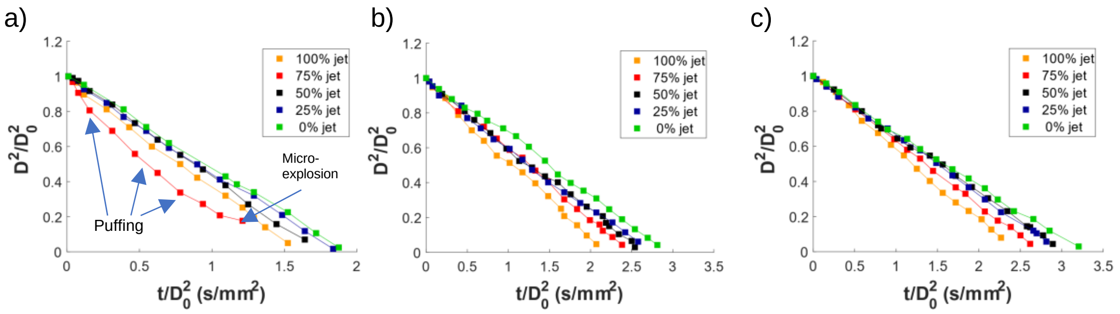

Figure 4: Normalized droplet diameter as a function of the normalized time at different temperatures.

Figure 5 shows the burning rate as a function of the normalized time at different temperatures. The burning rates were calculated from the data presented in Fig. 4 following the procedures described in [7]. With the exception of the fuel mixture with 75% of jet-A1, all droplets present a similar burning behaviour, with an initial rapid increase in the burning rate, followed by an almost constant evolution of it until the end of the droplet lifetime. The droplets with 75% of jet-A1 jet present a distinct behaviour due to the occurrence of puffing and micro-explosions, discussed earlier, that enhances K_b. It can also be concluded that the fuels with higher aromatic contents (cf. Table 1) tend to have higher burning rates.

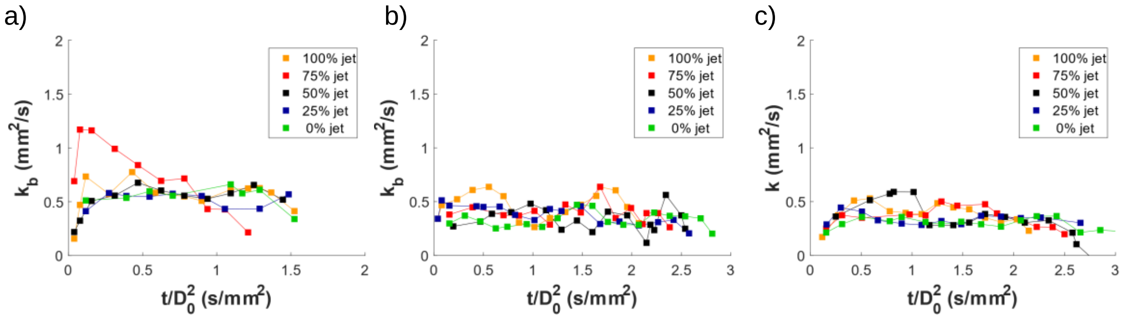

Figure 5: Droplet burning rate as a function of the normalized time at different temperatures. a) 1100 ºC; b) 1000 ºC; c) 900 ºC.

Figure 6 shows the global burning rates as function of the air temperature. It is observed that an increase in the air temperature leads to an increase in the global burning rate. Also, it is seen that as the jet-A1 increases in the fuel mixture, the burning rate also tends to increase. The exception to this behavior occurs for the air temperature of 1100 ºC, where the highest burning rate happens for the droplets with 75% of jet-A1.

When comparing the data for the three air temperatures, it is observed that the differences between the global burning rates of different fuels tend to be smaller at 1100 ºC. This can be attributed to differences in the volatility of each mixture, which tend to be larger at lower temperatures.

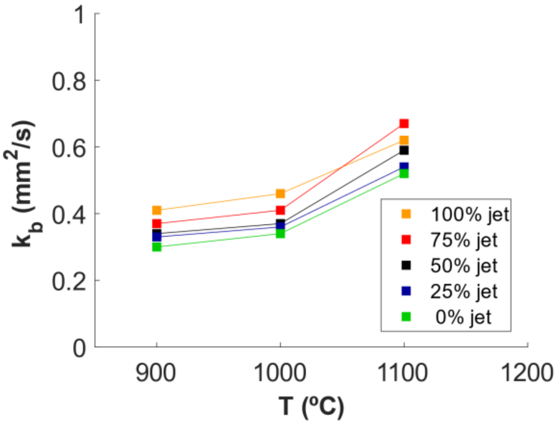

Figure 6: Global burning rates as a function of the temperature.

Conclusions

The main conclusions from this study can be summarized as follows.

1. After ignition, a flame is established at the wake of each droplet for all test conditions. Flame intensity decreases and the droplet lifetime increases as the air temperature decreases, regardless of the composition of the fuel mixture. As the percentage of jet-A1 in the fuel mixture increases, the flame intensity increases and the flame root moves closer to the droplet.
2. The occurrence of puffing followed by micro-explosions was observed for the fuel mixture with 75% of jet-A1. This phenomena enhanced the secondary atomization and reduced significantly the droplet lifetime.
3. The droplet diameters follow the D^2 law being quite similar for all conditions, except for the fuel mixture with 75% of jet-A1 at 1100 ºC. The droplets of pure HVO present the longest burning time and the droplets of pure jet-A1 the shortest one. The droplet burning time increases as the air temperature decreases.
4. An increase in the air temperature leads to an increase in the global burning rate. As the amount of jet-A1 increases in the fuel mixture, the burning rate also tends to increase.

Acknowledgments

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