Combustion behavior of Jet-A1 single droplets and its blends with Hydroprocessed Vegetable Oil in a drop tube furnace

G. Pacheco[1,2], A. Silva[1], M. Costa[2]

[1] AEROG-LAETA, Universidade da Beira Interior, Covilhã, Portugal
[2] IDMEC-LAETA, Instituto Superior Técnico, Universidade de Lisboa, Lisboa, Portugal

*Corresponding author: G.Pacheco, Email: sousapacheco@tecnico.ulisboa.pt

Abstract

The aeronautical sector contributes significantly to greenhouse gases and pollutant emissions. The negative impact of these emissions in the environment has raised awareness for the introduction of alternative and greener fuels. The implementation of alternative fuels remains one of the main challenges for this sector in the near future. The aeronautical industry is characterized by the dependence on single fossil fuel and by a long service time of its assets. For these reasons, the main research drive has been around the development of "drop-in" fuels, which are alternative fuels that can be used in the already existing fleet without significant modifications.

One of the proposed solutions is the blending of biofuels with jet fuel, which would allow the use of greener fuels and a reduction in greenhouse gases and emissions without significant changes in the existing companies' fleets. In this context, the present work evaluates the ignition and the combustion of single droplets of jet-fuel, hydroprocessed vegetable oil (NExBTL), and their mixtures in a drop tube furnace. The main research focus of this study is to evaluate the influence of the mixture composition in the fuel-burning characteristics.

Droplets with diameters of 155 ± 5 μm, produced by a commercial droplet generator, were injected into the top of the drop tube furnace. Three temperatures were investigated 900, 1000, and 1100 °C. The ignition and combustion of the droplets were evaluated through the images obtained with a high-speed camera (CR600x2) coupled with a high magnification lens (Navitar 6000 zoom lens) and treated with an edge detection algorithm. The images allowed for the observation of the burning phenomena, and the data reported the temporal evolution of the droplet sizes and burning rates. The pure fuels and mixtures followed the D^2 law, except for the mixture with 75% jet-fuel/ 25% biofuel at 1100 °C that reveals disruptive burning phenomena contributing to the enhancement of the single droplet combustion. The disruptive burning phenomena are related to the appearance of "puffing" and micro-explosions at the end of the droplet lifetime.

1. 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 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 promising candidates, essentially because of their low greenhouse gas emissions [4]. The use of biofuels poses a challenge because the aeronautical sector requires fuels with high energy density and with well-specified properties in order to comply with the current legislation. Currently, the commercially available biofuels can not comply with the current legislation. Any new aviation fuel must be fully interchangeable with the current jet fuel(JF) 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.

However, the use of biofuels raises other concerns. Sustainable aviation fuels must offer low carbon emissions over their lifecycles. The energy crops used as the production source should not challenge food production, ecosystems, and also do not harm the environment [5]. One of the most promising candidates is the hydroprocessed vegetable oil (HVO) called NExBTL. This fuel is very promising since it has already been approved for blending with the

conventional jet in fuel ratios of 50/50%v and promotes fewer pollutant formation. The hydrodeoxygenation of vegetable oils produces hydroprocessed renewable jet fuel(HRJ), from animal fats, waste grease, algal oil, bio-oil, and the primary side products are water and propane [6], the HVO in use comes from cellulosic feedstock [7]. One of the significant advantages of HRJs is the reduction in the emission of greenhouse gases such as carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NOx), and particulate matter (PM) [8]. The HRJs are free of aromatics and sulfur and possess a high cetane number, high thermal stability, and low tailpipe emissions [9]. These characteristics enable its use in conventional aircraft engines without further engine modification and do not raise any fuel quality issues.

Additionally, HRJs are fit for higher altitude flights due to their good cold flow properties. The cold flow properties are a limitation for other types of biofuels, such as biodiesel and bio alcohol [8]. On the other hand, the difference in the cetane numbers of hydroprocessed renewable jet fuels and conventional petroleum fuels affects the fuel ignition in the engine. These problems are better solved by blending HRJs with conventional fuels [10]. Aeroméxico, Air China, Air France, Finnair, Iberia, Air France KLM, and Lufthansa have performed commercial passenger flights with hydroprocessed esters and fats [11]. An excellent example corresponds to Japan airlines, which demonstrate that the feedstock independence of HRJs through incident free operating one of its Boeing 747-300. The roundtrip test flight operated one of four engines on a 50/50%v blend of conventional jet fuel and hydroprocessed biomass feedstock. The success of recent test campaigns has not only highlighted biomass product compatibility with gas turbines but also demonstrates the technological readiness and feedstock independence of the hydrotreatment process [11].

The performance of alternative fuels concerning particulate emissions has received considerable attention. Most of the studies which have evaluated BtL (biomass to liquid) or HRJ, indicated a reduction in particle matter emissions. This reduction is primarily due to the reduction in the aromatic content of the fuel. The main goal of this work is to study the burning characteristics of the different fuel mixtures, mainly to evaluate the effect of blending different amounts of HVO and JF in the burning behavior of droplets to increase the knowledge on multicomponent fuels. Even though engine studies provide beneficial information regarding fuel performance under realistic conditions, the results observed depend on several non-controllable variables. So, in a fundamental study such as single droplet ignition, the parameters and test conditions are well defined. In this way, it is possible to attribute the combustion characteristics observed to the fuel and permits a better comprehension of the observed phenomena, such as micro-explosions and puffing. These phenomena usually occur when there is a mixture with a high volatility difference between each of the component blends, ultimately leading to an improved combustion performance [12]. Ma et al. [13] studied the evaporation characteristics of (acetone-butanol-ethanol) and diesel blended droplets, and the author reported bubble formation and droplet rupture at high ambient temperatures. Puffing/micro-

explosions causes the fragmentation of droplets, which plays an essential role in improving the atomization. The fragmentation is considered an effective way of promoting efficient combustion.

The earlier affirmation is supported by engine experiments that have confirmed the overall benefits of micro-explosion of emulsion fuels [14, 15, 16]. Another significant benefit from the emulsion of different fuels was studied by Shinjo et al. [17], who also investigated the physics of puffing and micro-explosion in emulsion fuel droplets. The authors stated that it might be possible to control micro-explosion/puffing in a fuel spray by the appropriate mixing of fuel blends and ambient flow conditions. A possible new fuel is the hydroprocessed vegetable oil HVO) called NExBTL.

This fuel is very promising since it has already been approved for blending with conventional jet fuel in ratios 50/50 %v. 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.

2. 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.
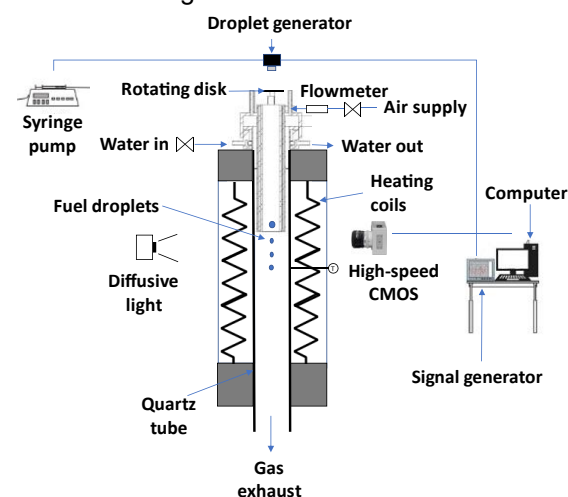

Fig. 1 Experimental setup.

The droplets were generated by a TSI (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 reasonable 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 setup required homogeneous background 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. The droplet diameters were automatically calculated employing an edge detection algorithm to obtain data on the burning rates. For each experimental condition, a minimum of 30 single droplets were analyzed.

2.1 Fuels characterization

Jet-A1(JF), NExBTL, and their blends were used in this study. Fuel mixtures were made with the aid of a volumetric pipette with 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 [18].

Tab. 1 Fuel properties.

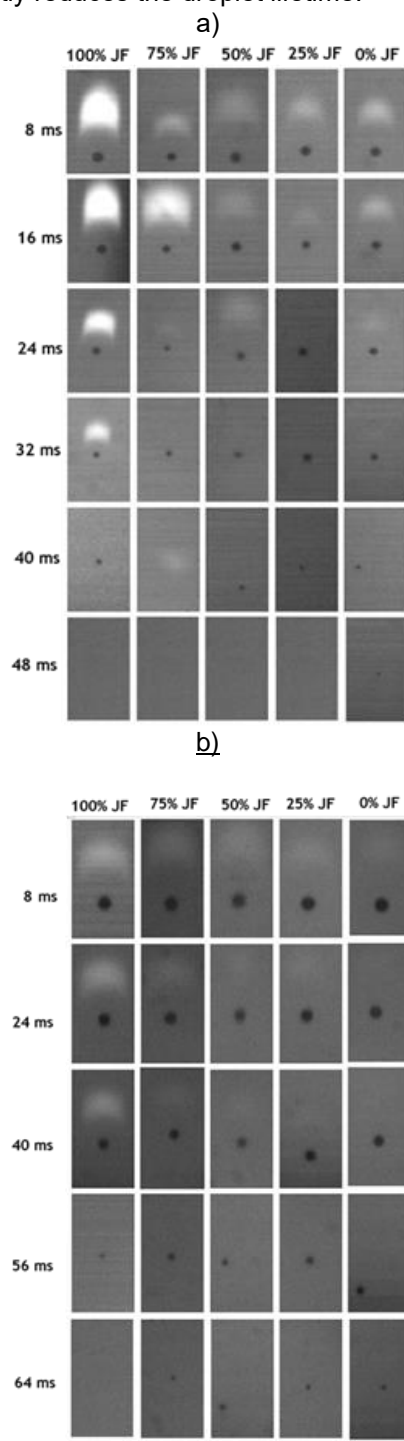| Parameter	100% JF	75% JF	50% JF	25% JF	No JF
Density (kg/m^3)	785.8	783.9	782.0	779.9	778.2
Viscosity (mm^2/s)	1.4	1.9	2.3	3.4	4.4
Aromatics (wt.%)	13.8	10.4	7.0	3.5	0.2
Boiling point (°C)	< 300	-	-	-	< 330
LHV (MJ/kg)	43.4	43.5	43.6	43.8	43.9
HHV (MJ/kg)	46.0	46,3	46.5	46,8	47.0

3. Results and discussion

3.1 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 decrease from 1100 °C (Fig. 2a) to 900 °C (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 [19]. 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 significantly reduces the droplet lifetime.
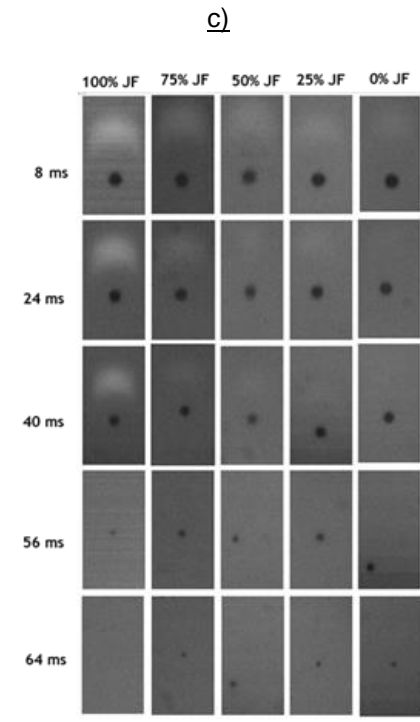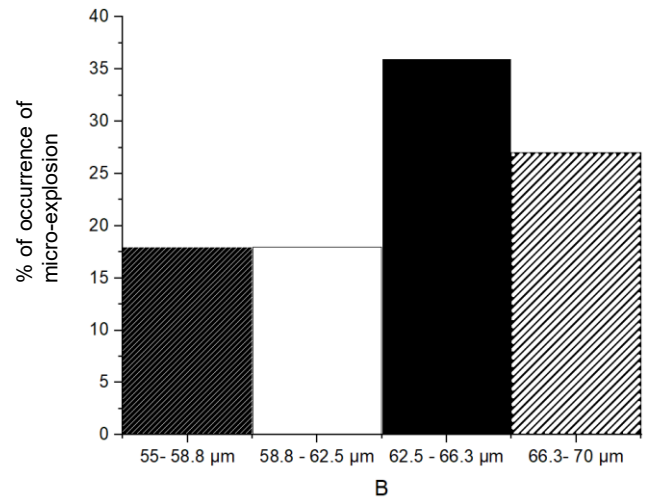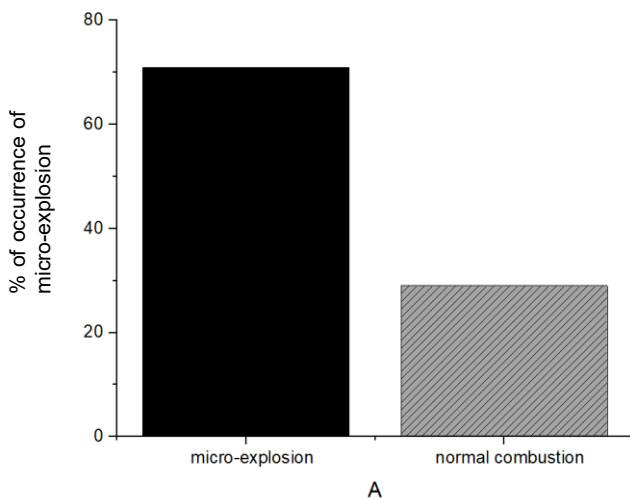
a)

b)

Fig. 3 Characterization of the micro-explosions for the fuel mixture with 75% of jet-A1 at 1100 °C. A) Frequency of micro-explosions; B) droplet diameter at the micro-explosion instant.

3.2 Droplet size evolution and burning rate

The analysis below is based on the well known D^2 law. Fig. 4,5,6 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 °C (Fig. 4). With the exeption of the 75% JF at 1100°C, 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 presents the most distinctive behavior because of the occurrence of puffing and micro-explosions, as discussed earlier. Finally, Figs. 4,5,6 reveal that the droplet burning time increases as the air temperature decreases.
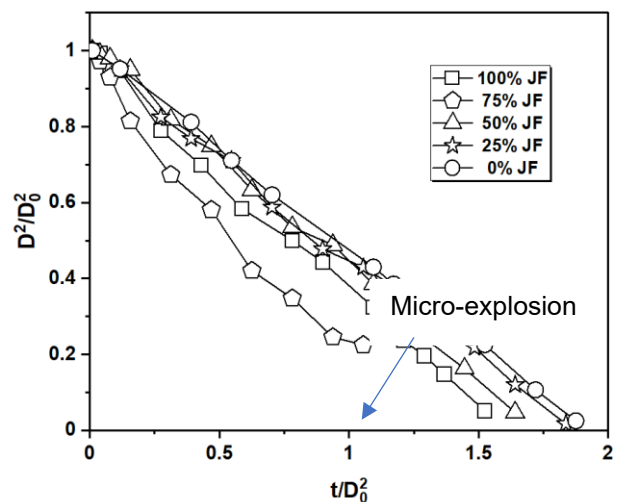

Fig. 2 Sequences of instantaneous images of burning droplets at different temperatures. a) 1100 °C; b) 1000 °C; c) 900 °C.

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 °C. 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 [17].
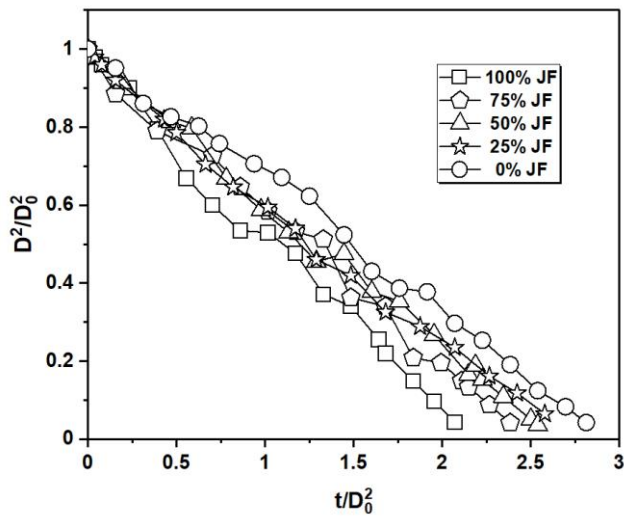

Fig. 4 Normalized droplet diameter as a function of the normalized time at 1100°C.

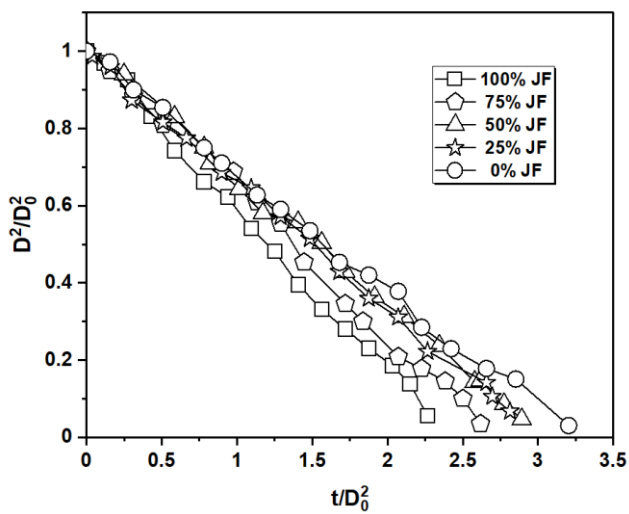Fig. 5 Normalized droplet diameter as a function of the normalized time at 1000°C.

Fig. 7 Droplet burning rate as a function of the normalized time at 1100 °C

Fig. 6 Normalized droplet diameter as a function of the normalized time at 900°C.

Fig. 8 Droplet burning rate as a function of the normalized time at 1000 °C

Figure 7,8,9 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. 4,5,6, following the procedures described in [20]. Except for the fuel mixture with 75% of jet-A1, all droplets present a similar burning behavior, 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 behavior 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.
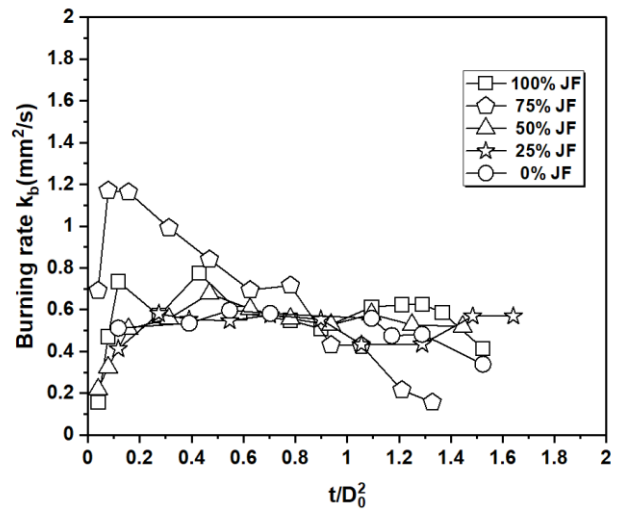

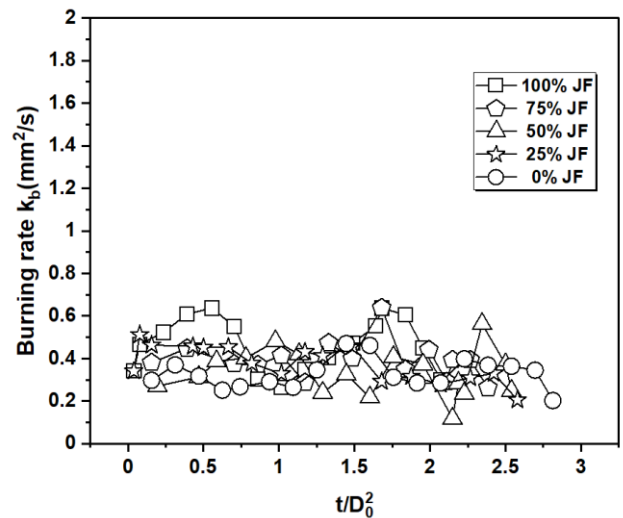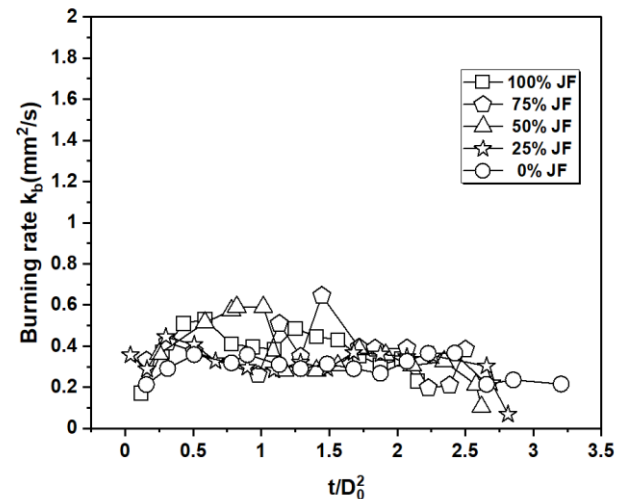Fig. 9 Droplet burning rate as a function of the normalized time at 900 °C

Figure 10 shows the global burning rates as a function of the air temperature. It is observed that an increase in 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 75% jet-A1 mixture exhibits the highest burning rate. 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 phenomenon can be attributed to differences in the volatility of each mixture and its boiling point, which tends to be more evident at lower temperatures.
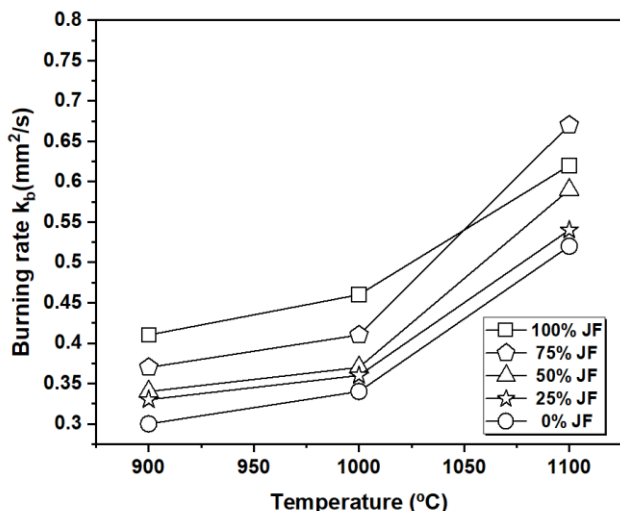

Fig. 10 Global burning rates as a function of the temperature.

4. Conclusion

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

-After ignition, the flame establishes in the wake of each droplet for all test conditions. Flame intensity decreases, and the droplet lifetime increases as the air temperature decreased, 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.

-The occurrence of puffing followed by micro-explosions was observed for the fuel mixture with 75% of jet-A1. This phenomenon enhanced secondary atomization and significantly reduced the droplet lifetime.

-The droplet diameters evolution follow the D^2 law quite similarly 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-fuel the shortest one. The droplet's burning time increases as the air temperature decreases.

-An increase in 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.

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