Single droplet combustion of aluminum nanoparticles added to a biofuel

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Abstract

The present work evaluates the evaporation and combustion of single droplets of a biofuel (HVO) added with aluminum nanoparticles (n-Al). Tests were carried out in a drop tube furnace that allows the control of the wall temperature and oxygen concentration, in which the single droplets were injected downward at the top of the furnace. Droplets with a diameter of 250 µm were generated from a commercial droplet generator. Experiments were conducted with two particle sizes (40 nm and 70 nm) and two particle concentrations (0.5 wt.% and 1.0 wt.%). The effect of the size and concentration of the aluminum nanoparticles added to the biofuel was studied at 1100 °C. Detailed measurements, namely the temporal evolution of the droplet size and burning rate, were analyzed post-processing images. The combustion of aluminum nanoparticles added to a biofuel reveals micro-explosions, a disruptive burning phenomenon that appears at the end of the droplet lifetime, which is greatly influenced by the particle concentration.

Introduction

Transportation has a notorious influence on the modern world. However, serious concerns regarding environmental problems are evident. The aviation sector is responsible for 2-3% of global carbon emissions and its fast growth leads to sustainable research solutions [1]. This sector operates with a conventional jet fuel, which is a multicomponent fossil fuel. High energy content, well-defined flow characteristics and thermal stability are several requirements of this fuel to be properly used in aero engines [2]. To reduce the dependence of fossil fuels and pollutant emissions, the introduction of potential clean alternative fuels has been the most viable solution. Nevertheless, these fuels have a difficult path to be incorporated in aero-engines due to innumerous restrictions. Any alternative fuel should be interchangeable with the current fleet and operate at extreme conditions, providing safety and reliable combustion [2]. Alternative fuels represent the beginning of sustainable development with a biological origin, hence can be easily replaced [3]. However, compared with fossil fuels, these alternative fuels present drawbacks, such as reduced specific energy, that results in increased fuel volume usage. Due to this, a novel type of fuel known as nanofuel has been studied. A nanofuel corresponds to nanoscale energetic metal particles added to a fuel that offers an improvement in energy content and leads to an increase in propulsion energy and payload [4, 5]. To evaluate the influence of nanoparticles in fuel, a methodic procedure to accomplish homogeneous, stable, long-term suspensions and a low-level of particle agglomeration is required [6]. Recent advances in nanofuels show that these rely on the physical, chemical, and electrical properties of nanoparticles. Tyagi et al. [7] noticed that the ignition probability of diesel with Al and Al_2O_3 nanoparticles is higher than pure diesel. More recently, Tanvir and Qiao [8] studied the addition of aluminum nanoparticles to ethanol and compared the combustion behavior with pure ethanol. In their experiments [8] also reported the effect of droplet size and noticed that the burning rate increases with the particle concentration. Additionally, the authors mention in [8] that the absorption of radiation energy emitted is a relevant mechanism to enhance the burning rate of nanofuels. Gan and Qiao [9] studied the evaporation characteristics of ethanol and n-decane blended with aluminum nanoparticles under natural and forced convection. The authors identified three distinct phases during droplet evaporation: the heating phase, the steady-state and finally, the dry-out phase, which is common in nanofuel droplet evaporation. The dry-out phase corresponds to the last stage of the droplet lifetime, where residual nanoparticles can be detected at the end of the steady-state phase or disruptive burning events [10]. In their study, for low forced convection temperatures and natural convection, the droplet evaporation does not follow the D^2 law. However, for higher temperatures, the droplet size evolution follows the classical liquid droplet combustion theory [10]. For nanofuels, during the combustion process, a disruptive burning phenomenon can be detected. A micro-explosion leads to the fragmentation of the primary droplet into smaller droplets, which can enhance the combustion process. Javed et al. [11] evaluated aluminum nanoparticles added to kerosene in a range of ambient temperatures from 400 ºC – 800 ºC. Three dense particle concentrations (2.5, 5.0, and 7.0 wt. %) were studied. The authors reported that increasing the ambient temperature and particle concentration promote the occurrence of micro-explosions earlier in the droplet lifetime. At a higher temperature (700 ºC – 800 ºC), the appearance of micro-explosions during the combustion mechanism significantly enhances the evaporation rate. Bennewitz et al. [12] studied the burning process of numerous liquid fuels blended with different nanoparticles and reported that ethanol with 5 wt.% soluble ammonia borane and RP-2 with 1 wt.% showed satisfying results to be further investigated in different applications. However, the sparse number of studies focusing on the use of nanoparticles presents contradictory observations. Topics regarding the enhancement of the burning rate, the occurrence of micro-explosion with the increase of the particle concentration variation need to be further explored in order to fully understood the potential of nanoparticles added to liquid fuels. Thus, the present work evaluates the combustion characteristics of micrometric nanofuel droplets at an elevated temperature, in order to study the effect of aluminum nanoparticle in a biofuel. The effect of nanoparticle size, concentration, and disruptive burning phenomena will also be addressed on evaporation and combustion of the fuel droplets.

2. Experimental section

2.1 Nanofuel preparation and characterization

In this work, four nanofuels composed of biofuel (HVO) and aluminum nanoparticles were used. The base fuel was NExBTL, which is an hydroprocessed vegetable oil (HVO). This alternative fuel, commonly referred to as renewable diesel, is a paraffinic biobased liquid typically made from vegetable oils [13]. Pure HVO was also tested for comparison purposes. Table 1 shows the physical properties of HVO [14,15].

Tab. 1 Physical properties of HVO. Adapted from [14,15].

Property	HVO
Density (kg/m^3) (at 15 °C)	778.2
Surface tension (N/m) (at 20 °C)	0.0265
Dynamic viscosity (Pa.s) (at 40 °C)	0.00340
Aromatics (wt. %)	0
Oxygen (wt. %)	0
Boiling point (°C)	< 330
Lower heating value (MJ/kg)	43.9
Higher heating value (MJ/kg)	47.1

Aluminum nanoparticles were considered due to its abundance, amount of energy release, and relatively low production cost [16]. Table 2 shows the aluminum properties, produced by Nanografi, used in [17].

Tab. 2 Aluminum properties adapted from [17].

Property	Value
Density (kg/m^3)	2700
Melting point (°C)	660
Boiling point (°C)	2519
Heat of combustion (MJ/kg)	31.1

Experiments were conducted with two particle sizes (40 nm and 70 nm) and two particle concentrations (0.5 wt.% and 1.0 wt.%). Regarding the nanofuel stability, it is important to follow a precise methodology to achieve a stable nanofluid and a low-level of particle agglomeration. Firstly, the aluminum nanoparticles were added to the biofuel and were intensively stirred for 20 minutes using a magnetic stirrer. Subsequently, a sonicator (model UP200Ht by Hielscher) was used to disperse the nanoparticles and avoid agglomeration. To ease the nanofuel preparation, the nanofuel was sonicated in an ice bath for 30 minutes. In the present work, no surfactant was added to the nanofuel. Table 3 shows the physical properties of the nanofuels prepared and used in the present work. The density was measured with the pycnometer method, and the surface tension was measured at room temperature (20 ± 3 ºC) with an optical tensiometer THETA (Attention). To determine the surface tension, the pendant drop method was used. A detailed description of the measurement procedures can be found in [18]. The viscosity was determined using a rheometer (TA instruments ARI 500 ex), at ambient temperature, with an accuracy of ± 5%.

Tab. 3 Nanofuel and their properties.

Fuel	Density [kg/m^3]	Surface tension [N/m]	Viscosity [Pa.s]
HVO + n-Al 40 nm (0.5 wt.%)	771.4	0.0265	0.020
HVO + n-Al 70 nm (0.5 wt.%)	771.6		0.025
HVO + n-Al 40 nm (1.0 wt.%)	773.1	0.0267	0.055
HVO + n-Al 70 nm (1.0 wt.%)	778.5		0.050

2.2 Experimental setup and procedures

Figure 1 shows a schematic of the experimental setup used to analyze the combustion of nanofuel single droplets. It consists of an electrically heated drop tube furnace (DTF), an illumination set, an image acquisition system, and an injector device. The drop tube furnace is composed of an electrically heated coil and a vertical quartz tube with an inner diameter of 6.6 cm and a length of 82.6 cm [19]. The DTF has two opposed rectangular windows with 2 cm width and 20 cm height to allow the visualization of single droplet combustion. The camera is in the opposite direction of the illumination set to enhance the contrast and visualize the droplet evaporation/burning process. The illumination set comprises a LED light and a diffusion glass. The image acquisition system is composed of a CMOS camera (CR600×2, Optronics), placed perpendicularly to the quartz tube and is manually triggered, with the aid of a computer. A high magnification lens (Zoom 6000® Lens System) was attached to the CMOS camera. The magnification lens is composed of a 6.5×Zoom, 12 mm FF, a 0.25× lens attachment and a 2.0× short adapter, with a magnifying range of 0.35-2.25. The image acquisition was pursued with 1000 fps with a resolution of 1280×500 pixels and an exposure time of 1/12000 s. The droplet injection is provided by a TSI device using a pinhole diameter of 200 µm. This droplet generator was placed on top of the drop tube furnace and was connected to a syringe pump and a frequency generator. This system allows generation of monosized droplets with an initial diameter of 250 ± 8 µm. To guarantee a single droplet phenomenon study, a rotating disk with a slot was placed between the injector device and the DTF in order to increase the space between droplets. The image data processing was performed through the edge detection algorithm and pixel values using ImageJ software. For the optical configuration, the pixel size value was 12 µm.

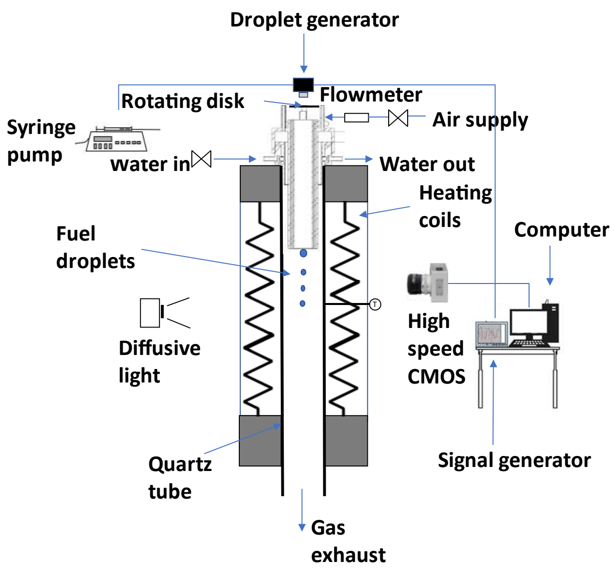

Fig. 1 Schematic of the experimental setup [19].

3. Results and discussion

3.1 Visualization and description of single droplet combustion

The present section refers to the visualization and qualitative analysis of the single droplet combustion of pure HVO and HVO + n-Al. Its purpose is to qualitatively compare the pure biofuel with the aluminum nanoparticles added to the biofuel.
Figure 2 shows sequential images of single droplet combustion at 1100 °C, from its ignition until the end of the droplet lifetime. Time (t) reference, considered as the initial time (t = 0ms) corresponds to the instant when the droplet enters the quartz tube, with an initial diameter (D_0). The droplets are released from the top of the drop tube furnace and when entering the quartz tube they ignite, forming a pronouncing diffusion flame at the droplet wake. This flame is noticed at early stages (t = 6 ms), meaning that its intensity decreases while the droplet lifetime increases. The droplet regression of pure HVO does not display any disruptive burning. As the pure HVO droplet burns, the flame intensity decreases, and diffusion of fuel vapor and oxidant occurs. However, when nanoparticles were added to HVO, independently of the particle size and concentration, micro-explosion occurs at the end of the droplet lifetime. The occurrence of micro-explosions is evident at the combustion last phase, the dry-out phase, and is responsible for a considerable reduction of the droplet size. At the instant t = 33 ms, the nanofuels present a smaller droplet size when compared to pure HVO, indicating a faster burning. Besides that, for HVO + n-Al 40 nm (1.0 wt.%) when the droplet reaches a critical size, a micro-explosion is detected through the ejection of particles agglomerates ignition. The appearance of micro-explosions is a consequence of particle agglomeration at the droplet surface as the fuel base is evaporating. The fuel outward diffusion is impeded due to the increase of particle concentration and promotes the creation of local hot spots, which lead to the fuel nucleation as a consequence of local droplet temperature increase. Subsequently, the primary droplet disrupts and particles ejection is detected through their ignition. A few moments later, an intense explosion occurs at instant t = 35 ms. At the end of this disruptive event, the particles released from the droplet fragmentation ignite, leading to several bright spots, indicating aluminum combustion. Comparing particle concentration, it was noticed that decreasing the concentration, the micro-explosions occur at later stages. Regarding the particle size, in this work, the micro-explosions occur earlier for smaller nanoparticles. These disruptive burning events are dependent on particle concentration, which also shows that the micro-explosions intensity increases for higher nanoparticle concentration. Additionally, decreasing the particle size, the micro-explosion occurs in early stages for smaller nanoparticles. The droplet regression and the occurrence of micro-explosions are dependent on ambient temperature, which greatly affects the droplet combustion. For the present work, an ambient temperature of 1100 ºC was considered, noticeably higher than the boiling point of the biofuel (HVO) and the melting point of aluminum nanoparticles.

3.2 Droplet size evolution and burning rate

In this section, the droplet size evolution of nanofuels droplets, at an ambient temperature of 1100 ºC will be discussed and compared with that observed for droplets of pure HVO, in order to understand the effect of adding aluminum nanoparticles to a biofuel. Figure 3 shows the square of the normalized droplet diameter as a function of the normalized time at 1100 ºC for pure HVO and four nanofuels. For each D^2 curve, 40 droplets were analyzed. Regarding the temporal evolution of droplet reduction for the pure HVO it can be seen that the temporal evolution of droplet diameter is in a good agreement with the well-known D^2 law. The classical liquid droplet combustion theory states that the normalized square diameter decreases linearly with time, with a nearly constant slope, defined as the burning rate (K). For pure HVO, the droplet burns as a fully liquid fuel droplet and no disruptive burning events are perceived. Similarly, Pacheco et al. [19] evaluated the burning characteristics of pure HVO in the same DTF and no disruptive phenomenon was noticed for

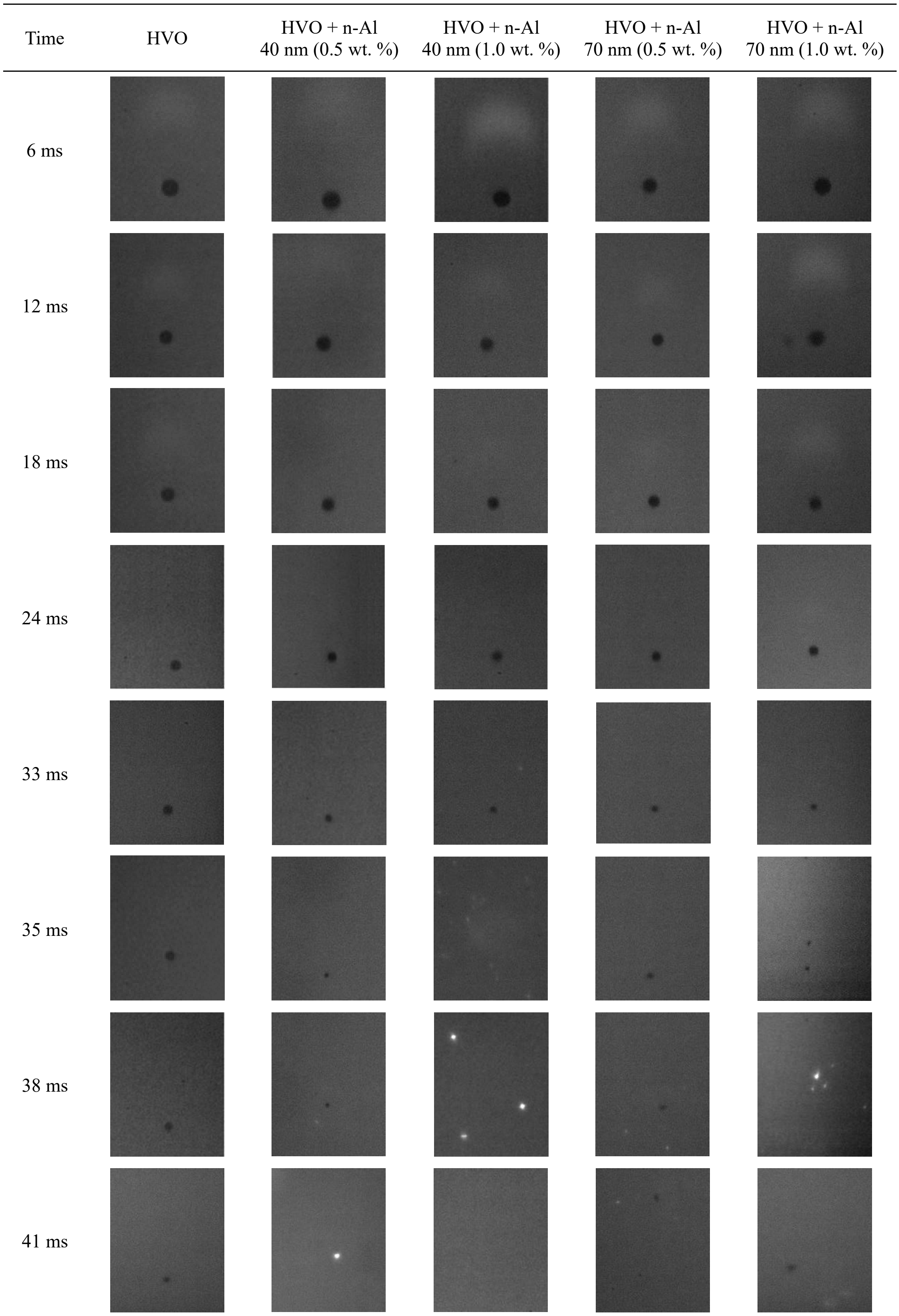

Fig. 2 Sequences of instantaneous images of pure HVO and four nanofuels droplets, burning at 1100 °C (D_0 = 250 µm, P = atmospheric).

this fuel. Additionally, the authors reported that pure HVO follows the D^2 law. On the other hand, adding aluminum nanoparticles to the biofuel, the combustion behavior is quite distinct from that observed in the combustion of the pure HVO droplets. Besides the fact that all nanofuels droplets depicted micro-explosions at the end of the droplet lifetime, as shown in Figure 2, Figure 3 also shows that the droplet size evolution for the nanofuels is not in agreement with the classical liquid droplet combustion theory. During the steady-state phase, the droplet suffers oscillations related to its swelling and contraction. However, no micro-explosions are detected at this stage. As the liquid fuel is evaporating, the particle concentration at the droplet surface increases, which difficulties the fuel diffusion from droplet to the surrounding environment, affecting the droplet evaporation.

At the dry-out phase, the droplet diameter is constant for a few instants, promoting a micro-explosion, as observed in the qualitative description of nanofuel droplet evaporation and combustion discussed in the previous paragraphs. Comparing the pure HVO with the nanofuel, the latter presents a steeper droplet size regression curve, indicating a considerably increase in the burning rate. Aluminum nanoparticles act as a heat supplier to the biofuel and, at the early stages increase the evaporation rate, displaying an advantage for this novel type of fuel [20]. Figure 3 shows that the pure HVO depicts a longer lifetime when compared with the nanofuels droplets. Comparing the nanofuels, the D^2 curves practically overlap, where a slight difference can be detected from each particle size and concentration. Regardless of the size and concentration of aluminum particles, a disruptive burning phenomenon occurs, pronouncing the end of the droplet lifetime. Increasing the particle concentration leads to an increase in the micro-explosion intensity and an earlier occurrence of this phenomenon for both particle sizes. Thus, droplets of HVO + n-Al 40 nm (1.0 wt.%) present an earlier micro-explosion and most intense when compared HVO + n- Al 40 nm (0.5 wt.%). This indicates that HVO + n- Al 40 nm (1.0 wt.%) has the shortest lifetime. Increasing the particle size, the droplet lifetime increases as the particle concentration increase.

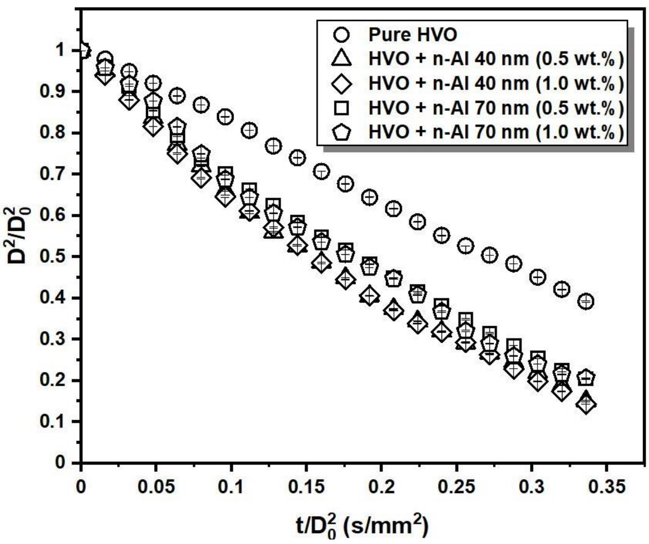

Fig. 3 Square of the normalized droplet diameter as a function of the normalized time at 1100 °C for pure HVO and four nanofuels (D_0 = 250 µm, P = atmospheric).

Figure 4 shows the burning rate of pure HVO and each nanofuel with an interval of confidence of 95%. It is important to mention that these results do not include the dry-out phase where micro-explosion is noticed. Similarly to the analysis of the droplet size evolution, 40 droplets were evaluated for the burning rate of each fuel. The lowest burning rate corresponds to the pure HVO with a burning rate of 1.81 mm^2/s. Adding aluminum nanoparticles, the burning rate shows a considerable enhancement when compared to the average burning rate of biofuel. Hence, for HVO + n-Al 40 nm (0.5 wt.%), the burning rate is 2.55 mm^2/s and HVO + n-Al 40 nm (1.0 wt.%) displays the higher burning rate, 2.58 mm^2/s. As aforementioned, increasing the particle size leads to a decrease in the burning rate. So, HVO + n-Al 70 nm (0.5 wt.%) presents a burning rate of 2.46 mm^2/s, while the lowest burning rate value, 2.52 mm^2/s is observed for HVO + n-Al 70 nm (1.0 wt.%). Overall, it was noticed that the higher burning was obtained for the nanofuel containing the smallest size of aluminum particles (40 nm). Regarding the particle concentration, it was observed that an increase in particle concentration promotes an increase in the burning rate. Diverse studies in the literature reported that the addition of nanoparticles in a biofuel truly contributes to the enhancement of the burning through the radiation absorption, thermal conductivity and micro-explosion. However, this topic is not fully understood and requires more findings regarding nanofuel combustion.

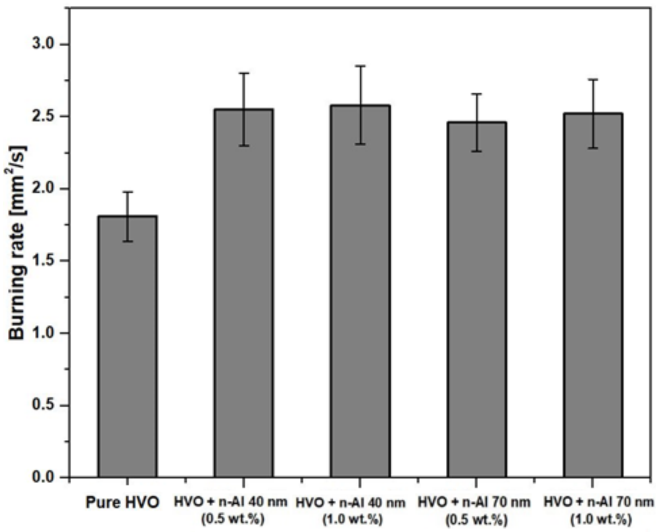

Fig. 4 Average burning rate of pure HVO and four nanofuels (D_0 = 250 µm, T = 1100 ºC, P = atmospheric).

4. Conclusion

The aim of the present work was to study the burning characteristics of pure HVO and the addition of aluminum nanoparticles to the biofuel. To achieve it, single droplets were experimentally investigated in a drop tube furnace at the ambient temperature of 1100 ºC. The analysis performed here addressed droplet size evolution and disruptive events. The qualitative results show that the falling droplets ignite when entering the quartz tube and a flame at the wake of the droplet was formed for each fuel. It was observed that the temporal evolution of the droplet diameter of pure HVO is in good agreement with the D^2 law. On the contrary, nanofuels droplets do not follow the D^2 law due to the oscillations in the droplet diameter and micro-explosions at the end of the droplet lifetime. Consequently, pure HVO presents the longest lifetime and lowest burning rate when compared to all nanofuels. Thus, the combustion characteristics of HVO were enhanced through the addition of nanoparticles. Micro-explosions were depicted at the combustion of nanofluid droplets. The results show that increasing the aluminum nanoparticles concentration promotes an increase in the intensity of the disruptive burning phenomenon. Additionally, the micro-explosion delay decreases with the increase of the particle concentration regardless of particle size. Subsequently, the nanofuel with smaller particle size and higher particle concentration presents a higher burning rate. This indicates that, in this study, increasing the particle size and decreasing the particle concentration promotes the decrease of the burning rate.

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Definitions, Acronyms, Abbreviations

D_0: Inicial droplet diameter

D: Droplet diameter

DTF: Drop tube furnace

HVO: Hydroprocessed vegetable oil

K: Burning rate

n-Al: Aluminum nanoparticles

t: Time