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COMBUSTION BEHAVIOR OF JET A DROPLETS AND ITS BLENDS WITH BUTANOL

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INTRODUCTION

In light of the potential of butanol as an alternative fuel for blending with petroleum fuels such as gasoline, diesel or Jet A, experimental data regarding the burning characteristics of these blends are required in order to better understand their combustion process. In this study, freely-falling droplets of butanol, Jet A, and their mixtures (10, 20 and 50% butanol by volume) were examined in a combustion chamber which provides representative conditions of real flames, both in terms of temperature and oxygen availability. The combustion characteristics reported here include evolution of droplet sizes, burning rates, soot measurements, and the occurrence of microexplosions and soot shells. Results show that the evolution of droplet diameter for butanol, Jet A and their blends are very similar, regardless of the obvious compositional differences. Sooting behaviors are found to be quite different, with a clear reduction in the sooting propensity as the butanol content in the fuel increases. These results are consistent with a previous study in a gas turbine showing similar performance among Jet A and its blends with butanol, suggesting that such mixtures are promising alternative fuels with very similar combustion characteristics to Jet A, but with much less propensity to soot. Moreover, this study provides new results on the combustion properties of Jet A/butanol blends, for which very scarce data exist in the open literature.

Initiatives to replace fossil fuels by fuels derived from biofeedstocks (i.e. biofuels) are recently gaining importance due to environmental and sustainability reasons. Even though fossil fuels are likely to remain dominating transportation and energy systems in the near future [1, 2], renewable biofuels have the potential to reduce their consumption, and therefore their environmental footprint, especially through usage as additives to conventional fuels. In contrast to fossil fuels, the biomass used to produce biofuel is renewable, carbon-neutral and domestically available [3, 4]. Furthermore, biofuels are reported to have negligible sulfur content and to inhibit PAH and soot formation [4, 5].

The most widely used biofuel today is by far bio-ethanol [2, 5], which is commonly added to gasoline for its use in spark-ignition engines. Ethanol production via fermentation of plants and starches was among the very first developments in biofuels because of the relatively low cost of production due to the existence of a well-established alcohol industry and infrastructure [1]. Although ethanol production from edible crops poses serious concerns, such as competition with the food industry or indirect land-use change, it remains nowadays as the major source for bio-ethanol feedstock [2]. These concerns over the so-called first generation biofuels have motivated efforts to find new feedstocks which do not compete with the food industry, such as lignocellulosic biomass or residual waste [1, 2]. Biofuels derived from such feedstocks are called second generation biofuels, and although ethanol can also be produced from cellulosic biomass [6, 7], there has been an important

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research on potential new fuel molecules which can overcome the significant drawbacks associated with ethanol properties. One of the most promising candidates is butanol, which has several well-known advantages when compared with ethanol [1, 2, 8-15]:

- Higher energy density.
- Lower propensity for water absorption.
- Higher miscibility with hydrocarbons.
- Boiling point closer to the gasoline/diesel fuel range: lesser impact on the fuel distillation curve.
- While its octane number is similar to that of gasoline, its cetane number is high enough to make blending with diesel for compression-ignition engines viable.
- Better material compatibility: corrosion towards ferrous metals and elastomers swelling are reported to be much less severe than in the case of ethanol.
- Lower vapor pressure, resulting in safer manipulation and less volatile organic compounds emission.
- Lower heat of vaporization, which leads to less ignition problems.
- Current engines can run on more enriched butanol blends without any modification.

These features have motivated a recent interest in bio-butanol, which can be both produced by fermentation of edible crops (first generation biofuel) or through advanced technologies using lignocellulosic biomass or algae as feedstock (second generation biofuel) [1, 8, 9]. Even though there is currently much less butanol production capacity compared to ethanol, several companies are developing technologies for bio-butanol synthesis and equipping existing ethanol plants with butanol production capabilities through cost-effective retrofitting [8, 11].

In recent years a comparatively large number of studies have analyzed the performance of both, pure butanol (particularly the isomer 1-butanol) and its blends with gasoline and diesel in spark-ignition and compression-ignition engines (e.g. [16-20]). Much less work has been performed regarding its possible use in gas turbine engines, being a recent study by Mendez et al. [11] the only reference found in the open literature. In this work, the performance of pure 1-butanol and its blends with Jet A (25, 50 and 75% by volume) in a 30 kW gas turbine was studied, concluding that mixtures of butanol with Jet A are promising alternative fuels with similar performance to that of Jet A, but with less CO and NO_x emissions. It is important to note that this potential of butanol as fuel for gas turbines is mostly related to its use in stationary gas turbines for power generation, being its use as fuel for aviation much less straightforward. Dziegielewski et al. [15] reviewed some important properties of butanol and Jet A blends with regard to their possible use in aviation, concluding that practically any addition of butanol to Jet A results in a flash point under the minimum dictated by the regulation, while blends above 10% butanol in volume can present conductivities and calorific values out of specification too. The aviation sector

is far more restrictive than any other regarding the evaluation of new alternative fuels, both for safety and logistical reasons. Moreover, its main research direction is the development of fully interchangeable, 100% hydrocarbon fuels such as Fischer-Tropsch Synthetic Paraffinic Kerosene (FT-SPK) or Hydroprocessed Esters and Fatty Acids (HEFA) [15, 21, 22]. However, the situation changes significantly when it comes to gas turbines for energy generation, where restrictions for alternative fuels are much lower and quite diverse bio-fuels have been successfully tested in experimental gas turbines: biodiesel [23, 24], ethanol [25, 26], wood-derived lignocellulosic alcohols [27] or the already cited butanol [11] are some examples which illustrate the flexibility of stationary gas turbines.

Successful use of a new fuel in complex applications requires a substantial knowledge of its combustion characteristics. Even though engine studies provide very useful information regarding fuel performance under realistic conditions, results can be dependent on several non-controllable variables (e.g. fuel spray patterns, temperature profiles inside the combustion chamber, etc.), and therefore results can depend to some extent on the experimental facility used. On the contrary, in the much more simplified single droplet configuration all the parameters affecting the results are completely known and controllable, and therefore the combustion characteristics observed are intrinsically attributable to the fuel. Given the increasing interest in butanol, recent studies have examined the combustion characteristics of butanol droplets, both pure [13, 14, 28-30] and blended with different fuels such as gasoline [12] or soybean oil [10]. In particular, butanol/Jet A blends have been proposed as a promising option for gas turbine engines [11]. The detailed characterization of the combustion behavior of these blends seems most desirable but, to the authors' knowledge, has not been addressed in previous studies. The main objective of this work is therefore to provide new experimental data on the combustion and sooting characteristics of unsupported, free-falling droplets of butanol/Jet A blends.

EXPERIMENTAL

Experiments were conducted in the Droplet Combustion Facility (DCF) developed at LIFTEC and shown in Fig. 1. Details of the facility can be found in a previous work [31], and therefore only the most important features of the experimental method will be explained here.

Droplet combustion facility

Fuel droplets were generated in the DCF by means of a piezoelectric device with initial diameters (D_0) $\sim$ 150 microns ($150 \pm 0.7 \mu\text{m}$ for all the cases studied), which is considered to be a good compromise between actual sizes in practical applications and a good accuracy of the experimental results. Droplet spacing always exceeded 120 droplet diameters, so that

interactions between droplets were negligible. As droplet generation stability is perhaps the most critical variable in these experiments, initial droplet size was thoroughly checked by means of repeated size measurements at a given location (2 mm after injection), at least at the beginning and end of each test; Standard deviation calculated from repeated tests was found to be as small as $0.74\text{ }\mu\text{m}$ (rms value), indicating negligible drifts in D_0 during the running of the experiments.

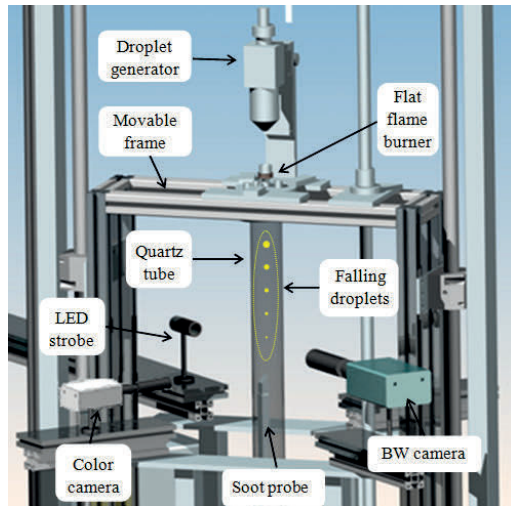


Fig. 1. Schematic of the droplet combustion facility.

The monosized droplets were injected along the axis of a quartz tube, coaxially with the combustion products generated by a flat-flame premixed methane-air burner (McKenna). This coflow provided a controllable and realistic environment to study the evolution of fuel droplets under representative conditions of real flames, both in terms of oxygen availability and temperature. As in real flames a droplet might be subjected to different oxygen conditions, the droplet combustion process was studied both at 3 and 10% of oxygen (by volume, dry basis) in the coflow. These two oxygen concentrations are believed to be good representatives of the range of conditions seen by burning droplets in real flames. Additionally to combustion, the vaporization process (i.e. with 0% oxygen) was also studied. The axial temperature profile along the tube centerline was measured with a fine wire thermocouple ($50\text{ }\mu\text{m}$, type S). The temperatures recorded in the first 30 mm were within the interval 1684-1600 K for the 0% O_2 condition and 1618-1560 K for the 3% O_2 (these intervals are the measured variations along the axis due to heat losses). The actual temperatures were not measured for the 10% O_2 case, but are expected to be slightly lower due to the increased excess air.

Different imaging methods were used to record visual information describing the various aspects of droplet combustion. Size and velocity evolution of droplets were

recorded through a black and white (BW) high sensitivity CCD camera (QImaging Retiga SRV, 12-bit Mono) fitted with a long distance microscope and backlit via LED strobe. This optical system was programmed to record two sequential shots of a droplet in the same frame with a time lapse of $500\text{ }\mu\text{s}$ between them. As it can be seen in Fig. 2a, this imaging method not only gives information about the droplet size and motion, but also about the existence of a soot shell for certain conditions. A color camera (Teledyne DALSA Genie HC1024, 8-bit) perpendicularly placed to the BW camera and faintly backlit was used to record the flame images. The faint backlight was provided in order to make the droplet distinguishable from the self-illuminated flame, capturing in the same image the free-falling droplet surrounded by its flame, as shown in Fig. 2b.

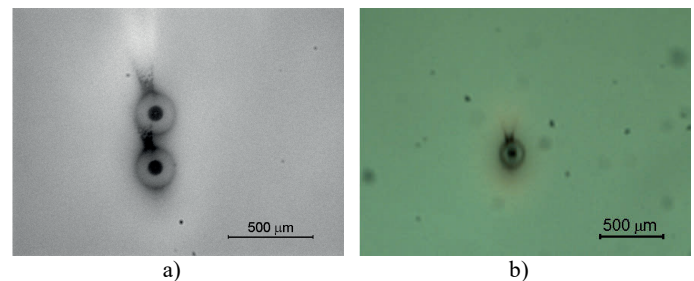


Fig. 2. Images taken by both cameras for the same droplet (Jet A, 10% O_2 , 17 mm after injection): a) Double-exposure BW picture showing the falling droplet surrounded by its soot shell; b) Color picture displaying the droplet, the soot shell and a faint flame.

The practically spherical shapes of the soot shells displayed in Fig. 2 are thought to confirm that convective effects are very weak and do not appear to disturb the spherical symmetry. The soot tail observed in the wake of the droplets is ascribed to the shedding of some soot agglomerates, which are dragged away due to the slip velocity of the gas. Therefore, the droplets can be assumed to burn under conditions of spherical symmetry, which facilitates the comparison with one-dimensional droplet combustion models.

Pictures taken by both imaging methods were post-processed in order to extract the relevant droplet combustion features in the most precise and repeatable way. As the BW images aimed to gather close-up information of the droplet (i.e. droplet diameter and velocity, soot shell morphology and microexplosions occurrence), their spatial resolution was fixed at $1.4\text{ }\mu\text{m/pixel}$, suitable to determine with good accuracy the size of droplets in the range $25\text{--}150\text{ }\mu\text{m}$. For every picture, a background image was taken and subtracted prior to the image analysis. Droplet diameter and velocity were automatically calculated by means of an edge detection algorithm. Color pictures had a spatial resolution of $6\text{ }\mu\text{m/pixel}$ and were processed to gather information regarding flame size and morphology. A background image was subtracted prior to the manual measurement of the flame diameter. However, for the

fuels and conditions examined in this study, the flames registered were so weak that the involved uncertainties are considered too high to extract reliable quantitative data.

In addition to the optical setup, a soot sampling technique was also applied for quantitative measurement of the amount of soot generated with the different fuels and blends. The soot and gases surrounding the droplet were laterally suctioned, quenched and cooled by a nitrogen flow. The aspirated soot was retained on a quartz filter, which was weighed after drying for 24 hours in a furnace at 150 °C to determine the amount of soot present at the probe position. A soot index was calculated in terms of the weight of soot per unit of mass of injected fuel.

Fuels

Commercial Jet A (obtained from a local airport) and 1-butanol (99.4% purity) were used for the tests. Additionally, three mixtures of these fuels were prepared with 10, 20 and 50% butanol by volume (B10, B20 and B50 respectively).

The main fuel properties for both pure fuels are shown in Table 1. Butanol properties are extracted from the literature, whereas a specific analysis of the Jet A sample was performed at the Instituto de Carboquímica (ICB-CSIC) in order to obtain its composition and most significant properties.

Table 1. Selective properties of the fuels investigated

	Jet A	1-butanol ^a
Molecular formula	C _{10.60} H _{19.63}	C ₄ H ₁₀ O
Molecular Weight (g/mol)	146.83	74.12
% C (mass)	86.62	64.86
% H (mass)	13.38	13.51
% O (mass)	-	21.62
Boiling point (°C)	99.1 – 285.8	117.6
Lower Heating Value (MJ/kg)	42.60	33.10
Density at 20 °C (kg/m ³)	791	810
Viscosity at 20 °C (cP)	0.91	2.54
Latent Heat of Vaporization (kJ/kg)	330 ^b	584
Adiabatic flame temperature (K)	2360 ^c	2233

^a From ref. [12, 14, 32, 33]

^b From ref. [11]

^c From ref. [34]

RESULTS AND DISCUSSION

Droplet size evolution and burning rate

As stated above, tests were performed for three different oxygen conditions: 0, 3 and 10% O₂ in the coflow. The first one corresponds to a pure evaporation process, whereas the last two are believed to be representative conditions of oxygen availability around droplets in real flames. Fig. 3 shows the evolution of Jet A droplet sizes for these three conditions. Based on the quasi-steady theory of droplet burning, measurements are displayed as normalized square diameter versus normalized time. Normalization is performed with the

droplet diameter value at injection (D_0). Even though Jet A is a highly multi-component fuel, results displayed in Fig. 3 are in good agreement with the ‘d² law’, and after a short heat-up period, the normalized square diameter decreases linearly with time with a nearly constant slope (the burning rate K). As oxygen concentration increases, so does the burning rate, accelerating substantially the droplet evaporation process. This is ascribed to the higher temperature in the shell flame around the droplet, leading to an enhanced heat transfer to the droplet.

With the pure Jet A curves as a baseline for comparison, tests were performed for neat butanol and their mixtures (B10, B20 and B50). These fuels were examined for the three oxygen conditions considered in the study: 0% (Fig. 4), 3% (Fig. 5) and 10% (Fig. 6).

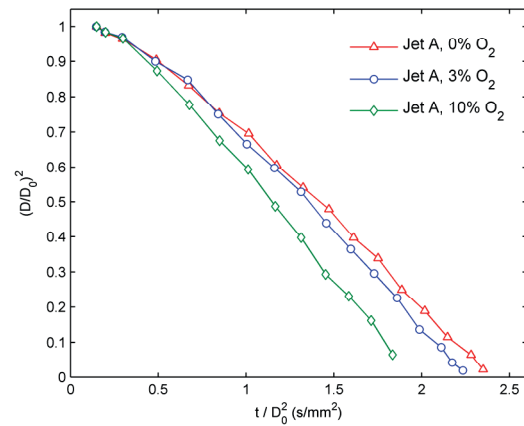


Fig. 3. Evolution of normalized droplet size for Jet A at three different oxygen conditions: 0, 3 and 10% O₂ in the coflow.

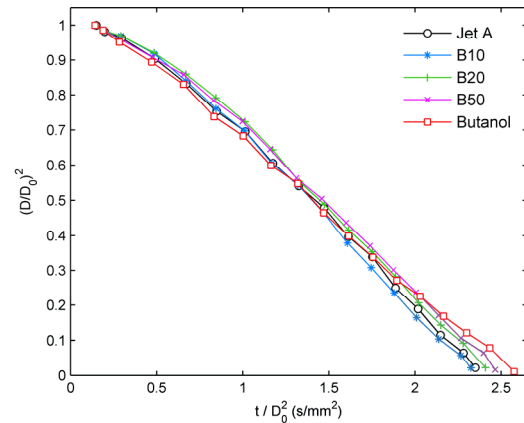


Fig. 4. Evolution of normalized droplet size for Jet A, B10, B20, B50 and pure Butanol with 0% O₂ in the coflow.

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