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Effect of fuel properties on the stabilization of a monodisperse spray flame

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Abstract

New fuels are being produced to replace conventional kerosene to meet the challenges of diminishing fuel resources and environmental issues [1]. However, these new fuels must meet the same standards as conventional kerosene, especially flame stability [2]. However, to optimize the use of these fuels, the choice of the injection system is critical because it will drive the spray characteristics, which will directly impact the flame dynamics. However, decoupling the injection system from flame dynamics in current combustion systems is challenging [3]. In this context, we have designed a burner with an injector capable of generating a spray independent of the fuel properties. The injector is the MTG-01-G3 injector from FMP technology which generates monodisperse droplets spray from a piezo actuator. The injector can generate droplets with diameters in the range of 45 μ m to 65 μ m that we control with great precision based on fuel flow rate and piezo frequency. The burner is swirled and turbulent with a mixing zone to properly mix the fuel and the air. The flame is stabilized at the exit of this mixing zone, where it burns in a quartz tube, allowing us to have optical access to the flame. Our study uses conventional and alternative kerosene surrogates with relatively high evaporation temperatures, making them tough to burn at ambient temperature. Thus, to stabilize the flame, we also inject methane which stands for less than half of the global equivalence ratio of the flame. Finally, thanks to this configuration, we have analyzed the effect of physical properties on the spray flame stabilization.

Introduction

The aviation industry needs to rapidly change the source of fuels because of dwindling oil resources and the need to limit pollution from aircraft engines. The short-term solution is to use drop-in fuels, which can be used in current engines with only minor changes [1].

These new fuels must meet the same safety standards as conventional kerosene, especially regarding flame stability. An essential parameter for characterizing the stability of a flame is the lean extinction limit [4].

To study this limit, it is necessary to reproduce the physics of actual engines, i.e. spray injection and swirling and turbulent flame. However, the poorly understood and very complex chemistry of the combustion of new fuels makes numerical analysis very difficult and expensive [1]. Similarly, the experimental study on actual engine-scale bench experiments is limited as the results will be largely determined by technological choice [3]. Finally, only the experimental study on a modest bench will allow us to estimate the real impact of the fuel modification on a spray flame. To answer this issue, we made the experimental setup MOCA.

However, we select the fuel we want to study since we cannot study of all existing fuels. Then, the first step is to analyze the essential parameters of the fuels to focus on the critical parameters. This will have the double advantage of limiting the number of measurements to be made and anticipating the flame dynamics of future fuels. We have therefore chosen a surrogate approach to study alternative kerosene.

Finally, this article will address the following issues:

- Why is the MOCA setup able to compare the fuels only based on their composition, and why is it relevant for real engines

- What are the essential parameters to study combustion stability for jet fuel

- How the properties of jet fuels impact the lean burning limit (LBO)

Fuels

Standard aviation fuels mainly comprise alkane with a homogeneous distribution of n-paraffin, isolation-paraffin, and cycloparaffin [1]. These alkanes, with only a few exceptions, have very similar properties. However, they differ significantly from the second group of fuel components, the aromatics. These generally have a lower calorific value and tend to generate more pollutants. However, aromatics are necessary for two main reasons:

- To guarantee the tightness because it makes the seals swell

- To increase the density of the fuel

In today's engines, aromatics represent between 8 and 25 percent of the total volume [4]. This fraction may change for future fuels depending on the evolution of standards. Thus, for the next generation of fuel, we know that it will include aromatics in its composition, and therefore, it is necessary to evaluate the effect of the amount of aromatics on the flame dynamics.

We started with decane, which is generally used as a kerosene surrogate [7], and mixed it with p-cymene, an aromatic with the same boiling temperature as decane, ensuring that both are available simultaneously when the mixture evaporates.

We made 5 mixtures with 0, 12.5, 25, 50 and 100 percent of aromatics in volume fraction. We have made several low-aromatic fuels to replicate real fuels. Moreover, we will compare these mixtures to the combustion of decane and p-cymene alone to have reference points.

For the analysis of the results, Table 1 lists some essential physical properties of the fuels we have formulated. Among these properties, we include the evaporation time. This is calculated by simulation from the Spalding model with the correction of Abramzon and Sirignano [5]. The model considers droplets of 45 μm injected at 300K in air at 1500K.

p-cymene [% $_{vol}$]	0	12.5	25	50	100
τ_{evap} [ms]	5.21	5.18	5.16	5.14	5.18
DCN	66	58	51	35	4
ρ [kg/m^3]	730	746	762	793	857

Table 1 - Fuel properties

Experimental setup

Setup

The MOCA experimental setup scheme is shown in figure 1. It consists of a first chamber where the droplets are injected from the top and where the primary air is injected by the side. The air injection passes through a grid to homogenize the flow. At the outlet of this chamber, a secondary inlet is added to generate the swirl. The air-fuel mixing takes place in the mixing chamber. At the outlet of this mixing chamber, the spray flame stabilizes in a quartz tube with a diameter of 16mm and length of 150mm. The Reynolds and swirl numbers are calculated in the mixing chamber, where the diameter is 8mm and the length is 40mm.

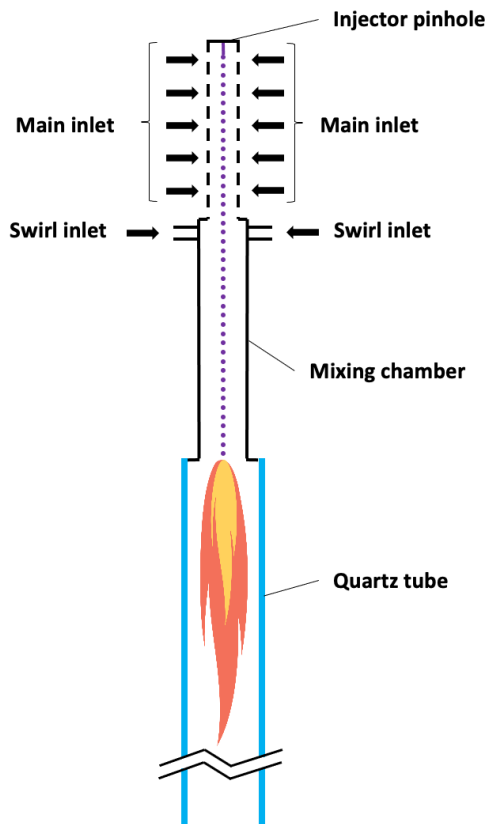


Figure 2 - MOCA scheme

The droplets injected during the experiments are all 45 μm regardless of the fuel used. In the experiments carried, the Weber number remained much smaller than 12, so there is no secondary atomization between the injection and the flame. Similarly, the residence time is low enough that there is no evaporation before the flame. No filming was observed, and as the spray was well-centered, we can assume that no droplets impacted the walls. Furthermore, no droplets were observed at the quartz outlet, which indicates that all the fuel evaporated in the quartz tube.

The pictures in figure 2 are photographs of a decane and p-Cymene flame at the exit of the premixing chamber.

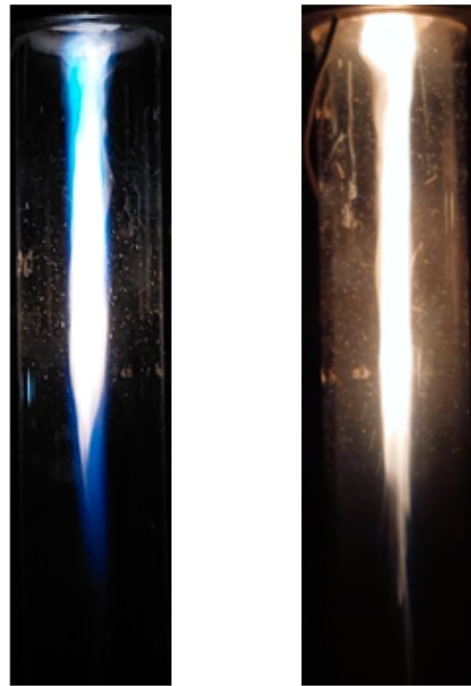


Figure 1 - Decane flame (left) and p-Cymene flame (right)

Monodisperse injection

The fuel dynamics depend strongly on how the fuel is carried to the flame [8]. To capture the effect of the spray on the flame as in real engines, we chose to inject the fuel as a spray. The spray is characterized by the droplets' size and velocity dispersion and spatial dispersion of the droplets. These parameters are highly dependent on the physical properties of the fuel. In order to eliminate the effect of the injection technology we have chosen to use a mono-disperse injector which injects a chain of droplets of the same size.

We use the MTG-01-G3 injector manufactured by FMP technology. The fuel exits through a 25 μm nozzle and is disrupted by a piezzo at a precise frequency generating instabilities in the jet. The frequency of these instabilities corresponds to the droplet rate per second.

This droplet string is injected at a velocity V and a size D , which we control from the mass flow rate Q_m and the piezo frequency f with the following formulas:

$$V = \frac{Q_m}{\rho \frac{\pi}{4} D_{inj}^2}$$

$$D^3 = \frac{6Q_m}{\pi f \rho}$$

The above theoretical formulas have been verified experimentally with a dispersion below 2% around the theoretical value. The figure 3 shows a picture of the droplet chain which diameter is around 45 μ m.

Experimental protocols

We have noticed that the test bench is quite sensitive to the composition of the fuel injected into it. Thus, to guarantee that the fuel announced is indeed injected, we have systematically purged the fluid system twice with the fuel we wish to study. Indeed, this double purge guarantees no trace of the previous fuel. In addition, we used the fuels starting from the one containing the least p-cymene to the one containing the most p-cymene to limit the difference between two successive fuels.

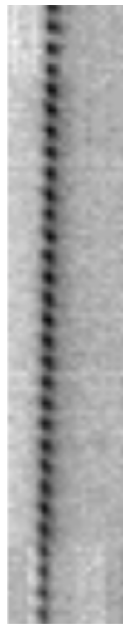


Figure 4 - Droplet chain at the outlet of the mono disperse injector.

The fuel flow and the number of swirls have been set. Then a computer controlled the gradual and constant increase in airflow. The initial air flow rate did not affect the measured LBO value, but the air flow rate ramp had a substantial impact on the result. Thus, the initial air flow rate was chosen to limit the measurement time as much as possible, and the ramp was set at an increase of +5 Reynolds/s. In addition, each experimental point is the mean value of 10 successive measurements.

Results

LBO measurements

For each fuel, we measured the LBO at 3 power

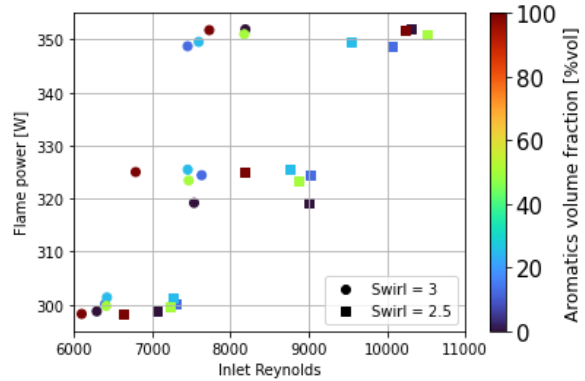


Figure 3 - LBO measurement

levels (300W, 325W, 350W) and 2 swirl numbers (2.5 and 3). The measurements were performed according to the protocol described above. The results are presented in figure 3.

We selected these three wattages because the flame could not be sustained below them, and above them, the extinction limit exceeded the flow limit of our bench. Also, a lower swirl number made it challenging to stabilize the flame, mainly at low power, and a higher swirl number generated droplet impact at the walls, making it challenging to analyze the amount of fuel burnt.

According to Lefebvre [6], we can analyze the LBO of spray flames by breaking down combustion into 3 stages: evaporation, mixing, and reaction. In our case, as in most aeronautical burners, the flow is turbulent and swirling. Thus, mixing can be assumed instantaneous, so only the evaporation rate and reaction will limit the combustion.

The overall equivalence ratio at extinction is between 0.2 and 0.25. This indicates that some air is bypassing the flame. When the bench is operated with methane, the lean extinction limit is around 0.7. Thus, the dispersion of the droplets becomes an important parameter since it changes the local equivalence ratio.

Pure components

When we look only at pure decane and p-cymene, we can see that decane combustion remains more efficient, as indicated by the DCN, and LBO occurs at higher rates. On the other hand, there is no clear trend for mixtures of p-cymene and decane.

As p-cymene droplets have greater inertia than decane, they will remain more concentrated in the center, and consequently, the local equivalence ratio will increase. We can see that the LBO gap between p-cymene and decane at 325W is more significant than at 350W, especially at a Swirl number of 2.5 where the extinction limit exceeds a Reynolds of 10,000. The high inertia of the p-cymene allows the droplets to remain in the center; therefore, the local equivalence ratio will be

higher, reducing the gap in high Reynolds and high injection speed conditions.

The effect of droplet inertia also explains the difference in LBO between the Swirl number of 3 and 2.5. With a Swirl number of 3, the radial dispersion of the droplets is more significant, and therefore the local equivalence ratio is lower, and so the LBO will be at a lower Reynolds.

Fuel mixture

To compare the effect of mixing decane and p-cymene, we reconstructed the Reynolds LBO at 325W from a quadratic interpolation of the measured points. In addition, to plot the Swirl number results on the same graph, we use the rescaled extinction limit Re^* :

$$Re^* = \frac{Re - Re_{p-Cymen}}{Re_{Decane} - Re_{p-Cymen}}$$

The result is shown in figure 5 below:

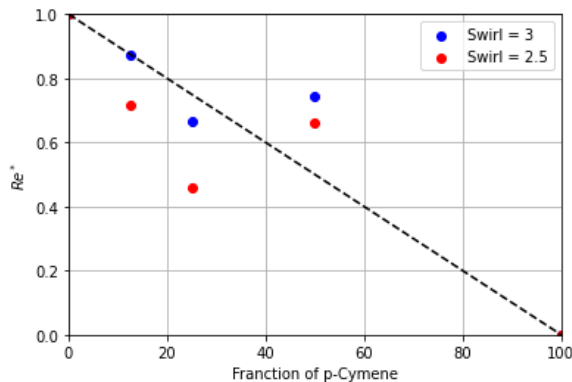


Figure 5 - Effect of p-Cymene fraction on the rescaled Reynolds number at LBO

We would expect a gradual decrease in the extinction Reynolds between pure decane and pure p-cymene since the density (indirectly the dispersion of the droplets) and the DCN (the ability of the fuel to ignite) decreases linearly with the mixture. However, we can see that at a fraction of 50% p-cymene and decane, we have an increase in the extinction limit compared to the mixture with 25% p-cymene. This local maximum corresponds with the minimum evaporation time (see table 1), one of the critical parameters that will drive the LBO, as Lefebvre points out. So although we have a global dynamic of decrease, the evaporation time of the components will boost the LBO creating this local maximum.

We have illustrated this trend at 325W, but it is also found at 350W. However, at 300W, the extinction limits are close and almost independent of the fuel composition. Indeed, below 300W, the bench will quickly switch off; therefore, the switch-off mode differs from at 325W and 350W. This corresponds more to a limit due to a lack of thermal power to maintain the flame than to a residence time limitation which will limit the time for the physical phenomena to take place.

Conclusions

As we have seen above, the comparison between fuels was possible because the MOCA experimental bench guaranteed the same fuel injection at the flame level with a very precisely controlled drop size, allowing to neglect the atomization effects.

The proportion of aromatics being a key parameter in the formulation of the new fuel, we mixed decane and p-cymene in different proportions to qualify the effects on the MOCA bench.

Finally, we could see, as expected, that the combustion of p-cymene is worse than that of decane. Nevertheless, the poor extinction limit does not decrease linearly from decane to p-cymene but follows a much more complex dynamic, notably linked to the evaporation delay. We have also seen that thanks to its high density, the p-cymene droplets can remain more clustered, thus increasing the local richness, which increases the LBO at high Reynolds.

A more detailed study of this flame could allow a better analysis of the phenomena described below. Also, this study is limited to the proportion of aromatics in aviation fuel; other fuel properties could have been studied on MOCA.

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