Chapter 2
Ignition Performances of Alternative Fuels Under Altitude Conditions According to Their Aromatic Content

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Nomenclature

ER	Equivalence ratio
MERCATO	Moyen Experimental de Recherche en Combustion Aérobie par Techniques Optiques
P	pressure, MPa
T	temperature, K

Subscripts

ch chamber

2.1 Introduction

During the last years, the introduction of alternative fuels, produced from other sources than oil, has been quickly developed because of environmental constraints and anticipated economical issues. For their use in aircrafts, the fuels must comply with accurate international specifications (ASTM, DefStan). The first produced alternative fuels, XtL fuels from the Fischer-Tropsch process and hydroprocessed

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Table 2.1 Fuel compositions

FUEL	AROMATICS (%)	ACRONYM
Jet A-1	20.6	JETA
SPK	2.5	SPK
Jet A-1 + SPK	8	SPK08A
SPK + aromatic cut	20.6	SPK20AC
SPK + aromatic cut	8	SPK08AC
Aromatic cut	100	AC

esters and fatty acids (HEFA), do not contain any aromatic compound and have to be mixed up to 50% with Jet A-1 to comply with the above quoted specifications which require at least 8% aromatics in the aviation fuel composition. Nevertheless, this specification of 8% aromatics has no absolute technical justification. Therefore, to widen the spectrum of the aviation fuels, it is important to understand the influence of the fuel composition and determine the true acceptable limit.

In the frame of an in-house program, EXPLIC (exploration of limits of hydrocarbon fuels), ONERA is investigating the influence of the fuel composition, aromatic content and carbon molecule distribution on the fuel behaviour under high and low temperature conditions. The present paper deals with the most critical issues for aeronautical engines and fuels operability, altitude relight and cold start, which has been rarely described in the open literature, especially for actual turbojet injection systems and combustion chambers [1].

In a first step, it was decided to investigate the influence of the content of aromatics in the fuel composition by measuring the ignition performances of the six fuels described in Table 2.1, under altitude conditions. The content of aromatics of the samples was measured by high-performance liquid chromatography according to ASTM D 6379-04 specifications.

Jet A-1 is used as a reference. The sample used contained 20.6% in mass of aromatic compounds. The SPK (synthetic paraffinic kerosene) fuel was purchased from SkyNRG. The fuel aromatic rate is 2.52%, exclusively mono-aromatics. The SPK was mixed with Jet A-1 to produce a fuel with 8% aromatics. In addition, the petroleum company TOTAL Marketing Services provided aromatic streams, representative of the aromatic composition of Jet A-1, named aromatic cut (AC). This aromatic cut was blended with SPK to form two mixtures with, respectively, 20.6% and 8% aromatics. Finally, the pure aromatic cut was also tested. Some physical properties of the main fuels tested in this work are presented in Table 2.2.

2.2 Methodology

2.2.1 Test Bench

The experiments were carried out at the MERCATO (Experimental Mean for Research in Air-breathing Combustion by Optical Techniques) test facility at

Table 2.2 Fuel properties at fuel temperature 20 °C

Fuel designation	JETA	SPK	SPK08A	SPK08AC
Density (kg/m^3)	799.6	756.9	775.1	766.0
Viscosity (mm^2/s)	1.70	1.65	1.67	1.60
Surface tension (mN/m)	28.3	27.5	27.5	25.8
H/C ratio (−)	1.9	2.1	2.0	2.1
Aromatics (vol%)	15.6	<1.0	8.2	8.2
Naphthalenes (vol%)	1.72	0.08	0.65	1.06
Sulphur dioxide (wt%)	0.066	0.003	0.0316	0.0024

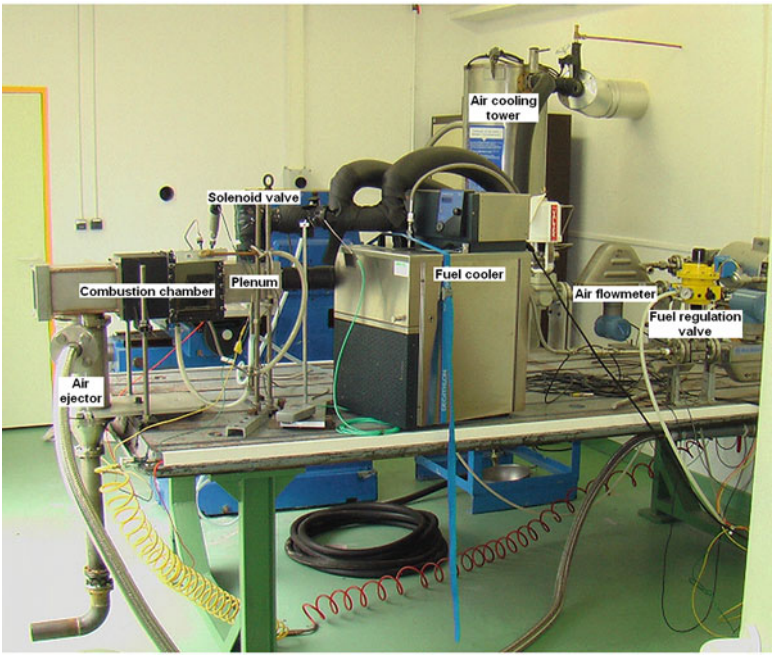


Fig. 2.1 MERCATO test bench

ONERA Fauga-Mauzac (Fig. 2.1). It is a small air-breathing propulsion research facility. Air and fuel are supplied at low flow rates, up to 100 and 10 g/s, respectively, but at a wide range of temperature from 233 to 473 K for air and from 233 K to ambient for fuel. Air is cooled through an air/LN2 cooling tower, fuel through a cooling bath. The pressure in the test chamber can be varied from 0.05 to about 0.4 MPa. This facility was extensively used to investigate the ignition phenomenon [2], especially under altitude conditions.

2.2.2 Test Set-Up and Conditions

We used the same experimental set-up as the one described in Lecourt et al. (2009) (Fig. 2.1). It is composed of a square section combustion chamber which is 129 × 129 × 235 mm^3 large. The injection system is implemented in a plenum chamber, upstream from the combustion chamber. Downstream from the combustion chamber, an interface part supports an air ejector, which is used to lower the pressure in the test chamber. The test chamber can receive four lateral windows for optical diagnostics. The injection system was provided by Turbomeca. Its geometry is fairly simple. The air circuit is composed of a radial swirler, an axial convergent and a cylindrical diffuser. Inside the convergent, an ovoid part holds a pressure swirl fuel atomizer on the axis. Figure 2.2 shows the set-up, equipped with one window facing the spark plug holder, on the opposite wall, and used with cold air (notice the presence of frost on the set-up walls).

The experiments were performed under altitude conditions, i.e. with low air pressure and temperature, but with fuel at room temperature. The characteristics of the operating point are described in Table 2.3.

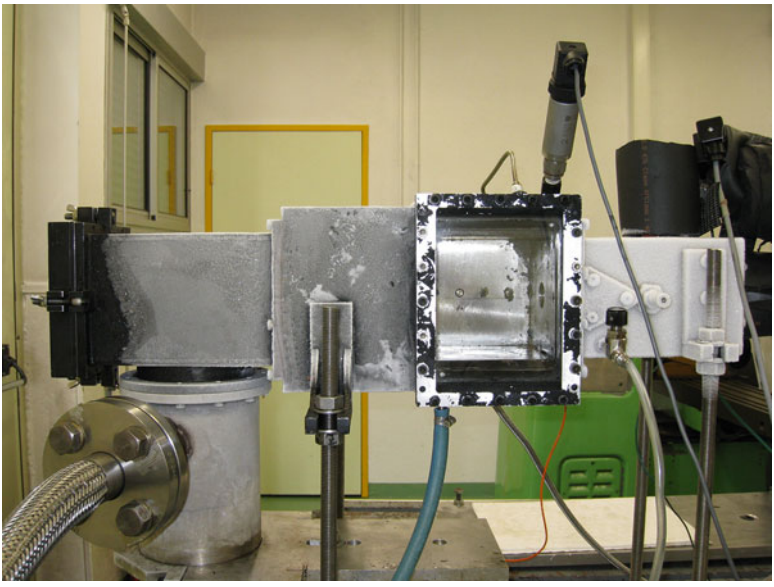


Fig. 2.2 MERCATO set-up under altitude conditions

Table 2.3 Operating point

Air flow rate (kg/s)	0.0192
Air pressure (MPa)	0.06
Air temperature (K)	233
Fuel temperature (K)	290

A Vibro-Meter ET64A1 spark plug was used to ignite the air/fuel mixtures. It is a high-voltage spark plug using air as dielectric. It is supplied with an ignition exciter HEP502T2 from Vibro-Meter and operated at a frequency of 6 Hz. It is located 56 mm downstream from the injection face and flush mounted on one of the lateral walls. The capacitive discharge energy of the ignition device is 2 J. The spark energy was evaluated with tension and intensity measurements at electrodes by the manufacturer. This evaluation gave a spark energy value of 0.4 J.

2.2.3 Test Procedure

The objective of the present ignition experiments was to determine the ignition boundary for each fuel (Table 2.1) at the chosen operating point (Table 2.3). In an engine, the ignition procedure is a short one, and then the test duration was only 6 s. The procedure was designed as follows:

- Air was flowed continuously at the right flow rate (0.0192 kg/s) and temperature (233 K).
- At $t = 0$ s, a fuel solenoid valve, close upstream from the injection system, was opened.
- In parallel, the fuel regulation valve was set from 0% to n % opening to inject the required fuel flow rate.
- Then, at $t = 0.5$ s, the time at which the fuel flow rate has reached steady state, the spark plug was triggered and flashed at about 6 Hz, during 4.5 s, producing about 28 sparks during the tests.
- At $t = 4.9$ s, the kerosene regulation valve was set down to 0% opening.
- At $t = 5$ s, the kerosene solenoid valve was closed.
- Finally, at $t = 6$ s, the data recording was stopped.

An example of an ignition test is illustrated through Figs. 2.3, 2.4 and 2.5.

The flow rate curves (Fig. 2.3) show that the air flow rate is nearly constant during the experiment. A steady measurement of the fuel flow rate is obtained only after 2 s, because of the long response time of the Coriolis flowmeter. It must be pointed out that the steadiness of the flow rate curves allowed an accurate calculation of the global equivalence ratio of each experiment. As air was flowed continuously, its temperature was perfectly constant during the test (Fig.2.4). The fuel temperature, measured in the fuel feeding line, where the feeding line enters the plenum chamber, shows an increase from the line temperature surrounded by the cold air flow to the fuel temperature flowing around the thermocouple after the start of the test.

As shown in Fig. 2.5, ignition is easily observed on the chamber pressure curve thanks to the steep pressure increase of about 150 hPa. Then, pressure goes down to a level of about 50 hPa higher than the one before ignition until full combustion of the fuel injected in the combustion chamber during the 5 s test. In parallel, a signal extracted from the ignition exciter is recorded and gives the sparking times (rising edges, except the last one) (Fig. 2.5). In this experiment, ignition was obtained with the 17th spark.

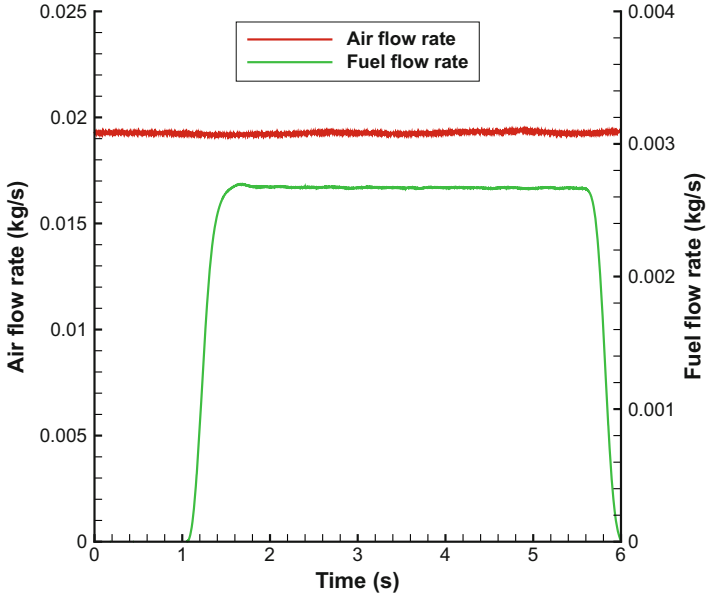


Fig. 2.3 Flow rates during an experiment

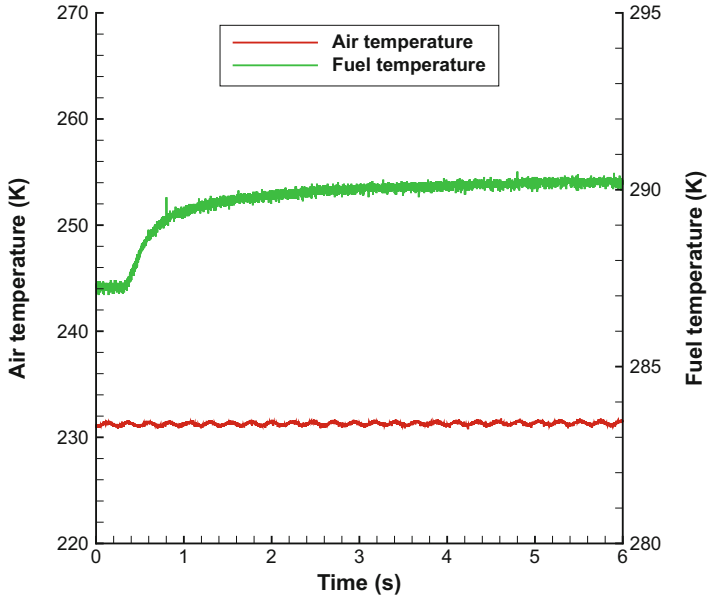


Fig. 2.4 Temperatures during an experiment

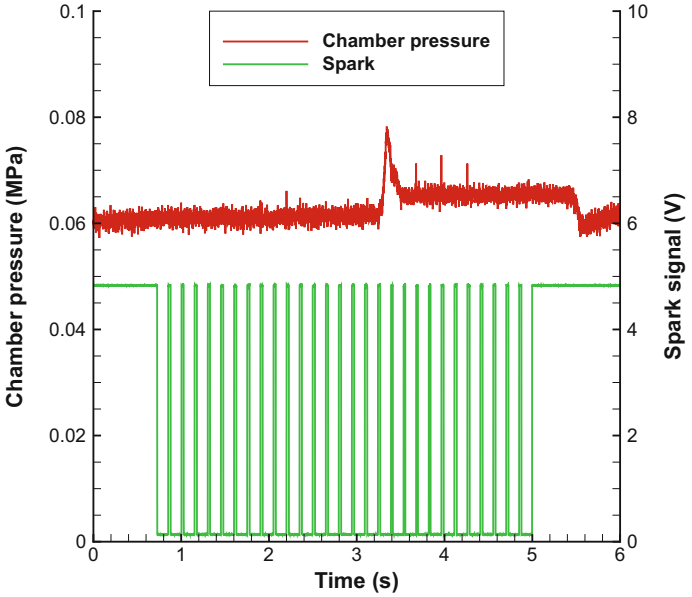


Fig. 2.5 Chamber pressure and spark plug operation during a successful ignition experiment

Finally, the steadiness of the flow rates, temperatures and chamber pressure during the experiments shows that the altitude conditions were well mimicked.

2.3 Results and Discussion

For every fuel, about 10 to 20 experiments were performed with different settings of the fuel regulation valve to obtain different global equivalence ratios from test to test. As ignitions were obtained with the highest values of equivalence ratio and misfires with the lowest values, an ignition boundary could be determined, as an equivalence ratio value, between these two sets of experiments:

$$ER_{\text{boundary}} = \left[\max(ER_{\text{misfire}}) + \min(ER_{\text{ignition}})\right]/2 \tag{2.1}$$

It must be pointed out that this equivalence ratio value was computed with one unique C-H composition, close to the one of an "average" Jet A-1, and not with the actual C-H composition of the tested fuels.

Some experiments were discarded because the targeted chamber pressure value, 0.06 Mpa, was not well reached. Finally, 10 to 12 experiments were kept by fuel. Table 2.4 gathers the characteristics of the experiments kept for the measurement of the ignition performances of the SPK08A fuel. From test to test, the discrepancies are within $\pm 2.5\%$ at most.

Table 2.4 Characteristics of the experiments for SPK08A fuel

Test #	P_{ch}(MPa)	Air flow rate (kg/s)	T_{air}(K)	T_{fuel}(K)
1	0.0600	0.0196	233	290
2	0.0607	0.0192	233	291
3	0.0613	0.0190	232	291
4	0.0604	0.0197	232	291
5	0.0586	0.0193	233	292
6	0.0600	0.0193	233	292
7	0.0597	0.0191	232	292
8	0.0608	0.0197	232	292
9	0.0595	0.0191	232	292
10	0.0607	0.0192	234	292
11	0.0614	0.0191	234	292

Table 2.5 Average characteristics of the experiments

Fuel	P_{ch} (MPa)	Air flow rate (kg/s)	T_{air} (K)	T_{fuel} (K)
JETA	0.0600	0.0194	233	289
SPK08A	0.0603	0.0193	233	292
SPK	0.0605	0.0193	232	290
SPK08AC	0.0601	0.0193	233	291
SPK20AC	0.0601	0.0193	233	290
AC	0.0601	0.0191	233	291

The average characteristics of the operating point of these experiments for every fuel are gathered in Table 2.5. Because of the good reproducibility from test to test, the average characteristics of the operating point are close to each other for all fuels. Therefore, their ignition performances will be able to be well compared.

Figure 2.6 gathers all the results, ignition or misfire, as the global equivalence ratio for each test and each fuel. First, on an overall, the results show that, under altitude conditions, a high equivalence ratio, about 2 and more, is needed to obtain ignition. Then, around the ignition boundary, we can observe misfires with equivalence ratio slightly higher than for some ignitions. This demonstrates the existence of a fuzzy zone around the ignition boundary because of the stochastic nature of the ignition phenomenon as it has been shown by [3] for one-phase flows and, which is more representative of aeronautical issues [4], for two-phase flows.

Concerning the influence of aromatics on the ignition performances (Table 2.6), a clear trend is observed with the SPK/AC blends. The fuels are easier and easier to ignite, for ER 2.03–1.91, when the aromatics content is increased from 0% to 20%. But the pure aromatic cut is the most difficult fuel to ignite with an ignition boundary of ER 2.3. Another surprising result is that SPK/Jet A-1 blend (SPK08A) is easier to ignite than each of its components. Nevertheless, we can observe that both the fuels with 8% aromatics (SPK08A and SPK08AC) have similar ignition boundaries, respectively, ER 1.93 and ER 1.96.

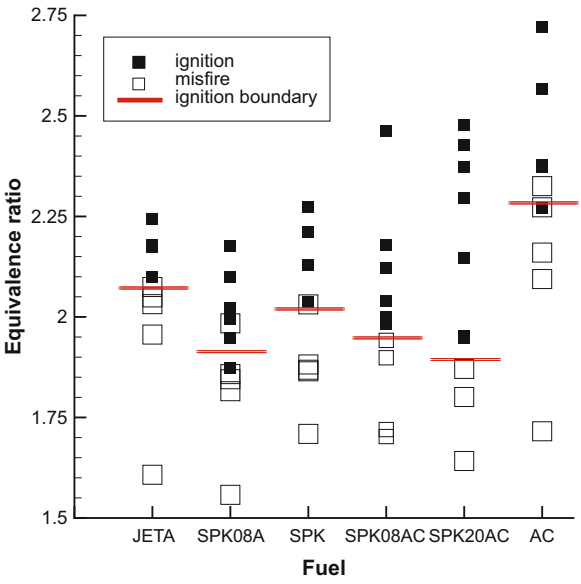


Fig. 2.6 Ignition results

Table 2.6 Ignition boundaries

Fuel	Fuel flow rate (kg/s)	ER (boundary)
JETA	0.00270	2.09
SPK08A	0.00253	1.93
SPK	0.00267	2.03
SPK08AC	0.00257	1.96
SPK20AC	0.00250	1.91
AC	0.00298	2.30

2.4 Conclusions

Successful measurements of the ignition performances of different fuel compositions have been performed under altitude conditions. In this first step, the main parameter was the content in aromatics. The results show that, to some extent, the ignition performances increase with the concentration in aromatics. Nevertheless, a part of the results show that other parameters play a role in ignition, which can work against the positive effect of the concentration in aromatics. Concerning the fuel specifications and with regard to the ignition performances, the results show that, because of the low influence of the aromatic content on them, 1.91 at most against 2.03 ER, it could be acceptable to lower the specification under 8%. Moreover, as the performances are similar for the SPK/Jet A-1 and SPK/AC mixtures, alternative fuels without Jet A-1 could be certified according to ignition properties.

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