Premixture ignition of Jet-A kerosene and some of its surrogates in flowing conditions

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1 Introduction

Impact of civil aviation on the environment is today a major issue with the expectation of air traffic to soar in coming years. Environmental international bodies as ACARE (Advisory Council for Aviation Research and Innovation in Europe), in partnership with the main international aeronautical groups, require more and more drastic objectives in terms of pollutant emission and consumption reduction [1]. To reach these objectives, innovative solutions with technological breakthrough are in development, as constant-volume combustion which could provide a 10 % to 20 % consumption reduction in comparison to current engines [2-3]. In the case of constant-volume combustion dedicated to aeronautical propulsion, a spark ignition combustion of kerosene-air premixture may be used [4]. To produce power, high frequency cycles are required. Hence air admission has to be as short as possible, implying high velocities at ignition point that can reach several tens of meters per second [5-6]. The ignition process is critical and must generate an ignition kernel able to expand in the overall chamber. This ignition process depends on several parameters: initial temperature, initial pressure, equivalence ratio or dilution of the mixture, aerodynamic conditions and also the history of these parameters when the kernel is moving.

Few data are available in literature concerning ignition of aeronautical jet fuel in presence of a flow at ignition point [7]. Studies have also been realized concerning ignition of jet fuel surrogates [8-10]. However, these data are necessary to understand the different phenomena involved in an aeronautical constant-volume combustion. Experimental measurements dedicated to the determination of energy necessary to ignite these mixtures in such conditions are central. This paper focuses on the comparison between Jet A and several surrogates. The aim is to evaluate the ability of these surrogates to represent the ignition behavior of Jet-A in lean and flowing conditions.

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2 Experimental methodology

2.1 Experimental set-up

The TUMBLE experimental set-up was designed to study flame-wall interaction in turbulent conditions (cf Boust [11]). The walls of combustion chamber are made of stainless steel. The chamber volume is 246 cm^3 and is constituted with a cube of side 66 mm and a roof face with a 120 degrees angle (Fig.1). The chamber has three K-UV optical windows allowing optical diagnostics. It also has two Synerject Orbital gas injectors fed with gaseous mixture at a pressure of 6 bar, located on the roof and generating the flow inside the chamber. Instrumentation plug can be set-up on some faces. Some adaptations were realized to meet the needs of this work. The chamber can be heated up to 470 K. The temperature regulation is performed using K-type thermocouples integrated inside the cartridges heaters.

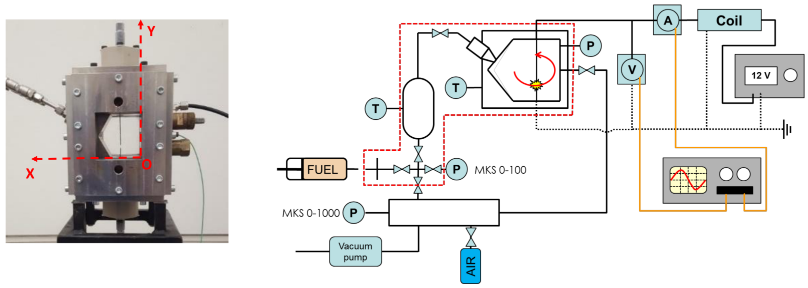

Figure 1: TUMBLE experimental set-up

The geometry of the combustion chamber with a 120 degrees angle roof on one face allows the generation of a quasi-bi-dimensional swirl during the injection of the mixture. After the end of injection, the rotational speed of the swirl will decrease as a result of turbulence by viscous friction. Ignition is then performed between two tungstene electrodes of 1 mm in diameter, with a half top angle equal to 22.5 degrees. The gap between electrodes is adjustable, set here to 1.80 mm, and placed at the quarter of the chamber where the swirl is generated, see Figure 1. An automotive inductive ignition system is used (Beru ZSE 041). The electrical energy deposed between the electrodes is adjusted using the coil charge duration time (0.3 to 3.5 ms) and the variation of the supplied voltage (8 to 16 V). With these conditions, the energy ranges from 2 mJ to 100 mJ. It is calculated with equation Eq. (1). Voltage $V(t)$ and current $I(t)$ signals are recorded respectively using a Tektronix P6015A high voltage probe and a LeCroy CP031 current probe. Both signals are sampled at 1 GHz using a LeCroy waverunner 104Xi oscilloscope. Examples of these signals, and the resulting electrical energy, are reported in Figure 2.

$$E = \int V(t).I(t)dt \tag{1}$$

As a result of the high velocity flow, the electrical discharge will bend, lengthen and eventually blow. To ensure the breakdown, an additional energy is needed compared to quiescent condition. When the energy necessary to create and maintain the discharge becomes too high, the electric arc breaks. If the voltage is still high enough, a new breakdown phase may occur: this is a multi-spark discharge. As a consequence of the turbulent flow, a scattering of electrical energies values is obtained for same operating conditions. Ignition is considered successful when pressure, controlled by a dynamic piezo-electric pressure sensor Kistler 601A, increases inside the chamber after ignition.

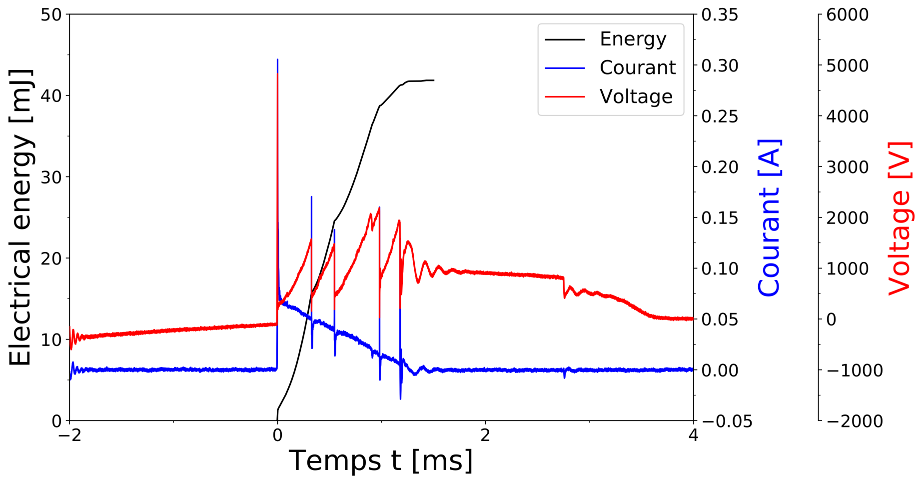

Figure 2: Energy, voltage and current versus time during electrical discharge phase in a *n*-decane/air premixed flame at initial pressure P_0 = 0.1 MPa, initial temperature T_0 = 400 K, equivalence ratio Φ = 0.7, and swirl mean velocity V = 25 m/s

2.2 Mixture preparation

A particular attention is paid to the mixture preparation that is carried out using the method of partial pressures. A system of heated pipes regulated in temperature was installed to make the mixture, preventing from any condensation phenomenon. The equivalence ratio is evaluated using two absolute pressure transducers (MKS Baratron) connected to the injection system: the first is a MKS Type 631C transducer heated up to 470 K and calibrated on 0-130 mbar scale dedicated to liquid injection, and the second one is a MKS Type 722B non-heated and calibrated on 0-13,000 mbar dedicated to gas injection. The 'zero' of these transducers are regularly controlled to prevent errors during mixture realization. Employing different scales pressure gauges provide a good accuracy on the equivalence ratio (uncertainty lower than 1.5 %).

Mixtures are prepared with high purity grade commercial chemicals: *n*-decane (Merck, $\geq$ 99 %), *n*-propylbenzene (Merck, $\geq$ 98 %), *n*-propylcyclohexane (Sigma-Aldrich, $\geq$ 98.5 %), *n*-dodecane (Merck, $\geq$ 99 %), iso-octane (Sigma-Aldrich, $\geq$ 99.75 %), 1,2,4-trimethylbenzene (Merck, $\geq$ 98 %), 1,3,5-trimethylbenzene (ACROS Organics, $\geq$ 98.5 %). The synthetic air is composed of oxygen and nitrogen (Air liquide, 99.99 %) with a ratio N_2/O_2 = 3.76. Jet fuel kerosene employed in this study is provided by Total and was analyzed in 2018. Its density is 797.6 kg/m^3, its flash point is 323 K and the LHV is 43.51 MJ/kg. Also, its chemical composition was analyzed using GC/MS techniques, giving an average chemical formula equal to $C_{10.51}H_{21.23}$.

For this study, three jet fuel surrogates were selected from single component up to four components: the *n*-decane; the Dagaut surrogate (74 % *n*-decane, 15 % *n*-propylbenzene and 11 % *n*-propylcyclohexane, % vol) [12]; and the MURI2 surrogate (40.4% *n*-dodecane, 29.5 % iso-octane, 7.3 % 1,3,5-trimethylbenzene and 22.8 % *n*-propylcyclohexane, % vol) [13]. These surrogates were selected for several reasons, and in particular they are able to reproduce fundamental burning velocities respectively on the rich side for *n*-decane/air premixed flames and on the lean side for the other two [14].

2.3 Experimental conditions

Measurements are performed for the different air-fuel mixtures at initial pressure P_0 = 0.1 MPa, initial temperature T_0 = 400 K, and equivalence ratio Φ = 0.7. To reach this pressure, with the injection system, injection duration is 70 ms. The resulting aerodynamic conditions in the TUMBLE combustion test rig have been measured with high frequency PIV technique [15]. Velocity at ignition point is then well-known decreasing with the time delay after the end of injection. For the present study, the most critical aerodynamic conditions was selected: ignition is performed 2 ms after closing the injectors (to prevent flashback), ie at t_0 + 72 ms, where t_0 corresponds to the beginning of injection. At this instant, mean velocity between electrodes is U = 25 m/s and the velocity fluctuations are close to u' = 2 m/s.

3 Results

3.1 *n*-decane/air mixtures

Figure 3.a represents the results of ignition tests for *n*-decane/air mixtures. Tests are ranked by decreasing order of electrical energy. The statistical nature of ignition, observed in the literature, see for instance Bane et al. [8], is also observed here by the overlap of successful ignitions and misfires for energy between 2.3 mJ and 11.3 mJ. From these tests, the probability density function can be calculated depending on the deposed energy using the same statistical regression method as Bane [8], e.g. using a logistical function (Figure 3.b). To be optimal, this method requires an important number of tests. For our experiments, only few data were obtained for the lowest energies. Thus, the interpretation of probability density curve obtained for these lowest values must be considered with caution, although the overall analysis is pertinent. From the probability density function curve, several authors define the minimum ignition energy (MIE) of the mixture as the energy corresponding to a 50 % successful ignition [8,16]. Following this definition, the MIE of *n*-decane in tested conditions is equal to 4.6 mJ (with a 95 % confidence interval (CI) between 3.0 and 6.2 mJ), which is consistent with the literature for lean *n*-decane/air mixtures [9,10]. Hence, ignition is ensured for electrical energy higher than 20 mJ and some successful ignitions are observed for energies around of 2 mJ.

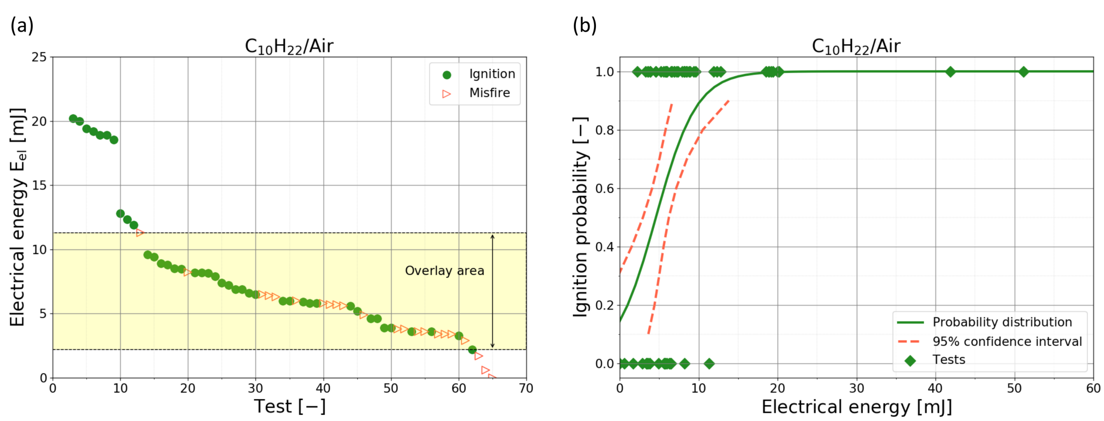

Figure 3: Test results and probability density function for ignition in the case of a *n*-decane/air premixed flame at initial pressure P_0 = 0.1 MPa, initial temperature T_0 = 400 K, equivalence ratio Φ = 0.7, and swirl mean velocity U = 25 m/s

3.2 Kerosene/air mixtures and surrogates/air mixtures

The results concerning lean commercial kerosene/air and jet fuel surrogates/air premixtures in flowing conditions are presented in Figure 4. A larger or smaller overlap region is observed for different cases, confirming the statistical nature of ignition. MIE values obtained for the different mixtures are: 3.3 mJ (with a 95 % CI between 2.4 and 4.1 mJ) for the Dagaut surrogate, 8.7 mJ (with a 95 % CI between 4.4 and 11.5 mJ) for the MURI2 surrogate and 9.8 mJ (with a 95 % CI between 3.3 and 16.3 mJ) for the commercial kerosene. The experimental methodology is different from the standard methods used in quiescent mixtures. Nevertheless, it is the same for all the investigated fuels. Moreover, even if additional experiments are planned to reinforce the experimental database, clear trends are observed in Figure 4. Therefore a classification and a comparison of the surrogates can be made.

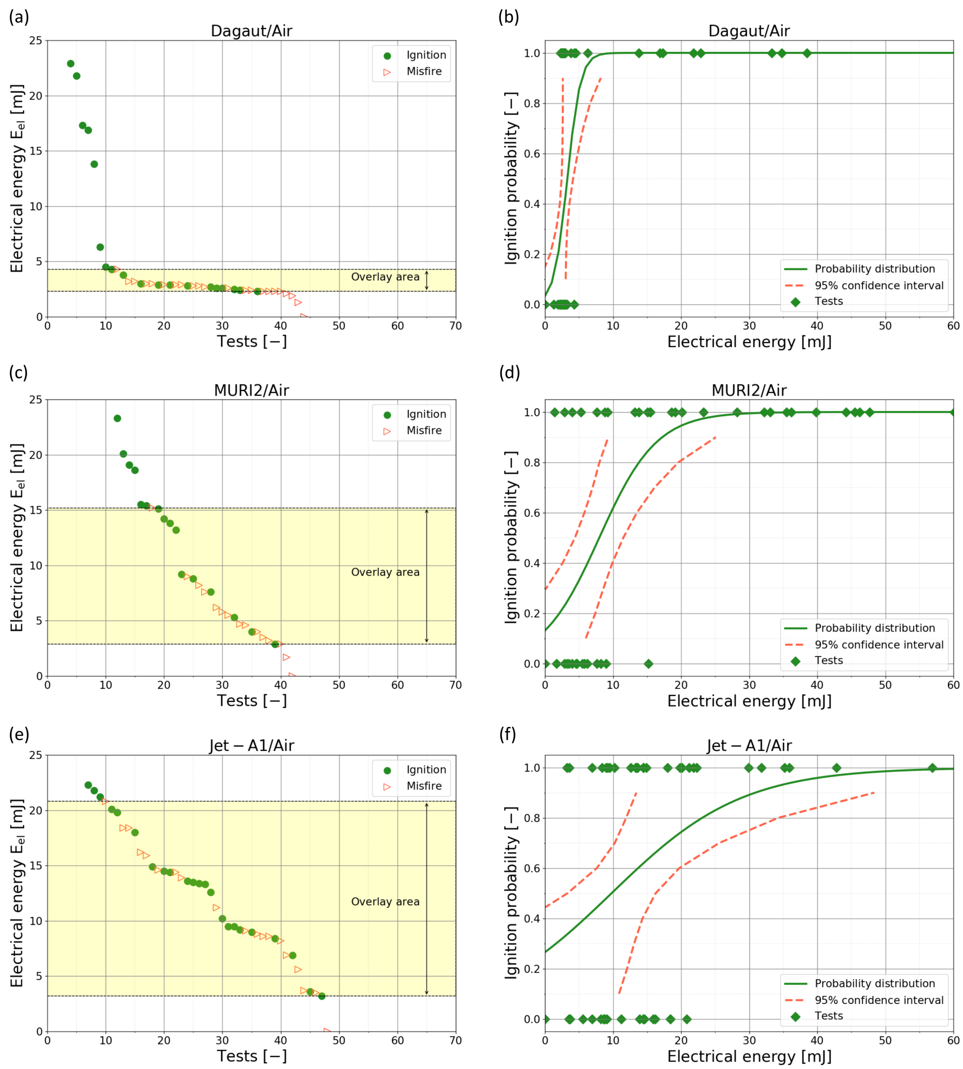

Figure 4: Test results and probability density function for ignition in the case of (a)-(b) Dagaut/air , (c)-(d) MURI2/air and (e)-(f) commercial kerosene/air premixed flames at initial pressure P_0 = 0.1 MPa, initial temperature T_0 = 400 K, equivalence ratio Φ = 0.7, and swirl mean velocity U = 25 m/s

Ignition of commercial kerosene seems to be difficult to reproduce with the surrogates for the tested conditions, excepted for the MURI2 surrogate. The measurements show that commercial kerosene requires higher energy to ignite than the mono and multi-component surrogates. As a conclusion, these surrogates, even if they are able to reproduce some chemical (fundamental flame speed) and physical properties of a commercial kerosene, are not able to reproduce the full-complexity of a real kerosene. Only the MURI2 surrogate, which is the more complex surrogate, tends to reproduce the commercial kerosene ignition phenomenon in the tested conditions. Also, despite differences between experimental methods, value of MIE for lean Jet-A/air mixture is consistent with that of Rao and Lefebvre [7]. A detailed analysis can not be presented here for brevity.

4 Conclusion

Ignition of kerosene/air premixed flames has been experimentally studied using a combustion chamber available at Institut Pprime, and capable of generating a flow during injection phase up to 25 m/s. Experimental measurements have been performed at initial pressure P_0 = 0.1 MPa, initial temperature T_0 = 400 K, and critical conditions for equivalence ratio (Φ = 0.7) and mean flow velocity (V = 25 m/s). The statistical nature of ignition process has been confirmed: ignition and misfire can occur for a same electrical energy for a given condition. The minimum ignition energy of a commercial kerosene has been determined in these conditions. MIE of some surrogates selected in the literature have also been measured. In the investigated conditions, the surrogates do not fully reproduce the ignition behavior of the real kerosene. Nevertheless, the results obtained for the MURI2 surrogate and Jet-A fuels are consistent.

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