

Laser spark ignition and flame expansion in swirl burners fuelled with n-heptane sprays

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1 Introduction

Spark ignition of recirculating spray flames is a topic of technological importance, being the key to determining relight capability of aviation gas turbines, but also contains significant fundamental challenges, as it involves complicated combustion phenomena. There are various phases associated with the successful ignition of a spray burner: (i) kernel initiation; (ii) flame growth; and (iii) overall flame stabilisation, with each of these phases involving a certain stochasticity, which leads to a wide range of different behaviours for a particular spark event [1]. The ignition probability, P_{ign} , defined as the percentage of sparks that lead to overall burner ignition, has been measured as a function of spark location in a swirling n-heptane spray injected from a hollow-cone atomizer [2] and very strong spatial variations were found. These variations, and the fact that the phenomenon is probabilistic in the first place, are not only due to the mixture fraction fluctuations. Very interesting behaviours have been observed [3] where sparking flammable mixture may not always lead to flame growth due to quenching, while sparking non-flammable mixture may result in successful flame due to transport effects. P_{ign} was also found to decrease with increasing flow rate [2], a finding attributed to the detrimental effect of high turbulence on kernel initiation, but also to the inability of the flame to propagate and stabilize as the flow rate increases. Overall burner ignition was found to be critically dependent on the capturing of flame elements by the recirculating flow to bring them towards the atomizer [2], something also borne out by recent large-eddy simulations of spark ignition [4-6].

In this paper, the investigation of Ref. [2] is extended by measuring ignition probability in flames close to extinction, considered as a more challenging phenomenon than ignition far from the blow-off limit. In addition, we consider sparks that are not created by electrodes, but by laser-induced breakdown. The work also aims to determine separately the timescales associated with phases of initiation, growth and overall flame establishment. Apart from further understanding, these measurements can also assist validation of modelling efforts.

2 Experimental methods

The burner was previously used by Marchione et al. [2], but was slightly modified here. It consists of an outer duct for air injection, a central inner duct for fuel injection, and a combustion chamber (Figure 1). Air is injected through two opposite slots located at the top of a 35 cm long circular duct of 37 mm inner diameter. Swirl is achieved by static swirl vanes (6 blades oriented at 60 degrees with respect to the flow axis along the flow passage between the inner and outer ducts). The direction of the air swirl is counter-

clockwise when looking at the nozzle from the combustor. The air flow rate is set through rotameters, calibrated by a mass flow controller (Bronkhorst, IN-Flow, [0–600] L/min). The fuel line is a 6 mm inner and 10 mm outer diameter pipe centred in the outer duct. The fuel used for this study is n-heptane. Due to the quick evaporation of the fuel, it is possible to stabilize spray flames at a laboratory-scale burner without preheating air. The fuel is pressurized with nitrogen in a feeding tank and then atomized through a pressure swirl atomizer (Lechler, axial flow hollow cone nozzle). The nozzle exit diameter is 0.15 mm, the spray cone angle is 60 degrees. The fuel flow rate is set by a mass flow controller (Bronkhorst, LIQUI-flow, L30, [0–2] g/s). The nozzle is centred inside a bluff body of diameter $d_{BB} = 25$ mm, with a 4 mm hole in the center. The combustion chamber has a square cross-section of side 95 mm ($3.8 d_{BB}$) and is 150 mm in length ($6 d_{BB}$). It is made of synthetic quartz designed for optical diagnostics (optically flat sides, deep UV transmission, fluorescence-free grade). The outlet is open to the atmosphere. Three different flames are studied. For all, the fuel mass flow rate is constant and equal to 0.12 g/s. The air flow rate is increased from a stable flame condition (500 L/min) to the lean blow-off limit (650 L/min); the flames studied are shown in Table 1. The burner is oriented vertically downwards in order to collect safely unburnt fuel during the ignition experiments.

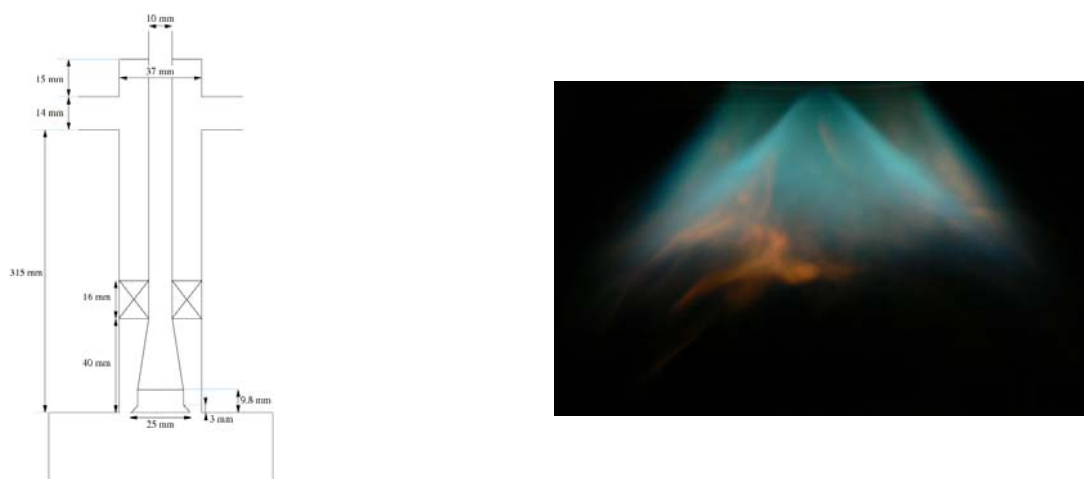


Figure 1. Schematic of the burner (left) and a photograph of the stable flame (right).

Name	$\dot{m}_{air}$ (kg/min)	U_b (m/s)	U_b / U_{BO}	Φ
SWH1	0.59	14.3	0.77	0.18
SWH2	0.68	16.0	0.89	0.16
SWH3	0.77	18.5	1.00	0.14

Table 1. Flow conditions studied. U_{BO} is the air bulk velocity at blow-off for this fuel mass flow rate (0.12 g/s).

The laser spark is created by focusing the beam from an 8 ns Q-switched Nd-YAG laser (Continuum Surelite operating at 1064 nm). The focusing lens is a 75 mm focal length biconvex quartz lens of 50 mm diameter. The energy of the spark can be adjusted by changing the Q-switch delay. The laser can operate in a single pulse mode or a pulsed mode (frequency set to 1 Hz or 10 Hz). In order to get a spark for each laser spot, the energy before the focusing lens must be above a threshold that depends on the properties of the laser and the presence of particles in the environment. In the case of a turbulent droplet-air mixture, the instantaneous properties of the mixture at the location of the spark can be strongly different from the mean properties. In the framework of this study, the energy is set to 140 mJ/pulse. This value is high enough to ensure the generation of a spark after each laser shot, for the three studied flow conditions and for all locations of the spark in the combustor. To measure the ignition probability (P_{ign}), with “ignition” defined as the event where the whole flame will ignite and stay alight for many seconds following a spark, a series of trials is performed and P_{ign} is computed as the number of successful events divided by the number of

trials. 30 single sparks at each location were used. This involves an uncertainty of 9% at 50% ignition probability. Moving the location of the spark, it is possible to get a map of ignition for the whole combustor (5 mm between two successive locations). The probability of initiating only a kernel which does not result in a whole-burner ignition, P_{ker} , has also been determined, although some small kernels that die quickly may have been missed.

The ignition event has been monitored by OH* chemiluminescence. The detection system consists of a LaVision High-Speed-Star 6 (HSS6) CMOS camera (1024×1024 px) fitted with a two-stage intensifier (High-Speed IRO, LaVision, 12 bits). Two UV aplanatic meniscus lenses back to back are used instead of a camera objective (clear aperture: 60.0 mm, focal length: 192.0 mm). The repetition rate of the camera is 5 kHz. The resolution of the images is 0.08 mm/px (image width: 45 mm). The highest sensitivity of the imaging system is in the UV range. To collect the OH* chemiluminescence signal, the flame luminosity is filtered by a UG11 filter and by adjusting the gate time to 3 500 ns. The beginning of collection is 0.04 ms from the spark to avoid intense light into the intensifier.

A replica burner has been installed at the University of Sydney, where fast OH-PLIF has been deployed to image the ignition transient and the stable flame structure. Excitation at 283.01 nm was achieved by two Edgewave (IS411-E) Nd-YAG lasers, with a power of 12 W each and a pulse length of around 10 ns. These pumped a SIRAH Allegro High Speed Dye Laser that produced a beam at 566 nm, which was then frequency doubled using a BBO crystal to produce a beam with an average power of 750 mW at 5 kHz (150 μ J/pulse). First and second harmonics were separated using a set of 4 Pellin-Broca prisms. The beam was then expanded to 60 mm in height using a diverging cylindrical lens before being focused into a sheet at the imaging axis using a fused-silica lens with 300 mm focal length. The detection system used to record the OH-PLIF signals is similar to the one used to record the OH-chemiluminescence signals. A WG295 filter and a WG305 filter are placed in front of the camera. More details and applications of this system are given in Ref. [7].

3 Results and Discussion

Results on the flame structure, the timescales of the expansion process, and the ignition probability are given in this Section.

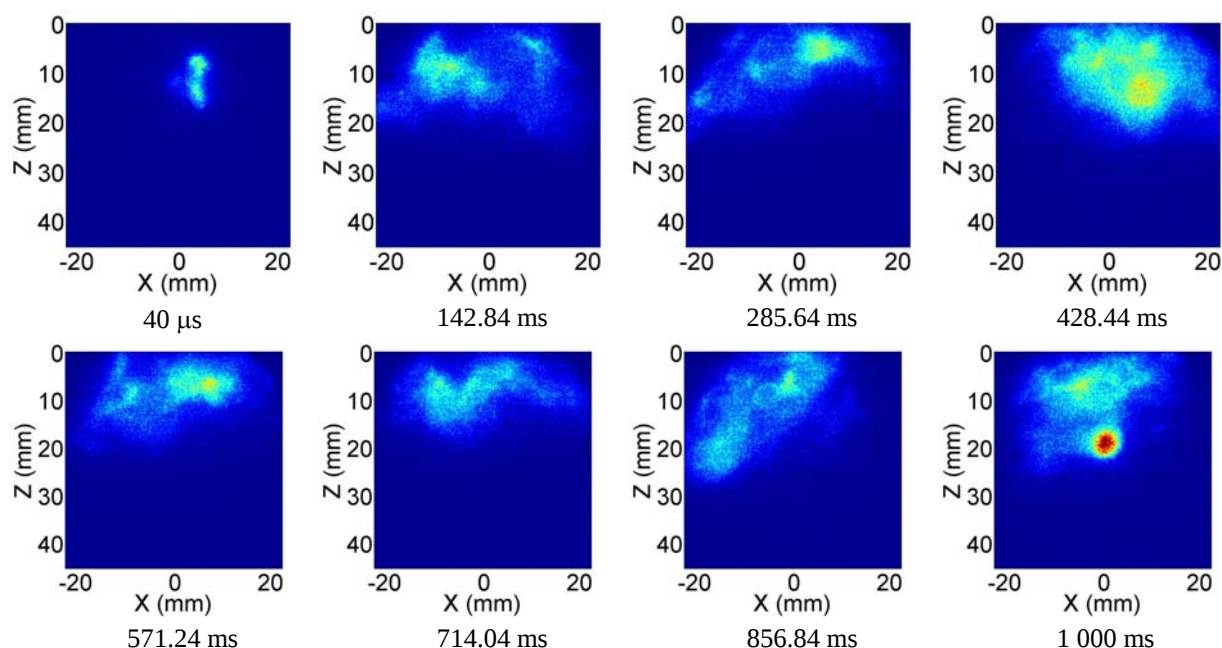


Figure 2. Typical OH* chemiluminescence sequence from a successful spark event for flow condition SWH1.

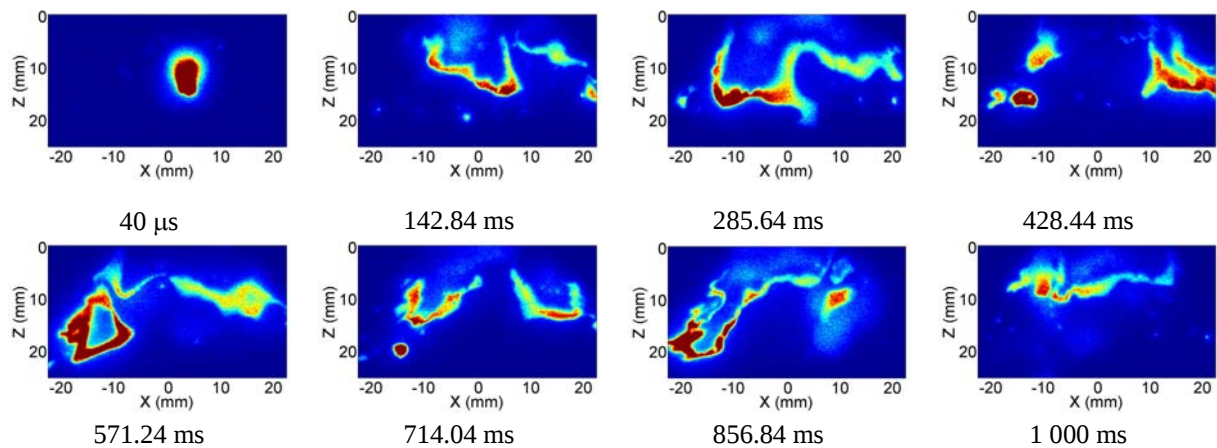


Figure 3. Typical OH-PLIF sequence from a successful spark event for flow condition SWH1.

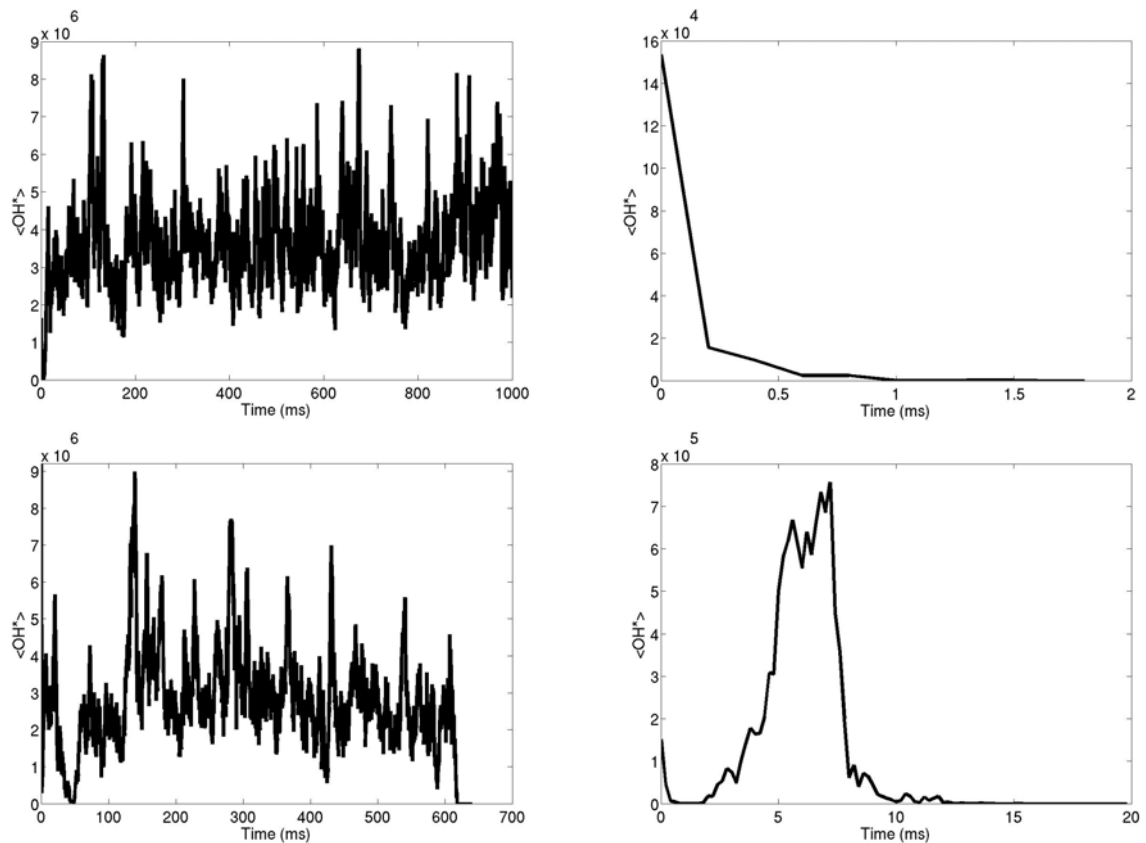


Figure 4. Typical area-integrated OH* chemiluminescence for a successful event (top left) and a “short-failure” event (top right) for SWH1, a “long-failure” event (lower left) for SWH2, and an “intermediate-failure” event (lower right) for SWH3.

Figure 2 shows a typical evolution of a successful spark as recorded by OH* chemiluminescence. It is evident that it takes significant time for the flame to grow and reach its steady-state size. This time is of the order of 10 ms, which is much longer than the timescale d_{BB}/U_{BO} . The shape of the stable flame is evident

more clearly in the photograph of Figure 1, where a double-conical reaction zone is visible. The OH-PLIF images (Fig. 3) show that the kernel grows in all directions from the spark location, while the reaction zone (likely to be the region of strong OH signal) is thin, very distorted, and eventually becomes anchored at the lip of the bluff-body. Very strong temporal fluctuations are evident. A reaction zone going across the burner is evident, but it seems broken occasionally. This may be due to out-of-plane motion or may point to the presence of localized extinction.

Figure 4 shows the area-integrated OH* chemiluminescence, denoted as $\langle \text{OH}^* \rangle$, as a function of time. This gives qualitatively the evolution of the overall heat release in the burner. It is evident that for successful ignitions, $\langle \text{OH}^* \rangle$ rises within about 10 ms to a state where fluctuations are present, but overall $\langle \text{OH}^* \rangle$ is high, corresponding to stable combustion. In contrast, in failed events, $\langle \text{OH}^* \rangle$ rises immediately after the spark, but then falls to zero. The timescale over which $\langle \text{OH}^* \rangle$ reaches zero defines the timescale of failed ignition, i.e. quantifies how quickly the kernels die. Three modes have been found. (i) A “short failure” mode (Figure 4, top right) where the flame is completely quenched within 1-2 ms from the spark. (ii) An “intermediate failure” mode, where the kernel grows, but eventually is reduced in size again and is quenched at a time of the order of 10 ms from the spark. (iii) Finally, in some occasions, a “long failure” mode has been observed, where the flame stays alight for a period of hundreds of milliseconds, but then eventually extinguishes. Note that the “long failure” mode is not confined to ignition attempts at the blow-off condition, but is found also at lower velocities. This mode of failed ignition may be related to the thermal inertia of the burner and possibly also to evaporation and drainage of the deposited liquid fuel before ignition.

Figure 5 shows the measured whole-flame ignition probability, P_{ign} , as a function of radius for the three flow conditions studied. It is evident that: (i) as the air velocity increases and the blow-off condition is approached, P_{ign} decreases and reaches zero at the blow-off condition; and (ii) P_{ign} decreases with radius and with distance downstream of the injector and eventually reaches zero. Figure 2 also shows the probability that a kernel is generated by the spark, but the flame is not fully ignited and long-term stability is not reached. It is evident that: (iii) P_{ker} is equal to P_{ign} for the low velocity condition; (iv) P_{ker} is greater than P_{ign} for the high velocity conditions; and (v) even for the blow-off condition, P_{ker} is greater than zero in many places: kernels are generated but these fail to grow or, even if they do, full-flame stable ignition is not achieved.

4 Conclusions

An experimental study of laser ignition on lab-scale swirl stabilized n-heptane spray flames has been conducted. The stability map of the burner was defined, including the lean blow-off curve. Fast OH* chemiluminescence movies allowed a classification of successful and failed events. Time-scales of initiation, full flame ignition and extinction were also extracted from the movies. Concerning the ignition behaviour, it was found that small kernels emanate very often from the spark: some of them die very quickly after the end of the spark, some of them survive during some time and move inside the combustor, and finally some kernels develop into a stable flame. OH-PLIF at 5 kHz identified the motion of thin flame sheets and some localized extinctions along the flame sheet are evident. The ignition probability becomes zero at large axial distances from the nozzle and is smaller than the probability of initiating only a kernel.

In the full paper, the above findings will be described in greater detail. The flow field will also be characterized through velocity measurements.

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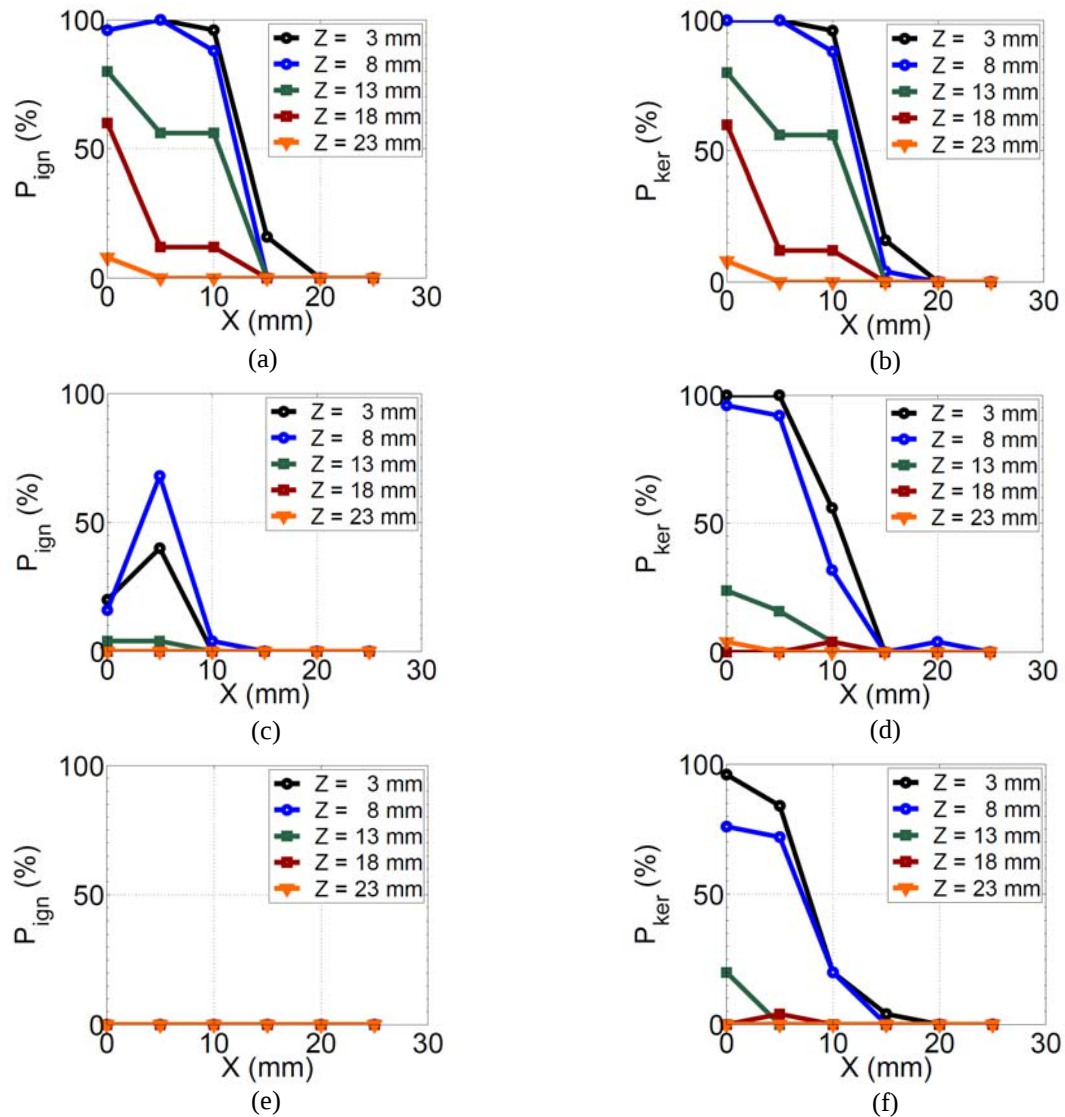


Figure 5. Full-flame ignition probability P_{ign} (a, c, e) and kernel-only probability P_{ker} (b, d, f) for flow conditions (a, b) SWH1, (c, d) SWH2, and (e, f) SWH3.