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# Influence of self-sustained jet oscillation on a confined turbulent flame near lean blow-out

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**Abstract**

Premixed methane–air turbulent flame is generated in a single-nozzle jet-stabilized combustor designed based on the FLOX® concept[1]. Confinement-induced, self-sustained jet oscillation is observed. Its influence on combustion stability near lean blow-out (LBO) is investigated using simultaneous particle imaging velocimetry (PIV), planar laser-induced fluorescence of OH radicals (OH PLIF), and OH chemiluminescence imaging at 5-kHz repetition rate. Via proper orthogonal decomposition (POD) of the velocity field and extended POD of the scalar fields, pronounced variations in the flame shape are observed during a cycle of jet oscillation. In extreme cases, flame is partially blown out in the combustor due to jet impingement on the wall during the first half of its oscillation cycle. In the subsequent half cycle following jet detachment, flame is restabilized after robust flashback and re-light. Statistical analysis shows that such pattern is by far the most prevalent mechanism for blow-out and restabilization to take place at the operating condition. Additionally, these events are found with much higher probability during slow-paced jet oscillations.



*Keywords:* Confined turbulent flames; Jet oscillation; Highspeed laser diagnostics; Proper orthogonal decomposition

## 1. Introduction

FLOX® combustion, also termed as flameless [1] or mild combustion [2], has recently gathered great interest for its low susceptibility to thermoacoustics and flashback [3] as well as its high fuel flexibility and low NO$x$ emission [4]. It is often regarded as a viable alternative to swirl-stabilized flames for stationary gas turbines. FLOX® combustors generally consist of circularly arranged nozzles issuing high momentum jets of reactants into a combustion chamber, generating strong flow recirculation and hence intense mixing of reactants and products. Characterization of various FLOX® combustors is an ongoing effort at our institute, with early investigations dedicated to obtaining quantitative data sets for validating numerical simulations [4–6]. With a recent focus on the stabilization mechanisms in this type of combustors, a laboratory-scale single-nozzle FLOX® combustor has been designed to allow more sophisticated optical diagnostics [5]. Subsequently,

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[1] FLOX® is a registered trademark of WS Wärmeprozesstechnik GmbH, Renningen, Germany

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confinement-induced periodic jet oscillation has been identified as the major source of instability in flames stabilized in this combustor [7,8].

Confinement-induced, self-excited and self-sustained jet oscillation is a well-documented phenomenon in non-reacting flows [9]. It is commonly understood that, the oscillation is triggered by obstructed shear layers (such as by a recirculation zone), and is sustained by a feedback loop between initial disturbances and the impinging points. Such feedback is most commonly hydrodynamic, as seen in jets experiencing sudden expansion [10,11] and jets issuing into a cavity [12,13]. Jet flapping and jet precession have been identified as the primary patterns of oscillation in confined jets [10–12]. The former case is often found in planar jets, where recirculation zones on each side of the jet move conversely upstream or downstream as the jet flaps with respect to the plane of symmetry. Through proper orthogonal decomposition (POD) of the 2-D velocity field [14], the spatial mode responsible for the jet flapping was found to contain large structures aligned along each side of the jet. In the case of a round jet expanding into a concentric cylindrical chamber [10,15], jet precession was found to induce a swirling flow in the confinement. Through parametric studies, oscillations in confined jets have been found to scale linearly with jet velocity and impingement length (e.g., nozzle diameter and confinement dimensions) [12,13]. They often possess a Strouhal number in the range of $St \sim 0.001–0.01$, much smaller than the instabilities generated within shear layers ($St \sim 1$) [10]. As its main influence on the flow field, jet oscillation can drastically increase jet spreading rate and enhance large scale entrainment of the ambient fluid while suppressing fine scale mixing [11]. In reacting flows, these features were found responsible for an increased flame volume and a subsequent reduction in NO$x$ production, compared with flames supported by non-oscillating jets [16].

Despite enduring interest in jet oscillation in various research fields, its implications on combustion stability have not been fully explored. With the development of the single-nozzle FLOX® combustor mentioned above, we recently reported on the complex pattern of jet flapping and its various influence on flame structure and flame stabilization when operating at stable conditions [8]. Since FLOX® combustors typically operate at fuel-lean conditions, mechanisms controlling the lean blow-out (LBO) process are of particular interest for extending their operational limits. Operating at a specific condition where flame blow-out occurs partially and sporadically, the current work examines the relationship between jet oscillation and the LBO mechanisms in the single-nozzle FLOX® combustor. To time-resolve the transient combustion dynamics at this condition, fluctuations in the flow field as well as the scalar fields are measured using 5-kHz-rate, simultaneous stereo particle imaging velocimetry (PIV), planar laser-induced fluorescence of OH radicals (OH PLIF) and OH chemiluminescence imaging.

## 2. Experimental

### 2.1. Combustor and operating conditions

The single-nozzle, single-channel combustor consisted of three identical sections stacked on top of each other. Each of these sections was 200-mm tall, had a cross section of 50 mm by 40 mm, and was enclosed by quartz windows to provide four-way, wall-to-wall clear optical access. The bottom section is illustrated in Fig. 1a. The entire combustor chamber was mounted on a three-axis translation stage, to allow repositioning relative to the diagnostic setup. Premixed methane–air mixture was delivered through a straight stainless steel tube ($ID = 10$ mm, $L = 400$ mm) into the combustor. The nozzle had a chamfered tip, rose 20 mm from the base plate, and was offset by 10 mm along the $x$-axis from the geometric center of the combustor chamber. The off-center positioning of the jet was designed to draw analogy to the situation around a jet nozzle in an actual FLOX® combustor [5]. The coordinate system used in this work is defined in Fig. 1a.

For this study, the combustor was operated with a jet exit velocity of 63 m/s, at initial temperature of 300 K and pressure of 1 bar. Methane and air were well mixed in a static mixer three meters upstream of the jet exit. During a measurement, flame was first stabilized initially at $\phi = 0.8$. Once the combustor was thermally stable, the methane flow rate was gradually reduced to reach a stoichiometry of $\phi = 0.77$, which was close to the lean blow-out (LBO) limit of about $\phi = 0.75$. At this condition, flame becomes unstable and undergoes sporadic processes of partial blow-out and re-light.

### 2.2. 5-kHz-rate diagnostic setup

The stereo PIV system utilized a dual-cavity Nd:YAG laser (Edgewave IS-6IIDE) and a pair of CMOS cameras (LaVision HSS8) equipped with $f = 200$ mm lenses ($f$/5.6). The two cameras were coupled with Scheimpflug adaptors, suspended on opposite sides of $x$–$y$ plane of the combustor, focused down onto the same field of view (FOV). For OH PLIF, a frequency-doubled dye laser (Sirah Credo) was pumped by an Nd:YAG laser (Edgewave IS-8IIE). The laser system was tuned to the peak of $Q_1(7)$ line in the OH $A$–$X$ (1,0) band. OH fluorescence was collected into an intensified camera system (Lavision HS-IRO and HSS6 CMOS) through a UV lens (Halle, $f = 100$ mm, $f$/2.8, coupled with a 310-nm bandpass filter). The OH PLIF excitation pulse was temporally placed between the