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# Bistability of a modulated downwards oriented laminar flame

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## Abstract

We present an experimental investigation of an original configuration where the laminar flame shape bifurcates when submitted to flowrate modulations. This combustor burns a gaseous methane-air mixture injected vertically in a downward direction. The global equivalence ratio is equal to 0.91, the overall heat release of around 800 W. By increasing the frequency of the mass flow rate modulation from 70Hz to 85Hz, the flame bifurcates from an anchored flame into a lifted flame. The precise switch frequency depends on temperature and flow rates. Some forcing cases lead to bi-stable flames presenting a random transition between the two shapes for a given mass flow rate and modulation frequency. Experimental data stand on high-speed optical diagnostics processed with optical flow and orthogonal decompositions. POD-based analysis reveals different dynamics depending on the flame's average position, particularly a transverse flow motion for detached flames.

## Introduction

In recent reacting systems, the fuel's multi-injection leads to a more uniform distribution while limiting long mixing chambers. For sustainable flames, a small central pilot is used to enable easier anchoring while preventing blow-off issues. However, this double-injection system has some drawbacks as potentially several flame shapes may be encountered [1]. It is then of profound interest to understand the mechanisms for shape transition. Most of the flame transitions happen for turbulent flames that make complex the fundamental investigation of the dynamics. In the present study, we propose a laminar configuration that presents a bistable behavior similar to dynamics observed in high-power turbulent combustors. The burner's dynamic is investigated here with a two-step method. First, optical flow processing is applied to the 2D Mie scattering images to render accurate velocity fields minimizing the discrepancy compared to correlation algorithms [2]. Second, we extract the POD (Proper Orthogonal Decomposition) modes from these fields and plot the most energetics spatial modes and phase portraits in a configuration where multiple resonant frequencies stem from the harmonic excitation.

## Experimental set-up

The overall dynamic of the Incopladis burner developed at the EM2C laboratory is studied. The burner is an inverted bunsen burner type with a heat release of around 800W. The experiment consists of a downward directed injection with an internal 20mm radius. A gaseous methane-air premix is injected with a global equivalence ratio of 0.91 and a typical Reynolds number

around 1200, which corresponds to a mass flow of 0.29g/s for the air and 0.015g/s for the methane.

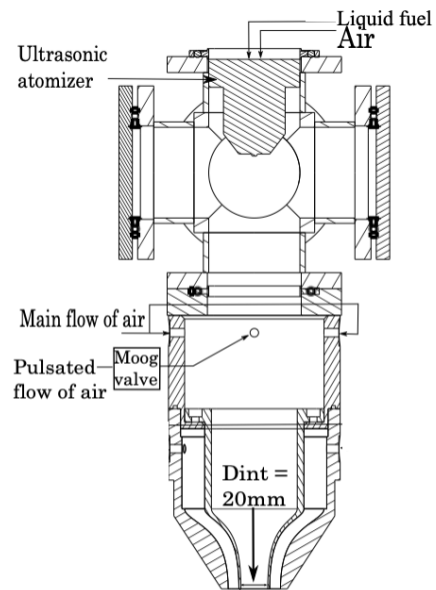


Figure 1. Inverted Bunsen burner set-up

The burner is protected from radiation with a shield and, water flow is used around the injection system to have a stable thermal condition. A servo proportional valve (*Moog*) is used to induce mass flow fluctuation by modulating the outlet with a sinusoidal signal with an offset of 5V and an amplitude of 5V. The valve is fully closed for a signal of 0V and fully opened for a signal of

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10V and has a frequency band ranging from 0Hz to 150Hz. The modulation of the air mass flow is acoustic beyond 50Hz.

This burner is equipped with several diagnostics to allow the study of its dynamics. Initially, heat release measurements are tracked with a photomultiplier tube at a sampling frequency of 10 000Hz. Subsequently, a continuous laser is used to measure the instantaneous velocity fields of fresh gases with oil particles injected into the flow. The oil droplets have a typical size below 2 $\mu$ m, leading to a small Stokes number. The flow velocities are measured using 2D Mie scattering images for a forcing modulation rate of 70Hz and 85Hz. A high-speed camera takes the images at a rate of 10000Hz. The camera has a resolution of 896x848 pixel, and images are acquired at 90° from the laser sheet.

This study focuses on the flame responses characterization to a flow modulated with a sinusoidal excitation. An optical flow algorithm (derived from [3]) is used to extract the velocity from 2D Mie scattering images. Furthermore, velocity fields are post-processed using Proper Orthogonal Decomposition (POD).

## Results

The lean premixed laminar flame operates first in a stationary regime then harmonic flow modulations induce a dynamic response. We want to show here that the flame's response at 70 and 85 Hz is drastically different and that in between these two frequencies, the flame features a bistable dynamic.

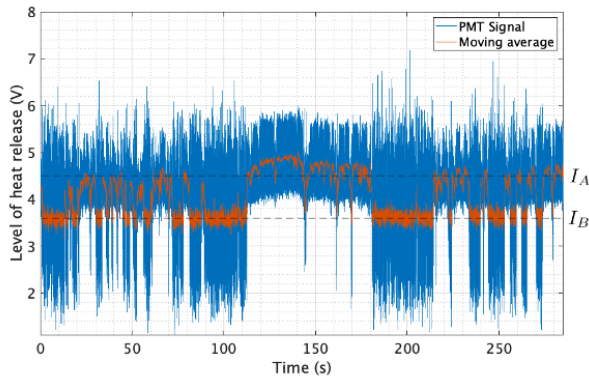


Figure 2. Photo-multiplier signal recorded during a five-minute long sequence (blue). The moving average (red) shows the alternation of the flame emission intensity while the modulation frequency remains constant.

Indeed, by modulating the mass flow rate with frequencies between 70 and 85 Hz, the flame spontaneously alternates between two steady states A and B. This alternation occurs without external forcing or modification of any parameter of the experiment. The temporal evolution of the flame luminescence, recorded by the photo-multiplier (Figure 2), shows intermittent switches between two average values  $I_A$  and  $I_B$ . Each

state is reached several times during a sequence and can last several tens of seconds. The sequence presented here lasts 3 minutes; the moving average of this signal is plotted in red.

The signal's PDF confirms that the flame emission is mainly distributed on one set or the other. The flame alternates between two combustion configurations, the choice between these two states is not controlled by an experimental parameter, the transition from one state to the other is spontaneous. The residence times on each plateau are long enough to observe the average flame shape and measure the average velocity field associated with these two situations. We do not bring here elements explaining the origin of these spontaneous transitions, but we wish to take the time to describe the two possible states for these flames. These two states differ in terms of average velocity fields in the vicinity of the flame and the dynamics of flame response.

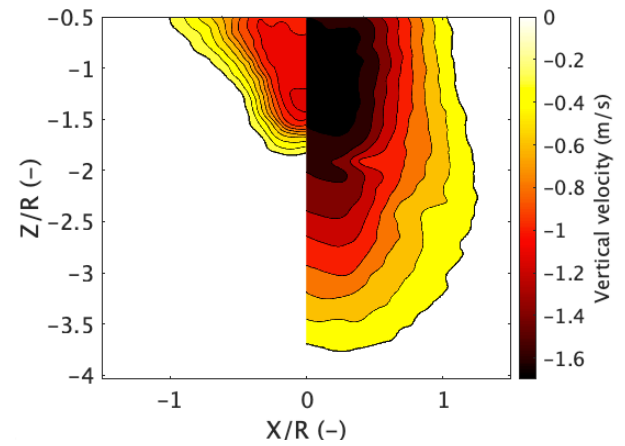


Figure 3. Vertical velocity fields for a forcing frequency of 70Hz (left section: state A) and 85Hz (right section: state B)

State A corresponds to the flame observed when modulated at 70 Hz, it features a compact flame anchored to the lips of the injector, and the average velocity field is similar to that observed around a circular laminar burner, its average shape is conical as shown in the left part in Figure 3. State B corresponds to the flame observed when modulated at 85 Hz, the flame is lifted with a fresh gas area extended downstream (right part in Figure 3). The shape of the flame is open, and the baseline is flat. This configuration is original insofar as the flow remains laminar and not swirling.

When modulated at frequency equals to 70 Hz, the flame's dynamic response looks consistent with what the literature reports for laminar flames [4]. The laminar flame is anchored to the burner lips, and the flow

modulation gives rise to vortices in the injection plane that are convected by the flow, then deform the flame front periodically. When modulated at 85 Hz, the flame looks different. To observe the flame's response in both states, the velocity field is decomposed into orthogonal modes (POD). In both situations, five modes contain most of the kinetic energy. The spectra and spatial distributions of these five modes for the two flame states are presented in Figure 5, Figure 7 and Figure 8.

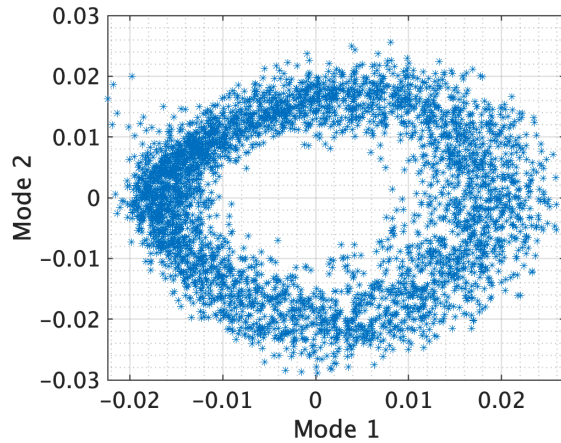


Figure 4. Phase Portrait of the POD mode 1 and 2 for a forcing modulation frequency of 70Hz (state A)

At 70Hz (state A), the spectra of modes 1 and 2 contain a single frequency, corresponding to the flame's response at the modulation frequency. The phase portrait of these two modes (Figure 4) shows that they are coherent in phase quadrature. They correspond to the propagation of the vortices created at the injector lips.

At 85 Hz (state B), modes 2 and 3 correspond to the same dynamics. Their spectra also show only the excitation frequency. Their phase portrait (Figure 6) shows the coherence and phase shift corresponding to the propagation along the vortices' flame front, as witnessed previously.

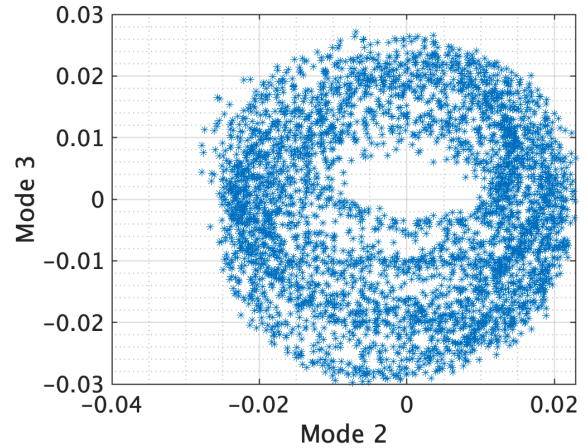


Figure 6. Phase Portrait of the POD mode 2 and 3 for a forcing modulation frequency of 85Hz (state B)

Concerning the other orthogonal modes, the 70 Hz modulation shows a non-identified stationary mode 3 while modes 4 and 5 spectra feature a single peak at twice the excitation frequency. The phase shift and coherence of these latter two modes indicate that this frequency doubling corresponds to half-size vortices propagating along the flame front (Figure 5, top line), as shown by these modes' spatial velocity distribution.

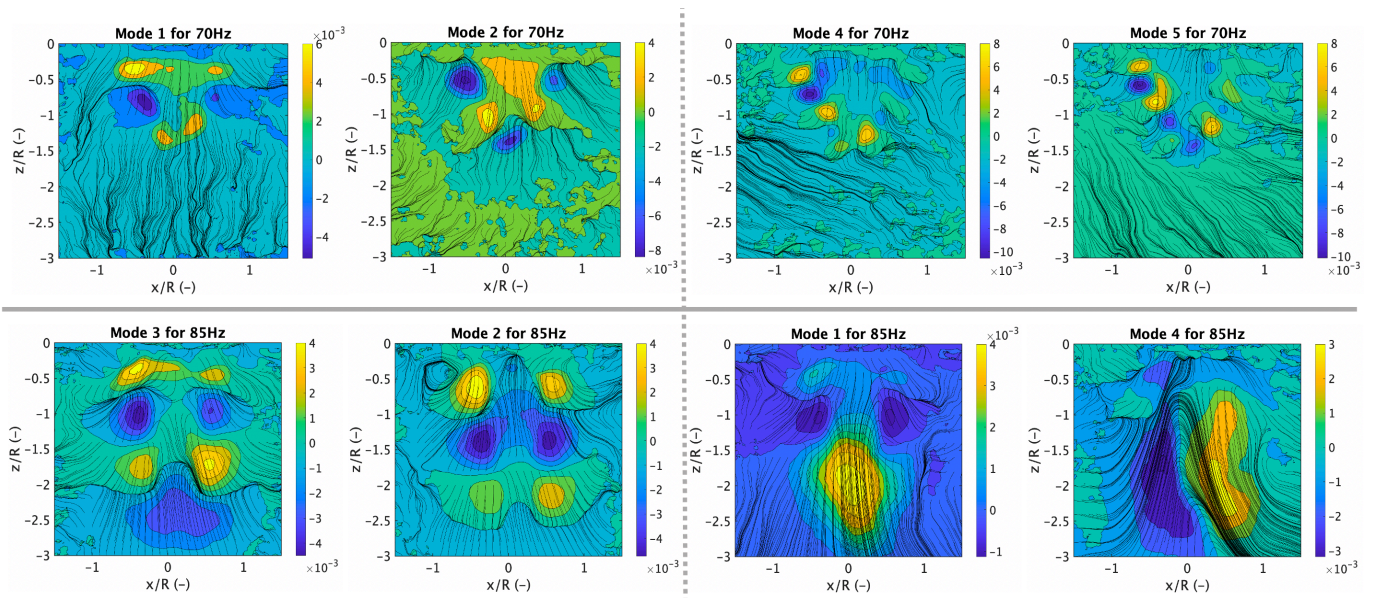


Figure 5. POD modes of the vertical velocity superposed with the streamline associated with the mode. First row: state A (modulation frequency of 70Hz). Second row: state B (modulation frequency of 85Hz)



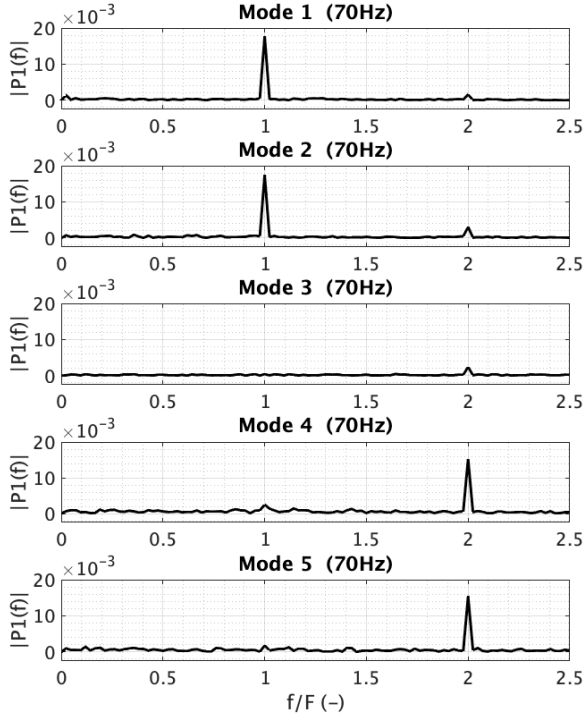


Figure 7. Power density spectrum of the first five most energetic POD modes for a forcing modulation frequency of 70Hz (state A)

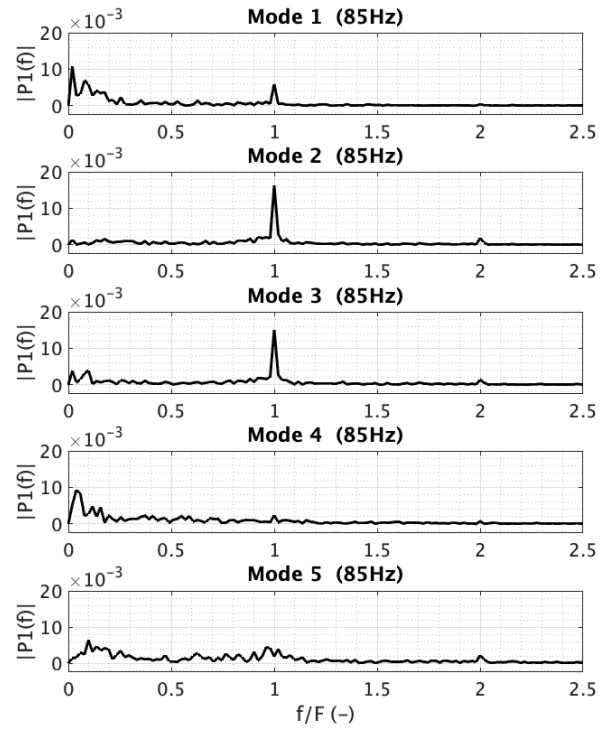


Figure 8. Power density spectrum of the first five most energetic POD modes for a forcing modulation frequency of 85Hz (state B)

Modes 1 and 4 observed during modulation at 85Hz are original in this configuration. These two modes have a denser and broader spectrum at low frequencies (Figure 8) but are not coherent with each other. They do not have a defined periodicity related to the modulation frequency. The spatial velocity distribution corresponding to these modes shows that they correspond to transverse movements (Figure 5, bottom line).

To understand the mode 1, we map the mode that reveals an asymmetry in the flow generating large diameter recirculations. This mode moves the flow transversely at low frequencies. Mode 4 shows an axial shear layer inducing a sinuous mode where the fluid is alternately deviated transversely. These transverse phenomena occur at a range of frequencies ten times smaller than the excitation frequency; they appear when the flame is detached (state B).

## Discussion

Velocity fields measured in the vicinity of a premixed laminar flame and spontaneous emission show that mono-frequency modulation can induce two stable states. In the first state, the flame is attached, its emission intensity fluctuates like the modulation. In the second state, the flame is detached and elongated, and two dynamics are superimposed: the first at the frequency of the excitation deforms the flame front, the second at a lower frequency generates sinuous modes keeping the flame lifted and causing the flame to oscillate.

For a given frequency range, the two states can be obtained alternately without any external control and without observing any apparent periodicity. Modulation of the mass flow rate appears to induce secondary instability at a lower frequency sufficiently intense to alter the average flame state and cause the flow to oscillate in the transverse direction.

## Conclusions

Several recent studies have reported the existence of bi-stable swirled turbulent burners, i.e., burners with two modes of flame stabilization that can be achieved either by variation of an experimental parameter (staging, flow rate, equivalence ratio, and so) often presenting a hysteresis phenomenon or by spontaneous alternation depending on the dynamics of the system. This study

shows that such a bi-stable system can appear in a pulsed laminar configuration where the Bunsen-like burner is oriented downwards. A lean methane/air flame is submitted to a flow modulation in a frequency range from 70 to 85 Hz. For a given frequency and during the same sequence, the flame alternately exhibits two different responses characterized by distinct average positions and dynamics. The study presented here relies on the velocity fields obtained by optical flow, the orthogonal mode processing of these fields, and the flame's spontaneous emission to describe the two states reached by the flame over time. The frequency and spatial dynamics are very different between the two states, confirming two stable states' presence reached alternately without evident periodicity. Obtaining a bistable regime in an elementary laminar configuration is the originality that makes it possible to perform accurate experimental measurements and modeling of these situations frequently encountered in more complex burners to understand the transitions.

### Acknowledgements

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