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Bistable behaviour and thermo-acoustic instability triggering in a gas turbine model combustor

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Abstract

In a liquid-fueled two-stage gas turbine model combustor, a bistable point where two different flame states can exist is studied in non-reacting and reacting conditions with the help of fast spray-PIV and chemiluminescence imaging. The first flame, named *sV*, is stabilized thanks to an internal reaction zone that modifies the air flow compared to non-reacting conditions. The second state, associated with a *lifted* flame, exhibits a strong thermo-acoustic instability linked to the quarter-wave mode of the chamber and piloted by a varying liquid-fuel supply to the flame. Using well-controlled air flow rate modulations, the switch from the quiet *sV* state to the *lifted* one is studied in a time-resolved fashion. The analysis shows that the sensitivity of the internal reaction zone of the *sV* state to perturbations is responsible for the change in flame shape which then triggers the onset of the thermo-acoustic instability.

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Keywords: Flame dynamics; Bifurcation; Liquid fuel; Staging control; Precessing vortex core

1. Introduction

Lean Premixed Prevaporized (LPP) combustion is an interesting candidate to replace diffusion flames in aeronautical gas turbines in order to reduce pollutant emissions. By supplying a relatively uniform lean mixture of fuel and air, the goal is to reduce flame temperature and thus the creation of thermal NOx. Such regimes are however often faced with stability issues such as uncontrolled dynamics, flashback or blowout [1,2]. In particular, thermo-acoustic instabilities can occur from the coupling between acoustic oscillations and heat release [3]. Staged injectors can help tackle this issue by injecting a small amount of fuel upstream to create a piloting region that stabilizes the system. They can be associated with a multipoint injection device for the main stage in order to promote a fast and efficient mixing and thus get closer to LPP requirements for most of the power generation. The dynamics of multipoint staged injector as well as the effects of staging remain yet to be fully understood. Indeed, numerical simulations [4] as well as experimental studies [5] show that the flame shape and behaviour can be highly dependent

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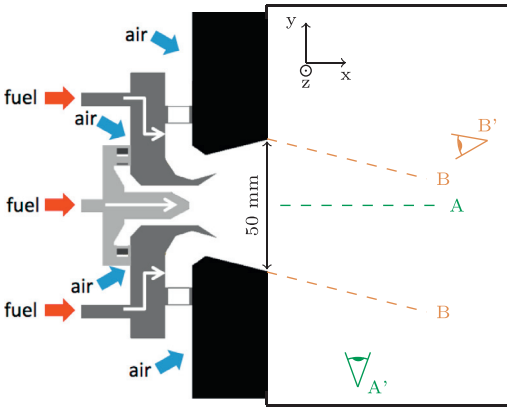

Fig. 1. Top view of the injection device positioned at the entrance of the combustion chamber, showing the two injection stages (pilot: light gray, take-off: dark gray). A laser sheet (A) illuminates the (x,z) plane in the center of the chamber to allow the observation (A') of the fuel droplets Mie scattering signal. An expanded laser beam (B) is sent in the injector hole to visualize (B') the fuel spray near the pilot fuel nozzle.

on the burner history and on potential external perturbations.

The purpose of this paper is to complete the study performed in Renaud et al. [6], which showed a naturally occurring transition between two states. For a fixed staging operating point that shows a bistable behaviour with completely different flame and air flow structures, stabilization mechanisms are presented and an artificially triggered transition from one state to the other is described.

2. Experimental setup and diagnostics

2.1. Experimental setup

The BIMER experimental device [6] revolves around a model of an industrial staged injector placed in a plenum before a 500 mm-long optically-accessible water-cooled combustion chamber with a square section (150 mm). The chosen fuel is dodecane and, to enhance vaporization, air flows through an electric preheater (Sylvania SureHeat Max) before entering the plenum. Details of the injector can be seen on the horizontal cut shown in Fig. 1.

The injector is composed of two stages each including its own air swirler and fuel injection. Both swirlers are co-rotating and the air flow, regulated by a mass flow controller (Bronkhorst In-Flow), is divided between the stages by the fixed geometrical design of the injector.

The upstream stage, called the pilot stage (light gray in Fig. 1), allows 13.5% of the air mass to flow through and is equipped with an 18-vane swirler with a geometrical swirl number close to 0.6. The fuel injection is made with a pressurized nozzle (MMP 6390-0-0-03) that creates a hollow cone of droplets. The take-off stage (downstream, dark gray), allows 86.5% of the air to flow through its 20-vane swirler with a geometrical swirl number around 1. The liquid fuel is injected through a multipoint device made by ten 0.3 mm holes placed in the cross flow of every other swirler vane to ensure proper atomization. A staging parameter is defined to characterize the fuel distribution in the injector. It corresponds to the ratio between the amount of fuel injected through the pilot stage and the total amount of fuel.

In order to perform controlled air flow rate modulations, a siren-like device (CBOne, Graz, Austria) is placed before the plenum. It works by rotating a toothed wheel in front of a nozzle through which the air flows. The rotational speed of the wheel controls the modulation frequency. The amplitude of the fluctuations are independently modified by changing the relative positions of the wheel and the nozzle. A thorough description of the system can be found in Giuliani et al. [7].

In this study, the chosen operating point corresponds to an air flow rate of 43 g/s (preheated at 433K) and a global equivalence ratio of 0.6. The thermal power generated by the combustion is around 72 kW. A similar operating point is presented in Renaud et al. [6] but, in the present case, the staging parameter is fixed at 15%, meaning that 15% of the fuel is injected through the pilot nozzle and the remaining 85% through the multipoint device. This take-off oriented injection represents the expected operation of a staged multipoint injector when high power with low pollutant emissions is needed.

2.2. Diagnostics

The fuel spray inside the chamber can be observed thanks to the Mie scattering signal of the droplets crossing a laser sheet. The associated setup is schematically shown as (A-A') in Fig. 1. The 1 mm thick light sheet is generated by two Nd:YAG lasers working at 10 kHz each with a delay of 20 μs between them. A high-speed camera (Photron Fastcam SA-5) equipped with a 50 mm, f:1.4 lens (Nikon) and a 532(± 10) nm filter records the light scattered by the droplets. The 704 × 520 pixels sensor size enables the recording of an equivalent 176 × 130 mm region. Each recording can last up to 1.56s, leading to 31,274 recorded images.

Thanks to the tunable delay between the lasers, it is possible to perform a Particle Image Velocimetry (PIV) processing on two consecutive fuel spray images. Because the Mie scattering signal from the droplets is used, the seeding is highly non-uniform and the resulting velocity field does not necessarily represents the underlying air flow. In the present study, the images are treated with the open source

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