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Stability analysis of a swirl spray combustor based on flame describing function

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Abstract

Self-sustained combustion oscillations observed at limit cycles in a swirl combustor equipped with a series of steam assisted liquid fuel injectors are analyzed with the flame describing function (FDF) framework. It is first shown that for globally fuel lean injection conditions, the spray flames investigated burn in a non-premixed mode. A non-sooty and a sooty regime are explored. Their frequency response to acoustic forcing is characterized by exploiting the OH^* chemiluminescence signal and a velocity signal measured by Laser Doppler velocimetry at the air injection unit outlet. It is found that the FDF of these non-premixed swirl spray flames features a distinct response compared to the FDF of lean premixed swirl flames. The gain and phase lag of these FDF are both a strong function of the perturbation amplitude. At a fixed forcing frequency, the FDF phase lag increases with the perturbation level for the non-sooty flame investigated and it decreases for the sooty flame case. The sooty flame has also a much lower cut-off frequency for the FDF gain than the non-sooty flame. It is then shown that these features are essential to reproduce the correct instability bands and oscillation frequencies observed at limit cycles in the experiments. For the sooty flame, combustion is always found stable in agreement with the low cut-off frequency found for the FDF. A linear analysis for the non-sooty flame fails to capture the low frequency instabilities observed in the experiments that have the largest oscillation levels. Only the use of the FDF yields the correct dynamical states observed in the combustor. It is further concluded that the OH^* chemiluminescence signal may safely be used to infer the frequency response of these non-premixed swirl spray flames at globally fuel lean injection conditions.

Keywords: Thermo-acoustic instabilities; Flame describing function; Nonlinear flame dynamics; Spray flame; Swirled flame

1. Introduction

Like those operated with gaseous fuels, combustors fed by liquid fuels are prone to combustion instabilities triggered by the dynamics of the fuel [1–3] or air [1,4,5] supply lines. To determine the

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stability margins of these non-premixed systems, it is useful to characterize the flame frequency response to external flow perturbations.

Analysis of the acoustic response of swirl spray flames remain relatively scarce. The first objective of this study is to complete these data over a broad range of excitation frequencies and amplitudes to reveal the main features of their frequency response to flow perturbations. The second one is to conduct a stability analysis and compare predictions with measurements made during self-sustained oscillations at limit cycles in a generic combustor. This allows to examine if tools developed for perfectly premixed systems can safely be used to infer the thermo-acoustic state of combustors operated with non-premixed spray flames.

In many studies of the dynamics of spray flames, the analysis is restricted to the examination of the limit cycle of a self-sustained oscillation taking place in the combustion chamber where pressure and OH^* or CH^* flame chemiluminescence measurements are correlated with the spray dynamics during the instability [3,5,6]. Characterizations of the response of swirl spray flames to liquid fuel flowrate modulations were realized in a few laboratory scale experiments [1,2,7]. Yi and Santavicca [2] found that the frequency response of their flame is sensitive to air mass flowrate, equivalence ratio and air preheat temperature variations, but it is invariant to fuel modulation amplitude. For liquid fuel injectors featuring a large pressure drop, thermo-acoustic oscillations result from a resonant coupling with the air feeding lines. Analysis of the response of swirl spray flames to air flowrate modulations are generally limited to a few specific forcing frequencies with a fixed amplitude [1,4,8]. It was demonstrated that the oscillation of the air flow leads to droplet clustering [1,7,9] and equivalence ratio fluctuations [6]. The frequency response of swirl spray flames submitted to air flow rate modulations was however not characterized yet over a broad frequency range.

Effects of excitation amplitude of the air flow rate are rarely considered for spray flames, it is then interesting to examine the main features of the frequency response of non-fully premixed flames fed by gaseous fuels to flow oscillations. Hield and Brear [10] found that the time lag between pressure and heat release rate oscillations is a strong function of the root-mean-square value of the acoustic velocity fluctuations during unstable operation of their non-premixed combustor. In an analysis of the response of fuel stratified lean-premixed swirl flames submitted to acoustic excitations, Kim and Hochgreb [11] found that the phase lag between heat release rate and velocity disturbances is a strong function of the fuel stratification and perturbation amplitude. The same type of features are observed for swirl flames submitted to equivalence ratio fluctuations [12]. It is then worth examining

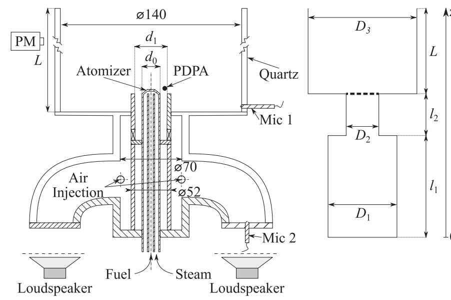

Fig. 1. Schematic of the main elements of the multiphase flow burner.

the response of spray flames to flow modulations at different input levels.

In this study, self-sustained combustion oscillations observed at limit cycles in a combustor with swirl-stabilized spray flames are analyzed with the help of the flame describing function (FDF) [13]. The experimental setup is presented in Section 2. The structure of the swirl-stabilized spray flames investigated is presented in Section 3. Self-sustained oscillations observed at limit cycles when the combustion chamber length is varied are examined in Section 4. The combustor acoustic response is determined in Section 5 and the FDF of two different flames are analyzed in Section 6. These data are combined in Section 7 to infer the system stability and compare results with experiments.

2. Experimental setup

The combustor is sketched in Fig. 1. It comprises a plenum, two loudspeakers (Monacor Number one, SPH-135/AD, 60w) which can be replaced by two rigid plates, a central cylindrical bluff body where a generic internal twin-fluid atomizer is installed [14], a radial swirler in the annular gap of the air injector and a cylindrical flame tube. This simplified configuration is used to stabilize spray flames in a swirl flow. Experiments are conducted at Reynolds numbers $Re = U_b d_0/\nu_a = 6500$ to 9000, where U_b is the bulk flow velocity in the annular air injection channel of internal diameter $d_0 = 30$ mm and external diameter $d_1 = 40$ mm, and ν_a is the air viscosity at temperature T_a. A preheated air flow is delivered to the plenum with a maximum mass flow rate $\dot{m}_a = 200$ N L min^{-1} regulated by a thermal mass flow controller at a temperature $T_a = 443$ K. The rotation of the air flow is generated by a radial swirler with a swirl number $S = 0.92$ that was measured at the burner outlet [15]. The combustion chamber is made of quartz allowing visualization of the flames in the near ultraviolet and visible ranges. It has a 140 mm internal diameter and a length $L = 0.50$ m. The