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Response of non-premixed swirl-stabilized flames to acoustic excitation and jet in cross-flow perturbations

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ABSTRACT

An investigation into the response of non-premixed swirl-stabilized flames to acoustic excitation and jet in cross-flow (JICF) perturbations was carried out. The fluctuations of OH* chemiluminescence emission measured simultaneously with the pressure were used to determine flame describing function (FDF). It could be seen that the three specific conditions exhibited stronger heat release oscillations coupled with pressure fluctuations under acoustic forcing and JICF perturbations, which were expressed by the in-phase delay and positive flame response indices originated from Rayleigh criterion to conduct the stability analysis. Low acoustic excitation amplitude triggered more significant response in the flame heat release rate than high acoustic excitation amplitude at the particular forcing frequency, indicating that nonlinear saturation characteristic of the FDF is also emphasized in JICF. Poincaré map was adopted to analyze the lock-in amplitudes of the dynamics system and JICF effects on combustion instabilities under acoustic forcing frequencies nearby/far from the natural frequency. It was found that lock-in occurred more easily when the forcing frequency was greater than the natural frequency, showing that JICF did not affect the system dynamics due to their little impact on the vortex/flame interactions in this work studied.

1. Introduction

In combustion engines, especially gas turbines, increasingly stringent pollutant emission regulations lead to lean premixed technological choices, which are susceptible to combustion instabilities and most harmful when the coupling of the heat release and acoustic pressure fluctuations in the chamber is achieved. A number of studies have been carried out to identify the various effects responsible for governing combustion oscillations, with special focus on turbulent swirled lean premixed flames [1–7] but less concerned with non-premixed flames applied to power station boilers. Various flame configurations including bluff body stabilized and swirling types of structures applied to premixed and non-premixed combustion can improve mixing and flame stabilization. However, their ability to form vortex-type recirculation zone has been the important motivation on thermoacoustic instabilities.

For non-premixed flames, several different studies have focused on flame stabilization and thermoacoustic instabilities as well as acoustic excitations upstream and downstream of the combustion chamber. Different fuel injection ways and premixing degrees on non-premixed flames imposed oscillations were varied to study nonlinear flame response by Hardalupas [8] and Kypraiou [9]. Kim et al. [10] performed the study on the flame characteristics of turbulent non-premixed flames using acoustic forced coaxial air with the resonant frequency chosen, and found the flame-vortex interaction on the effect of reducing flame length and NOx emission. Kang et al. [11] carried out the measurements of fuel/air mixing under acoustic oscillations for non-premixed jet flame and described that buoyancy was a key coupling mechanism in the flow field. The swirl intensities and fuel flow rates variation of non-premixed swirling flames related to acoustic perturbations were reported by Idahosa et al. [12] with chemiluminescence emission and velocity flow field analysis. They observed some criteria to assess the potential for a strong flame response, especially for the highly responsive modes. A representative burner geometry by Al-Abdeli et al. [13,14] was used to make the research on fuel mixtures, flow structure and flame radicals with two-stage coaxial air, and fuel staging was applied to the swirl stabilized liquid fueled burner to study flame shape transition [15,16]. Santhosh and Basu [17] established the transitions and blowoff analysis on unconfined non-premixed swirling flame by changing the swirl intensity by the time-averaged flame topology analysis. The flow characteristics of a diffusion flame under non-resonant forcing

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frequencies were carried out by Zhang [18] to investigate flame/acoustic interaction between the buoyancy driven instability and acoustic disturbance. As for the liquid spray flame in non-premixed combustion, the stability analysis of acoustic excitations and self-excited oscillations was conducted using flame describing function [19] and spray transfer function [20] by chemiluminescence measurement, Phase Doppler Particle Analyser (PDPA) system and Mie scattering technique. Other researchers studied non-premixed flames by using large eddy simulations on gaseous and spray combustion [21,22].

These studies above are fundamental mechanisms for thermoacoustic instabilities in non-premixed combustion. Controlling thermoacoustic instability is useful for our industry and life. Generally, active and passive controls are two strategies adopted to control instabilities in combustion systems. In the process of a combustion system, a certain change associated with passive control methods was established to eliminate the possibility of thermoacoustic instability, such as modulation of swirl intensities to decouple the flame-vortex interactions [12], changing the position of the swirl generator [2], varying the plenum and combustion chamber lengths [3], utilizing perforated plates to form strong damping of the combustion instabilities [1]. For the design of the combustion systems, active control methods were employed to optimize the combustion stabilities, for example, adjusting combustion equivalence ratio and combustor pressure [23], changing oxygen concentrations in ambient gas [24], imposing longitudinal and transverse flow perturbations [4,25], programming acoustic feedback algorithm [26]. Most active control methods are controlling the thermoacoustic instabilities by changing fuel and air mixtures [27]. Jets in cross-flow (JICF) find application in many combustion systems due to their rapid mixing characteristics and turbulent vorticity controlling, as well as film cooling, dilution air jets, which was well reviewed by Karagozian [28]. However, most jet in cross-flow studies in the past were limited to flow motions and vortex structure of non-reacting flows experimentally and numerically [29–32], and there are also fewer studies on reacting flows. Significantly, JICF reacting flows have the important feature of vorticity motions interacting with combusting flames in jet flow penetration and mixing process, which brings a significant influence on flame stabilization and thermoacoustic instabilities. To our knowledge, the nature of thermoacoustic instabilities controlled by the interaction between complex transverse jet flows and swirl-stabilized non-premixed flames has rarely been studied. Mcmanus [33] performed periodic flow excitation on lean premixed combustion zone to reduce the pressure fluctuation. They thought the forcing location and excitation frequency and amplitude were important parameters in effective combustion control. Active combustion control using secondary fuel injection was investigated by Yu et al. [34,35] to suppress vortex-driven combustion instabilities in premixed combustion. Both injections into the shear layer and into the recirculation zone were compared, including open-loop and closed-loop controllers. It was determined that the shear layer injection approach was preferable over the recirculation injection approach due to cleaner emission characteristics. Ghoniem et al. [36,37] studied premixed combustion instabilities on a backward-facing step combustor. Different injections in microjet injectors or from a small slot were adopted to suppressing thermoacoustic instabilities driven by flame-vortex interaction mechanism near the step. The equivalence, the inlet temperature and fuel composition were also concerned. For swirl-stabilized combustor, they conducted instability suppressing using microjet air injection by varying relative senses of swirl with respect to the main flow. It was observed that injecting air into the inner recirculation zone via counter-swirling radial microjets was effective to reduce combustion instabilities [38]. Lee gave the similar research on active control by varying three fuel injection locations [39]. It was different that Fugger et al. provided a premixed air-natural gas jet into acoustically oscillating lean premixed crossflow. The comparison of both fuel-lean and fuel-rich jets on combustion response was studied [40]. There were also some researches on combustion instability control on rocket combustor by secondary oxidizer injection [41,42]. Deshmukh and Sharma [43] conducted the experiment of the suppression of thermoacoustic instability using multiple air radial injection in horizontal Rijke combustor, the control technique of radial micro jets was found to completely suppress the thermoacoustic instabilities in a range of jet velocities depending on the burner position and the total air mass flow rate. Besides, our previous studies [44,45] proposed CO_2 and N_2 jet methods and controlled thermoacoustic instability by the analysis of the pressure amplitudes, temperature distributions and flue gas components in non-premixed swirling combustion. As the previous literature review shows, less work has been done on describing the interacting mechanism between jets in cross-flow and combustion instabilities in non-premixed swirl combustion.

In this paper, acoustic excitation including acoustic frequencies and amplitudes imposed on the swirl-stabilized flames are studied in non-premixed combustor, associated with jets in cross-flow controlling thermoacoustic instabilities. The flame response to velocity perturbation characterized by flame transfer functions is investigated using pressure and heat release fluctuations. Phase-delay analysis and the flame response index defined are employed to evaluate the coupling of the heat release and acoustic pressure fluctuations. The topology of reconstructed state space of Poincaré maps indicating the dynamics of the system are also adopted to conduct the stability analysis. The experimental setup and measurement technologies are described in Section 2. Experimental results and discussions for the flame response of acoustic excitation and jet in cross-flow perturbations are the subject of Section 3.

2. Experiments and diagnostics

In this work, the combustor is operated at atmospheric pressure with non-premixed propane and air as shown in Fig. 1, both metered with mass flow controllers (Alicat MC series, 0.2% FS). The combustion chamber has a square cross-section of $120 \times 120\ \text{mm}^2$ and a height of 840 mm. The plenum is 460 mm long and consists of three concentric tubes (inner diameters: 6, 14 mm and 34 mm from the center), which serve as central fuel tube, primary air tube and secondary air of direct flow or swirl flow tube, respectively. The secondary swirl air is split into three streams with 15° slopes arranged in the circumferential direction as a swirl generator. Nitrogen was selected as the JICF with the nozzle (inner diameter 5 mm) located 20 mm above the bottom of the chamber plane. The downstream ends of both central tube and primary air tube stretch 10 mm out of the chamber plane. Optical access to the chamber $250 \times 100\ \text{mm}^2$ is provided by quartz glass embedded on three stainless steel side walls. In this experiment, secondary non-swirl air was closed. The central fuel flames were surrounded by primary air having velocity less than 1 m/s, which was low and would not affect flame characteristics but sustain flame-stability compared to the secondary swirl air flow rate.

Pressure signals from the combustion chamber were recorded in order to determine the gas flow pulsation frequency. The pressure pulsation was measured using high frequency dynamic pressure transducers flush-mounted on the stainless steel wall. The pressure signal p1(t) was acquired from the center of the combustion chamber at the height of $x = 50$ mm, while p2(t) was captured from inlet pipeline of secondary swirl air at the height of $x = -50$ mm, adjacent to the pressure signal p3(t) by the distance of 25 mm. The acoustic velocity fluctuation was calculated using