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Effect of pressure variation on acoustically perturbed swirling flames

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Abstract

The current study aims to experimentally examine the effect of pressure variation on lean premixed low swirl flames, which were perturbed acoustically with three frequencies (61 Hz, 86 Hz, and 115 Hz). In the experiment, the hydroxyl (OH) chemiluminescence captured with a photomultiplier (PMT) indicated the global heat release. Furthermore, the phase-averaged flame surface density (FSD), which was calculated from the images of planar laser-induced fluorescence of the OH radical (OH-PLIF), was used to examine the local flame behavior. Global, local, and flame dynamics analyses were then used to investigate the flame oscillation. Results showed that when the perturbation level was sufficiently high, the fundamental oscillation tended to be amplified by the elevated pressure in the cases with perturbation frequencies of 61 Hz and 115 Hz. In contrast, in the cases with a frequency of 86 Hz, the fundamental oscillation was inhibited when the chamber pressure was elevated to 0.3 MPa. Analysis of flame dynamics and local flame response then showed that the effect of the pressure was affected by the phase delay between the pressure and the heat release oscillations. This was in turn dictated by the flame rollup process. Based on these analyses, it can be found that the general flame responses at different pressures showed similar trends when the perturbation frequency was the same. When the perturbation level and the pressure were sufficiently high, the fundamental mode oscillation was intensified by the elevated pressure when the heat release oscillation was in phase with the pressure fluctuation; otherwise, the fundamental oscillation tended to be inhibited. Moreover, both the strength and the distribution of the local heat release oscillations were affected by the elevated pressure.

Keywords: Elevated pressure; OH-PLIF; Flame surface density; Flame rollup; Lean premixed

1. Introduction

Lean premixed combustion is a technique that is used to inhibit NO_x emission by decreasing the combustion temperature. However, lean premixed flames tend to be more sensitive to pressure oscillations, which can lead to combustion instability [1]. When heat release and pressure oscillations couple together, thermoacoustic instability can result and

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cause unstable operating conditions or even device failure [2]. In real energy systems, the pressure is usually elevated. Therefore, understanding of the effect of the elevated pressure on flame behaviors is very important. However, the work examining changes to thermoacoustic instability as the pressure is elevated is still very limited [3–6]. This necessitates the need for further studies.

Investigations of the global and local heat release oscillations are useful in understanding thermoacoustic features. The global heat release oscillation is important in indicating the oscillation trend. Meanwhile, the local heat release oscillation is critical in understanding the global trend. This is most important for turbulent premixed flames, whose heat release shows notable spatial variation because of the highly deformed flame shape [7,8]. Moreover, the heat release oscillation associated with the flame shape deformation is a common mechanism for thermoacoustic instability [9,10]. Therefore, when examining the thermoacoustic instability, it is necessary to consider both global and local flame oscillation information, which includes flame shape, global and local heat release oscillation amplitudes, and global and local phases.

The CH* or OH* chemiluminescence is widely used as an indicator of the global heat release [7,11]. The amplitude and phase of the global heat release oscillation are then extracted from the chemiluminescence signal to analyze the instability behavior. To capture the local flame structure, planar laser-induced fluorescence of the OH radical method (OH-PLIF) is often employed [12]. However, the intensity of OH fluorescence cannot be directly used to represent the local heat release rate because of its long-life characteristic [13]. Instead, the local mean heat release rate can be qualitatively indicated with the flame surface density (FSD), which can be calculated from OH-PLIF images under both the atmospheric and elevated pressure conditions [4]. This method has been verified with chemiluminescence and direct local heat release imaging (simultaneous OH and CH_2O PLIF) measurements [3,7]. Another advantage of using FSD is that the mean flame shape can also be examined [7].

The current study focuses on the examination of the effect of pressure variation on the thermoacoustic features of a low swirl flame, which was artificially excited by the acoustic perturbation with different frequencies. Global and local analyses were applied to understand the behavior of the flame.

2. Experiment setup and analysis method

The schematic of the experimental system is shown in Fig. 1. The high pressure acoustic chamber, with the capacity of 1 MPa, comprises a vertical and a horizontal component. A low swirl burner (LSB), with an inner diameter of 25.4 mm and a swirl number of approximately 0.5, is used in the current experiment. The low swirl burner is mounted to the bottom of the vertical chamber that has an inner-diameter of 300 mm and a height of 1850 mm.

Air flow is controlled by a Hastings flow meter/controller with an accuracy of 0.2% of full scale plus 0.5% of reading values. Fuel (methane) flow is controlled by a Hastings controller with the same accuracy as the air flow controller. The chamber pressure can be adjusted by three electronic adjustable valves that are located at the downstream of the chamber. The acoustic perturbation system contains a signal generator, a 2000 W amplifier, and four loudspeakers. These four loudspeakers, which supply in-phase acoustic perturbation with a power up to 480 W in the range of 30–275 Hz, are installed in the horizontal part of the chamber. The acoustic perturbation is provided from the downstream of the burner such that the spatial variation of the pressure oscillation near the burner is small and can be neglected. A high-resolution piezoelectric pressure sensor (PCB 106B) with a sampling rate of 20 kHz is used to capture the pressure signal near the burner. The pressure sensor is installed in the chamber wall, 127 mm above the plate where the LSB is mounted. The global heat release rate is indicated with the OH* chemiluminescence, which is captured with a sampling rate of 20 kHz by a photomultiplier (Hamamatsu H8249-101) equipped with a bandpass ultraviolet (UV) filter (308 ± 10 nm).

In the PLIF system, a 10 Hz Nd:YAG laser (Continuum Powerlite 9010) is used to supply a 532 nm beam, which pumps a dye laser (Continuum ND6000) to change the wavelength of the beam to 564 nm. The beam frequency is then doubled to generate a 282 nm UV beam that is used for exciting A-X(1, 0) band of the OH radical. The intensity of the UV beam is approximately 30 mJ per pulse. An ICCD camera (Princeton Instruments) with a LEO (Lattice Eletro Optics) band pass filter (312.6F10-10) is utilized to capture the OH-PLIF images. In the current experiment, the ICCD camera captured images in an 8 cm × 8 cm region with a resolution of 512 × 512 pixels.

The tests were done with four different pressures, 0.1 MPa, 0.2 MPa, 0.3 MPa, and 0.4 MPa. In all cases, the bulk velocity and the equivalence ratio were kept at 3 m/s and 0.7, respectively. The velocity and equivalence ratio were chosen to ensure that the flame was stable under different test conditions, while avoiding overheating the loudspeakers that face the inside of the chamber. The forcing amplitude (P_A/P_c) was calculated by normalizing the amplitude of the pressure fluctuation (P_A) with the chamber pressure (P_c). Limited by the maximum power of the loudspeaker, the maximum normalized forcing amplitude decreases with increasing chamber pressure in most of the cases.