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Combustion instability of pilot flame in a pilot bluff body stabilized combustor

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Abstract Combustion instability of pilot flame has been investigated in a model pilot bluff body stabilized combustor by running the pilot flame only. The primary objectives are to investigate the pilot flame dynamics and to provide bases for the study of the interaction mechanisms between the pilot flame and the main flame. Dynamic pressures are measured by dynamic pressure transducers. A high speed camera with CH^* bandpass filter is used to capture the pilot flame dynamics. The proper orthogonal decomposition (POD) is used to further analyze the high speed images. With the increase of the pilot fuel mass flow rate, the pilot flame changes from stable to unstable state gradually. The combustion instability frequency is 136 Hz when the pilot flame is unstable. Numerical simulation results show that the equivalence ratios in both the shear layer and the recirculation zone increase as the pilot fuel mass flow rate increases. The mechanism of the instability of the pilot flame can be attributed to the coupling between the second order acoustic mode and the unsteady heat release due to symmetric vortex shedding. These results illustrate that the pilot fuel mass flow rate has significant influences on the dynamic stability of the pilot flame.

1. Introduction

In current afterburner and ramjet engine designs, thermo-acoustic instability which is excited by the feedback loop between dynamic combustion processes and one or more natural acoustic modes of the combustor is frequently encountered.[1] This oscillation can result in increased noise, thrust oscillations, and flame blowoff or flashback. In the bluff body stabilized combustor, the flame is stabilized by igniting the incoming fresh fuel–air mixture in the shear layer when the fuel–air mixture mixes with the high temperature combustion products from the recirculation zone downstream of the bluff body.[2] From a designer's point of view, the requirements for both static stability and dynamic stability should be met. According to Lovett et al.[3] and Ebrahimi,[4] static stability can be defined as the lean blowoff limit of a flame, while dynamic stability can be defined as combustion instability. In order to enhance the static stability of a practical augmentor, a pilot system is often adopted not only to ignite but also to

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anchor and maintain the flame over the whole range of operating conditions.[3,4] Therefore, the pilot flame is configured to be very stable. The composition of the pilot system is another fuel and air stream which will contribute to the local flame holder wake conditions, and therefore to the flame holder static stability. Fuel stratification can result in a piloting effect too.[5–7] It was shown in Cetegen's study[6] that an increase in stratification decreased the average blowoff equivalence ratio of the bluff body as the richer shear layer flame was effective in piloting the weaker flame branch. Chaudhuri and Cetegen[8] also studied the effects of spatial mixture gradient on response dynamics of the bluff body flame holder. The inner enrichment of the flame was found to be less susceptible to perturbations due to its robust inner core.

From the dynamic stability point of view, most of the previous research on thermo-acoustic instability focuses on the bluff body,[9,10] V-gutter[11,12] and backward-facing step[13,14] flame holders. There are few studies on combustion instability using pilot flame holder. The bluff body with a central fuel jet is commonly used as a pilot flame holder.[15–19] Pilot flame structures can be divided into three,[15] four,[16] five[17] or seven[18] different modes based on different ratios of fuel to air mass flow rate. The above pilot flames were all stabilized in an open surrounding, which means that no acoustic feedback process occurred. In a confined environment, the secondary fuel jets at the back face of the flame holder[20] were used to suppress thermo-acoustic instability of the integrated fuel injector/flame holder (IFF).[21] When the secondary fuel was continuously injected, the instability amplitude at 52 Hz was reduced, while the amplitude at 142 Hz was slightly increased. The secondary fuel was similar to the pilot fuel because it was located at the same location as the pilot fuel. But the primary objective of the secondary fuel in that work[20] was to prevent the pressure oscillations from igniting and anchoring the main flame. The heat release from the pilot flame has some effects on the flow field, which can be analyzed according to the vorticity transport equation.[22] Sengissen et al.[23] studied the effects of the pilot fuel on combustion instability in a gas turbine burner using large eddy simulations. In their study, when the pilot fuel mass flow rate was 2% of the total fuel mass flow rate, the flame was less stable with the precessing vortex core (PVC) being in the cold stabilization zone. The pressure oscillation amplitude was 6000 Pa in this case. When the pilot fuel mass flow rate increased to 6% of the total fuel mass flow rate, the pressure oscillation amplitude decreased to 500 Pa. In this case, the initial flame zone had a higher local equivalence ratio. The pilot flame formed, and can prevent the occurrence of PVC. Dhanuka et al.[24] discussed the flame–flame interaction when the main flame was anchored by the pilot flame. The planar laser induced fluorescence (PLIF) images of formaldehyde in their study showed that the pilot flame overlapped the inner edge of the main flame. The fluctuations of the pilot flame length increased as the pilot fuel mass flow rate increased with only the pilot fuel on. When the pilot fuel mass flow rate was sufficiently small, the main flame was observed to exist well in the upstream of the overlap region between the pilot flame and the main flame. At this condition, flashback oscillations and liftoff of the flame base occurred.[25]

The above three papers[23–25] have illustrated the importance of the pilot flame for the dynamic stability of the swirl combustor. Although the swirl combustor has some differences with the pilot bluff body stabilized combustor, it can be inferred from the previous works[23–25] that the pilot flame is also a key point for the dynamic stability of pilot bluff body stabilized combustor. Because the interaction processes of the pilot flame and the main flame are rather complicated, only the pilot flame has been investigated in this paper. Hence only the pilot fuel is supplied in the experiments. The main objectives are to investigate the pilot flame dynamics and to provide bases for the study of the interaction mechanisms between the pilot flame and the main flame. The pilot fuel has been mixed with a small portion of air before flowing into the shear layer and the recirculation zone. This is different from the fuel jet at the back face of the flame holder[15–21] because the fuel jets have some impacts on the flow field.[16,26] The pilot flame dynamic processes are captured by a high speed camera. The proper orthogonal decomposition (POD) is used to further analyze the high speed images to get the dominant flame processes. Based on the equivalence ratio distributions and the one dimensional acoustic mode analysis results, the combustion instability of the pilot flame has been investigated.

2. Experimental systems

2.1. Test facility introduction

The experimental facility consists of air supply system, fuel supply system, test section and measurement system. The air flow is supplied by a 0.6 MPa high pressure air storage facility. The air flow passes through a pressure valve and then a honeycomb to ensure a uniform flow field into a vortex flow meter. The accuracy of the vortex flow meter is within ±1.5%. Methane with purity of 99.9% is selected as the fuel. A methane flow meter with an accuracy of ±0.5% is used to control and measure the pilot fuel mass flow rate.

The test section starts with a choked perforated plate as shown in Fig. 1. The critical flow through the choked plate ensures not only a constant mass flow rate but also a fully reflecting acoustic boundary condition. The combustor outlet is connected to the atmosphere. Therefore, the outlet acoustic boundary condition is pressure release. The combustor consists of a rectangular duct with a cross section being 60 mm high and 80 mm wide. The test section length L_{tot} is 2100 mm from the choked plate to the combustor outlet. The distance from the choked plate to the flame holder trailing edge L_1 is 1500 mm. The distance from the flame holder trailing edge to the combustor outlet L_2 is 600 mm. In the downstream of the flame holder, there is a quartz window for the high speed camera.

The dynamic pressures are measured by four integrated water cooled dynamic pressure transducers (American PCB 106B50). The transducers' dynamic range is ±34.45 kPa with frequency response being up to 40 kHz and resolution being ±0.48 Pa. The response time is less than 12 μs. The distances between four dynamic transducers and the choked plate are $L_A = 0.14$ m, $L_B = 0.8$ m, $L_C = 1.5$ m, and $L_D = 1.9$ m, respectively. The dynamic data acquisition system is developed based on Labview software. During the experiment, the sampling frequency of the dynamic pressure transducers is 8 kHz, and the acquisition time is 2 s for every operating condition.

A high speed image intensified complementary metal oxide semiconductor (CMOS) camera is used in this study as the key