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Combined effect of spatial and temporal variations of equivalence ratio on combustion instability in a low-swirl combustor

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Abstract

In this experimental study, the combined effect of spatial and temporal variations of fuel–air mixture on self-excited combustion instabilities in a gas-turbine model combustor (~60 kW) with a low-swirl injector is reported. Detailed measurements were performed in 4 fuel split (to upstream/downstream injections) conditions while keeping the total equivalence ratio constant. The combustion stability was found to be very sensitive to the fuel split parameter which determined the local equivalence ratio distribution. The majority of the heat-release oscillations was generated in the flame-to-wall impingement region in a manner that satisfied the Rayleigh criterion. The driving force of the instability was considered the periodic interaction between the traveling vortex filled with fresh mixtures and the flame in the near-wall region as reported in the previous study on homogeneous mixture flame. However, the strength of the instability was sensitively modified by the change in the local equivalence ratio distribution. In the strongest oscillation case with inhomogeneous mixture, temporal variations of equivalence ratio exhibited a positive contribution to the thermoacoustic coupling. This suggested that temporal variations in equivalence ratio were enhancing the driving factor of the thermoacoustic instability in addition to the vortex-flame interaction mechanism.

Keywords: Combustion instability; Low-swirl; Lean premixed combustion; Inhomogeneous mixture flame

1. Introduction

In this study, the effects of spatial and temporal variations of the fuel–air mixture on combustion instability in a gas-turbine model combustor were investigated. A low-swirl injector (LSI), which is known to result in ultra-low emissions,

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was incorporated into the experimental combustor employed during the work. The LSI was originally developed at the Lawrence Berkeley National Laboratory [1,2] and has been widely adopted during studies focusing on fundamental aspects of turbulent premixed combustion, since its use results in a detached flame that is a close approximation of a freely propagating planar turbulent premixed flame. Many studies related to practical aspects of gas-turbine combustion have revolved around the adaptation of this technology to gas turbines and the associated flow field and emission characteristics have been reported for various gaseous fuels, including natural gas, hydrogen and syngas [3–5]. In addition, several groups have examined the dynamic features of low-swirl flames [6–10]. In one of the most recent studies, Therkelsen et al. [9] reported unstable flame behaviors in the case of CH_4 and H_2/CH_4 fuels experiencing self-excited combustion instabilities. Phase-resolved flow fields of the CH_4 flame demonstrated that ring vortices were shed from the LSI rim and that their convection speed along the outer shear layer (OSL) corresponded to the dominant frequency of the acoustic and flame oscillation spectra. The trailing edge of the flame brush impinged on the combustor wall and the vortices were trapped below this impingement point.

All such previous studies have considered solely the flame dynamics of homogeneous mixtures. The objective of the present study, however, was to clarify the effects of mixture inhomogeneity on flame dynamics. In practice, the fuel for gas-turbine combustors is injected at a specific distance upstream in relation to the combustor inlet and in many cases shortened mixing distances are necessary so as to avoid flame flashback and/or auto-ignition events. For this reason, inhomogeneous fuel distributions commonly result along the incoming flow of the combustion chamber. It is not simple to address the effects of mixture inhomogeneity on combustion instability since this is not an independent factor but rather interacts significantly with other factors such as acoustic velocity and pressure fluctuations. There have been several studies which have attempted to examine this issue, either through CFD analysis [11–13] or experiments with optical diagnostics [14,15]. Lee et al. [14] performed secondary fuel injection controls on combustion instabilities in a high-swirl premixed combustor and showed that the control effectiveness was strongly dependent on spatial and temporal fuel distributions.

Our focus in the present study is rather oriented to clarify physical mechanisms that cause the sensitivity to fuel inhomogeneity in self-sustained combustion instabilities. In such experiments, precise measurements of the local equivalence ratio are required and, in the work reported herein, the local equivalence ratio was determined using laser induced plasma spectroscopy (LIPS) directly within the unstable combustor, in the same manner as reported in a previous publication [16]. Phase-resolved data can be acquired by applying phase-locked processes utilizing the simultaneous recorded data for dynamic pressure and measurement timing signals. Here we report the combined effects of spatial and temporal variations of the equivalence ratio on combustion instability in a low-swirl combustor.

2. Experimental arrangements

2.1. Experimental systems and conditions

Figure 1 shows a schematic of the experimental setup, incorporating a low-swirl injector developed jointly with Lund University and Technische Universität Darmstadt [17]. The LSI nozzle has an inner diameter of 50 mm with a swirler situated 68 mm upstream of its exit plane. The annular section of the swirler is fitted with eight constant thickness curved vanes, each having a discharge angle of 37°. The central channel is 38 mm in diameter and is fitted with a perforated plate that has 37 holes, each with a diameter of 3 mm. The effective swirl number of this nozzle was approximately 0.55 [17]. The combustion chamber is composed of an inlet face plate and a cylindrical quartz glass tube with length and inner diameter of 495 and 146 mm, respectively. Methane gas is used as the fuel and is supplied through two fuel lines; the primary fuel is injected upstream of a static mixer before entering the burner plenum while the secondary fuel is injected into the burner through 12 orifices (each 1 mm in diameter) at an axial location 143.5 mm upstream of the combustion chamber inlet. The local stoichiometric distribution can be modified by varying the fuel split condition while keeping the total equivalence ratio constant. The fuel split parameter (λ) is defined as the ratio of the downstream fuel flow rate to the total fuel flow rate.

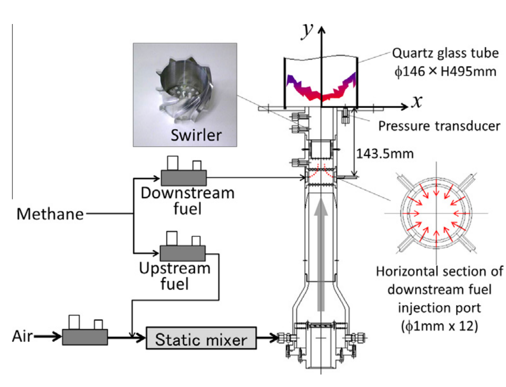

Fig. 1. Schematic of the experimental setup.