Applied Thermal Engineering 54 (2013) 92–101

Contents lists available at SciVerse ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Effect of fuel–air mixture velocity on combustion instability of a model gas turbine combustor

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HIGHLIGHTS

► Combustion instability characteristics are classified based on inlet mixture velocity.
► Major instability frequency shifting effect occurs at low velocity region.
► Flame vortex core is major parameter on the combustion instability at low velocity conditions.

ARTICLE INFO

Article history:
Received 9 August 2012
Accepted 28 January 2013
Available online 6 February 2013

Keywords:
Flame structure
Fluid dynamic instability
Combustion dynamics
OH* chemiluminescence
Gas turbine combustor

ABSTRACT

Nowadays, it is easy for unstable combustion phenomenon to develop in a gas turbine that is working in a lean premixed condition. To eliminate the onset of these instabilities and develop effective approaches for control, the mechanisms responsible for their occurrence must be understood. The flame recirculation zone is very important, as it can modulate the fuel flow rate and may be the source of instability, plus its flame structure has a major impact on heat release rate oscillation and flame stabilization. In this study, we conducted experiments under various operating conditions with a model gas turbine combustor to examine the relation of combustion instability and flame structure by OH chemiluminescence. Swirling CH_4 - air flame was investigated with an overall equivalence ratio of 1.2 to lean blowout limit and dump plane velocity of 30–70 m/s. Phase-locking analysis was performed to identify structural changes at each phase of the reference dynamic pressure sensor under conditions of instability. At an unstable condition, flame root size varies a lot compared to stable condition which is because of air and fuel mixture flow rate changes due to combustor pressure modulation. After this structural change, local extinction and re-ignition occur and it can generate a feedback loop for combustion instability. This analysis suggests that pressure fluctuation of combustion causes deformation of flame structure and variation of flame has a strong effect on combustion instability. In this study, we observed two types of combustion instability characteristics related to the instability of both the thermo-acoustic and flame vortex type.

1. Introduction

At the turn of 21st century, problems related with the depletion of energy and environmental pollution have become among the most important of issues [1]. Under these circumstances, emission regulations are becoming stringent to suppress pollution. Accordingly, many researchers have tried to develop a new type of combustor that burns the fuel more efficiently and produces significantly lower emissions [2]. In the context of such an effort, lean premixed and RQL (Rich burn Quick mix and Lean burn) combustors have been introduced [3].

By burning the fuel at a low temperature, a lean premixed combustor produces a significantly lower amount of NOx than conventional gas turbines. Conventional gas turbines that burn fuel in near-stoichiometric conditions have some advantages in terms of the stability of combustion, but those produce locally high temperature regions that generate large amounts of NOx and soot production. On the other hand, lean premixed combustors can decrease the combustion temperature significantly by burning the fuel at near-lean equivalence ratio conditions [4,5]. However combustion instabilities occur under the lean conditions where

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http://dx.doi.org/10.1016/j.applthermaleng.2013.01.032

Nomenclature

$P'(x,t)$	perturbation of dynamic pressure
$q'(x,t)$	heat release oscillation
V'	vortex shedding oscillation
$\Phi(x,t)$:	combustion instability damping source
D_{inlet}	diameter of inlet mixing section
D_{comb}	diameter of combustor
L_{inlet}	axial distance of inlet mixing section
L_{comb}	axial distance of combustor
Φ	equivalent ratio
v_{mix}	fuel–air mixture velocity
f_0	resonance frequency
f	combustion instability frequency
c	speed of sound
P	static pressure
T_{comb}	combustor temperature
T_{inlet}	inlet mixing section temperature
St	Strouhal number
L_c	characteristic length
L_{flame}	flame length
S	swirl number
α	flame angle
ω	angular frequency
u_2	axial velocity at swirler downstream section

they are designed to operate. To eliminate these instabilities and develop effective approaches for their control, the mechanisms responsible for their occurrence must be understood.

Combustion instability is sustained high-amplitude pressure fluctuations in a combustion chamber. It occurs when different combustion processes such as acoustic fluctuations, unsteady combustion and vortex shedding are combined in such a way that inherent disturbances in the system are self-excited via interactions with the combustion process. These are caused by complex, feedback-type interactions between periodic flow and combustion processes that produce a periodic heat addition, exciting large-amplitude acoustic oscillations in the combustor. Combustion instabilities usually generate a typical noise. If the combustion process occurs in a free field, the generated sound simply radiates away. However, if sound is generated in a confined region, it can be reflected from the boundaries, allowing the reflected waves to interact with the combustion process. Since the combustion process is sensitive to these flow field variations, a feedback loop is created and combustion instability can result [6].

In addition, a recent study by Meier et al. [7–9] has shown the relation between ignition delay time and combustion instability occurrence by CFD and experimental studies using the PIV and PLIF measurements in a model gas turbine combustor. Candel et al. [10,11] investigated the flame response by measuring the unsteady phase-averaged heat release induced by an imposed velocity perturbation and phase-averaged dynamic fluctuation. As concerns the flame vortex interaction research field, Kim et al. [12] investigated the effects of acoustic forcing on flame length and NO_x emission in turbulent hydrogen non-premixed jet flames with coaxial air, which was acoustically forced at the resonance frequency of the combustor. Also, in order to examine mixing and dynamic behaviors during flame–vortex interaction, the local properties on the flame surface were characterized quantitatively. The behavior of the processing vortex core (PVC) is also significantly altered by combustion heat release and by the system parameters (e.g. swirl number, axial velocity and geometry). Previous studies [13,14] suggest that the type of combustion (i.e., premixed or non-premixed) can affect the PVC frequency and its intensity.

However, there is no other research about the interaction of vortex structure and combustion instability phenomenon. The flame recirculation zone (flow patterns in combustion region) is very important, as it can modulate the air flow rate at instability condition and may be the source of instability by modulation local equivalence ratio. In this study, we conducted experiments under various operating conditions with a model gas turbine combustor to examine the relation of combustion instability and flame structure using the OH* chemiluminescence and multi-channel dynamic pressure sensing system.

2. Experimental apparatus and methods

2.1. Model dump combustor

Fig. 1 shows a schematic of a lean premixed, variable-length, model gas turbine combustor. It consists of an air heater, an inlet mixing section, which is called the plenum, a swirl injector, an optically accessible quartz combustor section, a steel combustor section, and an exhaust duct. An air heater provides heated air (673 K) to a combustor through an air inlet section. There is a choking orifice at the entrance of the air inlet section to provide a well-defined acoustic boundary condition and to protect the fluctuation of inlet air. In the inlet mixing section, the mixing process between the fuel and heated air is done by a swirl injector, which provides a spatially and temporally homogeneous reactant mixture to the combustor. The combustor consists of a stainless steel dump plane, an optically accessible quartz combustor, and a steel combustor. The downstream end of the quartz combustor is connected to a stainless steel variable-length combustor section. The length of the steel combustor can be varied continuously from 850 mm to 1100 mm by moving a water-cooled plug nozzle along the axial direction of the combustor. The overall combustor length is defined as the distance from the dump plane to the plug nozzle. The temperature of plug nozzle varies from 350 to 490 K, which is based on inlet velocity conditions. PCB 102A05 piezoelectric transducers are used to measure unsteady pressure perturbations in the inlet mixing section and combustor section. Five pressure transducers are installed in the mixing section, and six pressure transducers are installed in the combustor, respectively. Five static pressure sensors made by Valcom Inc. are used to measure the combustion static pressure and control the mass flow rate of inlet air and five K-type thermocouples are also used. Temperature was measured at two positions, which were 520 mm and 660 mm from the dump plane, and it was the wall temperature, which means a distance of 65 mm (half of the combustor diameter) away from the center. The averaged value of this temperature was used for analysis.

2.2. Swirl injector

Fuel injection and mixing efficiency is a very important factor for combustion emissions and gas turbine efficiency. Nowadays, most gas turbines use swirl injectors. Using this kind of injector affects flame stabilization and mixing quality. A central recirculation zone and an outer recirculation zone are induced by swirl injector. This central recirculation zone re-circulates combusted hot gas to the nozzle part and it works as a heat source of the combustion and central recirculation zone, making a shear layer of the mixture and re-circulated flow, which will help the mixing efficiency.