Experimental Thermal and Fluid Science 35 (2011) 1409–1417

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

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

Measurements of ensemble averaged flame dynamics using spatially resolved analysis

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ARTICLE INFO

Article history:
Received 9 September 2009
Received in revised form 17 September 2010
Accepted 26 May 2011
Available online 2 June 2011

Keywords:
Thermoacoustic instabilities
Combustion

ABSTRACT

When applying flame sheet models to predict the dynamics of turbulent flames, it is common to model turbulence using ensemble averaging of the velocity. Measurements of the flame dynamics were made to support use this type of methodology, by measuring the dynamic volume of the flame using phase averaged images of the CH* chemiluminescence. The dynamics agreed with the common behavior described in the literature, namely frequency scaling according to Strouhal number based on flow convective timescales. However, slightly different timescales were observed for the response magnitude and phase, indicating the possibility of different scaling mechanisms at work between these phenomena. The flame heat release rate dynamics were found to be identical to the dynamic response of the flame volume to inlet velocity perturbations, suggesting a simple proportionality between heat release rate and the flame volume. This result supports the use of ensemble averaging for modeling of the turbulent velocity for predictions of flame dynamics.

1. Introduction and background

In modern gas turbine designs, premixed combustion strategies have been employed in order to take advantage of their lower flame temperatures, and thus their reduced emissions characteristics. However, these premixed combustion strategies have been observed practically to exhibit an increased incidence of thermoacoustic combustion instabilities. Thermoacoustic instabilities are described as a closed-loop coupling between the flame heat release rate and the system acoustics. These instabilities result in high amplitude pressure and velocity oscillations which prove detrimental to the system reliability. Despite a substantial body of research on the topic, thermoacoustic instabilities continue to represent a serious practical problem in low-emission gas turbine combustion [1].

Thermoacoustic coupling may occur through a variety of coupling mechanisms. A system-level model describing two commonly observed mechanisms [2,3] is shown in Fig. 1. The inner loop represents direct coupling between the flame and acoustics through velocity fluctuations. The flame heat release rate acts to drive acoustic pressure and velocity oscillations. The velocity oscillations directly excite the flame, resulting in an oscillating delivery of reactants to the flame. Pressure oscillations however, have been shown not to result in a significant coupling mechanism, thus they are not discussed further here [5]. The second mechanism, equivalence ratio coupling, occurs through interaction between the acoustic velocity and the fuel injection and mixing process. Due to their significant differences in bore sizes, fuel and air injection ports have a dissimilar acoustic response, resulting in time varying equivalence ratio pulses which may be advected to the flame. Both of these coupling modes have been observed experimentally in unstable combustion [6].

Due to the breadth of research on thermoacoustic instabilities, a wide variety of approaches to the problem exist. One approach which has received much attention [7–9,32] is that of modeling instabilities through analysis of the individual transfer functions making up the system model shown in Fig. 1. Though this approach demands prior knowledge of how the individual transfer functions vary with the operating conditions, it allows a versatile framework with which to divide the problem for study.

Obtaining knowledge of the flame dynamics remains a significant area of research and many studies, both experimental [10–14,28–32] and theoretical [2,3,9,15–18], have been aimed at achieving greater understanding of the flame response to perturbations. The flame is known to behave as a low pass filter with respect to excitations, exhibiting a response at low frequencies which rolls off at higher frequencies. The transfer function's overall behavior is characterized by the low-frequency (or "DC") gain, the cutoff frequency, and the time delay between changes in the combustor inlet velocity and the observed change in heat release.

Bandwidths of the flame transfer function have been observed through both experiment and models to be a function of the Strouhal number, based on convective length scales and the mean

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doi:10.1016/j.expthermflusci.2011.05.009