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The effect of fuel composition on flame dynamics

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Abstract

As fuel sources diversify, the gas turbine industry is under increasing pressure to develop fuel-flexible plants, able to use fuels with a variety of compositions from a large range of sources. However, the dynamic characteristics vary considerably with composition, in many cases altering the thermoacoustic stability of the combustor. We compare the flame dynamics, or the response in heat release rate of the flame to acoustic perturbations, of the three major constituents of natural gas: methane, ethane, and propane. The heat release rate is quantified using OH^* chemiluminescence and product gas temperature. Gas temperature is measured by tracking the absorption of two high-temperature water lines, via Tunable Diode Laser Absorption Spectroscopy. The flame dynamics of the three fuels differ significantly. The changes in flame dynamics due to variations in fuel composition have the potential to have a large effect on the thermoacoustic stability of the combustor.

Keywords: Flame dynamics; Flame transfer function; Tunable diode laser absorption spectroscopy; Chemiluminescence

1. Introduction

The ability to use fuels with a wide range of compositions will be a significant advantage for gas turbine power plants as fuel sources become more diverse. Utilizing a variety of fuel compositions allows utilities better control of fuel costs, supply, and environmental impact. Natural gas can vary significantly in composition depending on the source [1]. Biogas, becoming increasingly popular, also varies widely in composition due to the large array of sources. Richards et al. [2] give a review of fuels from many sources and their properties. In addition to meeting requirements to operate on a variety of fuel compositions, gas turbines must also meet strict emissions standards. The lean, premixed combustion required to control emissions makes gas turbines susceptible to thermoacoustic instability. The dynamic characteristics of the combustion process are also modulated by the fuel composition, increasing susceptibility. Controlling thermoacoustic instabilities, coupled with varying fuel composition and emissions requirements, represents a significant challenge. To meet this challenge, an understanding of the effect of fuel composition on flame dynamics is essential.

Fuel composition affects flame properties including flame speed, heating value, and adiabatic flame temperature. In turn, these properties have a pronounced effect on flame dynamics. Flame dynamics are defined as the response in heat release rate to acoustic perturbations, and are frequently presented as frequency response functions, also referred to as flame transfer functions [3–5]. Thermoacoustic instabilities are large-scale pressure oscillations that result from the coupling of the flame dynamics to the acoustics of the combustor. Thus, by affecting flame dynamics, fuel composition directly influences the stability of the combustor. Janus et al. [6] observed changes to the dynamic stability of a self-excited combustor with a natural frequency of 500 Hz by switching from propane to natural gas. Kushari et al. [7] studied the effects of fuel composition on the stability of a low-frequency (50 Hz) pulse combustor. Scholz and Depietro [8] observed that variations in pipeline

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Table 1
Properties of the main constituents of natural gas [14]

Fuel	Molecular weight [kg/kmol]	Enthalpy of formation [kJ/kmol]	Flame temperature [K]	Laminar flame speed [cm/sec]
Methane (CH_4)	16.043	−74831	2226	40
Ethane (C_2H_6)	30.069	−84667	2259	43
Propane (C_3H_8)	44.096	−103847	2267	44

natural gas affected engine dynamics in practical field tests. Fuel composition has also been observed to alter static stability (lean blow-out). A comprehensive review of the issues involved with fuel flexibility is given by Richards et al. [2].

In this paper, the flame dynamics of the primary components of natural gas (methane, ethane, and propane) are compared. Table 1 shows several properties of these fuels. The flame dynamics of methane, ethane, and propane characterize the range of dynamics expected for natural gas, as well as illustrating the effect of fuel composition on flame dynamics. The measurements are performed by imposing acoustic perturbations on a laminar, flat flame resulting in a fluctuation of the mass flow rate of the fuel–air mixture. The heat release rate is quantified using two measurements. OH^* chemiluminescence provides a measurement of the chemical heat release, or the energy released from the chemical reaction. The simultaneous absorption of two high-temperature water lines, via Tunable Diode Laser Absorption Spectroscopy (TDLAS), allows a dynamic measurement of the product gas temperature [9–11]. The temperature is an indicator of the enthalpy of the product gases, or the acoustic forcing function [12]. The acoustic forcing function is the energy from the flame that is available to couple with the acoustics, including heat transfer from the gases and burner.

2. Experimental setup

2.1. Laminar burner

The laminar, flat-flame burner was designed to eliminate effects of fluid mechanics, e.g., flowfield structure and turbulence. The acoustic field was forced via a loudspeaker, and the effect of mass flow perturbations on the heat release rate of the flame was observed. To maintain realistic flame temperatures similar to industrial gas turbine combustors, the flame was stabilized on a ceramic honeycomb, 18 mm thick and 68 mm in diameter. The flame is protected from ambient flows with a 75 mm diameter quartz tube. A planar, uniform flow-field was insured at the flame front by mixing the reactants well upstream of the burner. The premixed reactants entered the apparatus through 1.5 mm diameter holes drilled in two feed tubes, minimizing acoustic coupling to the inlet tubing and feed stream. A 135 mm diameter, 60 W loudspeaker was used to impart velocity fluctuations in a controlled manner. Combustion occurred at atmospheric pressure.

2.2. Diagnostics

A schematic of the experimental setup is shown in Fig. 1. The mass flow fluctuation imparted on the flame was measured using a two-microphone acoustic intensity probe mounted upstream of the flame [13]. The acoustic probe provides a mass flow measurement with an estimated maximum error of 0.5 dB in magnitude and 0.5° phase. The response in reaction rate was measured via hydroxyl radical (OH^*) chemiluminescence. A lens system collected the emission from an area slightly larger than the flame and focuses the light into a fiber optic cable. A 0.5 m Ebert monochromator was used to separate the light due to OH^* chemiluminescence at 309.6 nm. The light corresponding to OH^* chemiluminescence was converted to an electric current using a R955 (enhanced UV) Hamamatsu photomultiplier tube. Based on repeated measurements, the maximum error of the OH^* signal is estimated to be 0.25 dBV. The response in product gas temperature was measured using Tunable Diode Laser Absorption Spectroscopy (TDLAS). Using two semiconductor diode lasers, emitting at 7444.37 cm^{-1} and 7185.59 cm^{-1}, the absorption by two H_2O transitions in the product stream was measured simultaneously. Outside of the combustor section, the beams were sent through tubes that were purged with nitrogen to reduce absorption from moisture in the ambient air. AR-coated objective lenses (6.2 mm focal length) are used to collimate the emission from the diode lasers (Laser Components GmbH, Inc.). Mirrors (AR-coated) then direct the laser beams across the flame twice and to

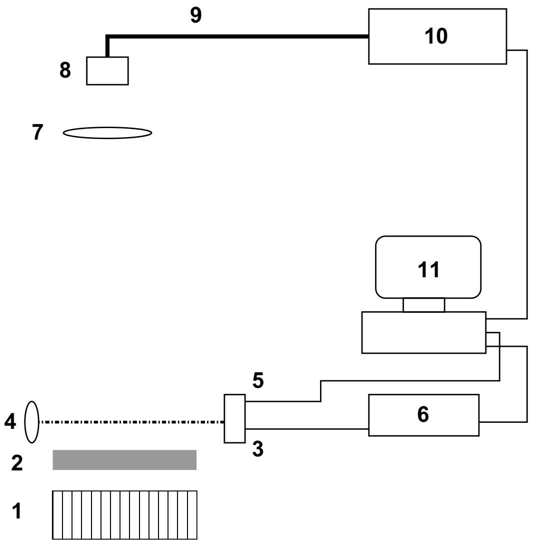

Fig. 1. Experimental setup (1) ceramic honeycomb flameholder (2) laminar, flat flame (3) diode lasers (4) mirror (5) photodiode detectors (6) laser controller (7) lens system (8) fiber optic coupling (9) fiber optic cable (10) monochromator and photomultiplier tube (11) PC and data acquisition system.