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Thermo-acoustic behavior of a swirl stabilized diffusion flame with heterogeneous sensors

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HIGHLIGHTS

- ▶ Heterogeneous sensors used to examine the thermo-acoustic behavior of flames.
- ▶ Examined the interdependence of high temperatures on acoustic source localization.
- ▶ Acoustic sources do not occur in the regions of high temperature fluctuation.
- ▶ Fluctuating temperatures occur in regions of high temperature gradients.
- ▶ Noise generation regions in high temperature regions of a flame identified.

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ABSTRACT

Next generation combustors are expected to be significantly more efficient while reducing pollutants and eliminating carbon emissions. In such combustors, the challenges of local flow, pressure, chemical composition and thermal signatures as well as their interactions require understanding to seek for optimum performance of the system. The current practice of using a single sensor to measure certain parameters at a single location cannot provide sufficient information to achieve desirable and optimum overall performance of the combustor. A high density sensor network with a large number of sensors will be required in future smart combustors to obtain detailed information on the various ongoing processes within the system. As an initial step towards the development of such sensor networks, the effect of mean and fluctuating temperature distribution on the distribution of acoustic sources within the flame has been examined by using a thermocouple and condenser microphone using swirl stabilized diffusion flames. The measurement of high frequency temperature signal allowed observation of characteristic mean and fluctuating temperatures, and thermal stratification characteristics from within the flame. Specifically mean and fluctuating temperatures, integral and micro-thermal time scales have been determined at various spatial locations in the flame. Investigation of the thermal field and their effect on the localization of acoustic sources in the two flames formed at different equivalence ratios has been examined. The thermal characteristics data obtained provided a better insight on the thermal behavior of co-swirl diffusion flames. Noise spectra for varying air–fuel ratios were determined. Results of time average and fluctuating temperature and sound pressure level spectra showed noise emission in flames to lie near to the regions of high temperature which result in pressure fluctuations within the flame. The results are complemented with 3D CFD simulations that supported the localization of the acoustic sources within the turbulent diffusion flames.

1. Introduction

As the emissions from commercial combustors become an object of increased concern, it is imperative that one must develop functional value clean-burning smart combustors. The functional value refers to output property of a unit or a plant. In gasifiers no combustion is desired while in reactors the output property or desired degree of conversion of some or all of the chemical reactions is important. In the actively controlled combustors one would use sensor networks and advanced diagnostic techniques to accurately, reliably, and inexpensively detect local flow, thermal and chemical conditions within the combustor to obtain information about the integrated global performance of the combustor [1]. Therefore such

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Nomenclature

T_g	gas temperature within the flame	ρ_b	density of the thermocouple bead
T_b	thermocouple bead temperature	c_p	specific heat of the thermocouple junction
τ	thermocouple time constant	r_b	radius of the thermocouple bead
γ	ratio of radiative effects to convective effects	ρ	density of fluid
T_{surr}	temperature of the surrounding	K	gas thermal conductivity
ε	emissivity	D	outer diameter of the burner
σ	Stefan Boltzmann constant	$R(\tau)$	correlation coefficient of temperature
m_b	mass of the thermocouple bead	t_{int}	thermal integral time scale
h	convective heat transfer coefficient	t_{mic}	thermal micro-time scale
A_b	area of thermocouple junction	Δt	time delay

sensor networks and advanced diagnostics will have a wide spectrum of applications including industrial furnaces and incinerators, chemical reactors and distillation towers, high temperature fuel cells, and gas turbine and piston engines for process monitoring, performance enhancement and preventative maintenance. An example of the application of such sensor networks is the development of coal gasification systems, next generation of green gas turbines engines for stationary power. In combustion systems, the minimization of the noise sources, namely noise from the turbulent flow, combustion noise and noise caused by periodic instabilities and fluctuations of the ignition zone is required. Swirl is often used in flames to provide the source of high ignition energy, wider stability and operational ranges. Frequently, the complex interplay between local flow, pressure, chemical composition, and temperature within these high performance combustors means that they must be carefully monitored in order to maintain favorable combustion condition. The complex coupling between fluctuating temperatures within the turbulent flame affects the localization of acoustic sources within the flame, which in turn affects the flame characteristics and combustion phenomenon as a whole. Understanding the coupling mechanisms between acoustic waves and flames have become an important issue in the development of combustion systems, which will use smart heterogeneous sensors to reduce noise and to avoid the structural damage that such an interaction may produce in case of thermo-acoustic instabilities. Currently little is known about the coupling between fluctuating temperatures and acoustics. The complexity of such an interaction is higher for turbulent flames due to the large variety of fluid dynamic and thermo-chemical scales involved both in space and time.

Swirl is used in practically all types of combustion systems, including gas turbine combustion, furnaces and boilers. In combustion systems, the favorable effect of imparting swirl to combustion air and/or fuel has been extensively used for flame stabilization, high heat release per unit volume, and clean efficient combustion [2]. Currently little is known about the mechanisms by which the flame responds to acoustic feedback and understanding these mechanisms is an area of active investigation. Non-premixed combustion, although expected to be stable, is susceptible to inherently unsteady high acoustic pressure fluctuations [3]. Swirl flows and their associated flames can generate periodic flow instabilities, which lead to an increase in noise emission and problem of flame stability [4]. Instabilities in swirl flames have been investigated by a number of investigators and reveal the importance of coherent structures in the forward flow surrounding the inner recirculation zone [4]. The existence and the influence of coherent structures on the noise emission of the flame and thus of the combustion system requires further physical knowledge to minimize combustion noise in all industrial applications. Swirl flames can result in high noise levels, in particular at high intensity reaction rates. It is therefore essential to understand the noise generation mechanisms and noise emitting regions in a swirl flame. Noise suppression can then be accomplished with predefined methods and control.

The extent of thermal non-uniformity in non-premixed flames is poorly characterized but can be expected to depend upon the combustor configuration, the degree and distribution of swirl in the combustor, and other input and operational parameters of the combustor [2,5]. The non-uniformity in the thermal field can have an influence on the efficiency of the combustor as well as on the emission levels, including NOx [6]. It is therefore essential to characterize the mean and fluctuating thermal field in non-premixed turbulent flames.

Significantly different combustion characteristics have been obtained by altering the radial distribution of swirl in a burner [7]. Marshall and Gupta [8] determined thermal characteristics of different premixed flames performed through various combinations of swirl and axial inlet momentum distributions in a double concentric swirl burner. Fluctuating temperature measurements were obtained for several flames at various spatial locations in the flames. By maintaining a constant equivalence ratio, a comparison of the dimensions and distribution of temperatures for different flames was achieved. These results provided information on the important role of radial distribution of swirl and jet axial momentum on the flame thermal characteristics.

In order to characterize the combustion phenomenon completely in a turbulent flame, there is a need for a multi-sensor heterogeneous network to be placed around the combustor, for seeking detailed information that can allow for better control to achieve higher efficiency and performance [1]. Micro- and nanoscale sensors with improved performance are rapidly developing and have started to play more important roles in many applications. Our envisioned heterogeneous sensor networks in future combustors involve a variety of different sensors, including novel micro- and nano-scale sensors for pressure, flow, temperature, fuel fraction and various gas species concentration measurements. The heterogeneous sensor system can provide both complementary and competitive information about a combustion system [1]. Complementary information refers to the measurements of different characteristics of the combustion process, while competitive information refers to the measurements of the same characteristic but from different sensor units. Such a heterogeneous sensor system can provide a more reliable view and a higher confidence level of the operational status of an advanced combustion unit and power plant system. In this paper, two different sensors (heterogeneous) were employed to examine the complex coupling between the two responses. This information will be useful to develop heterogeneous sensor network that can be employed in combustors for obtaining detailed information about the turbulent reacting flow field. The results presented here show the influence of fluctuating and mean temperature distribution on the localization of acoustic sources within the turbulent diffusion flame. The results reveal