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Non-premixed acoustically perturbed swirling flame dynamics

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ABSTRACT

An investigation into the response of non-premixed swirling flames to acoustic perturbations at various frequencies (f_p = 0–315 Hz) and swirl intensities (S = 0.09 and 0.34) is carried out. Perturbations are generated using a loudspeaker at the base of an atmospheric co-flow burner with resulting velocity oscillation amplitudes $|u'/U_{avg}|$ in the 0.03–0.30 range. The dependence of flame dynamics on the relative richness of the flame is investigated by studying various constant fuel flow rate flame configurations. Flame heat release rate is quantitatively measured using a photomultiplier with a 430 nm bandpass filter for observing CH^* chemiluminescence which is simultaneously imaged with a phase-locked CCD camera. The flame response is observed to exhibit a low-pass filter characteristic with minimal flame response beyond pulsing frequencies of 200 Hz. Flames at lower fuel flow rates are observed to remain attached to the central fuel pipe at all acoustic pulsing frequencies. PIV imaging of the associated isothermal fields show the amplification in flame aspect ratio is caused by the narrowing of the inner recirculation zone (IRZ). Good correlation is observed between the estimated flame surface area and the heat release rate signature at higher swirl intensity flame configurations. A flame response index analogous to the Rayleigh criterion in non-forced flames is used to assess the potential for a strong flame response at specific perturbation configurations and is found to be a good predictor of highly responsive modes. Phase conditioned analysis of the flame dynamics yield additional criteria in highly responsive modes to include the effective amplitude of velocity oscillations induced by the acoustic pulsing. In addition, highly responsive modes were characterized by velocity to heat release rate phase differences in the $\pm\pi/2$ range. A final observed characteristic in highly responsive flames is a Strouhal number between 1 and 3.5 based on the burner co-flow annulus diameter ($St = f_p U_{avg}/d_m$). Finally, wavelet analyses of heat release rate perturbations indicate highly responsive modes are characterized by sustained low frequency oscillations which accompany the high amplitude velocity perturbations at these modes. Higher intensity low frequency heat release rate oscillations are observed for lean flame/low pulsing frequency conditions.

1. Introduction

In modern gas turbines, the use of swirl in stabilizing combustion processes is critical in enhancing efficiency, reducing emissions as well as optimizing engine performance. These improvements are highly correlated to the enhancement of the mixing process in the combustor with swirl inducing mechanisms such as swirl vanes. However, swirl enhanced lean combustion has been observed to be characterized by dynamic feedback mechanisms between equivalence ratio, heat release rate and pressure perturbations particularly at the combustor natural modes [1–4]. These feedback mechanisms can lead to self-excitation in cases where the relevant perturbations are in-phase (as defined by the Rayleigh Criterion), amplifying the response of the system and resulting in undesirable installation damage, inefficient operation and increased NOx emissions among other effects [3,5,6]. The prediction of the onset of instability requires a thorough understanding of the physical processes that govern the dynamic response of the combustion process [1,3,7]. Several significant physical phenomena contribute to the dynamics of the combustion process including heat release rate, swirl intensity, flow field properties (vortex formation and shedding), flame surface area fluctuations and fuel dependent chemical kinetics.

Several numerical and experimental studies have focused on a wide range of issues including differences in premixed and diffusion flame dynamics as well as flame response to upstream equivalence ratio and velocity perturbations [3,5,8–11]. However, a majority of existing flame response literature is dedicated to the analysis of the dynamics of premixed flame response. Huang and Yang [5] carried out a large eddy simulation (LES) based numerical study of flame dynamics in a lean-premixed, swirl-stabilized combustor, establishing the inlet temperature and equivalence ratio as primary parameters related to combustor stability. Energy interactions between combustion zone chemistry and acoustic oscillation in the chamber were found to be characterized by a closed-loop

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Nomenclature

a	continuous wavelet transform (CWT) scale
$A_{favg,fp}$	time-average flame surface area from acoustic pulsing at frequency, f_p
$A_{favg,\phi}$	average flame surface area at phase angle, ϕ from acoustic pulsing at frequency, f_p
C	continuous wavelet transform coefficient
d_m	mean burner annulus diameter: $d_m = r_i + r_o$
f_a	frequency equivalent of wavelet transform scale, $f_a = f_c/a\Delta$
f_c	center frequency of "mother wavelet"
f_p	acoustic pulsing frequency
$F(x)$	complex fast Fourier transform (FFT) of signal, x
$F(x,f_p)$	complex fast Fourier transform (FFT) of signal x at frequency bin f_p
I_{CL}	CH* chemiluminescence image centerline intensity
I_U	velocity fluctuation intensity
m_f	fuel flow rate
m_{fr}	baseline fuel flow rate ("richer" flame)
p'_1	burner base pressure perturbations
p'_2	burner exit pressure perturbations
q	flame CH* chemiluminescence (heat release rate) intensity
q'	CH* chemiluminescence (heat release rate) intensity fluctuations ($q' = q - q_{avg}$)
$q'_{avg,fp}$	time-average CH* chemiluminescence (heat release rate) from acoustic pulsing at frequency, f_p
$q'_{avg,\phi}$	average CH* chemiluminescence (heat release rate) at phase angle (ϕ) from acoustic pulsing at frequency, f_p
r	radial coordinate relative to burner axis

R_i	inner radius of burner annulus
R_o	outer radius of burner annulus
Re	Reynolds number: re = $\rho u_{avg} d_m/\mu$
S	swirl number
t	time
t_P	total data acquisition period
T_P	acoustic pulsing period: $t_P = 1/2\pi f_p)$
$u_{fp}(t)$	time trace of velocity at pulsing frequency, f_p
u'	velocity fluctuations: $u' = u - u_{avg}$
$u'_{avg,\phi}$	average velocity fluctuation at phase angle (ϕ) from acoustic pulsing at frequency, f_p
u_{avg}	spatial average velocity at burner exit plane
$u_{avg,fp}$	time-average velocity from acoustic forcing at frequency, f_p
z	axial coordinate vertically from burner exit plane
Greek	
Δ	signal sampling period
ϕ	phase angle
ϕ_p	acoustic pulsing signal phase
$\phi_d^{x'-y'}$	phase difference from input perturbation, x' to output perturbation, y'
λ	dynamic fuel flow rate decay constant
μ	air dynamic viscosity
ρ	air density
$\tau_d^{x'-y'}$	time delay from input perturbation, x' to output perturbation, y': $\tau_d^{x'-y'} = \phi_d^{x'-y'}/(2\pi f_p)$

feedback coupling between combustion chamber acoustics, the fluid dynamics of vortex shedding and oscillations in heat release rate. An aggregate estimate by Lieuwen [1] of these energy interaction/feedback timescales based on premixed flame speeds and thicknesses led to timescales of the order of 0.002–0.07 s for methane/air flames. This established the likelihood of prominent flame response to acoustic perturbations in the 20–500 Hz frequency range associated with these time scales.

The use of transfer functions to characterize the flame response to upstream velocity oscillations has been analytically investigated by several authors [12–16]. Several of these studies were based on using flame surface area fluctuations as heat release rate markers. The flame response to upstream velocity perturbations was analytically found to be dependent on the normalized acoustic frequency (Strouhal number, St). High frequency velocity oscillations were found to pass through the flame with minimal effect on heat release rate, while low frequency perturbations triggered significant response in the flame heat release rate. A transfer function was used to relate the velocity oscillation to the heat release rate response of the flame introducing the concept of a time delay between the velocity oscillation input and heat release rate output. The time delay is maximum at high frequency and smallest at low frequency, translating to minimum phase shift at the low frequencies [12]. Schuller et al. [13] also found a dependence of the flame transfer function on the flame angle with respect to the mean flow direction in the case of laminar flames. They concluded that V-shaped and conical flame behaviors were analogous to low-pass filters. In the case of V-shaped premixed laminar flames, amplifications in heat release rate were observed even for moderate velocity oscillation amplitudes.

Analytical and experimental investigations into flame response to velocity and equivalence ratios have been carried out by Durox et al. [2], Kulsheimer and Buchner [3], Chaparro et al. [9,11] and Bellows et al. [17] among others. Various flame configurations including bluff body stabilized, swirling and laminar flames have been studied but the majority of these flame configurations are premixed. Durox [2] and Fritsche [18] found that for laminar inverted conical flames and atmospheric swirl stabilized premixed flames the flame response excitation was observed at bulk modes of the burner (or its components) and in particular Helmholtz modes of the burner in the low frequency regime as suggested in the laminar flame analyses by Lieuwen [1], Fleifill et al. [12] and Schuller et al. [13].

Additional characterization of various flame configurations, albeit mostly premixed flames were carried out by Kulsheimer and Buchner [3], Bellows et al. [17], Kang et al. [19] and Tachibana et al. [20] using various imaging methodologies to quantify the heat release rate of the flame. These methods included the use of photomultiplier tubes (PMT) centered at 430 nm and 310 nm to observe the chemiluminescence of CH* and OH* radicals emitted due to the combustion process. CCD imaging phase-locked to the perturbation signal was also used to allow the correlation of the observed flame geometry to the acoustic oscillation. Kulsheimer and Buchner [3] found that the $Pu \approx 1/St$ relationship is a necessary condition for the initiation of a flame response. The pulsation amplitude (Pu) was defined as the ratio of the rms to mean mass flow rate of the fuel–air mixture, with St being the Strouhal number. Ayoola et al. [21] utilized a combined OH and CH2O planar laser induced fluorescence (PLIF) to investigate the spatial resolution of heat release rates in turbulent premixed flames. Chaudhuri and Cetegen [10,11] investigated the frequency signature of stoichiometrically stratified flames dynamically approaching extinction using the continuous wavelet transform (CWT) methodology [23]. The use of the continuous wavelet transform (CWT) for identification of impending flame extinction is investigated by Nair and Lieuwen [4] for premixed flame configurations.