

Flame Spectra of a Turbulent Liquid-Fueled Swirl-Stabilized Lean-Direct Injection Combustor

Tongxun Yi* and Domenic A. Santavicca†
 Pennsylvania State University, University Park, Pennsylvania 16802

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Flame spectra within the UV/visible-light range are measured for a turbulent, liquid-fueled, swirl-stabilized, lean-direct injection combustor. The flame spectra are quite similar to those of lean premixed combustion, which can be attributed to the small droplet size and fast fuel/air mixing. Broadband background emissions around 431 nm, which mainly consist of CO₂ chemiluminescence, are found to be self-similar with wavelength for both stable and unstable combustion. Chemiluminescence from OH*, CH*, and CO₂* is found to be a nonlinear function of the airflow rate, the equivalence ratio, preheat temperature, and pressure. Procedures for the determination of the instantaneous heat release rate and equivalence ratios along the flame front are developed. For both combustion instability and forced flame responses, the prediction errors are within 2.0% in the mean heat release rate, the mean air consumption rate, and the mean equivalence ratio. The assumption that chemiluminescence is proportional to the instantaneous heat releaser rate is generally invalid. Probably the proportionality is valid only in the weakly turbulent or wrinkled flamelet region in the absence of equivalence ratio variations and strong acoustic oscillations.

Nomenclature

$CH(s)$	= Laplace transform of CH* chemiluminescence
$I(t)$	= instantaneous chemiluminescence intensity, AU
L_f	= curvilinear flame front
$\dot{m}_a(t)$	= instantaneous air consumption rate, g/s
$\tilde{m}_a(t)$	= instantaneous air consumption rate divided by 100 g/s
$\tilde{p}(t)$	= instantaneous combustor pressure divided by the atmospheric pressure
$p'_a(t)$	= acoustic pressure near the heat release zone, Pa
$p_f(t)$	= instantaneous fuel pressure 0.29 m upstream of the fuel nozzle, Pa
$\dot{Q}_R(t)$	= instantaneous heat release rate, kW
S_L	= laminar burning velocity, m/s
\mathcal{L}	= symbol of the Laplace transform
\bar{T}	= mean temperature in the heat release zone, K
$T'_a(t)$	= acoustic temperature near the heat release zone, K
T_i	= preheat temperature, K
$X(s)$	= Laplace transform of $x(t)$
$ W(s) $	= gain of the transfer function $W(s)$
$\angle W(s)$	= phase angle of the transfer function $W(s)$, deg
α	= thermal diffusivity, m ² /s
ΔH_R	= lower heating value of fuel, J/kg
δ_L	= thickness of the laminar flame, m
ϕ	= fuel/air equivalence ratio
λ	= wave length divided by 431 nm
λ	= wavelength, nm
ρ_a	= air density, kg/m ³
ρ_u	= reactant density, kg/m ³
τ_c	= chemical reaction time, s

I. Introduction

THE instantaneous heat release rate and equivalence ratios are key parameters for combustion analysis and control. HCO is a good indicator of the instantaneous heat release rate, even in the presence of large strain rates [1]. However, both HCO* chemiluminescence and planar laser-induced fluorescence (PLIF) suffer from low signal-to-noise ratios. An alternative method is to use the PLIF product of OH and CH₂O, as demonstrated by Paul and Najm [2] and Ayoola et al. [3]. However, this method requires a rather complicated optical setup including lasers, cameras, lenses, and optical filters. In contrast, chemiluminescence-based heat release measurements may just require an optical access, an optical fiber, an interference bandpass filter, and a detector such as a photomultiplier tube (PMT). Chemiluminescence is the spontaneous emission of photons from electronically excited species when they return to the background state. The formation of radical species, such as OH*, CH*, and C₂*, are directly associated with chemical reactions.

The equivalence ratio can be determined from the PLIF signal, line-of-sight infrared absorption, and chemiluminescence from radical species. With excitations at 266 nm, the one- and two-ring aromatics in kerosene generate PLIF signals within 270–420 nm, which can be used to determine the droplet/vapor concentration [4]. The stretching C–H band, which is strongly absorbing around 3.39 μm, is prevalent in almost all hydrocarbon fuels. A path-integrated equivalence ratio can be determined from the line-of-sight extinction measurements [5]. The absorption method can also be extended to determine fuel vapor concentration for liquid/vapor mixtures [6]. Usually two laser beams, with one in the infrared light range and the other in the visible-light (VIS) range, are used. Chemiluminescence from radical species has been used to determine equivalence ratios for different combustion systems, including premixed laminar, premixed turbulent, and even spray flames [7–9]. Compared with PLIF and absorption measurements, chemiluminescence-based methods do not require a complicated optical setup. Local measurements of chemiluminescence can be performed using Cassegrain receiving optics, as demonstrated by Hardalupas and Orain [10]. Local measurements of chemiluminescence along the flame front can be used to examine the fuel/air mixing uniformity.

For unstretched, premixed, laminar flames, the flame zone structure, the flame speed, and the relationship between chemiluminescence and heat release are intrinsic properties of the fuel/air mixture. However, the situation is different for turbulent flames. In modern combustion theory, turbulent flames are conceived as a series of cascaded laminar flamelets, which drift with the local velocity and propagate normally toward the reactant. The location and orientation

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*Postdoctoral Fellow, Department of Mechanical and Nuclear Engineering; tzy1@psu.edu. Member AIAA.

†Professor, Department of Mechanical and Nuclear Engineering; das8@psu.edu. Member AIAA.