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5 kHz thermometry in a swirl-stabilized gas turbine model combustor using chirped probe pulse femtosecond CARS. Part 2. Analysis of swirl flame dynamics

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ABSTRACT

We have performed a detailed analysis of the temperature field in a turbulent swirl flame operating with a self-excited thermo-acoustic instability. The temperature field was measured using 5 kHz chirped-probe-pulse (CPP) femtosecond (fs) coherent anti-Stokes Raman scattering (CARS). The measurements are described in detail in the part 1 companion article. In this paper, part 2, a detailed analysis of the time-resolved temperature measurements and simultaneous pressure measurements is performed to provide insight into the dynamics and structure of the swirl-stabilized flame. This work is the first to capture the dynamics of the flame, flow, and coupled flow-flame processes using high-fidelity, spatially- and temporally-resolved thermometry in a flame of practical relevance. The time-averaged contour plot of the temperature field indicates that the flame is very flat and stabilizes approximately 10 mm downstream of the burner face. In this region, there are very significant temperature fluctuations indicating a very high level of unsteadiness. The temperature probability distribution functions (PDFs) are clearly bimodal in this region near the injector face. A Fourier analysis of the temperature time series revealed multiple coherent oscillatory modes. The strongest oscillation was found to be coherent and in-phase with an acoustic resonance at 314 Hz, as expected from the Rayleigh criteria for the unstable flame. An analysis of the phase-conditioned average temperature fields clearly shows an axial pumping of low-temperature reactants, which are consumed after a convective delay and result in a spike in the global heat-release rate. Continued analysis also revealed a 438 Hz oscillation that was found to correspond with the dynamics of convective transport by a helical precessing vortex core (PVC). The structure of the PVC, and its interaction with the flame, were studied based on the presence of this characteristic frequency in the power spectral densities computed throughout the flow. The precision and time-resolution of the CPP fsCARS measurements was also sufficient to enable computation of the integral time-scales as well as the PDFs of the temporal temperature gradients. A sample of state space trajectories were used to provide insight into the nature of coupling between the narrowband acoustic resonance and the broadband spectrum of turbulent flame processes.

1. Introduction

High power-density combustion technologies are designed to achieve flow characteristics that support sustained, elevated rates of chemical heat release. Often, swirling flows are used in such designs, as they effectively promote turbulent transport and enhance mixing processes that lead to rapid progress of chemical reactions and a compact flame shape. Beyond a critical level of swirl, vortex breakdown results in the formation of the central recirculation bubble (CRB), which transports heat and active chemical species from the combustion product gases back to the flame root. This central aerodynamic blockage serves as a self-sustaining ignition source, stabilizing the high-power flame and supporting increased levels of reactant mass consumption [1–4].

The hydrodynamic structure of swirling flows is three-dimensional and unsteady, with multiple large-scale turbulent structures interacting over a broad spectrum of spatial and temporal scales. With combustion present, chemical reactions modify

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the behavior of the flow through spatio-temporal evolution of the thermo-chemical state and thermo-physical properties. Under certain conditions, the local interaction of turbulence and chemistry with the resonant acoustic field can also give rise to global instabilities. Fundamental understanding of these processes is necessary to advance combustion technologies and avoid the harmful impacts of such conditions [5–7]. One strategy to study these effects has been to develop laboratory-scale, gas turbine model combustors (GTMCs) that represent the flow structure, geometry, and other complexities found in systems of practical relevance [8–12]. As such, the Dual-Swirl GTMC (developed at the German Aerospace Center, DLR) has become a widely-used platform for detailed experimental and numerical investigations of these very important flows.

Weigand et al. [13] and Meier et al. [14] performed the first detailed characterization of this burner. They studied three flame conditions: one which burned stably (Flame A), one with pronounced self-excited thermo-acoustic pulsations (Flame B), and a third operating near the lean blow-out limit (Flame C). Utilizing laser Doppler velocimetry (LDV), laser Raman scattering, and planar laser induced fluorescence (PLIF) imaging of hydroxyl (OH) and methylidine (CH), they reported the time-averaged flow and flame structure as well as a statistical analysis of the planar distributions of temperature, species concentrations, and mixture fraction. It was found that, despite having very similar time-averaged velocity fields, each flame showed pronounced differences in the structure of the reaction zone due to changes in unsteady mixing and finite-rate progress of chemical reactions. In all cases, the flames were lifted, stabilizing approximately 10 mm downstream of the fuel injection plane. Within the CRB, the gas mixtures were almost completely reacted, with a thermo-chemical state very close to equilibrium. Partially-reacted mixtures were detected within the Inner Shear Layer (ISL) formed between the fresh gas injection jets and the CRB, where the measurements showed significant variation from the equilibrium temperature and composition. At the thermo-acoustically unstable condition (Flame B), additional periodic oscillations in the velocity field led to enhanced mixing effects between the reactants and hot gases within the CRB. This resulted in the rapid progress of chemical reactions and significantly more compact flame structure.

To improve understanding of the coupled mechanisms underpinning the thermo-acoustic oscillation observed in Flame B, Meier et al. [15] acquired a phase-locked measurement set which captured the periodic fluctuations in heat release (estimated by OH^* chemiluminescence), flow velocity, mixture fraction, and fuel distribution occurring at the known oscillation frequency. Fluctuations in pressure and heat release were found to be nearly in-phase, as expected from the Rayleigh criterion. The combustion chamber pressure oscillation resulted in phase-dependent variations in the inflow velocity and, consequently, the reactant mass flow rate. Phase-locked laser Raman measurements revealed that the periodic reactant inflow was correlated with a phase-dependent equivalence ratio oscillation, likely due to mismatched impedances in the fuel and oxidizer supply manifolds. Evidently, the periodic inflow oscillation of fuel-rich mixture was found to have a direct phase relationship with the heat release oscillations, corresponding to the convective time delay from the nozzle to the reaction zone.

Planar particle image velocimetry (PIV) and scalar field imaging (specifically, planar laser induced fluorescence, or PLIF) measurements were then performed to reveal the spatial structure of the unstable flame and the combustor flow-field. Sadanandan et al. [16] used both techniques, simultaneously, to study the structural coupling of flow-flame interactions. The measurements revealed vortices within the Inner Shear Layer (ISL) that were staggered across the flow centerline with increasing distance from the nozzle exit. Stohr et al. [17] continued to study these structures and correlated their presence to a single, large scale coherent turbulent structure; a helical Precessing Vortex Core (PVC). Residing within the ISL, the PVC was found to enhance transport of burned and unburned gases within the spatially developing mixing layer, thus promoting flame stabilization through entrainment of reactants with high-temperature gas.

In recent years, the rapid development and commercial availability of high-repetition-rate, diode-pumped solid-state (DPSS) lasers with short pulse durations has made temporally-resolved planar measurements in laboratory-scale flames an accessible option. The simultaneous integration of these systems has supported concurrent velocity field and (qualitative) scalar field measurements at kHz interrogation frequencies to yield greater understanding of the space-time evolution of flow-flame interactions [18–23]. Measurements in the Dual-Swirl GTMC have shown that heat release takes place, primarily, in two interconnected regions of the flow: 1) at the lower stagnation point of the central recirculation bubble and 2) in a helical zone coupled with the presence of the precessing vortex core within the inner shear layer. The influence of the PVC on flame stabilization is attributed to low strain rates and enhanced mixing of burned and fresh gases (due to large scale transport). Fluctuations in the position or size of the CRB were found to result in an enmeshed motion of the reaction zone while the flame remains, locally, within the low-velocity regions of the ISL. The flame dynamics are coupled to the CRB in that the stagnation point serves as the leading point of ignition for the reactions within the ISL [24–28].

As a planar technique, PLIF can provide detailed spatial information about the structure of the flame. However, it does not yield quantitative information with respect to the thermo-chemical state of the flow. Linear scattering techniques, such as laser Raman and Rayleigh scattering, can provide detailed, quantitative, single-shot measurements of many gas properties, including temperature and major species concentrations. However, the signal generated by these processes is very weak, hence, the measurements require very high laser fluence and have, historically, been limited to low-bandwidth (single-shot) detection. In the case of Rayleigh scattering, the Rayleigh cross-section assumptions required in data processing also limit the applicability of the technique to *clean* flames with tailored fuels.

Coherent anti-Stokes Raman scattering (CARS) is a third-order, nonlinear spectroscopic technique that can also provide high-fidelity measurements of temperature, species concentration, and other flow properties. The signal generated by the CARS process is a coherent beam emitted from the probe volume. This unique aspect of the CARS technique makes it suitable for application in hostile flame environments where the signal can be efficiently collected with spatial, spectral, and polarization filtering. The CARS technique does not require tailored reactants, making it a robust tool for measurements in highly unsteady, practical reacting flows [29–39]. In recent years, there has been considerable progress in the application of high-peak power, ultra-fast laser sources for high-fidelity CARS thermometry at interrogation frequencies sufficient to time-resolve the large-scale, dynamic processes in turbulent flames [40–48].

In this study, ultrafast CARS temperature measurements were performed in the DLR Dual Swirl GTMC operating with high-amplitude, self-excited thermo-acoustic oscillations. As fully-described by Dennis et al. (part 1 of this work) [49], the measurements were shown to have excellent accuracy and precision. A comparison of time-averaged statistics computed from the chirped-probe-pulse (CPP) femtosecond (fs) CARS measurements and laser Raman measurements performed at DLR [14,15], also showed good agreement. The objective of this effort (part 2) is to report the utilization these unique new measurements in