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Responses of combustor surface temperature to flame shape transitions in a turbulent bi-stable swirl flame

Zhiyao Yin *, Patrick Nau, Wolfgang Meier

Institute of Combustion Technology, German Aerospace Center (DLR), Pfaffenwaldring 38-40, 70569 Stuttgart, Germany

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ABSTRACT

Turbulent swirl flames are known to exhibit intermittent transitions between V- and M-shapes at certain operating conditions. A diagnostic apparatus based on a commercial highspeed laser system is developed in this work to investigate the influence of such transient phenomenon on the surface temperature of an atmospheric-pressure gas turbine model combustor. The transition of flame shapes is monitored by planar OH laser-induced fluorescence (OH PLIF) at 1-kHz repetition rate. Simultaneously, the same laser beam is used to perform 1-D surface thermometry on the base plate and the bluff body of the combustor, which are coated with Mg_4FGeO_6:Mn, a commonly used thermographic phosphor (TP). Temperature is inferred from the decay of phosphorescence recorded by a highspeed CMOS camera operated at 70 kHz. During transitions between attached (V-) and lifted (M-) flames, pronounced temperature variation as much as 100 K is observed on the tip of the bluff body. In the spectral domain, temperature measured during the M-flame period exhibits a peak at 475 Hz, in good agreement with the measured frequency of the precessing vortex core (PVC) at the same operating condition. This peak does not appear during the V-flame period when PVC is suppressed. The uncertainty of the measurements and the sensitivity of the technique are discussed in detail.

1. Introduction

Confined turbulent flames are commonly encountered in practical combustion systems such as gas turbines and IC engines. Studies of these systems have traditionally treated the confinement (combustor surfaces) as isothermal or adiabatic, while focusing primarily on its role in combustion aerodynamics and acoustics. In recent years, increasing attention has been drawn to heat loss to the confinement, and its influences on combustion chemistry and flame stabilization [1] as well as on flame flashback [2]. Consideration of heat loss to surfaces have proven critical in improving large eddy simulations (LES) for different combustor configurations [1,3]. Such considerations may also be needed for understanding and predicting unsteady phenomenons such as periodic fluctuations and transient behaviors in certain combustion systems.

This work concentrates on such a phenomenon that is encountered in swirl stabilized flames, namely the intermittent transitions between attached (V-shape) and lifted (M-shaped) flames at so-called bi-stable operating conditions [4,5]. The transition from V- to M-flame occurs as a sequence of local extinction near the flame root, formation of a helical precessing vortex core (PVC) [6] and an eventual total lift-off. The opposite happens when PVC is suppressed and flame becomes attached again. PVC has been well characterized for turbulent swirl flames and is recognized as an essential player in combustion stabilization [7]. As the formation of PVC is highly sensitive to the local density (temperature) field [4], knowledge of temperature on flame holders (e.g., bluff body) is important for gaining a full picture of the stochastic nature of these events.

The aim of this work is to develop a diagnostic apparatus to resolve, temporally and spatially, the effect of flame shape transitions on the surface temperature of a swirl-stabilized combustor. With the rapid development of surface thermometry using thermographic phosphors (TP) [8,9] and highspeed laser/acquisition systems, various approaches have been recently demonstrated to achieve spatially [10–15] and temporally-resolved [16] surface temperature measurements in different combustion environments. These approaches have conventionally employed harmonic outputs from YAG lasers and are generally decoupled from other laser-based techniques. For the current purpose, however, direct correlation between transient combustion events and responses of surface temperature is required. In this work, planar laser-induced fluorescence of OH radical (OH PLIF) is used to monitor

* Corresponding author.
E-mail address: zhiyao.yin@dlr.de (Z. Yin).

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flame shape at 1 kHz. Simultaneously, surface thermometry is carried out by using the same UV laser to excite the TP coated on the base plate and the bluff body of the combustor. The focus is placed on identifying the location which experiences the largest temperature variations during flame transitions. The uncertainty of the measurements and the sensitivity of the technique are also addressed in detail.

2. Experimental setup

2.1. Combustor and operating condition

The atmospheric-pressure gas turbine model combustor used in this work is based on an industrial design by Turbomeca and has been the subject of extensive experimental [17–19] and numerical [20–22] investigations. The combustor, as illustrated in Fig. 1a, was operated at a perfectly premixed mode [18] in this work. Methane and air mixture at an equivalence ratio of $\phi = 0.7$ and a thermal loading of 20 kW was first delivered into the cylindrical plenum (Ø = 78 mm) of the combustor. It then went through a swirl generator with 12 radial vanes before entering into the combustion chamber via a converging nozzle (Ø = 27.85 mm) with a central conical bluff body (Ø = 29 mm at the bottom and 34-mm tall). The combustion chamber featured a square cross-section of 85×85 mm^2, 114-mm tall and was capped such that combustion products exited through a conical converging section into an exhaust duct (Ø = 40 mm). The side walls of the chamber were made of quartz, providing access to optical diagnostics. A sonic nozzle was installed upstream of the plenum to isolate the combustor acoustics from that of the gas supply lines. For the operating condition, the Reynolds number at the exit of the nozzle based on the average cold flow exit velocity of 14.4 m/s and the nozzle diameter, is about 28,000. The swirl number, derived from the velocity measurements at 1.5 mm above the exit is approximately 0.6 [17].

At the thermal loading of 20 kW, flame was observed to transition from being attached at the bluff body (V-shape) to being completely lifted off (M-shape) as equivalence ratio was reduced from stoichiometric to $\phi = 0.65$ [4]. At the target operating condition of $\phi = 0.7$, flame alternated randomly between V- and M-shape (bistable). Fig. 2 shows averaging OH chemiluminescence images illustrating the V- and M-flames taken at this condition. OH chemiluminescence signal was acquired using an intensified CMOS camera (LaVision HSS5 with HS-IRO, active sensor size 512×512 pixels, 40 µs gate) coupled with an achromatic UV lens (f = 64 mm, f/2.0, Bernhard Halle Nachfl.) and a bandpass filter (300–325 nm). The camera was operated at 1 kHz in order to resolve the transitions between the two flame shapes. The two images in Fig. 2 were obtained by averaging frames collected during either of the flame periods. As can be seen, while flame is directly attached at the bluff body during the V-shape period, it becomes lifted during the M-shape period.

2.2. Diagnostic arrangement

The layout of the combined OH PLIF and 1-D surface thermometry is shown schematically in Fig. 1a. A commercial highspeed laser system consisted of a Sirah Cobra-Stretch HRR dye laser pumped by the second harmonic output from an Edgewave IS-811E diode-pumped solid state Nd:YLF laser. The dye laser was frequency doubled and tuned to 283.2 nm (1 kHz, 50 µJ/pulse) to coincide with the Q1(7) transition in the OH A-X (1,0) band. For OH PLIF, the UV beam was expanded into a laser sheet with two cylindrical lenses ($f_1 = -50$ mm and $f_2 = 250$ mm), which was then softly focused waist-wise with an $f_3 = 1000$ mm cylindrical lens and aligned across the geometric center of the combustion chamber. After passing through the chamber, the same laser sheet was redirected via a periscope to excite the TP coating on the surface of the combustor for thermometry. The forward and backward laser sheets were overlapped spatially such that the obtained surface temperature could be correlated to the OH signal distribution. The laser sheet was adjusted to slowly expand vertically, from about 50 mm tall for OH PLIF to about 80 mm tall for surface thermometry.

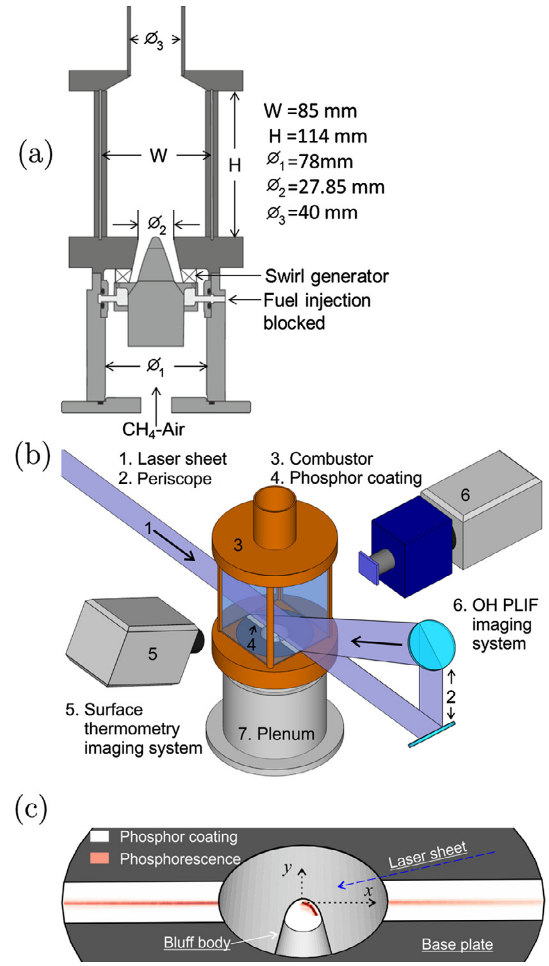

Fig. 1. (a) Schematic of the gas turbine model combustor, (b) arrangement of the diagnostic system, (c) single-shot raw image of phosphorescence at room temperature overlaid on top of a detailed sketch of the burner surface (not to scale).

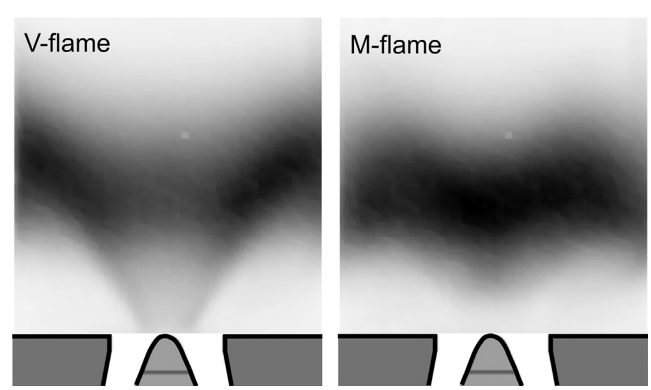

Fig. 2. Average OH chemiluminescence taken during the V- and M-flame periods.