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Temperature measurements in confined swirling spray flames by vibrational coherent anti-stokes Raman spectroscopy

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ABSTRACT

A gas turbine model combustor for swirling spray flames has been operated at atmospheric pressure with *n*-hexane, *n*-dodecane and kerosene Jet A-1. Temperature measurements were performed using single-shot broadband shifted vibrational coherent anti-Stokes Raman spectroscopy (SV-CARS). Series of 1200 single-shot measurements were performed at different radial and vertical locations in the flames from which the temperature distributions were deduced. In regions with high droplet load a significant number of CARS spectra were discarded due to large signal background from laser-induced breakdown effects. Results from the flames burning different fuels were compared and revealed considerable differences in the temperature profiles. The temperature measurements are part of a comprehensive research program that aims at the design of alternative fuels for aero engines and stationary gas turbines. In addition to the experimental characterization of the spray flames, the datasets are used for the validation and improvement of computational models.

1. Introduction

The design and production process of alternative jet fuels are an active field of research due to ecological reasons, limited resources and concerns of import dependency [1,2]. The main focus is towards drop-in fuels which can be used without modifications of the engine or penalizations in terms of performances and safety [3]. Understanding the influence of the fuel composition on the combustion behavior offers the opportunity for more suitable blend formulations which could reduce emissions and provide more efficient combustion performance [4]. Here, validated numerical models are the key step to improve design tools. However, the effects of individual hydrocarbons, hydrocarbon groups, and their ratio in blends on combustion processes are not fully understood. In particular, well documented test cases and comprehensive experimental data sets are needed to improve the understanding. To achieve this goal, a model combustor was designed [5] at the German Aerospace Center (DLR) to simulate key features of a real aero-engine combustor: air-blast atomization of liquid fuel and a turbulent swirling flow field inside a confined combustion chamber. In the current work, single-component fuels were tested to reduce + Experiments were performed with two fuels from the chemical class of linear hydrocarbons (*n*-hexane and *n*-dodecane). For comparison, kerosene Jet A-1 was used as technical reference. The burner was operated at ambient pressure. This provided simplified conditions to validate numerical models [6] in order to gain a fundamental understanding of the influence of single-component fuels before working at realistic high pressure conditions and complex fuel mixtures.

The capability of the burner to provide optical access from multiple sides makes it particularly suitable for non-intrusive laser diagnostics techniques. Stereo particle image velocimetry (SPIV), CH^* chemiluminescence imaging, Mie scattering off fuel droplets, and phase Doppler anemometry (PDA) were already employed in previous measurement campaigns [5,7,8]. However, for modelling and validating combustion process simulations, reliable temperature measurements are essential. Among non-intrusive (laser-based) techniques for combustion diagnostics, coherent anti-Stokes Raman spectroscopy (CARS) [9,10] has long been established as a temperature measuring tool in numerous combustion environments. CARS is a non-linear spectroscopic technique that provides spatially and temporally resolved temperatures and species concentrations by probing molecular Raman shifts. Three coherent laser beams (pump, Stokes and probe) are focused and crossed in the region of interest generating a CARS signal beam as shown in Fig. 1a. The frequencies of the three beams are chosen such that their interaction excites the molecular vibrational transitions of the N_2 Q-branch. In broadband vibrational CARS the probe beam has a broad bandwidth that covers several vibrational and rotational transitions of the molecule.

The resulting signal beam carries the Raman spectra of N_2. Processing of the spectra allows temperature to be obtained by fitting the spectral shape. In broadband vibrational CARS, a spectrum is

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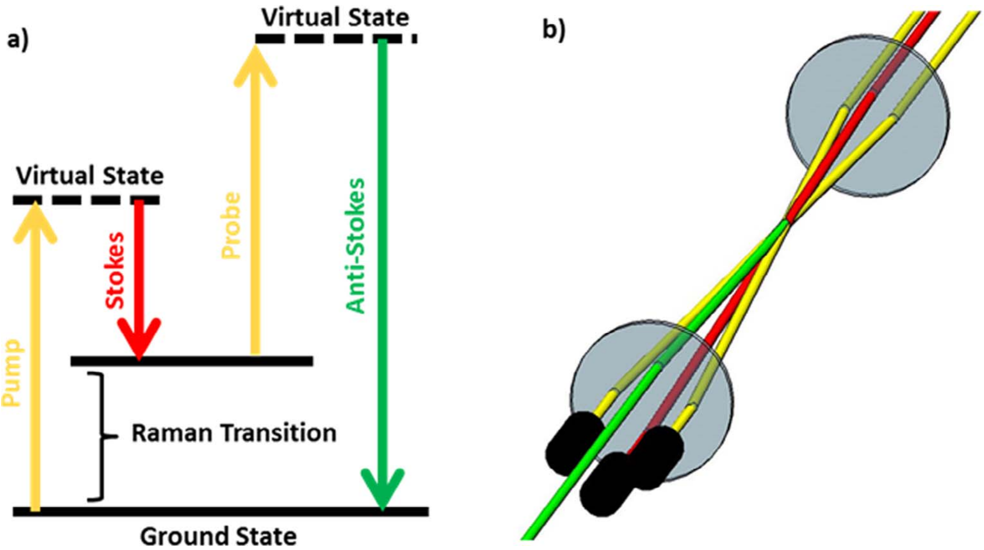

Fig. 1. (a) SV-CARS energy level diagram; (b) folded BOXCARS phase matching configuration.

obtained with each single laser shot and the temperature distribution (probability density function, pdf) is obtained from the measurement of a large number of single spectra. The temperature pdfs carry important information about the combustion process. They reflect the reaction progress, quantify effects of heat loss and are an important quantity for analyzing NO formation. An additional aspect addressed in this paper is to analyze and understand the influence of different fuels on the temperature distribution. To support the interpretation, also results from previous measurements in the same burner are taken into consideration.

2. Experimental setup

2.1. Facility

The description of the gas turbine model combustor and the corresponding facility and fuel supply system has already been described in detail by Grohmann et al. [5]. Hence, a minimal description of the facility will be provided. The nozzle of the burner, shown in Fig. 2a, consisted of two co-axial, co-rotating swirlers with a diameter of 8 mm (inner) and 11.6 mm (outer) respectively. An annular ring with a sharp edge separated the two air flows. A pressure-swirl atomizer (*Schlick 121*) sprayed the fuel onto the inner surface. The thin liquid film formed was then re-atomized at the atomizer lip and then injected into the combustion chamber. The combustion chamber (85 × 85 × 169 mm) was equipped with four quartz windows with anti-reflective coating and provided full optical access. The combustor was mounted on a three-axis translation stage. The facility setup scheme is shown in Fig. 2b. A compressor supplied dry air which was preheated by an electric heater (~6 kW) before being sent to the combustor; a thermal mass flow controller (*Bronkhorst EL-FLOW select F-203AV*, accuracy ± 0.1% full scale) regulated the air mass flow rate. Fuel was pressurized inside a steel cylinder and sent to the burner through a mass flow controller (*Bronkhorst mini CORI*-FLOW M14, accuracy ± 0.2% full scale). The air temperature was measured by a thermocouple inside the plenum and kept constant at 323 K: this value was chosen to provide a stable and repeatable boundary condition. The fuel temperature was measured upstream of the first atomization and kept constant at 303 K. All tests were performed at a global equivalence ratio $\Phi = 0.8$ and at atmospheric pressure.

2.2. Optical setup

A frequency doubled Nd:YAG laser (*Quanta Ray Pro 290*) with a

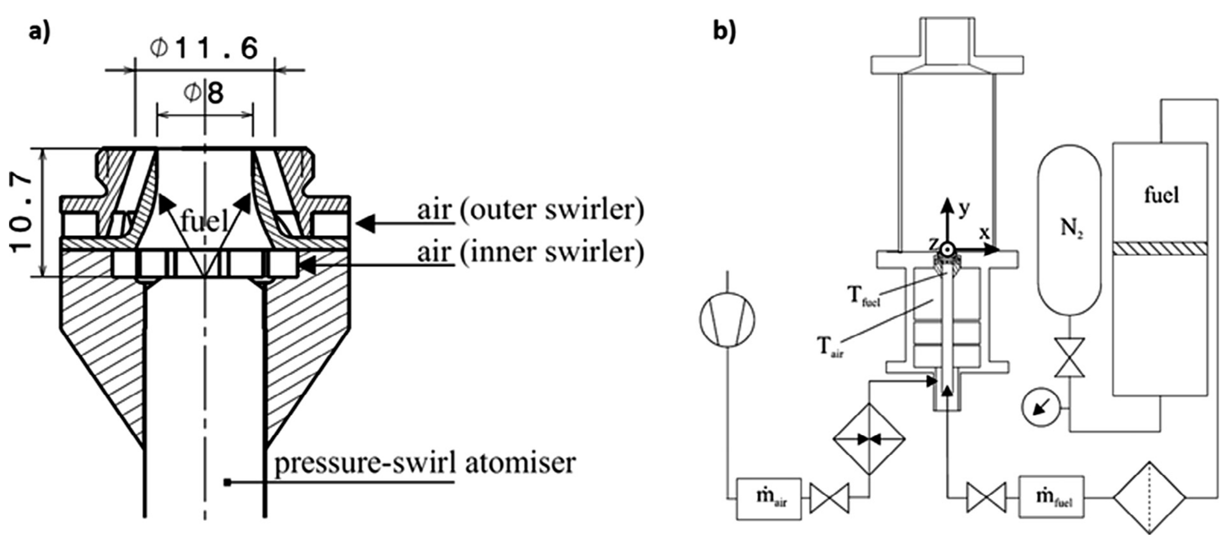

Fig. 2. (a) Nozzle; (b) rig (not in scale).