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Scalar structure of turbulent partially-premixed dimethyl ether/air jet flames

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Abstract

This work presents results of temperature and major species measurements from two turbulent piloted, partially-premixed dimethyl ether (DME)/air jet flames with Reynolds numbers of 29,300 and 58,600. These results are intended to provide a first set of multi-scalar data from a new flame series for the investigation of turbulence–chemistry interaction and the validation of turbulent combustion models using a complex, oxygenated fuel, DME. The current work investigates two Reynolds number cases from the complete DME flame series (five flames) that were formulated to be similar to the well-known Sydney/Sandia piloted jet burner flame series A–F using methane fuels. The flame structure is examined using ensemble mean and rms radial profiles at various axial positions downstream of the nozzle exit as well as statistics conditioned on mixture fraction. Finally, selected results of the two cases are compared to the original methane-based configurations. Finite-rate chemistry effects such as local extinction and re-ignition and their impact on the scalar flame structure are found to be different in the DME/air jet flames as compared to the methane-based jet flames.

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1. Introduction

The validation of turbulent combustion models from benchmark experimental data sets has been a primary goal of the International Workshop on Measurement and Computation of Turbulent Flames (TNF) [1]. In order to provide experimental results on the flow field and the scalar structure of well-defined target flames, a variety of laser-based diagnostics have been applied. One important tool to gain information on the interaction between the turbulent flow field and the combustion chemistry is 1D Raman/Rayleigh scattering. Comprehensive data sets of temperature, major species (CO_2, O_2, CO, N_2, CH_4, H_2O, H_2), and derived quantities, such as mixture fraction, and their gradients have been used in various turbulent flames to assess and validate turbulent combustion models [2]. In recent years, there have been efforts made to extend these diagnostic methods to fuels with increased complexity as compared to the predominately studied hydro-

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gen and methane flames. Dimethyl ether (DME) has been selected as a promising target fuel, primarily due to its low tendency to form soot and consequently, its accessibility by 1D Raman/Rayleigh measurements [3,4]. Frank and coworkers [5,6] introduced a series of partially-premixed DME/air flames following the well-documented methane/air flame series A–F in the Sydney/Sandia piloted jet burner geometry [7,8].

In this work we present experimental results from 1D Raman/Rayleigh/CO-LIF measurements of seven major species (CO_2, O_2, CO, N_2, DME, H_2O, H_2) and temperature from two turbulent flames DME-D and DME-F, which correspond to Reynolds numbers of 29,300 and 58,600, respectively. These flame conditions represent the lowest and second highest Reynolds number (based on nozzle diameter) within the new DME flame series. The experimental setup and details concerning accompanying laminar flame calculations are described in Section 2. Results, including mean/rms temperature and mixture fraction radial profiles at six downstream locations, as well as conditionally-averaged statistics, are presented in Section 3. A summary and concluding remarks are given in Section 4.

2. Experimental method

Simultaneous 1D Raman/Rayleigh scattering and CO laser induced fluorescence (CO-LIF) were used to measure instantaneous species concentrations and temperature at the Combustion Research Facility of the Sandia National Laboratories [4,9,10]. Four sequentially-fired frequency-doubled Nd:YAG lasers operating at 532 nm were used to determine species mole fractions and temperature along a 6 mm-line segment via spontaneous Raman/Rayleigh scattering. In addition, an Nd:YAG-pumped tunable dye laser was used for the simultaneous CO-LIF measurement. For the Raman/Rayleigh measurements, optical pulse stretchers and reduced laser power were used to avoid optical breakdown at the probe volume, where a combined energy of 1 J/pulse at 532 nm was focused by a lens with a focal length of 500 mm to a projected beam waist of ~200 μm as determined from the width at $1/e^2$ from the Rayleigh scattering image. Laser energy fluctuations were monitored using a thermoelectric joule meter. The precision in the Rayleigh temperature measurement vary between 0.25% and 1% for room and flame temperatures, respectively.

The emitted Raman, Rayleigh, and CO-LIF light is collected with a combination of f/2 and f/4 achromats and focused into a custom spectrometer as described in [11]. Within the spectrometer, the Raman, Rayleigh, and CO-LIF signals were separated by dichroic beam splitters. In order to reduce the crosstalk of depolarized broadband and C_2-fluorescence interferences and chemiluminescence, the Raman-scattered light passed through a thin-film polarizer before dispersion via a high-transmission grating (1200 lines/mm). A low-noise cryogenically-cooled CCD camera (Roper Scientific, VersArray 1300) in conjunction with custom-built rotating wheel shutters, were used to collect the dispersed Raman signals from 550–700 nm with exposure times as short as 3.9 μs (FWHM). The data was acquired using spectral and spatial hardware on-chip binning to decrease camera readout noise and readout time [10,12]. In the spatial direction a 10-pixel on-chip binning was applied, yielding sixty spatial Raman superpixels along the line segment with a spatial resolution of 102.6 μm/pixel. The images were processed using the hybrid matrix inversion method with extensions for processing DME-data as outlined in [4,3,10]. One laminar flame calculation was used to derive Raman response and crosstalk curves and a temperature-dependent Rayleigh scattering cross section model to account for DME decomposition into smaller hydrocarbon molecules which were not measured separately. This adds additional uncertainties to the species and temperature measurements with a peak uncertainty around 1400 K as shown in [4,3]. For example, the uncertainty in the temperature measurement around 1400 K is increased from ±2% to ±5%. Air, cold gases diluted with nitrogen, and laminar methane/air flat flames were used for calibration of species signals and temperature.

Piloted turbulent DME/air jet flames, as introduced previously by Frank and coworkers [5,6], with a stoichiometric value of the mixture fraction of $\xi_{st} = 0.35$ were investigated in the burner configuration of the Sydney/Sandia piloted flame series A–F [8,13–17]. The inner diameter of the main jet tube was measured as $d = 7.45$ mm, the pilot annulus inner and outer diameter were 8 mm and 18.2 mm, respectively, and the co-flow was 25.4 cm × 25.4 cm. In the current work, results of DME flame D and F are presented. Table 1 gives the unburnt gas compositions for the main jet, pilot, and co-flow. Table 2 gives the operating conditions (bulk velocity and Reynolds number) of the main jet, pilot, and co-flow for the two flames. Pilot flows of C_2H_2, H_2, air, CO_2, and N_2 are selected to match the product composition and temperature of a premixed DME–air flame at 0.6 equivalence ratio, but with higher flame speed.

Laminar flame calculations were conducted using CHEM1D [18–21] and the DME reaction mechanism from Zhao et al. [22]. Experimental results are compared to calculations at two strain rates based on the equal Lewis number assumption (Le = 1) for all species. For all comparisons mixture fraction was derived consistently from species mole fractions for both the experimental data and the calculations. The important interme-

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