Development of two-beam fs/ps CARS for high-fidelity thermometry in flames

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Advanced optical diagnostics are important tools for quantitative combustion analysis

1. Validation/development of a model require multi-parameter diagnostics

2. Parameter determination in reacting flows (e.g. temperature, flow-field and species)

3. Measurement challenges
   Spatial / temporal / spectral resolution – data acquisition

\[ \Delta t \rightarrow \quad t \sim \mu s \]

\[ x \quad \lambda \quad y \]

Temperature maps
Large Eddy Simulation

Advanced optical diagnostics are important tools for quantitative combustion analysis
Why use CARS for flame diagnostics?

- Most accurate technique for **thermometry** in reacting flows (wide range of operational conditions).

  ![Graph showing true temperature vs evaluated temperature with error bars](image)

  - Inaccuracy ~2-3%
  - Single shot precision ~4-5%

- Nanosecond CARS characteristics:
  - Non-intrusive, in-situ probe
  - High temporal resolution (~10 ns)
  - High spatial resolution (~100 µm x 100 µm x 1-2 mm)

- Vibrational CARS, Rotational CARS

  ![Energy level diagram of N2](image)

  - Fractional population for T=300 K and T=1700 K
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- Two-beam femtosecond/picosecond CARS
  - Picosecond temporal resolution
    (Near collision independent - Raman linewidths)
  - Improved spatial resolution
    (40 µm x 40 µm x 0.5 mm)
  - 1D and 2D imaging capabilities

Inaccuracy < 2-3%
Single shot precision ~1%

Inaccuracy ~2-3%
Single shot precision ~4-5%
Two-beam femtosecond/picosecond CARS

Energy conservation

Phase-matching (momentum conservation)

Spectroscopy in the time-domain

Laser driven transitions (Q and S)

Molecular internal energy levels

Vector mismatch

\[ \Delta k = k_{\text{physical}} - k_{\text{geometrical}} > 0 \]

Beam crossing angle (\( \theta \))

All parallel beams

Raman shift

Molecular response

fs Stokes

fs pump

ps probe

0

Time delay / ps

Simplified generic phase-matching-scheme for CARS signal generation
Direct coherent Raman temperature imaging and wideband chemical detection

- Canonical sooting hydrocarbon flat-flame used to benchmark the new techniques.

 Burner design (Michelsen group, Sandia)
Motivation
Flame-wall interaction plays a key role in the formation of pollutants in a combustion chamber, such as UHC and CO.
CARS imaging of flame-wall interaction
- Temperature contour mapping at side-wall quenching burner

- Motivation
Flame-wall interaction plays a key role in the formation of pollutants in a combustion chamber, such as UHC and CO.
Near-wall ultrabroadband CARS imaging: Measurement of thermochemical states

Simultaneous detection of $\text{N}_2$, $\text{O}_2$, $\text{H}_2$, (CO), $\text{CO}_2$, and $\text{CH}_4$ is achieved.

The excellent imaging resolution allows for thermochemical states of the thermal boundary layer to be probed to within $\sim 40 \, \mu\text{m}$ of the interface.

*In-situ* measurement of pressure broadening coefficients
FWI at enhanced turbulence intensities
(Work-in-progress)

Turbulence generating grid (blockage 45%, turbulence level $u'/\bar{u} = 6-7\%$), V-flame operating in the wrinkled flamelet regime

- Single-shot spatially dependent statistics of the 1D flame-front gradient / thickness / position become possible (improving heat transfer models)
Single-shot hyperspectral CARS in the gas-phase

Temperature imaging

Wideband chemical imaging

Probe

Mask

Relay imaging

Beam stop

Plate polarizer

CCD

Diffraction grating

Pump/Stokes

Cylindrical lens

Split mirror

Imaging lens

TUDelft

Sandia National Laboratories
Dispersive Fourier Transform for MHz detection of CARS/CSRS signals

- CARS (~300 cm\(^{-1}\))
- Fast read-out in time
- 90 ps fwhm
- 1 km single-mode optical fiber

Graphs showing intensity over time for N\(_2\) and H\(_2\).
Synchronized ps/fs laser system for time-resolved non-linear optical spectroscopy/microscopy

- Femtosecond laser (ultrafast amplifier)
  7 mJ/pulse @ ~780-810 nm (~35 fs)
- Picosecond laser (SHBC)
  2.0 mJ/pulse @ 400 nm (~10 ps)

Distributed auto-ignition combustion modes with reduced NOx emission

Current activities at TUD: “Ultrafast Laser Diagnostics in Renewable Aero-Propulsion”
Conclusions

• Two-beam femtosecond/picosecond CARS
  - Relevant for 0D, 1D, and 2D temperature measurements in flames when high-fidelity information is needed (inaccuracy <2-3%, precision ~1%)
  - Single-shot quantitative measurements for major species in combustion are within reach (species specific dephasing times, spectroscopy models)

• This ultrafast 1D-CARS technique has been successfully employed at:
  1. Flame-wall interaction burner (head-on and side-wall quenching)
  2. Sooty flames provided on a McKenna burner

• Can this advanced laser diagnostics technique be employed for measurements in engines?
  - Technical challenges for the stability of operation (facility temperature and humidity control, propagating TL-beams through optical ports)