Tunable Diode Laser Sensors for Monitoring Combustion and Gasification Systems

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1. Fundamentals of TDL absorption sensing
2. TDL sensing for coal gasification
   - T and H₂O sensing*
   - CO, CO₂, CH₄, H₂O sensing**
3. Monitor of syngas heating value

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My main message today is that:
TDL Absorption is Practical in Harsh Environments

- Utilizes economical, robust and portable TDL light sources and fiber optics
- Can yield multiple properties: species, T, P, V, & m in real-time over wide conditions
  - T to 8000K, P to 50 atm, V to 15km/sec, multiphase flows, overcoming strong emission, scattering, vibration, and electrical interference
- Demonstrated in harsh environments and large-scale systems:
  - Aero-engine inlets, scramjets, pulse detonation engines, IC engines, gas turbines arcjets, shock tunnels, coal-fired combustors, rocket motors, furnaces….
- Potential use in control of practical energy systems

Coal-fired Utility Boiler
IC-Engines @ Nissan
Coal Gasifier @ U of Utah

Chao, Proc Comb Inst, 2011
Jeffries, SAE J. Eng, 2010
Jeffries, Pittsburgh Coal Conf, 2011
Absorption Fundamentals: Species

Absorption of monochromatic light

- Scanned-wavelength line-of-sight direct absorption
  - Beer-Lambert relation \( \tau_v \equiv \frac{I_t}{I_o} = \exp(-k_v \cdot L) = \exp(-n_i \cdot \sigma_v \cdot L) \)
  - Spectral absorption coefficient \( k_v = S(T) \cdot \Phi(T, P, \chi_i) \cdot \chi_i \cdot P \)
Absorption Fundamentals: Velocity

- Shifts & shape of $\Phi$ contain information $(T, V, P, \chi_i)$

\[ \Delta v \propto v \frac{V}{c} \]
Absorption Fundamentals: Temperature

- $T$ from ratio of absorption at two wavelengths

\[ \tau_v \]

\[ v_1 \quad v_2 \]
Absorption Fundamentals: Multiplexed

- Wavelength multiplexing is often utilized
  - To monitor multiple parameters or species
  - To assess non-uniformity along line-of-sight
TDL Sensors Provide Access to a Wide Range of Combustion Species/Applications

- Small species such as NO, CO, CO\textsubscript{2}, and H\textsubscript{2}O have discrete rotational transitions in the vibrational bands.
- Larger molecules, e.g., hydrocarbon fuels, have blended features.

Two primary TDLAS sensor strategies:
Two Absorption Measurement Techniques: Direct Absorption (DA) & Wavelength Modulation Spectroscopy (WMS)

- Direct absorption: Method of choice when applicable
- WMS: More sensitive especially for small signals (near zero baseline)
  - WMS with TDLs improves noise rejection
  - 1f-Normalized WMS-2f/1f: Provides \( I_o \) without a baseline
High P, T Sensing Enabled by WMS

- **High P, T challenges**
  - Broad and blended spectra at high P
  - Decreased absorbance at high T

![Simulated Absorbance Spectra](image)

Simulated Absorbance Spectra

- 2500 K
- 12% H$_2$O

**Solution**

- **1f-**Normalized WMS-2f
  - Recovers strong peaks
  - No baseline $I_0$ needed!
  - Also suppresses noise and transmission losses

![Simulated WMS Spectra](image)

Simulated WMS Spectra

- 2500 K
- 12% H$_2$O
- 25 atm
WMS-2f/1f Accounts for Non-Absorption Losses

- Fixed λ WMS-2f/1f
- Ambient H₂O (T=296 K, 60% RH)
- L=29.5 cm, ~6% absorbance

Demonstrate normalized WMS-2f/1f in laboratory air
- 2f/1f unchanged when beam attenuated (e.g., scattering losses)
- 2f/1f unchanged when optical alignment is spoiled by vibration

WMS-2f/1f signals free of window fouling or particulate scattering

WMS has other advantages too
Sensing with Large Transmission Losses from Scattering Enabled by WMS

Transmission of laser light at non-absorption wavelengths

- Measurement in syngas product line before particulate filtering
  - Particulate loading increases with pressure (99.9% loss at 150psig)
  - Varies with gasifier performance, fuel, temperature, etc.

**Solution:** Stanford’s 1f-normalized WMS-2f scheme

What might we measure in syngas?
Vision: Sensor for control signals to optimize gasifier output and gas turbine input

Goals:
- Two flow parameters considered: gas temperature and heating value
  - Gas temperature determined by ratio of H\textsubscript{2}O measurements
  - Measurements of CO, CH\textsubscript{4}, CO\textsubscript{2}, and H\textsubscript{2}O provide heating value
    - H\textsubscript{2} determined by gas balance as other species ignored
- Four measurement stations considered: spanning reactor core to products
Oxygen-blown, Down-fired, Entrained-flow Coal Gasification Facility at the University of Utah

Pilot scale gasifier

- Rated to 450 psig
  - Current data to 200 psig
- Rated to 3100 °F
- Coal throughput: 1 ton/day
- Overall dimensions
  - 5.1 m (17’) tall
  - 0.76 m (30”) OD
- Reactor dimensions
  - 1.5 m (60”) long
  - 0.20 m (8”) ID

- Four measurement campaigns to test Stanford TDL sensors:
- Ideal facility for instrumentation testing:
  - Rapid transition from 1 atm flame to 20 atm gasification conditions
  - Reactor kept hot with 1 atm natural gas flame between runs
Sensor Setup in Utah Gasifier: T and H$_2$O

Two reactor locations tested
- Position 1: Reactor core
- Position 2: Quench location
Two reactor locations tested
- Position 1: Reactor core
  - Highest T
  - Largest scattering losses
  - Emission interference
  - Time limited by slag flow
  - Successful measurements demonstrated
Transmission at 50 psig 0.13% dropping to 0.02% at 150 psig
  - Normalization scheme successful
  - Very strong optical emission - optical filtering scheme successful
- Optical access tube successfully stayed open in presence of flowing slag
  - Later unsuccessful with different coal (and different atomizer)
Temperature in Reactor Core

- Normalization scheme successful with low transmission (< 0.02%)
- TDL sensor time response can capture flow changes
Sensor Setup in Utah Gasifier: T and H₂O

Two reactor locations tested

- Position 2: Quench location
  - Modest purge flow keeps windows clean
  - Lower T – different line pair
    - Amplifier available
    - Increase power x10
  - Successful measurements even with 10⁻⁵ attenuation
Normalized WMS accounts for varying transmission ($10^{-3}$ at 160 psig)

- Measured $T$ at reactor pressures of 90, 120 and 160 psig stable
- Measured $T$ at 200 psig identifies potential fuel/O$_2$ input instabilities
Temperature @ Quench Location

- Different gasifier conditions, different coal, more particulate scattering
- High SNR, time-resolved measurements of $T$ using fiber amplifier
  - Less than $10^{-5}$ of the laser light transmitted

Location 2, $P \sim 200$psig
Transmission $\sim 7 \times 10^{-6}$
- CO, CO$_2$, and CH$_4$ lasers use lasers 2-2.3 $\mu$m
  - Fiber technology less available
  - TDLs controlled remotely but located near measurement
- Syngas can by-pass sensor location for window maintenance
- Similar setup before and after particulate filter (similar results)
- Multiple-lasers directed through one window
  - Rapid (10 Hz) switching from one species to another
  - Time-resolution ~1/3 second
Laser absorption measurements of CO, CO$_2$, H$_2$O and CH$_4$ over 1 hour
CH$_4$ added to syngas to test sensor response and vary gas composition
Gasifier feed rates changed to test sensor response
Syngas Composition Including N₂ and H₂

- N₂ in flow from gas purges – determined by metering and GC data
- Assume the rest of the syngas is H₂
  - Enables determination of lower heating value (LHV)
One hour time record of syngas lower heating value (LHV)

- CO, CO₂, CH₄ and H₂O from TDL sensor and N₂ from facility data
- Assume balance of syngas H₂
- LHV contribution of small concentrations of H₂S and NH₃ are estimated to be less than 2% (accounted as H₂)
Summary

- A novel modulation strategy enables measurements in high pressure environments with extinction by scattering
  - Scheme validated for extinction as large as $10^5$
- Sensor demonstration measurements made in four locations of a pilot-scale, entrained-flow, coal gasifier
  - Time-resolved measurements capture small changes in gasifier operating conditions
- Current work focused on sensor validation and demonstration

Next Steps:
- Transition sensor to real-time for continuous unattended monitoring
- Add $\text{H}_2\text{S}$ and $\text{NH}_3$ to sensor suite
- Package next-generation sensor for industrial-scale applications (test Utah?)
- Find suitable industrial-scale demonstration opportunities

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