Tunable Diode Laser Sensors to Monitor Temperature and Gas Composition in High Temperature Coal Gasifiers

Professor Ronald K. Hanson, Dr. Jay B. Jeffries, and Kai Sun
High Temperature Gasdynamics Laboratory, Dept. of Mechanical Engineering, Stanford University

Professor Kevin J. Whitty and Randy J. Pummill
Institute for Clean and Secure Energy, The University of Utah
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- Vision for tunable diode laser (TDL) sensors
- Goals
- Challenges
- University of Utah sensor test bed
- Stanford sensor concept
  - TDL fundamentals
  - Prior measurements reduce risk
- Proposed work plan
- Current status
Vision and Goals for TDL Sensing in IGCC

**Vision:** Sensor for control signals to optimize gasifier output and gas turbine input

**Goals:**
- Two control signals investigated: gas temperature and heating value
  - Measurements of CO, CH₄, CO₂, and H₂O provide heating value
    - H₂ determined by gas balance and H₂S ignored
    - Gas temperature determined by ratio of H₂O measurements
  - Four sensor locations investigated: (1) reactor core, (2) pre-quench, (3) post-quench, and (4) post-particulate clean-up
  - Locations 1 & 2 yield faster control, but have the biggest challenges
Challenges to TDL Sensing in Coal Gasification

- Gasifier pressure, temperature, particulate, and slag present window difficulties
  - Successful preliminary measurements in Utah fluidized bed reactor provide guidance for next generation window design
  - Fiber-coupled lasers require modest clear aperture
  - Stanford modulation schemes can accommodate time varying window transmission

- High pressure broadens spectral features making absorption difficult
  - Prior success for high-pressure measurements in IC engines, laboratory gas cells, and behind shock waves provides design criteria for modulation schemes (reduces risk)

- Particulate scattering attenuates laser transmission making absorption difficult
  - Prior success in Utah fluidized-bed reactor provides proof-of-concept

Prior work reduces risk, but gasifier has a unique environment: Hence demonstration measurements in large-scale gasifier at Utah are crucial to research effort
University of Utah Gasification Facility

Pressurized Fluidized Bed Gasifier

Pressurized Entrained-Flow Gasifier
University of Utah Entrained-Flow Gasifier

- Max. 450 psi
- Max. 3100 °F
- Throughput (coal)
  - 1 ton/day
  - 0.4 MW
- Overall dimensions
  - 17 feet tall
  - 30 inch vessel
- Reactor dimensions
  - 8 inch ID
  - 60 inch length
- Analytical
  - Continuous analyzer for H₂/CO/CO₂/CH₄
  - GC for 18 gases
Sensor Locations

- **Location 1**
  - Reactor “core”
  - ~2600°F / 250 psi
  - Molten slag

- **Location 2**
  - Pre-quench
  - ~2000°F / 250 psi
  - No slag blockage

- **Location 3**
  - Post-quench
  - ~250°F / 250 psi
  - Possible particles

- **Location 4**
  - Post filter
  - ~200°F / 250 psi
  - Particle-free
Stanford Has Long History of Successful TDL Measurements in Harsh Environments

- Utilizes cheap, 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
- Proven in harsh environments and large-scale systems:
  - Aero-engine inlets, scramjets, pulse detonation engines, IC engines, arcjets, gas turbine combustors, shock tunnels, coal-fired combustors, rocket motors,….
- Potential use in control of practical systems

IC-Engines @ Sandia NLL

SCRAMJET @ WPAFB
Rieker et al., *Applied Optics* 48 (2009)

PDE at NPS
Absorption Fundamentals: The Basics

- TDL absorption: non-intrusive, time-resolved line-of-sight measurements

  Fiber-coupled lasers are small and robust

  Visible & near-IR λ’s

  Multiplexed-lasers

  \[ \tau_{\nu} \equiv \frac{I_t}{I_0} = \exp(-k_{\nu} \cdot L) = \exp(-n_i \cdot \sigma_{\nu} \cdot L) \]

  Beer-Lambert relation

  Spectral absorption coefficient

  \[ k_{\nu} = S(T) \cdot \Phi(T, P, \chi_i) \cdot \chi_i \cdot P \]

  Wavelength-multiplexing for multi-parameters

  Ratios of two (or more) lines yield \( T \)

  \( T \) and \( \tau_{\nu} \) yield \( \chi_i \) (mole fraction) or \( n_i \) or \( \rho \)

  \( V \) from Doppler shift of spectra

  Mass and momentum flux from \( \rho \) and \( V \)

  Many-line data for non-uniform \( T(x) \), \( X_i(x) \)...

- Approaches: fixed \( \lambda \) and scanned \( \lambda \)
  - Direct absorption
  - WMS with harmonic detection
Absorption Fundamentals:
Direct Absorption & Wavelength Modulation Spectroscopy

- **Direct absorption**: Simpler, if absorption is strong enough
- **WMS**: More sensitive (x10 or more); better noise rejection
  - WMS-2f signal approximates 2\textsuperscript{nd} derivative of line shape at small modulation amplitude
  - Ratio of two WMS-2f signals provides T
  - Injection current FM produces intensity modulation @If \implies enables normalization
Measure ambient H₂O (T=296 K, 60% RH, L=29.5 cm, ~6% absorbance)

- Attenuate the beam by partial blocking: Normalized 2f/1f signal constant
- Attenuate the beam by mechanical vibration: Normalized signal constant
- Expect strategy to provide immunity from window fouling and particulate loading

Experiments Demonstrate WMS Normalization

1392 nm, Partially Blocking Beam

1392 nm, Vibrating Pitch Lens
Examples of Stanford TDL Sensing in Harsh, High-P, High-T Environments

- **IC-Engines**
  - Crank-angle-resolved measurements of temperature and EGR
    - T-sensing for HCCI research with Sandia National Labs
    - Development of WMS-based T-sensor for production engines
  - Crank-angle-resolved measurements of gasoline

- **Fluidized-bed gasification of black liquor (funded by EPRI)**
  - TDL absorption measurements in the presence of particulate
    - Successful measurements with 92% beam attenuation
    - Provides proof-of-concept for gasification application
  - TDL in the Utah fluidized-bed rig discussed below
Measurements in two ports investigated different types of particulate interference for the laser-absorption measurements:

- Lower port views the “splash zone” where optical transmission experiences time-varying interference as bed particulate (~200μm) splashes up and down in the beam.
- Upper port views the gasifier products where transmission is obscured by char particulate (~10μm).

EPRI funded proof-of-concept demonstration experiment.
Two lasers ($\lambda_1$ & $\lambda_2$) wavelength-modulated at 40 and 60 kHz respectively

- Signals detected @ 2f and 1f for each laser scanned at 2 kHz across H$_2$O absorption line
- Normalization of 2f by the 1f signal corrects each laser for scattering losses
- Temperature from the ratio of 2f/1f signals @ $\lambda_1$ & $\lambda_2$
- Concept tested with EPRI support in U Utah fluidized-bed gasifier

EPRI funded proof-of-concept demonstration experiment
Fiber-coupled lasers and electronics located in the control room
- Transmitted light collected onto a fiber to allow remote location of detector
- Two different diode laser detection strategies tested
  - Wavelength-scanned direct absorption
  - Normalized (1f) wavelength-modulation spectroscopy with 2f detection (WMS-2f/1f)

Just looking at the raw signals shows potential of TDL sensing

EPRI funded proof-of-concept demonstration experiment
Char particles made during gasification attenuate the transmitted signals by 92%.
Normalization of 2f by 1f signals recovers a quantitative WMS-2f signal.
Excellent SNR provides proof-of-concept for TDL sensing in highly scattering reactor environments.
Time record of temperature agrees well with facility thermocouple

Statistical temperature uncertainty used to characterize precision of sensor

TDL measurements on lower port without bed in nitrogen-diluted steam

Single-scan data at 2kHz (measurement time = 0.5ms)
- Temperature uncertainty increases with pressure for direct absorption
  - Less than 15K uncertainty at 2kHz for all pressures available with WMS-2f/1f
  - Wavelength modulation signal significantly less sensitive to pressure increase
- Potential to further increase signal-to-noise ratio by averaging (reducing bandwidth)

TDL measurements on lower port without bed in nitrogen-diluted steam

Single-scan data at 2kHz (measurement time = 0.5ms)
- Picture/movie shows cold flow model of fluidized bed
  - Large bed particles (200 μm) are splashing in the bed of the reactor
- This particulate bounces up and down through the beam, sometimes completely blocking the beam
- TDL data taken in actual fluidized bed reactor and 300 seconds of data is binned by transmission for analysis of T vs transmission

EPRI funded proof-of-concept demonstration experiment
Temperature Uncertainty With Particulate

Splash Zone

TDL measurements on lower port with bed fluidized by steam flow

Beam attenuated by scattering from bed particle splash

Single-scan data at 2kHz (measurement time = 0.5ms)

- Bed particle splash produces time-varying transmission (2kHz data rate)
- Wavelength modulation less sensitive to signal attenuation
- Signal binned by transmission, analyzed for temperature uncertainty
- Less than 15K uncertainty at 2kHz for >5% transmission with WMS-2f/1f
- Illustrates potential for WMS-2f/1f strategy for DoE gasifier measurements
Proposed DoE Work Plan

2010
- Design TDL sensors for H₂O and CO (SU)
- Design and fabricate optical access for pre-quench, post-quench, clean output (Utah)
- Validate H₂O and CO spectroscopic database (SU)
- Controlled environment sensor tests (SU)
- Field measurements at Utah with SU sensor for H₂O and CO (SU & Utah)
- Designs to extend the TDL sensor for methane and carbon dioxide begin (SU)

2011
- Validate CO₂ and CH₄ spectroscopic database (SU)
- Laboratory tests of gas composition (H₂O, CO, CO₂, and CH₄) (SU)
- Optical access for the reactor core will be designed and tested (Utah)
- The water and temperature sensor design will be finalized (SU)
- Initial field measurements for gas composition (H₂O, CO, CH₄, CO₂) (SU & Utah)

2012
- Optical access to the reactor core will be completed (Utah)
- Sensor design will be finalized (SU)
- Final field measurements of gas composition (heating value) & T (SU & Utah)
Progress & Current Status: Sensor Design

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>T</td>
<td>1500K</td>
<td>1200K</td>
<td>500K</td>
<td>500K</td>
</tr>
<tr>
<td>P</td>
<td>7-18 atm</td>
<td>7-18 atm</td>
<td>7-18 atm</td>
<td>6-17 atm</td>
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<tr>
<td>Path Length</td>
<td>20 cm</td>
<td>34 cm</td>
<td>5 cm</td>
<td>5 cm</td>
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<tr>
<td>CO</td>
<td>34%</td>
<td>34%</td>
<td>44%</td>
<td>44%</td>
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<tr>
<td>CH$_4$</td>
<td>1.6%</td>
<td>1.6%</td>
<td>2%</td>
<td>2%</td>
</tr>
<tr>
<td>H$_2$</td>
<td>20%</td>
<td>20%</td>
<td>26%</td>
<td>26%</td>
</tr>
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<td>H$_2$S</td>
<td>1.3%</td>
<td>1.3%</td>
<td>1.6%</td>
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<tr>
<td>CO$_2$</td>
<td>17%</td>
<td>17%</td>
<td>21%</td>
<td>21%</td>
</tr>
<tr>
<td>H$_2$O</td>
<td>26%</td>
<td>26%</td>
<td>6%</td>
<td>6%</td>
</tr>
</tbody>
</table>

Estimate gas composition, temperature, pressure and path length @ Utah
- Use this data to estimate relative contributions to lower heating value
- Use this data to simulate absorption spectra for sensor design
Progress & Current Status: Contributions to Lower Heating Value

Test locations 1& 2

<table>
<thead>
<tr>
<th>Species</th>
<th>LHV (MJ/kg\textsubscript{mixture})</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH\textsubscript{4}</td>
<td>0.556</td>
<td>7.7%</td>
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<tr>
<td>H\textsubscript{2}O</td>
<td>0</td>
<td>0%</td>
</tr>
<tr>
<td>CO\textsubscript{2}</td>
<td>0</td>
<td>0%</td>
</tr>
<tr>
<td>CO</td>
<td>4.247</td>
<td>58.6%</td>
</tr>
<tr>
<td>H\textsubscript{2}</td>
<td>2.162</td>
<td>29.8%</td>
</tr>
<tr>
<td>H\textsubscript{2}S</td>
<td>0.288</td>
<td>3.9%</td>
</tr>
</tbody>
</table>

Mixture LHV(MJ/kg): 7.253MJ/kg

Test locations 3 & 4

<table>
<thead>
<tr>
<th>Species</th>
<th>LHV (MJ/kg\textsubscript{mixture})</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH\textsubscript{4}</td>
<td>0.673</td>
<td>7.7%</td>
</tr>
<tr>
<td>H\textsubscript{2}O</td>
<td>0</td>
<td>0%</td>
</tr>
<tr>
<td>CO\textsubscript{2}</td>
<td>0</td>
<td>0%</td>
</tr>
<tr>
<td>CO</td>
<td>5.140</td>
<td>58.6%</td>
</tr>
<tr>
<td>H\textsubscript{2}</td>
<td>2.616</td>
<td>29.8%</td>
</tr>
<tr>
<td>H\textsubscript{2}S</td>
<td>0.350</td>
<td>3.9%</td>
</tr>
</tbody>
</table>

- TDL sensor measures CH\textsubscript{4}, H\textsubscript{2}O, CO\textsubscript{2}, and CO and assumes that H\textsubscript{2} is the balance of the gas (ignoring H\textsubscript{2}S and N\textsubscript{2})
  - Although H\textsubscript{2}S has 4% of the LHV assuming “balance” as H\textsubscript{2} results in an error for the gas mixture of only 0.3%
  - If N\textsubscript{2} is approximately known, similar errors in the LHV result
- Model calculations show that heating value can be monitored with TDL measurements of CH\textsubscript{4}, H\textsubscript{2}O, CO\textsubscript{2}, and CO
Progress & Current Status: Sensor Design

- Use HITRAN database to simulate the expected absorption signals

- At 500K there are many laser wavelengths where H$_2$O, CO, CO$_2$, and CH$_4$ can be detected with minimal interference

- Increase in pressure broadens the transitions, but still good separation between the different species
Progress & Current Status: Sensor Design

- Use HITRAN database to simulate the expected absorption signals

- At 1500K, H$_2$O and CO can be detected with minimal interference
  - H$_2$O in the bands near 1.4 $\mu$m and the bands near 1.8 $\mu$m
  - CO in the first overtone band near 2.3 $\mu$m

- Selection of laser wavelength for CO$_2$ and CH$_4$ must carefully avoid interferences
Progress & Current Status: Sensor Design

- Use HITRAN database to simulate the expected absorption signals

- Simulations show, H₂O is the major interference species

- There are gaps or “windows” in the H₂O where CO₂ and CH₄ detection should be possible

- Careful validation of the spectroscopic database is required (especially for H₂O in the region for CO₂ and CH₄ detection)
Progress & Current Status: Spectroscopic Database

- Laboratory measurements to validate spectral database
  - Three-zone furnace with quartz cell for measurements to 1500K
  - Measurements versus pressure (at low values) to determine spectral data
- Current status:
  - Lasers for H₂O and CO purchased and on-hand
  - Initial line selection for CH₄ and CO₂ complete
Progress & Current Status: Optical Access

- Sensor locations 3 and 4 (post-quench in piping)
  - Assessing optimum optical pathlength
  - Either “tee” (across pipe) or along length of pipe
  - Nitrogen purged sapphire window
    - Purge provides air curtain to avoid fouling
  - Developed technology – minimum fabrication time
- Sensor location 2 (pre-quench below reactor)
  - Use existing quench spray ports (two opposing)
  - Axially split spray lance to allow optical access in upper half and quench spray in bottom half
  - Optical pathlength (14” or 35.5cm)
  - Requires fabrication and testing
- Sensor location 1 (gasification reactor)
  - Modeling work planned to assess options to keep slag layer from blocking windows (fiber technology can minimize needed aperture)
  - Plan reactor modifications for opposing ports on the completion of the window design
  - Required for Year 3 experiments
Critical Milestones: TDL Measurements in Gasifier

Field measurements using Stanford sensor technology in Utah gasifier facilities

- 2010: Field measurements for H₂O and CO concentrations
- 2011: Initial field measurements for gas composition (H₂O, CO, CH₄, CO₂)
- 2012: Final field measurements of gas composition (heating value) & T