Time-resolved infrared imaging and spectroscopy for engine diagnostics

Volker Sick, Lucca Henrion, Ahmet Mazacioglu, Michael C. Gross
Department of Mechanical Engineering, University of Michigan
Contact: vsick@umich.edu
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What are the questions?

• Is radiative heat transfer important in spark-ignited engines?
  • How do we find out?

Ferreyo-Fernandez et al., Comb. Flame 2018
What are the questions?

• Can alternative ignition systems enable leaner HD NG combustion?
  • How do we find out?
Goals and objectives

• Develop high-speed infrared diagnostics to
  • Study radiative heat transfer in spark-ignited engines
  • Study ignition and flame kernel growth in a HD NG engine

• Identify spectral features

• Examine impact of ignition source in HD-NG engine
Radiative Heat Transfer
High-speed IR spectroscopy and imaging

- Spectrally resolved information
- Volume-integrated 2D imaging for flame kernel growth
Key IR emissions & detection issues

- CO$_2$ and H$_2$O emission good to track combustion
- Strongest peaks get attenuated by quartz windows
Time- and wavelength resolved data

- Full spectrum every CAD
- Continuously measured 100 cycle sequences
- Species-selectivity
- Cycle-to-cycle variation
TCC-III optical engine

• Research engine
• Free download of geometry, experimental data, CFD setup, ....
• https://deepblue.lib.umich.edu/data/collections/8k71nh59c?locale=en
Flame growth and spectral signatures

- 2D images of water radiation
- Flame growth
- Simultaneously recorded spectra provide more details
Spectra and images correlate well

- Spectrally-resolved data accurately reflect cycle-volume radiation
Pressure-based and spectral indicators

- Magnitude of radiative emission strongly varies through cycle
- Peak ~ MFB\textsubscript{90}
Spectral power as timing predictor

- Spectral power at fixed CAD
- Correlation with MFB\textsubscript{x}
Spectral power and IMEP

- Spectral power at TDC is an indicator for IMEP
Take-aways

• Experimental facility to measure infrared emission spectra
• Connected IR emissions to engine parameters
• Current work (Haworth et al.) addresses simulations and radiative trapping
Heavy-duty Natural Gas Engine
Improve Heavy-Duty NG Engines

• How can we burn leaner and more dilute?
• Investigate combustion limits for two ignition sources
  • Conventional inductive discharge spark system
  • Corona discharge system
Why endoscopic, why infrared imaging?

• Production engine
• High loads
• Short project duration
• OH* would be a good flame marker
  • Complexity/cost of setup of ultraviolet detection
• Visible light (CH*) is very weak
Six-Cylinder Weichai engine

- Top View
  - Camera 2
  - Borescope
  - Borescope Sleeves
  - Camera 1
  - Intake Manifold

- Right View
  - Camera 2
  - Borescope
  - Intake Port
  - Prop Shaft
  - Crankcase
  - Cooling Hose
  - Borescope Sleeves
  - Sleeve
  - Camera 1
  - Cooling Hose
  - Borescope
  - Pressure Transducer
  - Sleeve
  - Intake Manifold
Extracting information from images

- IR images binarized
- Flame area
- Radius of gyration

![Images showing extracted information]

Area: 4939
$r_{gyr}$: 32.5

Area: 4925
$r_{gyr}$: 40.7

Area: 8875
$r_{gyr}$: 40.4
Flame growth in the HD NG engine

- Endoscopic imaging access to cylinder #6
- Flame kernel growth (shape and rate) strongly depends on ignition source
Lean operation can be enhanced

- 1000 RPM, IMEP 6.8 bar
- Standard deviation of flame images connect to COV of IMEP

\[ \lambda = 1.0, \ 3\% \ EGR \quad \lambda = 1.6, \ 10\% \ EGR \]

<table>
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<th>COV:</th>
<th>0.3%</th>
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<td>λ=1.6, 10% EGR</td>
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Flame shape is important for lean case

- For lean combustion
  - Radius of gyration (shape) affects IMEP
  - Impact on flame spread
Early flame shape predicts MFB phasing

Conventional, $\lambda=1.6$, 10% EGR

Corona, $\lambda=1.6$, 10% EGR
IR imaging provides view into early flame development

- Cross-correlate $r_{\text{gyr}}$ from time of ignition to @ MFB\textsubscript{00.5}
- By MFB\textsubscript{00.5}, flame shape shows strong impact on timing
Take-aways

• Borescopic high-speed infrared imaging provides useful information
• Early flame kernel geometry is indicative of the fate of the cycle
• Large matrix of engine conditions currently under evaluation
Conclusions

• Demonstrated ability to measure radiative heat transfer properties with temporal, spectral, and spatial resolution

• Employed non-intensified high-speed borescopic IR-imaging to study why and how different ignition sources affect lean, dilute natural gas combustion in heavy-duty engine