Characterizing of Radiative Heat Transfer in a Spark-Ignition Engine through High-Speed Experiments and Simulations

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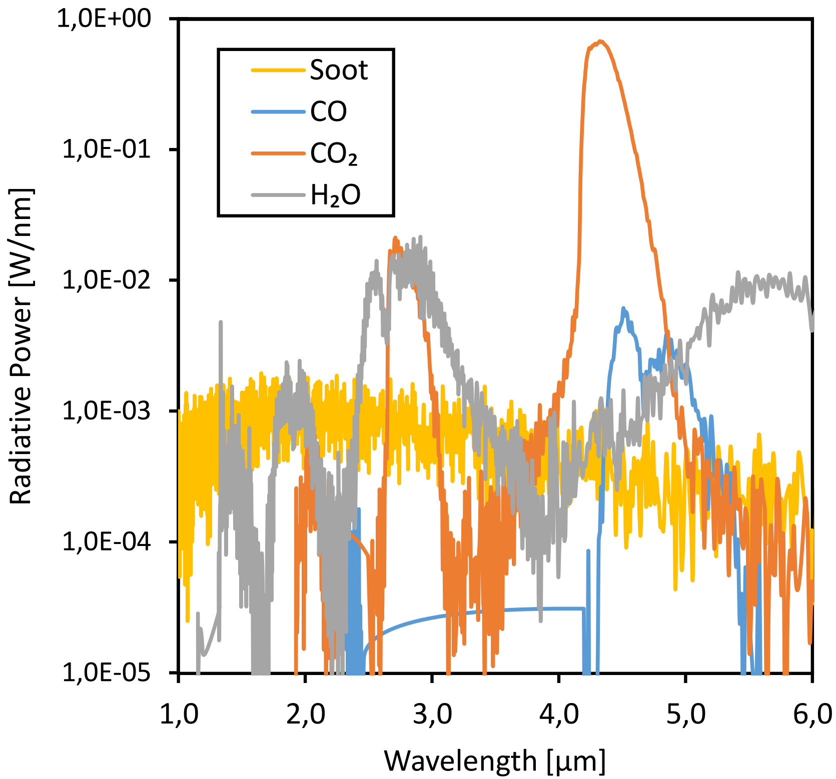
Radiative heat transfer

- Broadband soot radiation
- Modest *et al.* [1] and Fernandez *et al.* [2] have demonstrated need to study molecular radiation
- Molecular radiation occurs in the infrared (IR)

Molecules in combustion

- H_2O, CO_2, CO



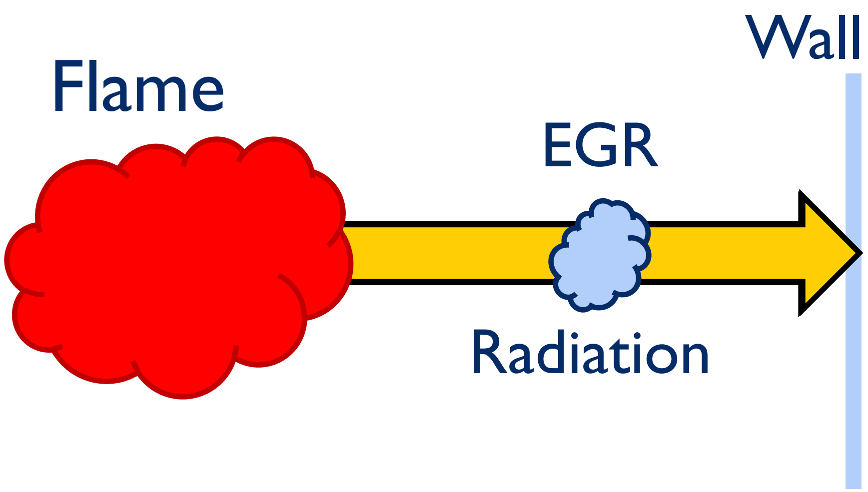
Simulated Diesel-engines emission spectrum [3], data provided by D. C. Haworth

[1] M. F. Modest. *Radiative Heat Transfer in Turbulent Combustion Systems: Theory and Applications*. 2015
[2] S. F. Fernandez, *Combust. Flame*, vol. 190, pp. 402–415, 2018.
[3] C. Paul. *U.S. National Combustion Meeting*, 2017, vol. 10.

Molecular radiation in engines

Reabsorption

- Energy redistribution
  - Change local conditions
- Exhaust gas recirculation
  - Burnt gas made of H_2O and CO_2
  - Radiative trapping [1]



Radiative Variance

- Multi-cycle experiments [2]
- Large eddy simulations [3]

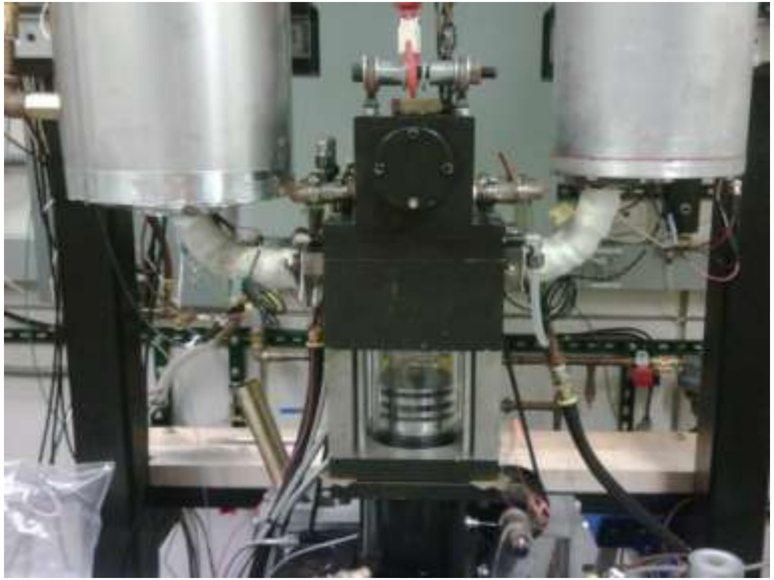
[1] M. F. Modest . *Radiative Heat Transfer in Turbulent Combustion Systems: Theory and Applications*. 2015.
[2] V. Sick, *13th AVL Intl. Symp. on Propulsion Diagnostics Proceedings*, 2018.
[3] Y. Shekhawat. *Oil Gas Sci. Technol.*, vol. 72, no. 5, 2017.

TCC-III Engine

- Third-generation Transparent Combustion Chamber (TCC-III) engine [1]
- Operated on stoichiometric and homogenous **propane - air mixture**
- Optical access provided through cylinder

Operating Conditions

- Engine ran at 1300 rev/min
- Spark at -18° aTDC
- Intake pressure 40 kPa, exhaust pressure 101.5 kPa

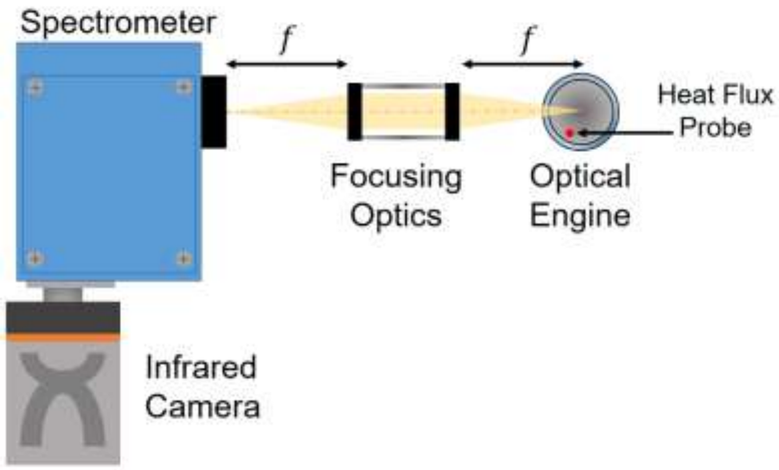


Courtesy of the TCC Engine Collection on the University of Michigan Deep Blue Data Archive [1]

[1] D.L. Reuss,TCC Engine Collection," *Deep Blue Data*. [Online].

Experimental setup

- Sensitive from 1-5.5 μm
- Windowed operating >4 kHz
- Spectral range up to 460 nm
- Spectral resolution of 2.43 nm/pixel
- Spectra captured every 2 CAD



Schematic of high-speed spectroscopy experimental setup (not to scale)

Simulation setup

LES simulations using STAR-CD

- 19 consecutive cycles
- Smagorinsky subgrid-scale turbulence model
- Modified thickened flame combustion model [1]
- Radiative heat transfer not considered

[1] Y. Shekhawat. *Oil Gas Sci. Technol.*, vol. 72, no. 5, 2017.

Radiation post-processing

- Emission obtained from HITEMP spectral database [1]

- 2 radiation models used for radiative reabsorption [2]

  - Photon Monte-Carlo method with line-by-line spectral resolution

  - Lowest order spherical harmonics method (a P1 method) with full-spectrum *k* distribution (P1/FSK)

[1] L. S. Rothman, *J. Quant. Spectrosc. Radiat. Transf.*, vol. 111, no. 15, pp. 2139–2150, 2010.
[2] C. Paul, *Combust. Flame*, vol. Accepted, 2018.

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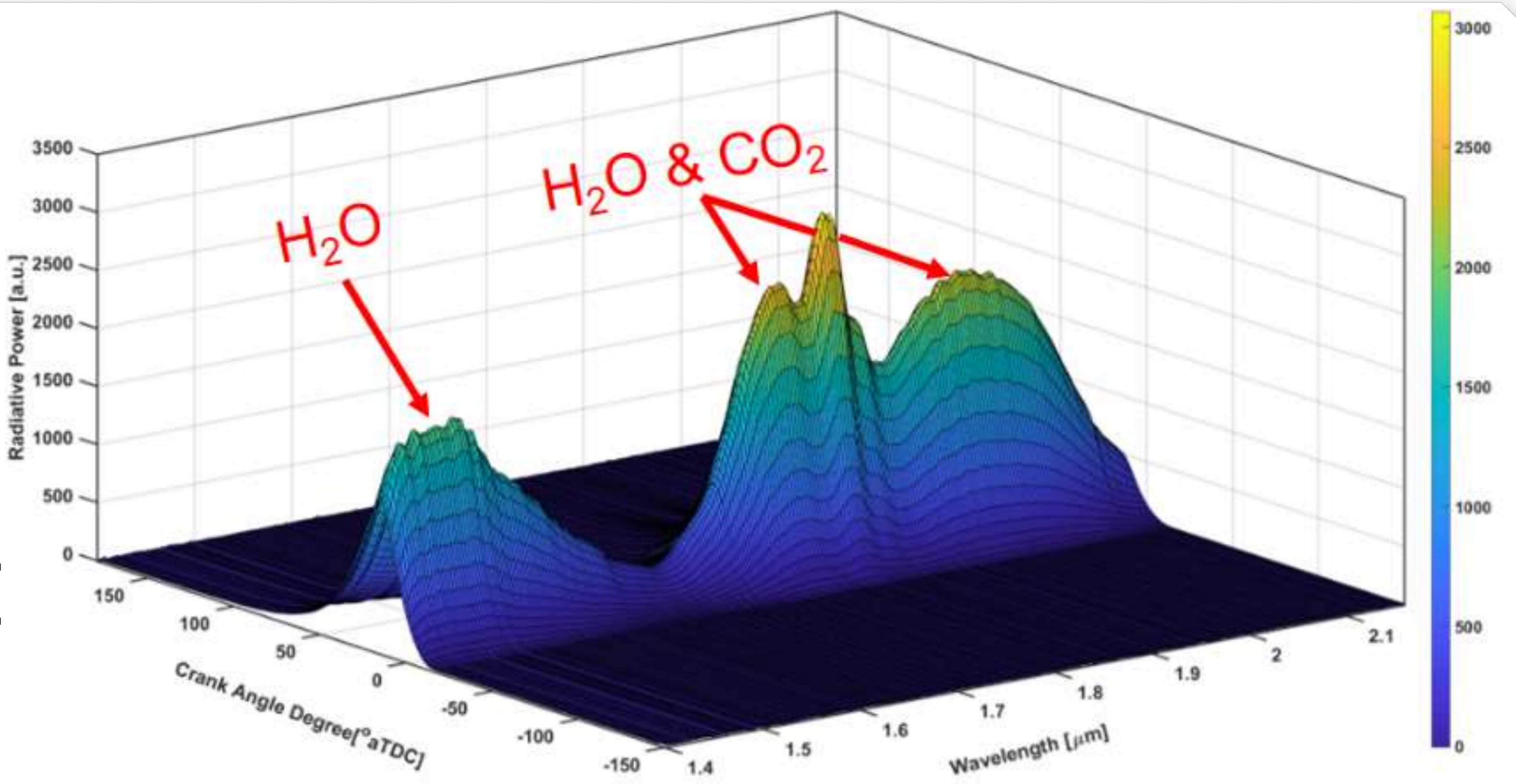


Radiative Power [a.u.]

1,4 1,5 1,6 1,7 1,8 1,9 2 2,1

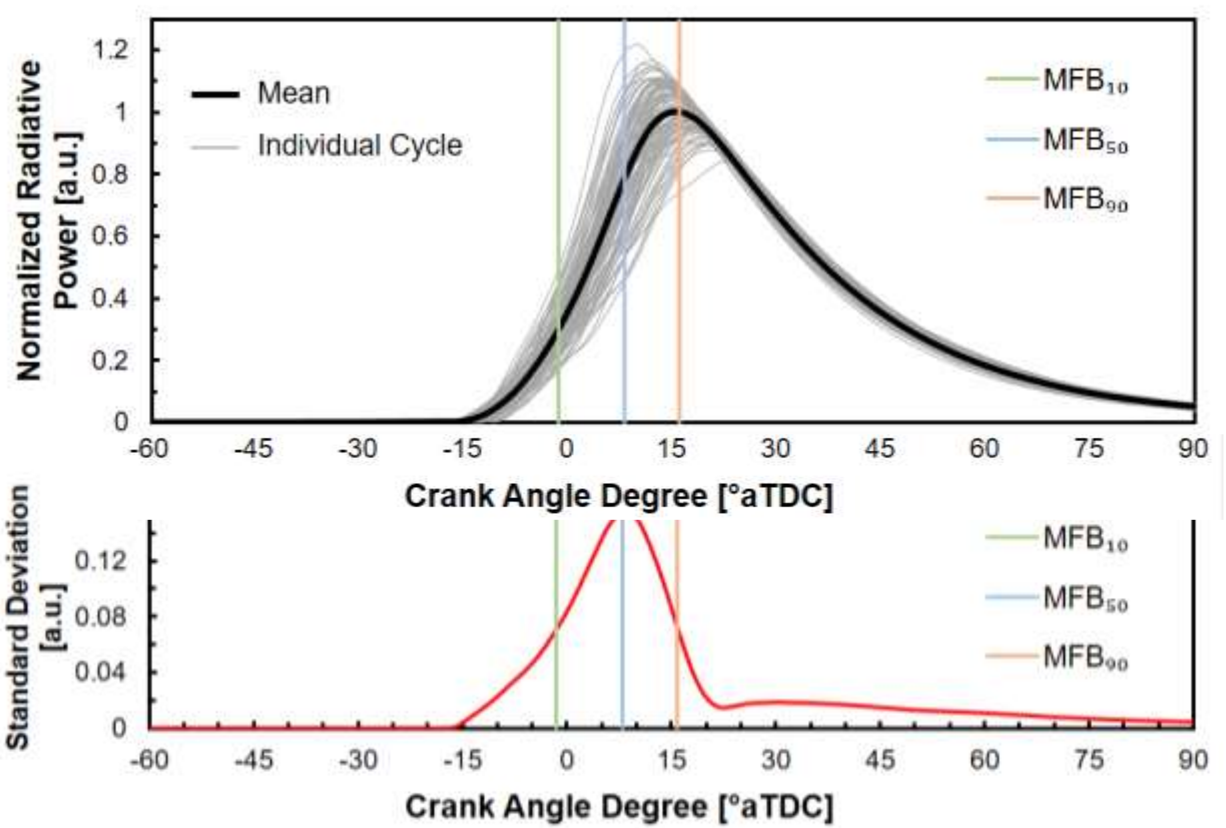
Crank Angle Degree [°aTDC]

Wavelength [μm]

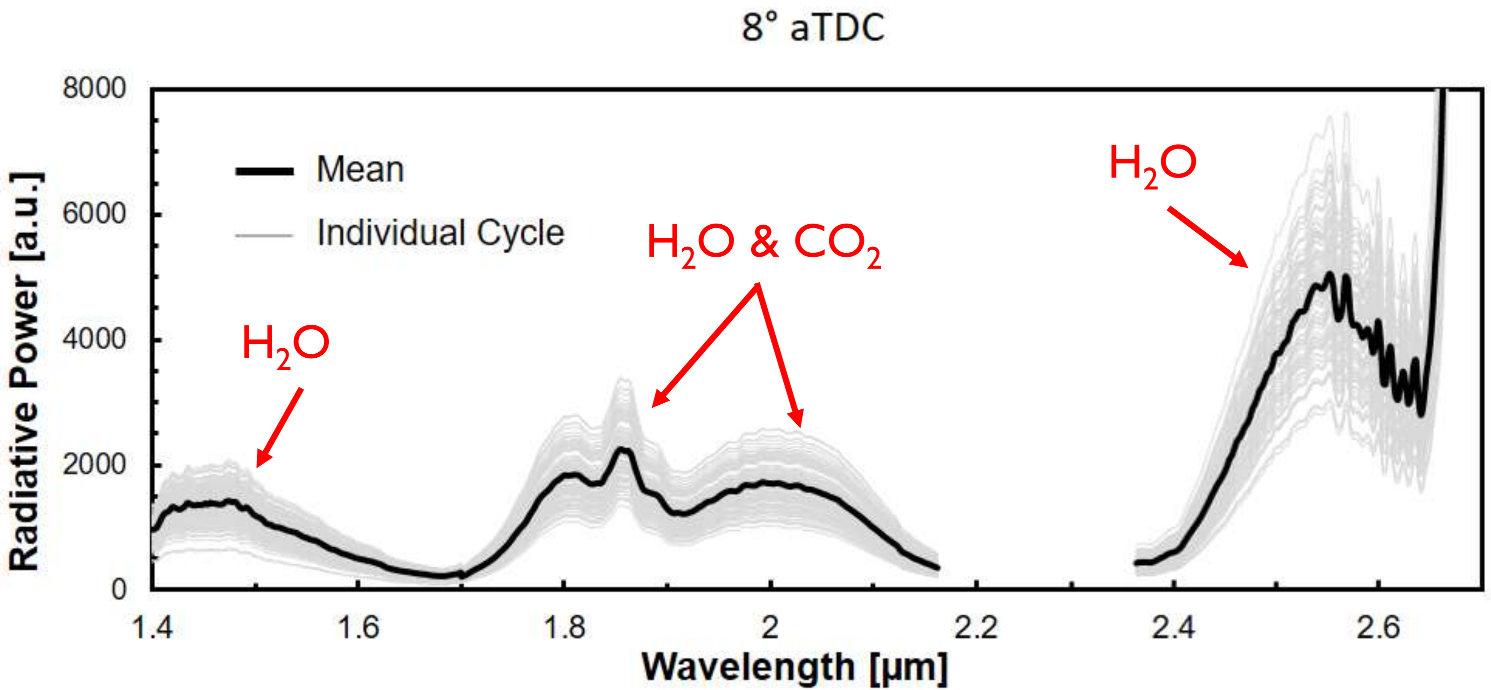
100-cycle ensemble-average of crank angle resolved net radiation

Radiative power peaks at MFB_{90}

Radiative variation peaks at MFB_{50}

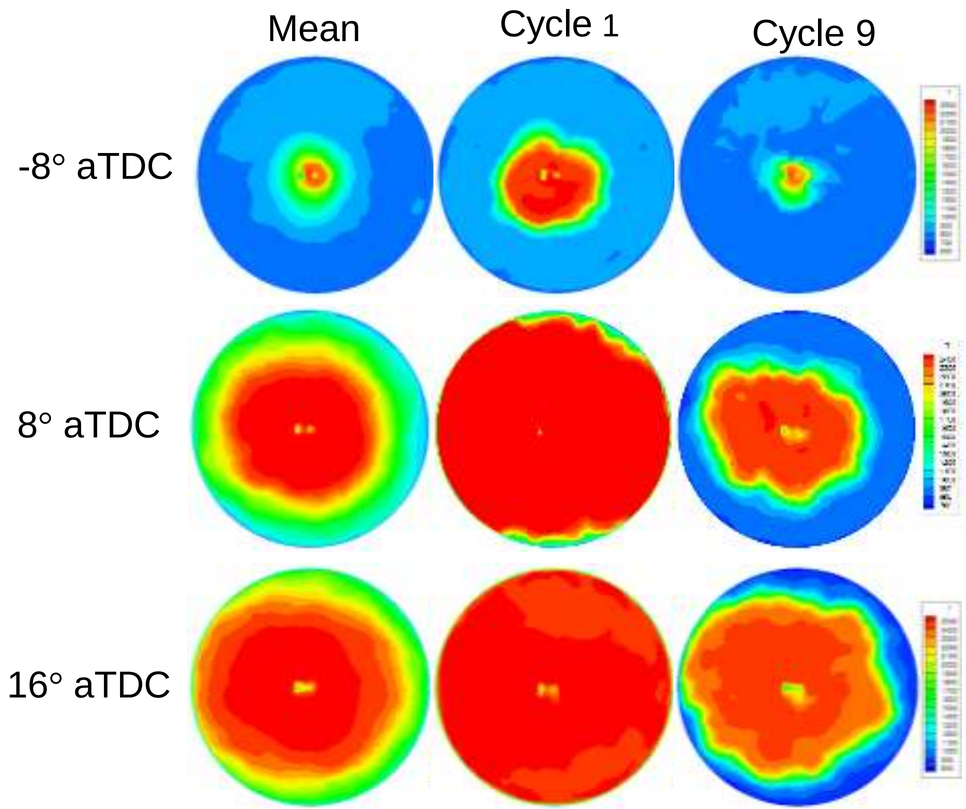


Spectral variation of radiation



Crank angles used for model assessment

Simulated cut planes

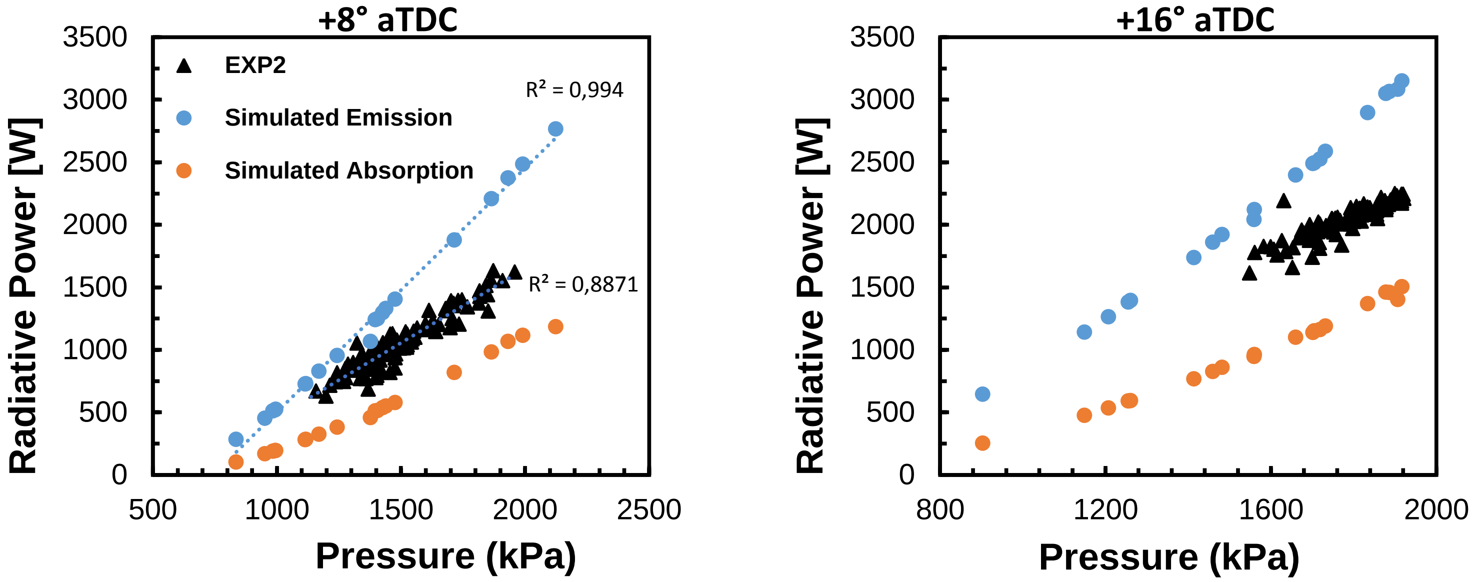


Unburned gas region

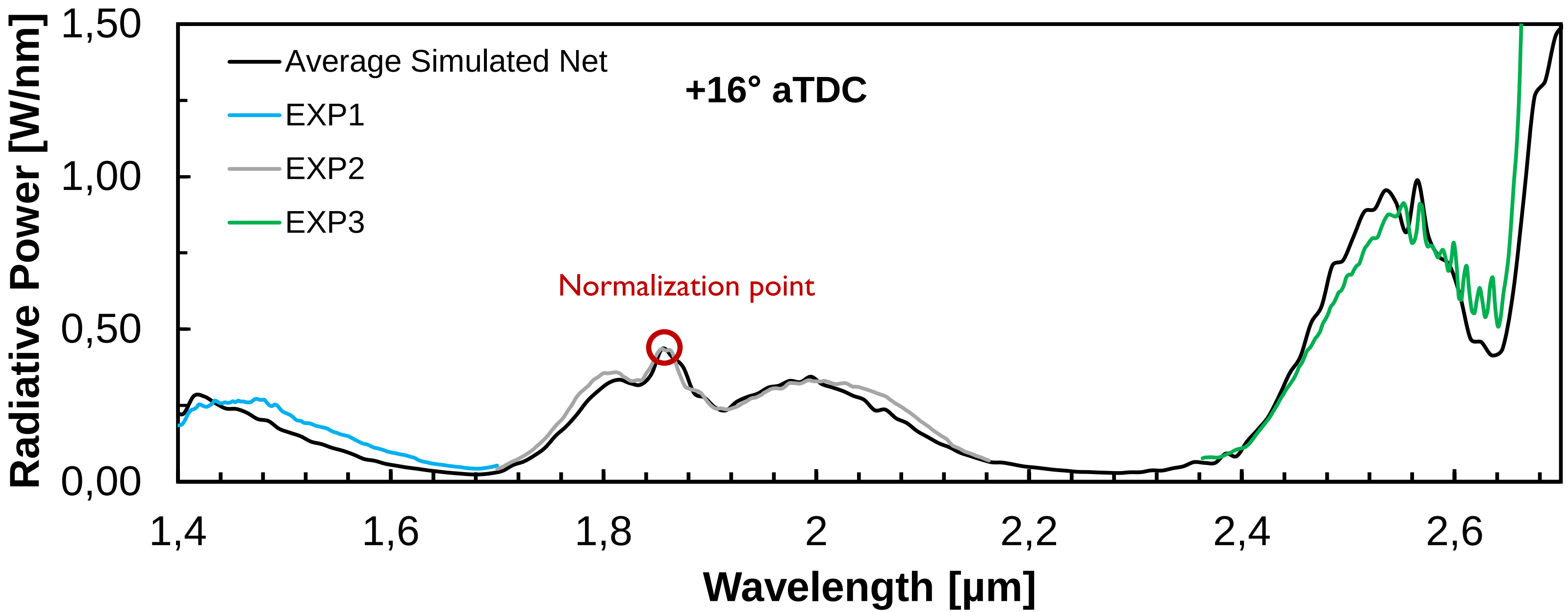
Near MFB_{50} and max radiative variation

Peak net radiation

High pressure cycles have higher radiative properties

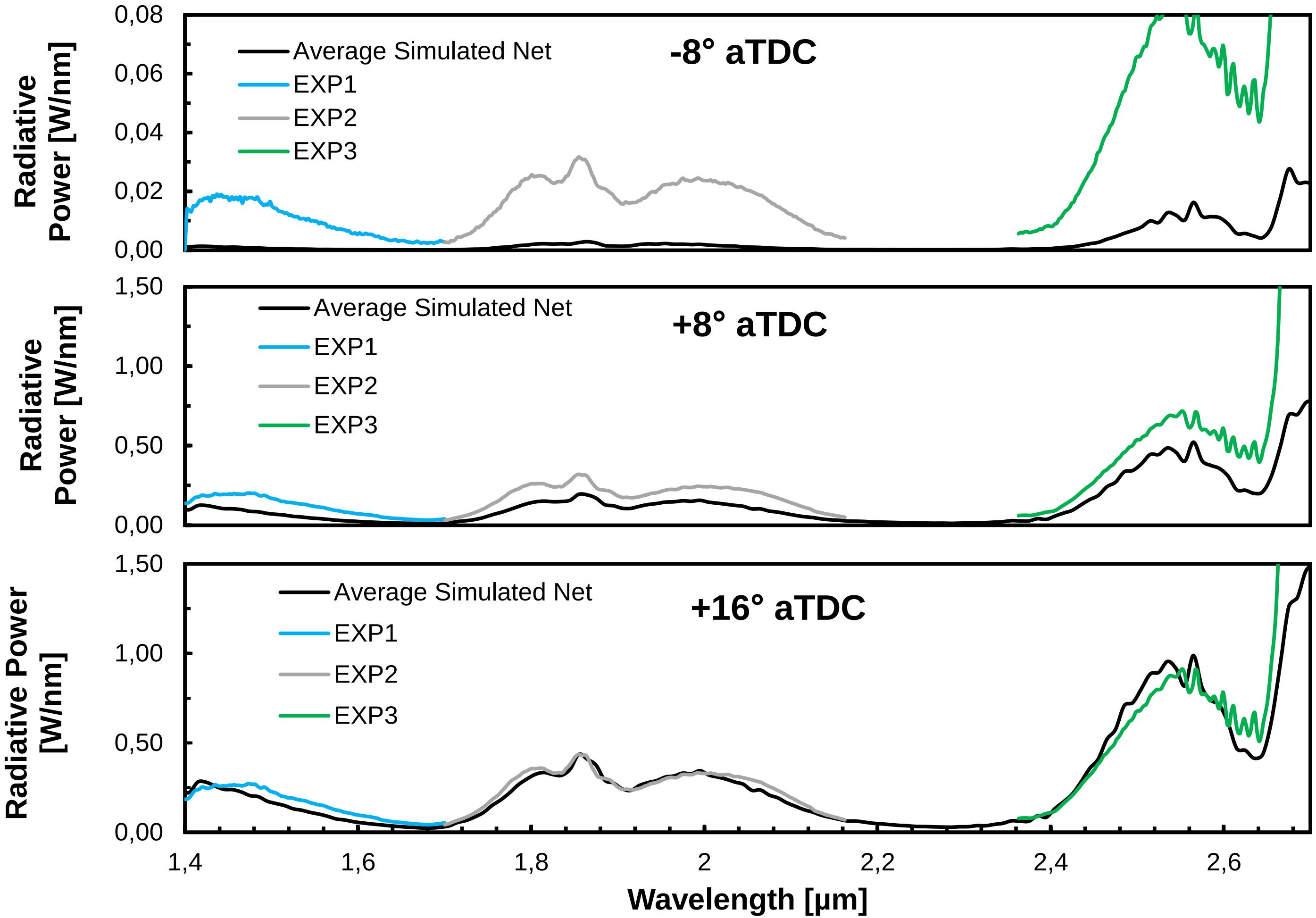


Simulations capture spectral details of radiative emissions



100-cycle average of three experimental locations (normalized)

19-cycle average of LES simulations

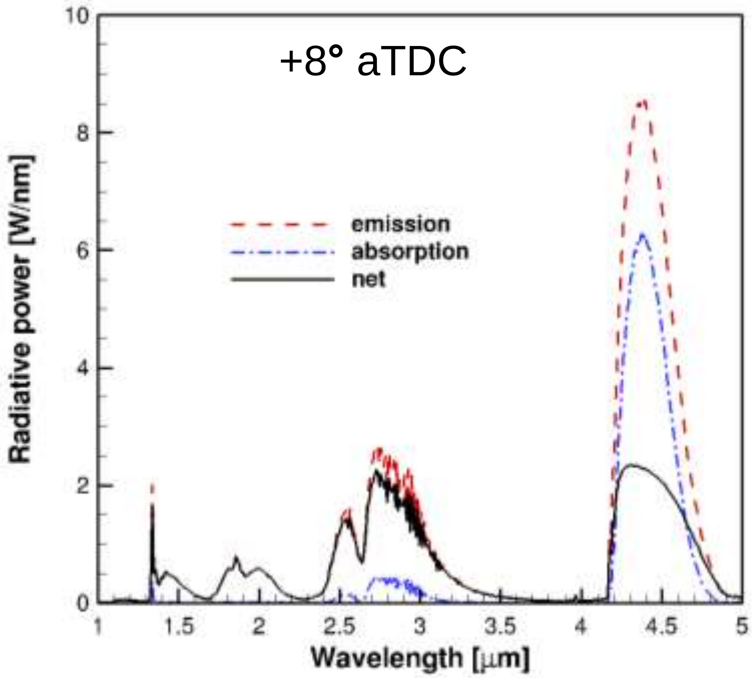


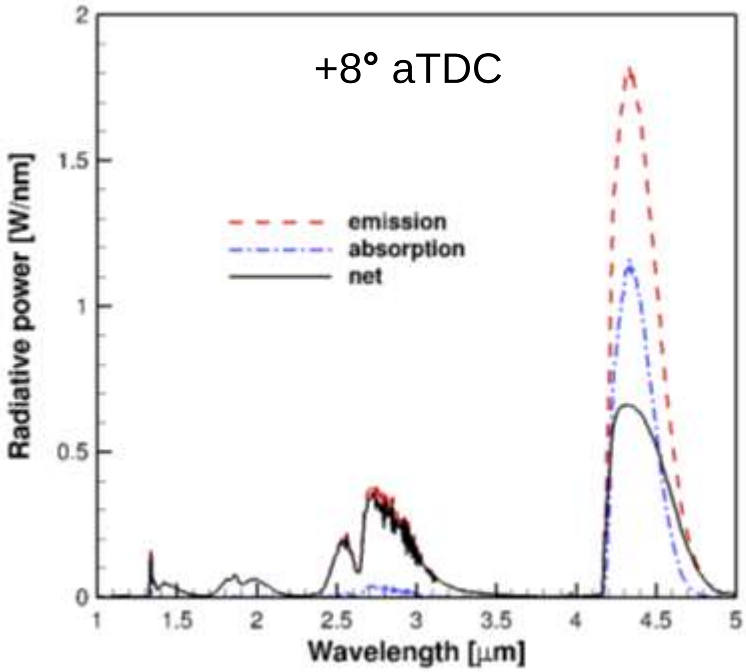
-8° aTDC
Average Simulated Net
EXP1
EXP2
EXP3
Radiative Power [W/nm]
0,08
0,06
0,04
0,02
0,00
+8° aTDC
Average Simulated Net
EXP1
EXP2
EXP3
Radiative Power [W/nm]
1,50
1,00
0,50
0,00
+16° aTDC
Average Simulated Net
EXP1
EXP2
EXP3
Radiative Power [W/nm]
1,50
1,00
0,50
0,00
1,4
1,6
1,8
2
2,2
2,4
2,6
Wavelength [µm]

Photon Monte Carlo spectral simulations

Cycle 1 (fast)

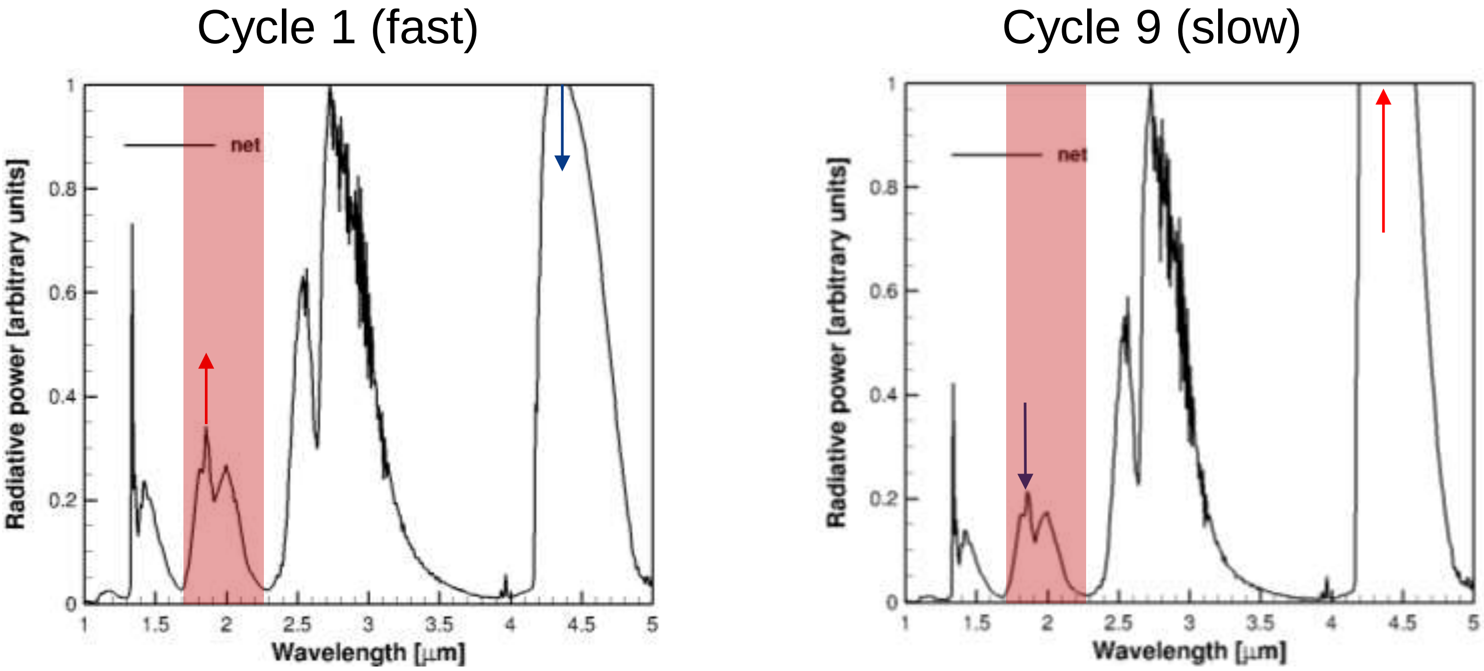
Cycle 9 (slow)





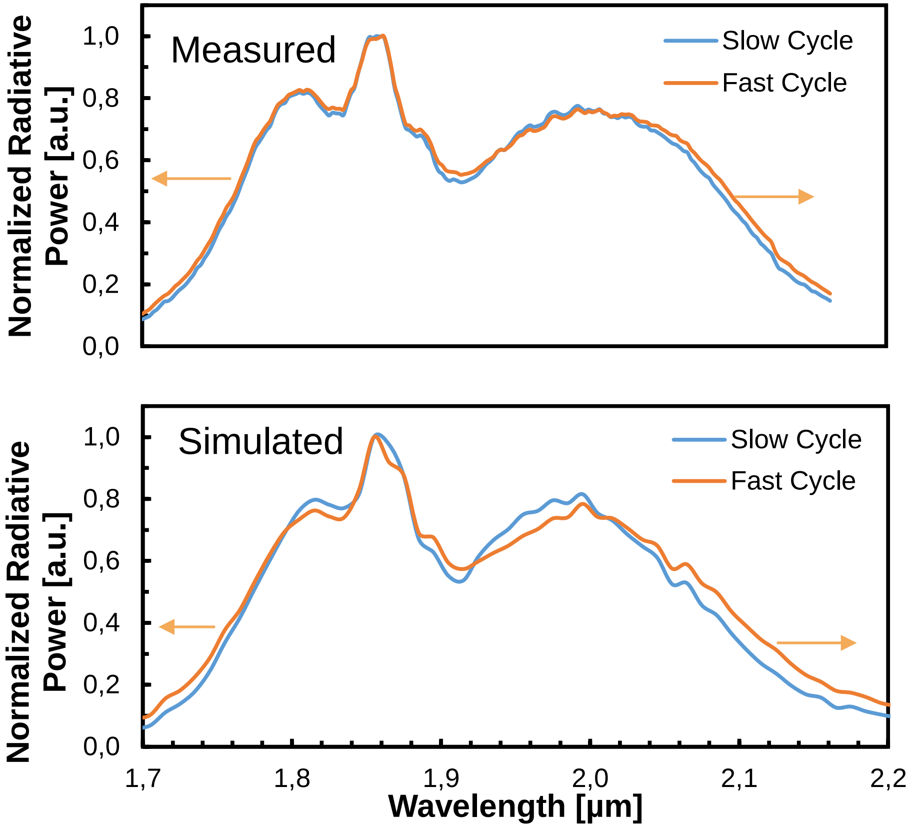
Total reabsorption varies for fast and slow cycle

Normalization shows impact of radiative trapping



Normalization shows the relative change of features

Spectral shape contains information on thermodynamic conditions



- Normalized fast and slow cycles
- Wings larger for fast cycle
- Trends consistent
- Potential to develop robust method to extract thermochemical quantities [1]

L. A. Kranendonk, *Appl. Opt.*, vol. 46, no. 19, pp. 4117–4124, 2007.

Conclusions

- Combined experimental and simulated approach to characterizing radiative heat transfer
- Influence of pressure, burn time, and mass fuel burn on radiation
- Relative spectral features are captured well in wavelength
- Radiative variation captured in both experiments and simulations

Acknowledgments

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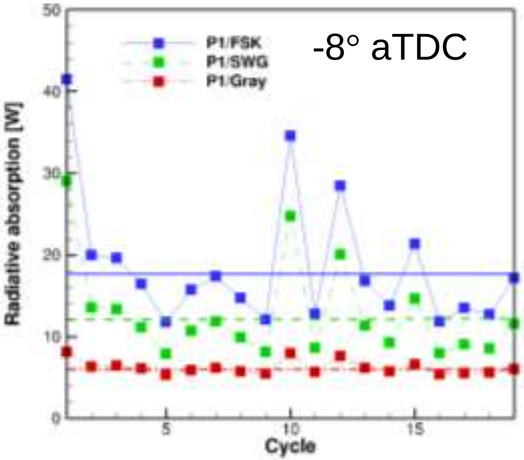
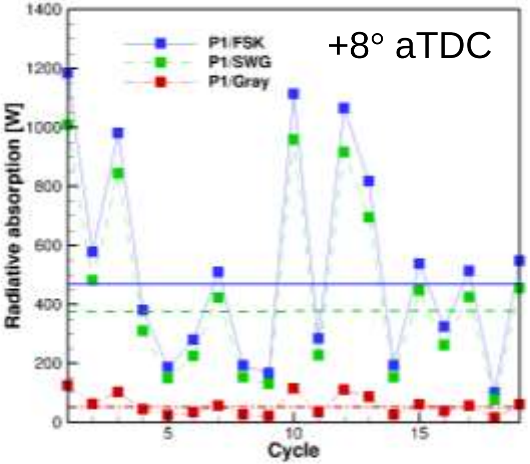
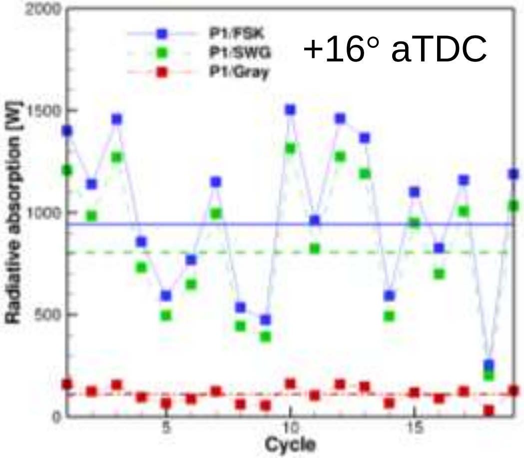
Cycle to cycle variation in radiation

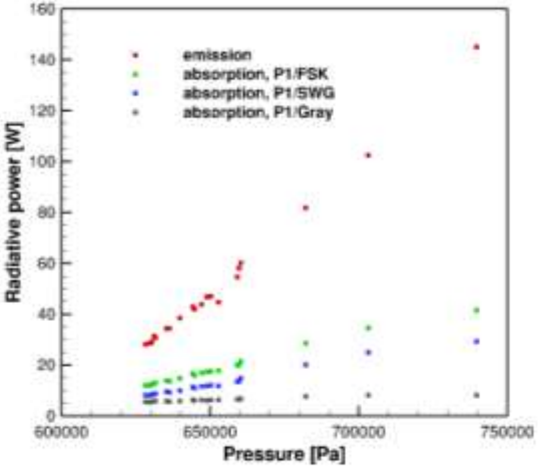






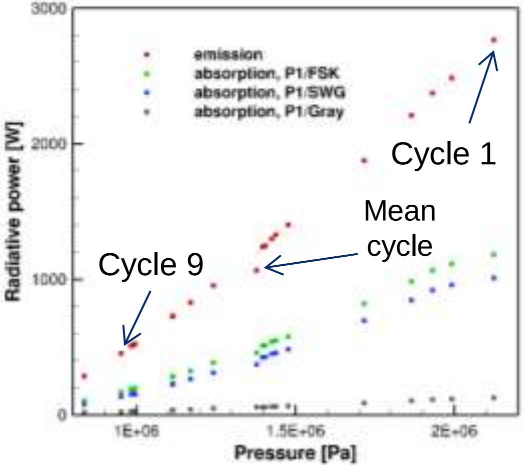
High pressure cycles have higher radiative properties

-8° aTDC



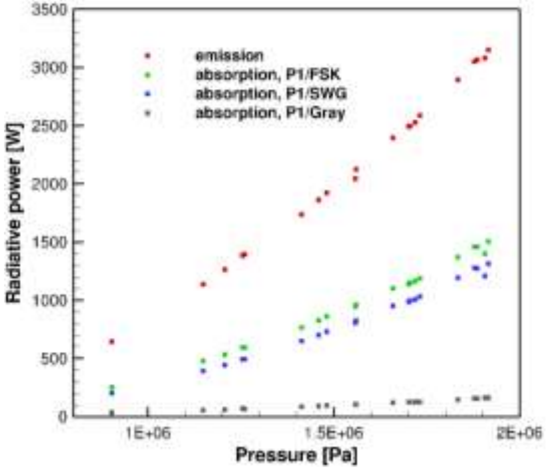
34.8% reabsorbed

+8° aTDC



44.1% reabsorbed

+16° aTDC



46.4% reabsorbed