Infrared Spectroscopy for High Temperature Estimation in Gases

Yudaya Sivathanu
En'Urga Inc.
1291 Cumberland Av., West Lafayette, IN 47906

Nancy Ulerich
Siemens Westinghouse Power Corp.
1310 Beulah Rd., Pittsburgh, PA 15235

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Outline

- Background
- Laminar Flow Results
- Turbulent Flow Issues
- Applications to Turbulent Flow

Measurement Methods (High Temperature Gas)

Contact	Non-contact
Thermocouples (thin film, bead)	Absorption Spectroscopy
Resistance Temperature Devices	Raleigh Scattering
Optical Fiber	Spontaneous Raman Scattering
Semiconductor sensors	Coherent Anti-Stokes Raman
Thin Filament Pyrometers	Laser Induced Fluorescence
Phosphor Thermometry	Ultrasonic thermometry
Noise thermometry	Emission spectroscopy (UV, NIR, IR)
Spectroscopy using probes	Tomography

Sample Studies: Laminar Flows

- **Infrared Emission/Absorption Spectroscopy for major gas species concentrations and temperature (Hanson et al., 1980; Best et al., 1991)**
- **Ultraviolet Emission/Absorption Spectroscopy for temperatures, OH concentrations (Vaidya et al., 1984)**
- **Coherent Raman Anti-stokes Spectroscopy (CARS) for radical concentrations and temperatures (Eckbreth et al., 1981, Durao et al., 1992)**
- **Laser Induced Fluorescence for pollutant concentrations and temperature (Dec and Keller, 1986)**
- **Infrared emission spectroscopy for major gas species concentrations and temperature (Zhu et al., 1997)**

Sample Studies: Turbulent Flame

- **Two wavelength Near Infrared Emission Spectroscopy for temperatures and soot concentrations (Sivathanu and Faeth, 1990; Sivathanu et al., 1991, Hamins et al., 1995; Gritzo et al., 1998)**
- **Four Wavelength Infrared Temperature Sensor for Gas Turbine Applications (Glasheen et al., 1998)**
- **Intrusive Infrared/NIR for temperatures, gas and soot concentrations (Sivathanu and Gore, 1991)**
- **CARS and Thin Filament Pyrometer for Temperature Measurements (Kelkar et al., 1997)**

IR Emission Spectroscopy

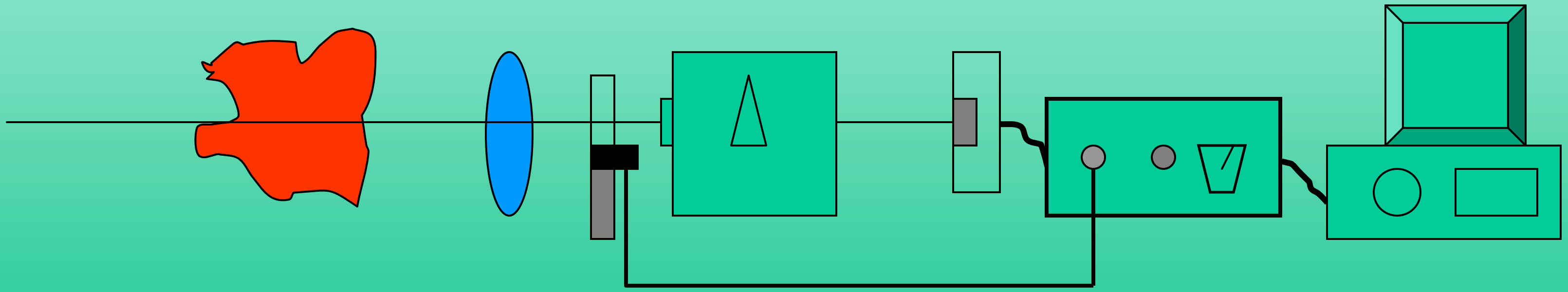
- ***Basic method is to obtain multi-wavelength spectral radiation intensity measurements***
- ***Utilize these measurements to obtain structure information***
- ***Measurement technology is well developed.***
- ***Data reduction methods require additional development.***

Issues in Laminar Flows

- Steady state systems (low frequency)
- Spatial resolution critical
- Absolute accuracy critical
- Relatively well established methods

Principally used for validating chemical kinetics and flow models

Experimental Arrangement



- Lens
- Chopper
- Spectrometer
- Detector
- Data acquisition system

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Calibration and Measurement Procedure

Voltages (V_λ) obtained from a standard blackbody at temperature T for different wavelengths (λ)

$$V_\lambda = K_\lambda I_{\lambda b}$$

$I_{\lambda b}$ is the Blackbody intensity, K_λ is a calibration constant

$$I_{\lambda b} = \frac{C_1}{\lambda^5 (\exp(C_2 / \lambda T) - 1)}$$

C_1 and C_2 are known first and second radiation constants

For unknown signal:

$$I_\lambda = V_\lambda / K_\lambda$$

Note: K_λ can be a function of I_λ requiring a more extensive calibration procedure.

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Data Analysis Requirements

- Spectral radiation intensities measured from a path in the hot gas.
- Obtain structure information from the measurements
- For laminar flames, different system specific methods of data reduction available

Inversion Method

- **Guess temperature and concentration**
- **Utilize narrow band calculations to obtain intensities**
- **Compare with measured intensities**
- **Update guess of temperature and concentration**
- **Iterative program needed**
- **Difficulty is that emissivity depends on both concentration and temperature**
- **Convergence problems for some iterative schemes**
- **Simultaneous absorption measurement allows easier methods**

HOMOGENEOUS PATHS

Spectral Radiation Intensity(I_λ) for homogeneous path

$$I_\lambda = \varepsilon_\lambda (X_i, P_i, T) I_{\lambda b}$$

Emissivity (ε_λ) depends on mole fraction (X_i), partial pressures (P_i) and thermodynamic temperature (T).

- **Gas species of interest: CO_2, H_2O, CO and CH_4**
- **Emissivity: Narrow band model (RADCAL, Hitran)**
- **Amplitude uncertainty: 10%**
- **Wavelength uncertainty: 40 to 50 nm at 4.5 microns**
- **Maximum pressure range: 10 atmospheres**

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NARROW BAND MODEL (RADCAL)

Species	**Band**	**Method**
CO_2	2.0 µm	modeled
	2.7 µm	modeled
	4.3 µm	modeled
	10.0 µm	modeled
	15.0 µm	tabulated
H_2O	1.38 µm	tabulated
	1.88 µm	
	2.70 µm	
	6.30 µm	
	20 to 200 µm	
CO	4.6 µm	modeled
CH_4	2.4 µm	
	3.3 µm	tabulated
	7.7 µm	tabulated
soot	0.4 to 2000 µm	modeled

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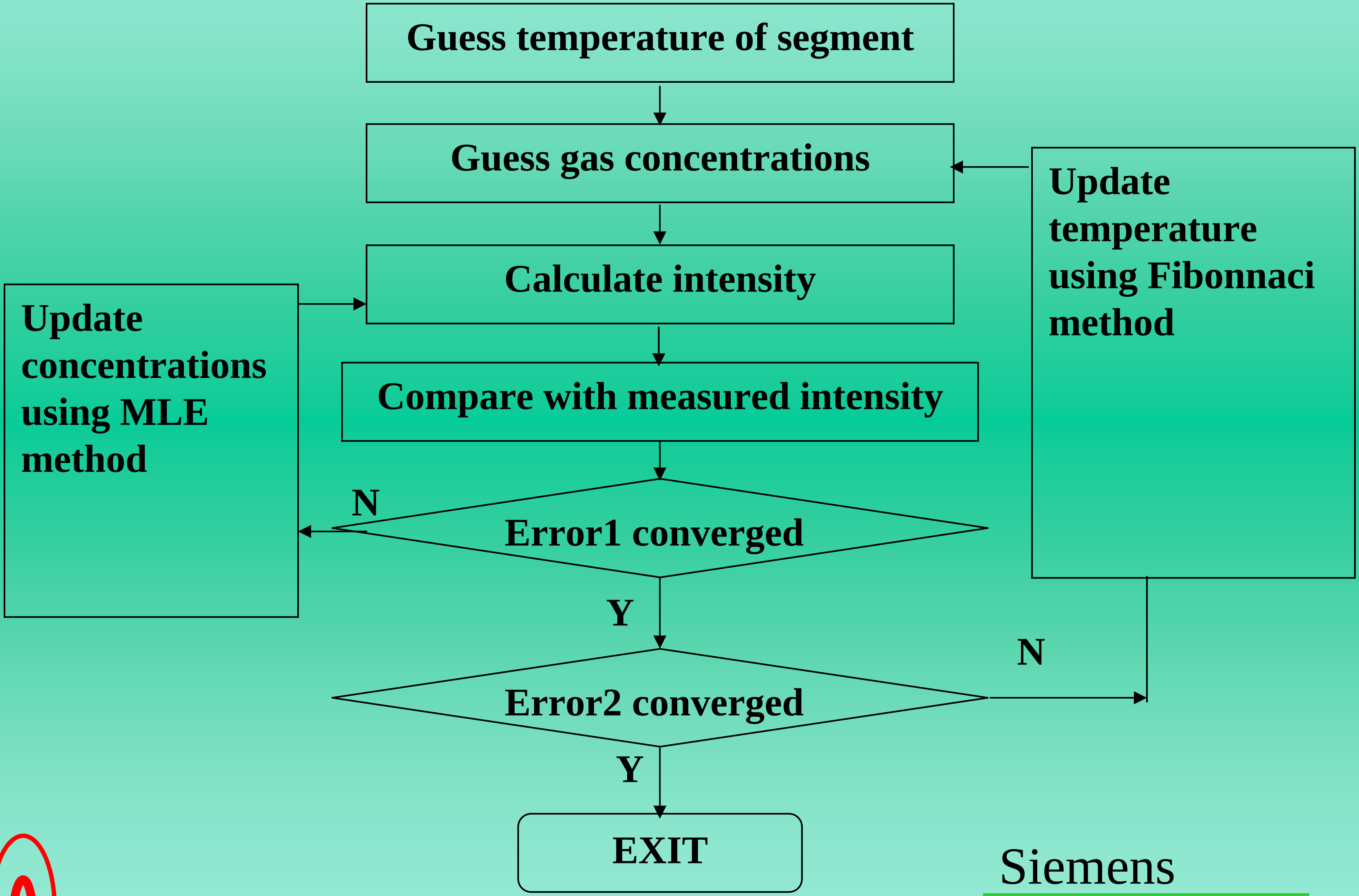
Flow Chart for Iterative Program



Guess temperature of segment

Guess gas concentrations

Calculate intensity

Compare with measured intensity

Error1 converged

N

Update concentrations using MLE method

Y

Error2 converged

N

Update temperature using Fibonnaci method

Y

EXIT

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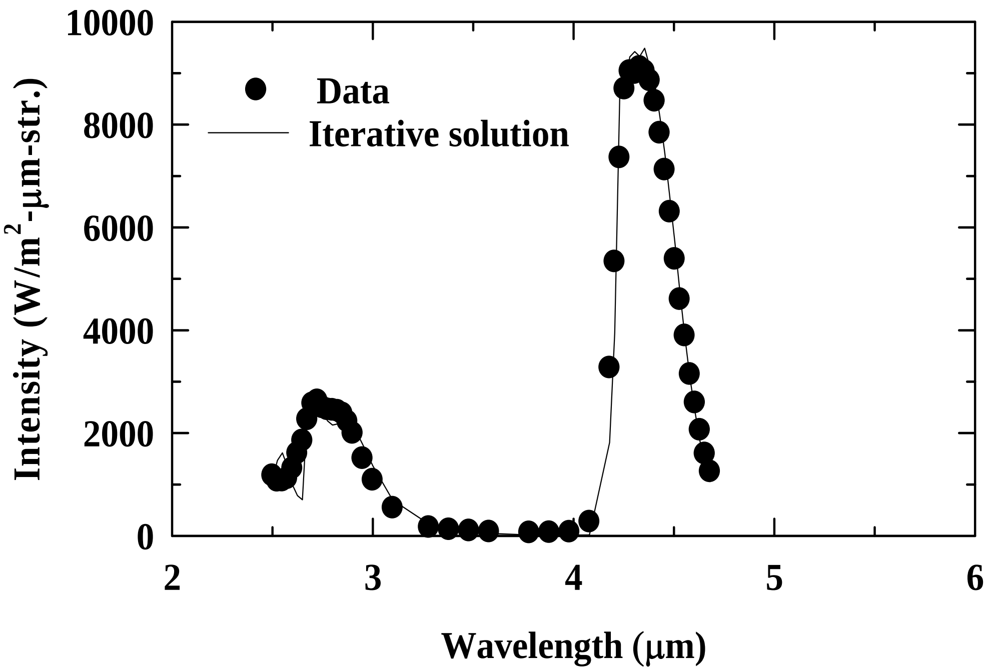
Evaluation in Laminar Flame



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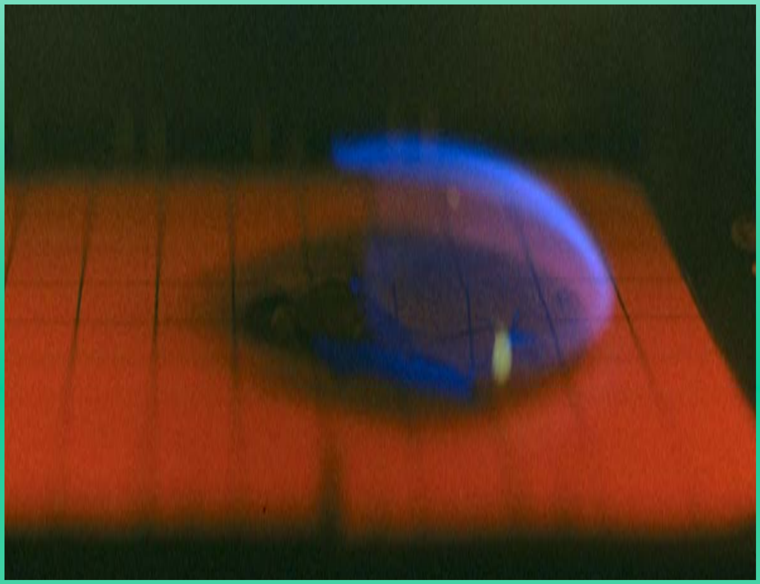
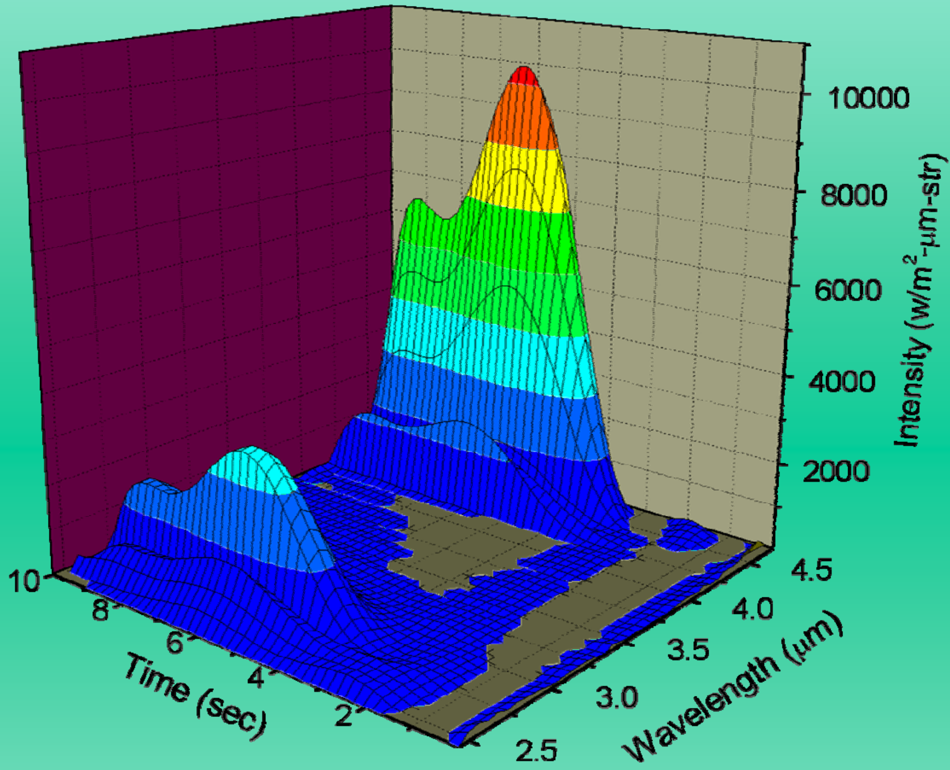
Deconvolution Results

Quantity	Emission spectroscopy	Thermocouple/GC	Theoretical (Adiabatic)
CO_2 (Φ = 0.81)	0.070	.078	------
H_2O (Φ = 0.81)	0.158	-------	0.157
T(K) (Φ = 0.81)	1940	1840	2034
CO_2(Φ = 0.86)	0.074	0.083	------
H_2O(Φ = 0.86)	0.168	-------	0.166
T(K) (Φ = 0.86)	2011	1840	2112

Intensity Data from Microgravity Experiment





Sample Radiation Intensities from a Transient Flame Experiment at the Japanese Microgravity Facility

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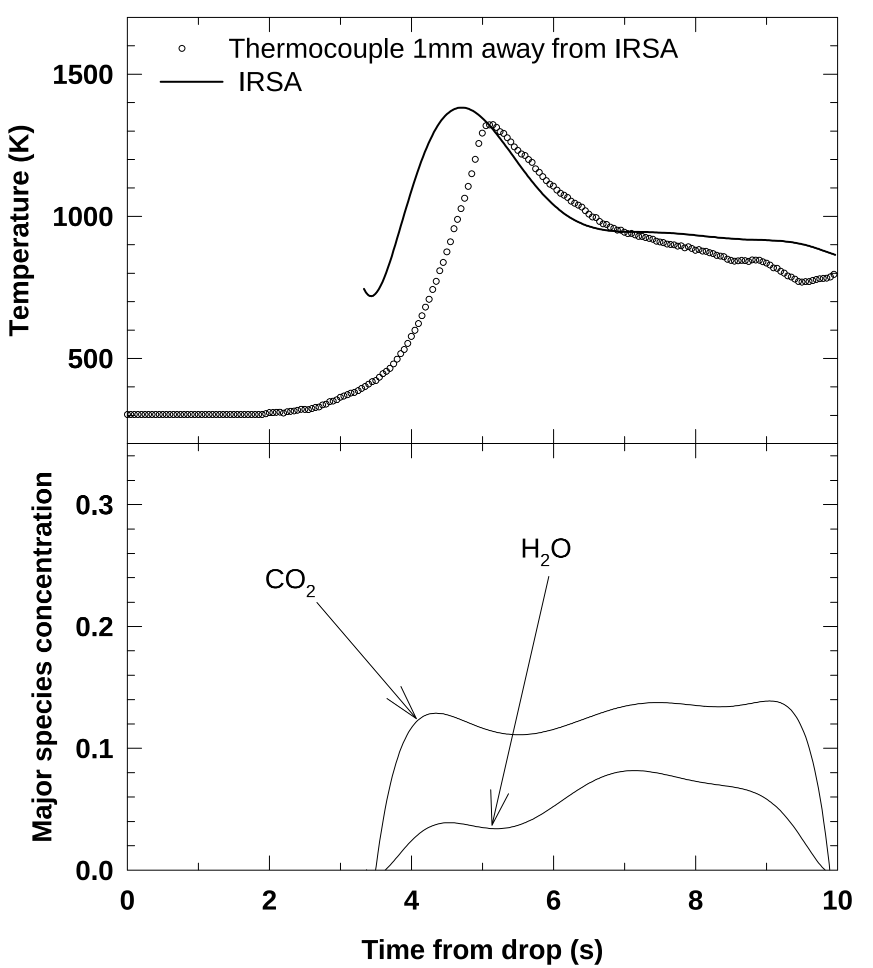
Deconvolution Results



- Spectral intensity data collected using a stand alone data logger
- Ten seconds of data collected at a scan rate of 300 Hz
- Temperature and gas concentrations obtained assuming homogeneous paths

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Issues in Turbulent Flow

- Intrusive probes – effect on structure
- Tomography – turbulence/radiation interactions
- Temporal resolution – sufficiently fast
- Spatial resolution – small scales

Principally used for validating turbulent flow models. Most industrial high temperature flows are turbulent.

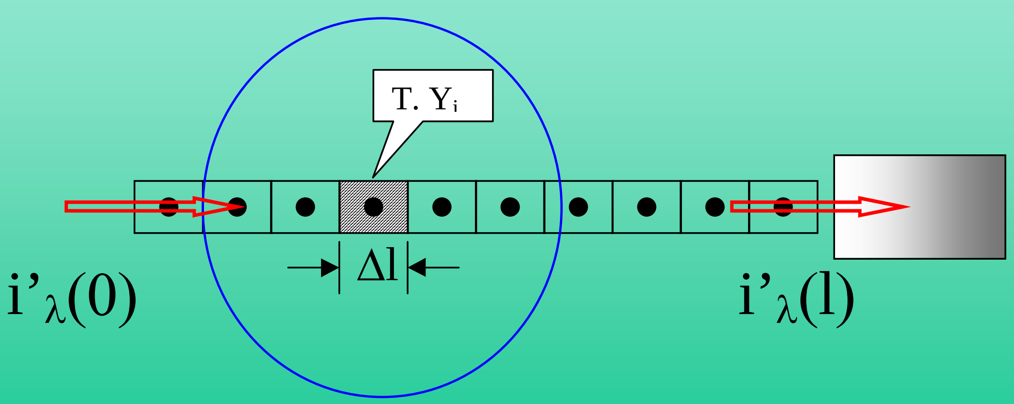
Issues faced by Industry

Control of the combustion process: reduce pollutants, increase efficiency, product lifetime

- **What temperature and where?**
  - **Instantaneous/average temperature**
  - **At all locations/highest temperature location**
- **Control signals?**
  - **Absolute values/trends?**
  - **Correlated with pollutants, efficiency, thermal stress**

Ideal situation is to have a single control variable that is "indicative" of the parameter being monitored. Eg. Total pollutant emitted, Stability index

Equation of Radiative Transfer (Non-homogeneous Paths)

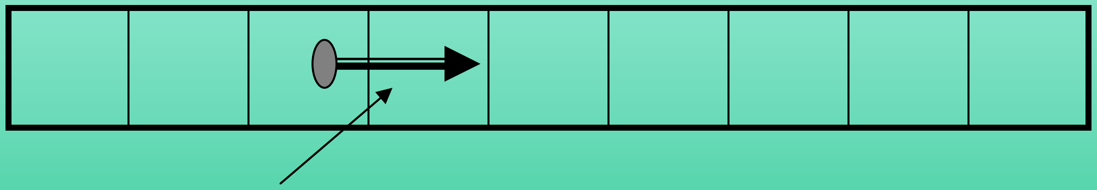


$$\frac{di'_\lambda}{dl} = -\alpha_\lambda i'_\lambda + \alpha_\lambda i'_{\lambda,b}$$

$$i'_\lambda(l) = i'_\lambda(0) e^{-\kappa_\lambda(l)} + \int_0^{\kappa_\lambda(l)} i'_{\lambda,b}(l^*) e^{-[\kappa_\lambda(l) - \kappa_\lambda(l^*)]} d\kappa_\lambda(l^*)$$

$$\kappa_\lambda(l) \equiv \int_0^l \alpha_\lambda(l^*) dl^*$$

Intensity Calculations for Turbulent Flows



$$I(J) = I(J-1)\tau_J + \varepsilon_J I_{\lambda b}(J)$$

- **Discretized equation of Radiative Transfer**
- **Calculation started from cold or hot boundary**
- **For laminar flames, relative straightforward**
- **For turbulent flames, turbulence/radiation interactions are important**
- **Spatial and temporal correlations modeled using Monte Carlo or Time Series Methods**

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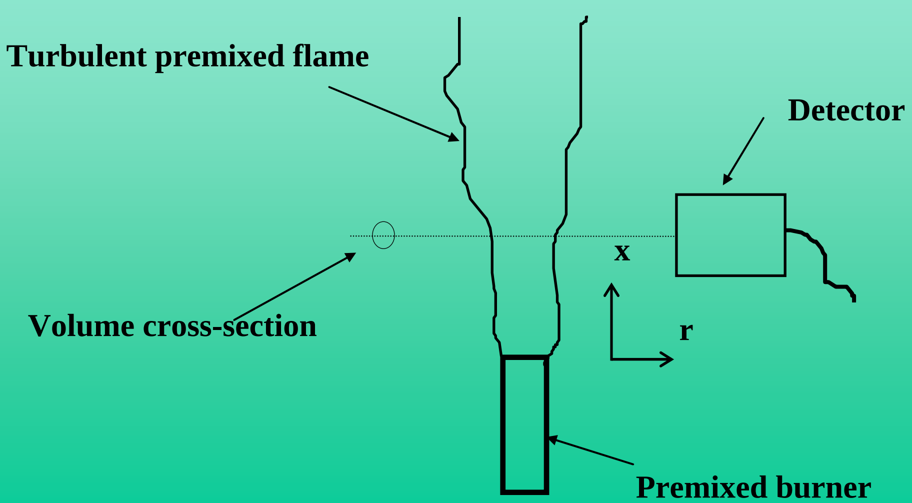
Statistical simulation of Combustor Volume



- Statistically simulate the instantaneous temperature and gas concentrations in a small control volume
- Obtain total heat release rate and pollutants produced in the control volume
- Simultaneously obtain signatures of possible measurement variables within the control volume

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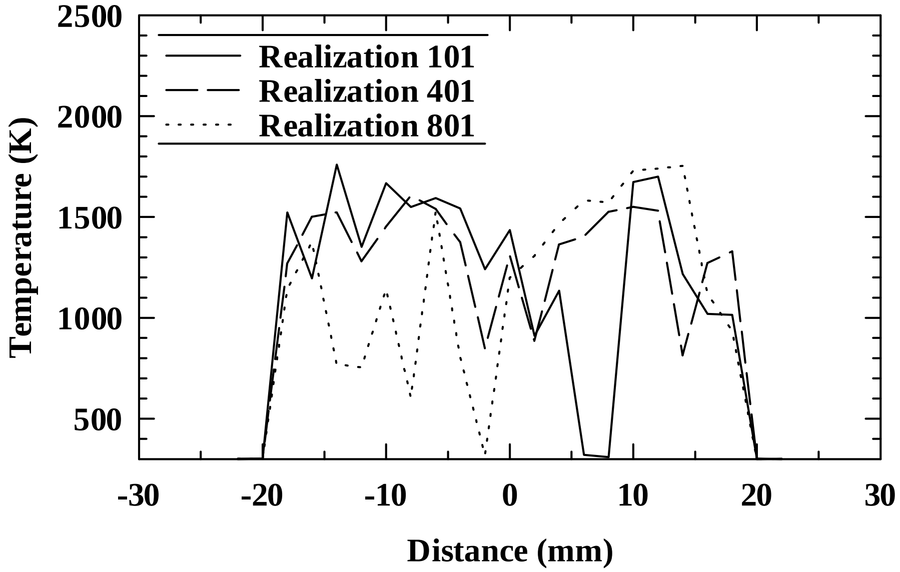
Sample temperature realizations in the control volume



- Temperature and gas concentrations fluctuate
- Experimental data used to create 1000 sample realizations
- Simple reaction models for heat release rate and pollutant formation

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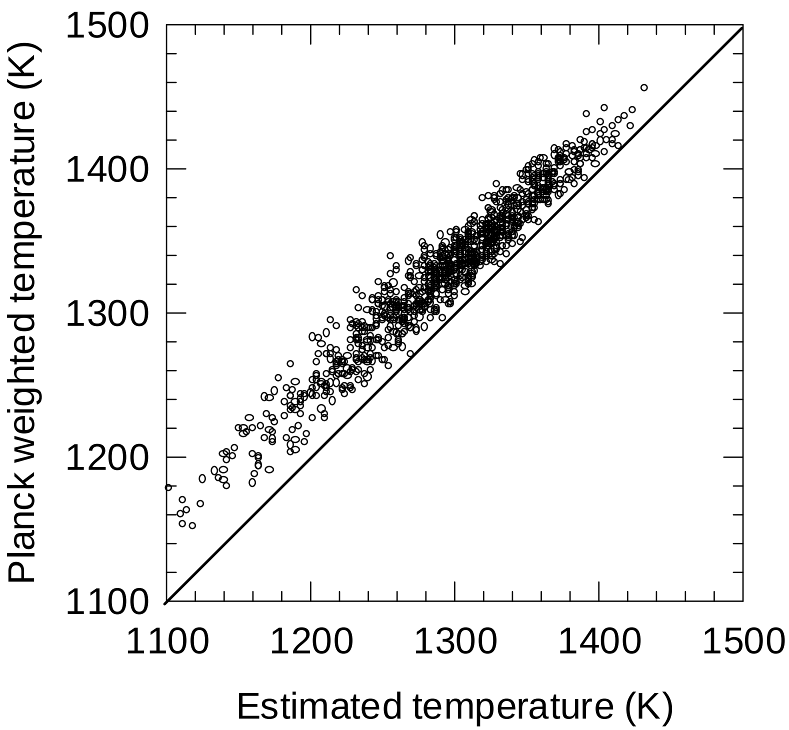
Correlation between Planck Function Temperature and Temperatures Estimated using Emission Spectroscopy



Correlation of different variables with the instantaneous heat release

Quantity	Mean	RMS	Correlation
T^* (0.30 μm)	1611 K	36 K	0.6011
T^* (2.52 μm)	1327 K	54 K	0.995
T^* (4.26 μm)	1255 K	60 K	0.984
T_{max}	1529 K	295 K	0.293
$T_{max/2}$	1294 K	325 K	0.289
$T_{C/L}$	1118 K	301 K	0.176
T_{avg}	1118 K	71 K	0.925
T (ES100)	1285 K	59 K	0.965
a_λ (2.64 μm)	0.991	0.00055	-0.224
a_λ (4.26 μm)	0.493	0.0237	-0.315

T* is the Planck-Function weighted average temperature of the control volume (function of wavelength)

$$T^* = \frac{C_1}{\lambda(\ln(C_2 / I_\lambda \lambda^5) + 1)}$$

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Industrial Ranking of Methods

Category	Thermo-couples	Absorption Spectroscopy	UV Emission	IR Emission
Detector	1	4	4	10
Sources	0	8	8	0
Development cost	2	10	5	20
Manufacturing cost	2	10	10	8
Utility	10	4	4	2
Intrusive	15	4	4	1
Operational ease	1	3	3	1
Longevity	10	2	2	2
Maintenance	5	8	8	2

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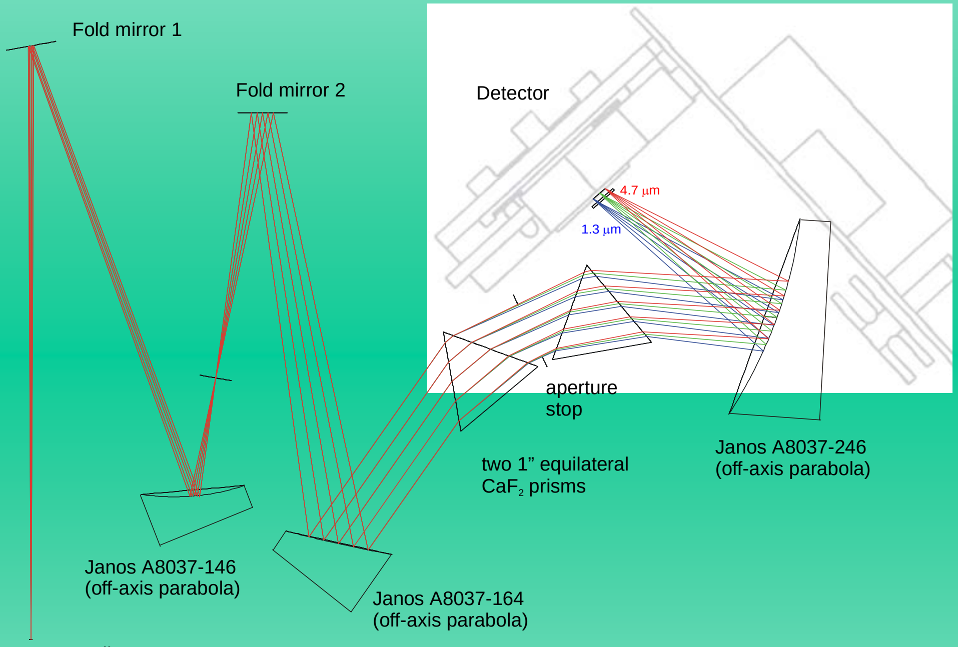
High Speed Spectrometer

Model ES100



Fold mirror 1

Fold mirror 2

Detector

4.7 µm

1.3 µm

aperture stop

two 1” equilateral CaF_2 prisms

Janos A8037-246 (off-axis parabola)

Janos A8037-146 (off-axis parabola)

Janos A8037-164 (off-axis parabola)

Entrance slit

SPECTRALINE™

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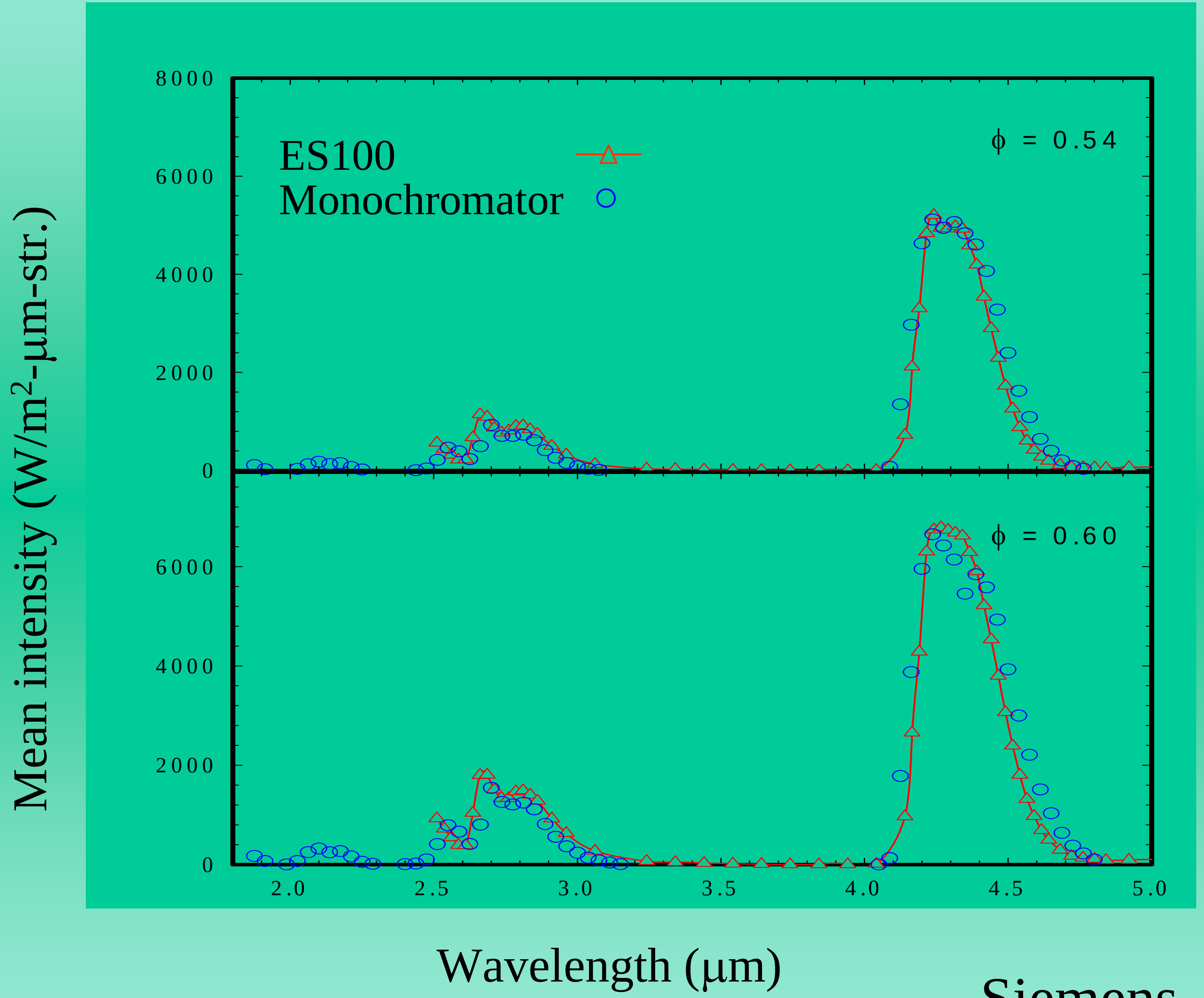
Validation of ES100 Measurements



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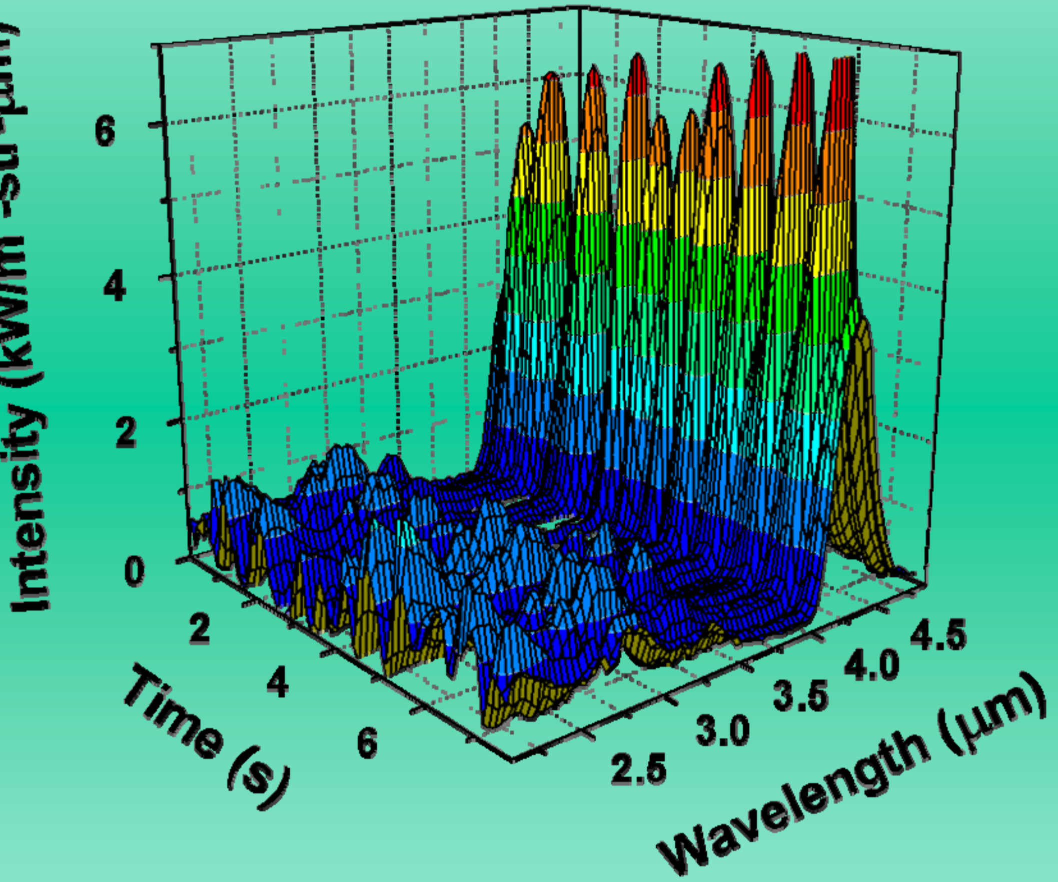
Typical Spectra from a Turbulent Flame



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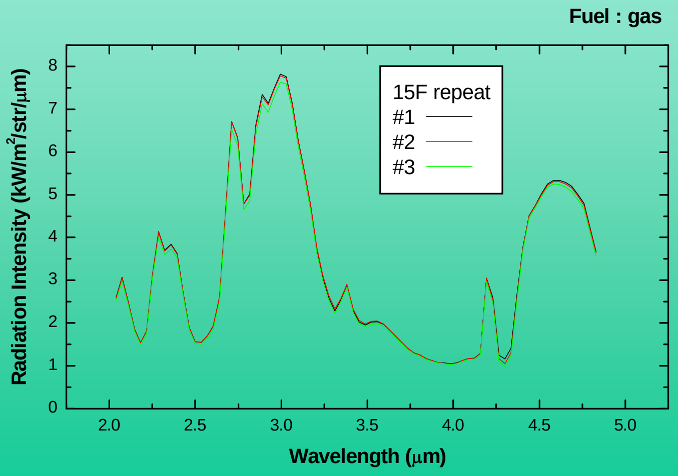
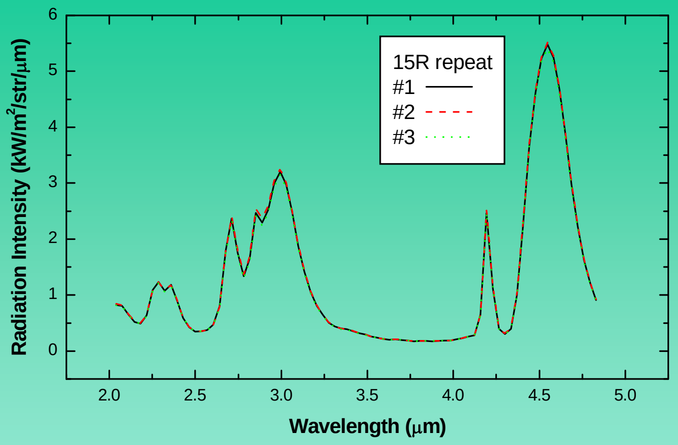
Measurements from a Turbine Inlet





- Spectral intensity data collected at 1320 Hz
- Very high repeatability for mean intensities
- Temperature and gas concentrations obtained assuming homogeneous paths

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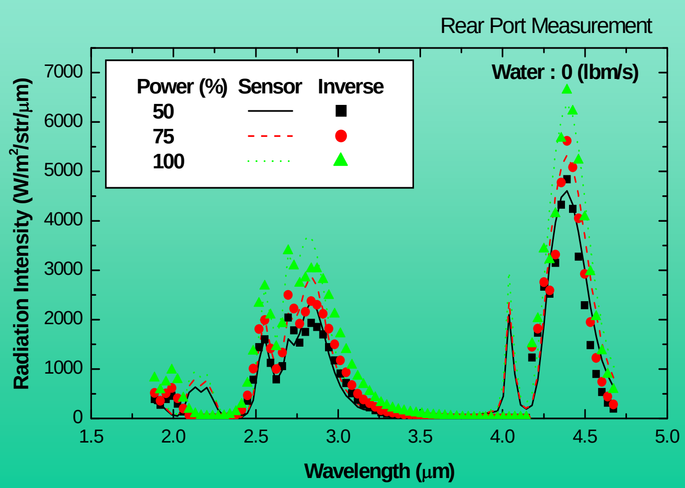
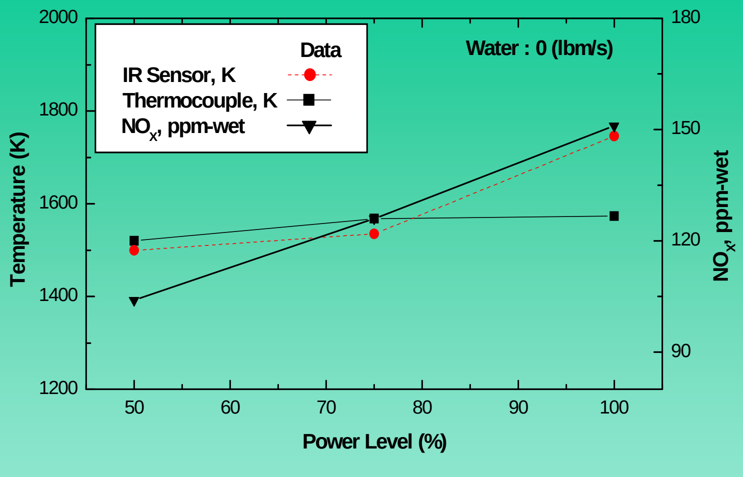
Westinghouse Turbine at NRC





- Temperature and gas concentrations obtained using iterative algorithm
- Calculations assumed lack of methane and CO in the primary zone
- Temperature from ES100 correlated with NO_X
- Temperature from thermocouple is not correlated with NO_X

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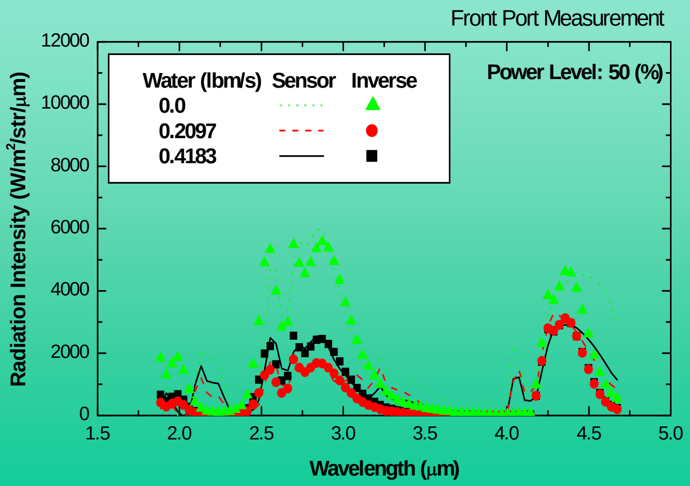
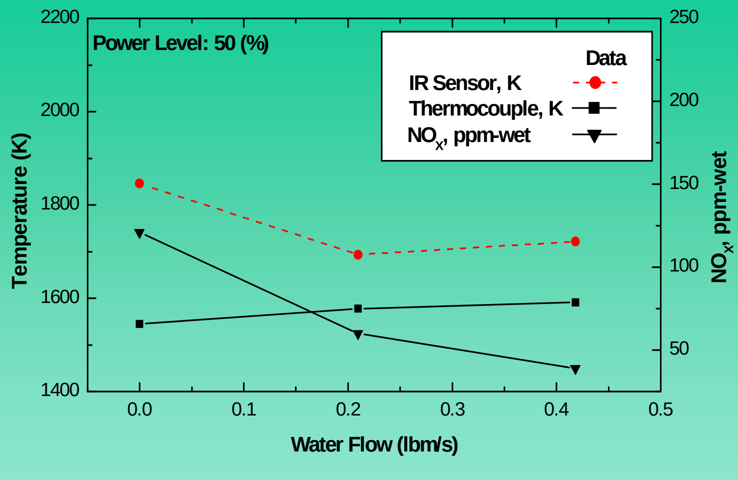
Westinghouse Turbine at NRC





- Results similar for data obtained with water addition
- Temperature from ES100 correlated with NO$_X$
- Temperature from thermocouple is not correlated with NO$_X$

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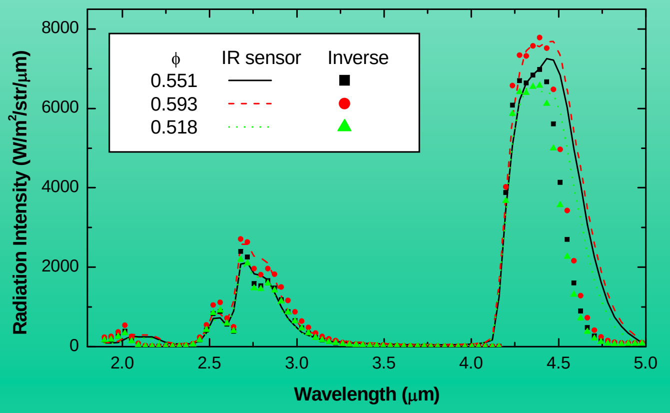
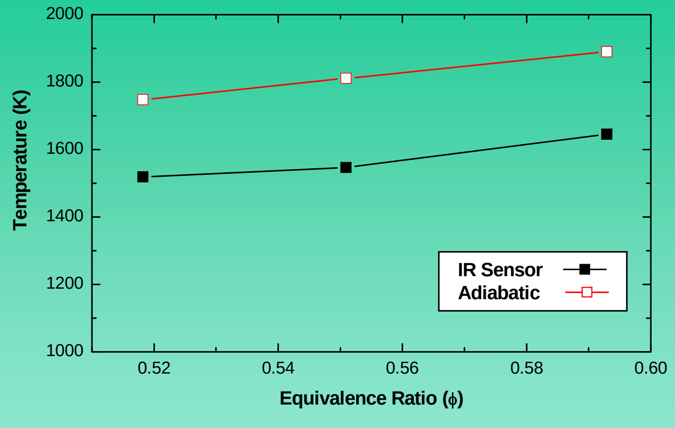
Kerosene Spray Flame Data

General Electric Corporation (CRD)
Kerosene Spray Flame





- Temperature from ES100 correlated with global equivalence ratio
- No thermocouple data available
- Global equivalence ratio is also a direct measure of power output or heat release rate

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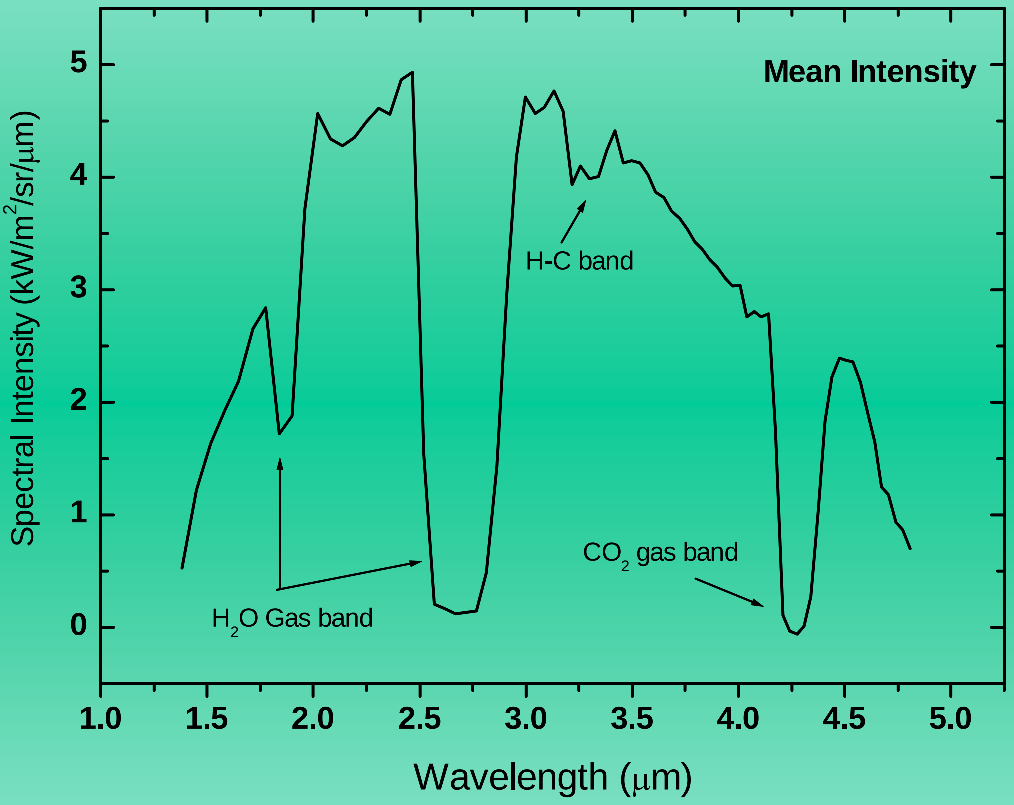
High Pressure Data including Blade Radiation



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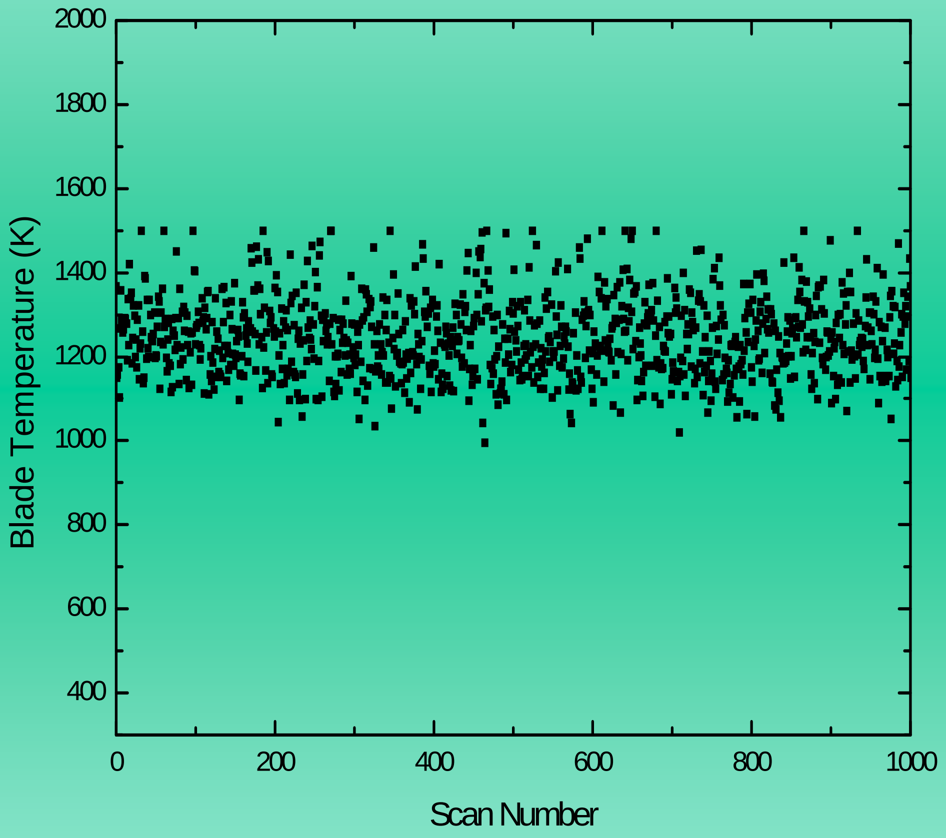
Blade Temperature Estimation



- Radiation from blades synchronized to data collection
- Intensity measurement spread over three blades
- Four gas band free wavelengths used to estimate temperature
- Mean Temperature is 1273 K and mean emissivity is 0.85

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Current Uses of Infrared Emission Spectrometer

Fundamental studies of turbulent flame structure

- Sandia National Laboratories, NIST, NASA, DoD, varied universities

Radiation from turbines and internal engines

- Westinghouse, KIMM

Steel, Aluminum, and Molten Glass Manufacturing

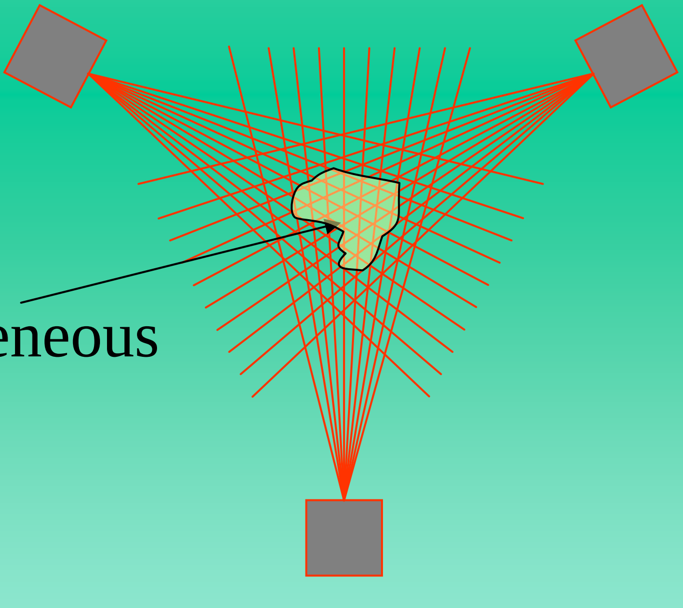
- Pohang Steel Company, KAIST, Alcoa, etc.

Future Directions in Infrared Emission Spectroscopy

- Hyper spectral scanning
- Multiple Element Sensors
- Advanced deconvolution algorithm
- Hyper speed spectral scanning

Non-Homogeneous Fields

- Multiple view angles and slices
- Tomography for Local transmittances/emission intensities
- Absorption measurements are typically required



Non-homogeneous
field

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