SAND2008-4926C

Validation Experiments to Determine Radiation Partitioning of Heat Flux to an Object in a Fully Turbulent Fire

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Albuquerque, New Mexico, USA

32nd Symposium (International) on Combustion
Montreal, Canada
August 3-8, 2008

This work was supported by the United States Department of Energy and was performed at Sandia National Laboratories. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under Contract No. DE-AC04-94AL85000.

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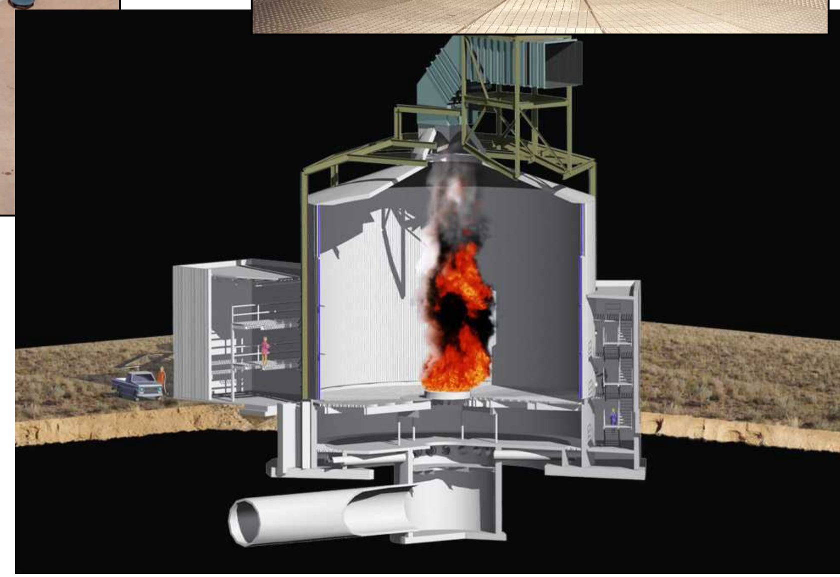
Validation Quality Fire Tests

1. Fundamental interest for heat transfer studies and are commonly used in "abnormal thermal environments" experiments for high-consequence hardware qualification at Sandia National Laboratories.
2. A special class of experiments: specifically designed for direct comparison with computational predictions.
3. Requires careful characterization and control of the experimental features or parameters used as inputs into the computational model.
4. Validation experiments must be designed to capture the essential physical phenomena, including all relevant initial and boundary conditions.
5. The cylinder is one of the canonical geometries for heat transfer, and is a relevant geometry to study the heat flux incident to an object located within the fire plume for the validation of fire models and thermal response codes

Test Goal

1. The goal of the current study is to obtain separate estimates of the radiation and convection for a large turbulent methanol fire.
2. Methanol was used both to permit laser-based diagnostics and to enhance the relative contribution of convection. For methanol, the thermal radiation is from gas band emission (H_2O and CO_2), and is not as large (relative to the convection heat transfer) as for most hydrocarbon fuels.
3. A cylindrical calorimeter with sufficient instrumentation to allow direct measurement of heat fluxes was designed, fabricated, and deployed in 2 m diameter methanol pool fires.
4. Data taken during each test included measurement of the incident total and incident radiative heat flux to the calorimeter, the temperatures and velocities of the convective flow near the calorimeter, and the thermal response of the calorimeter in a fully turbulent fire.
5. The placement of the calorimeter off-axis (so that one side is engulfed and the other is intermittently exposed) also permits the variation of convection to radiation within a single experimental data set.

The FRH Test Cell



FRH cell: 18.3 m diameter, 12.2 m tall.

Walls: water-filled steel channel sections

Well-characterized/controlled air flow.

The FLAME/Radiant Heat (FRH) test cell is part of the new Thermal Test Complex (TTC) ($40M) at Sandia National Laboratories (SNL).

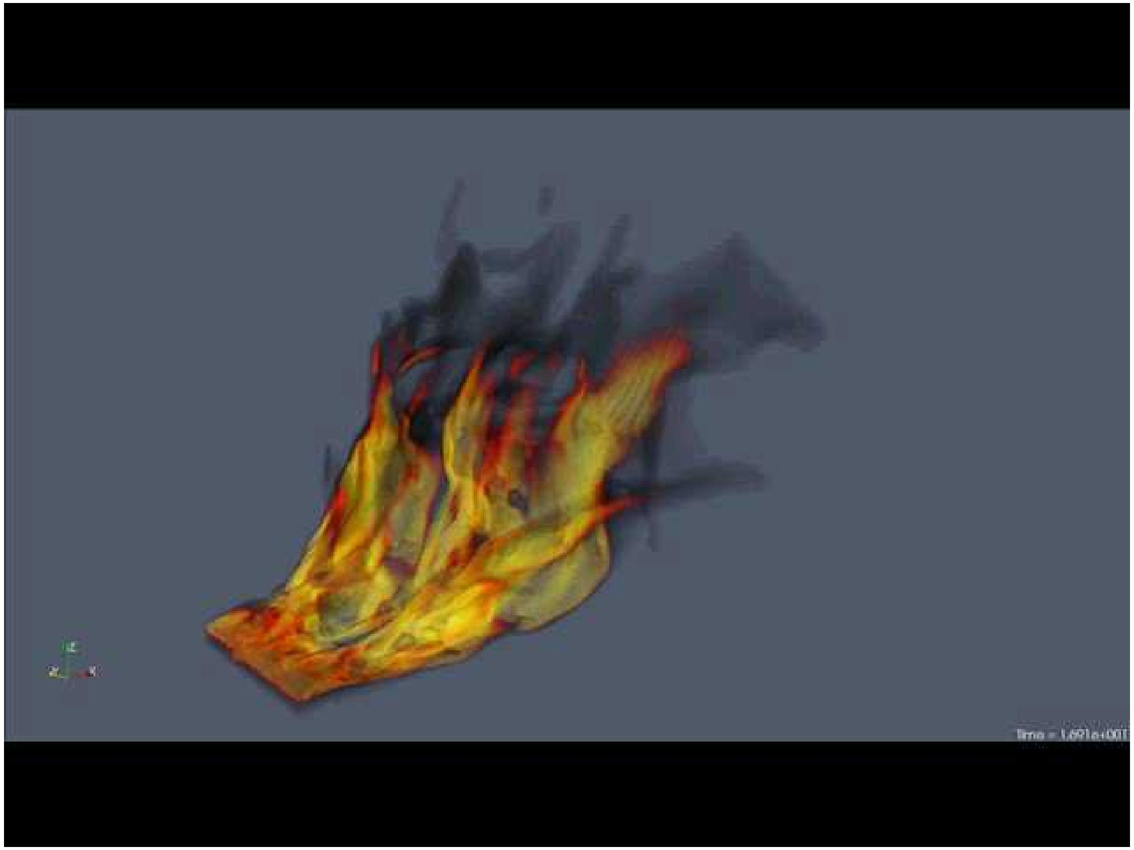
Fire Simulation Capability

Fuego

- **Simultaneously solve fire, the radiative and convective heat transfer to surroundings, and transient heating of objects**

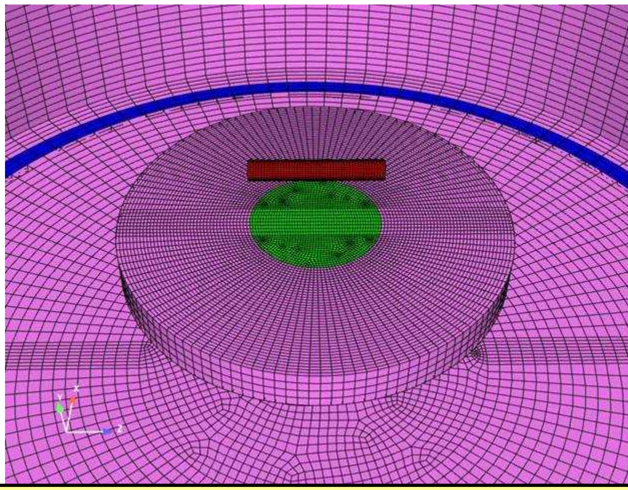
  - **fluid mechanics**
  - **multiple-species chemical kinetics**
  - **participating media radiation heat transfer**
  - **unstructured finite volume approach**
  - **optimized for parallel execution**

The design of the qualification experiment in the new cross-wind test facility with Fuego represents the accreditation test of our modeling and simulation capability by the weapons community.

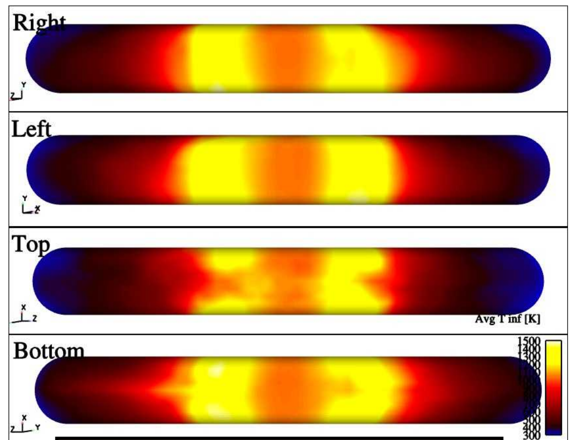


Pretest Simulations Identified Data Requirements

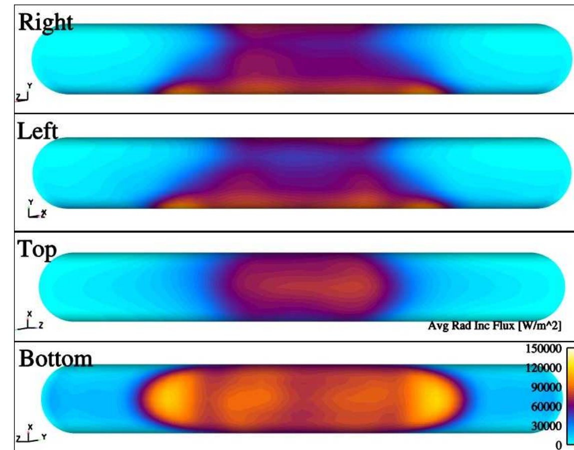
- FUEGO – Predicted object surface and freestream gas temperatures, average convective heat transfer coefficients, and incident radiation and convective heat fluxes



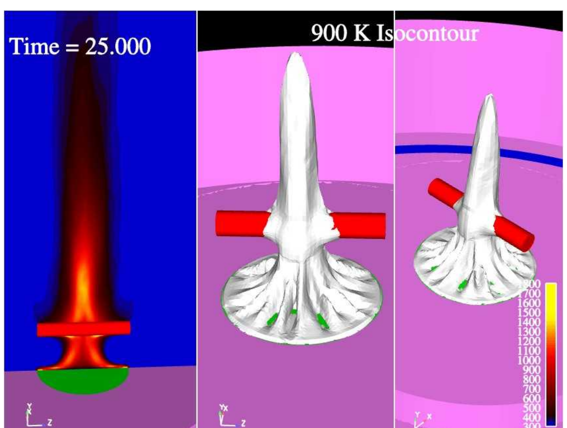
Fine grid for pretest sims of calorimeter in FRH



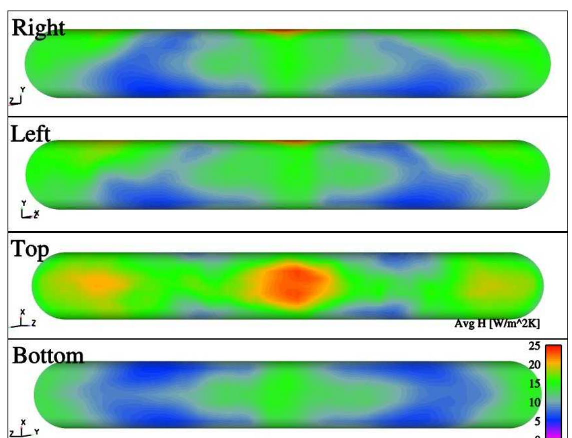
Freestream gas temperature around calorimeter



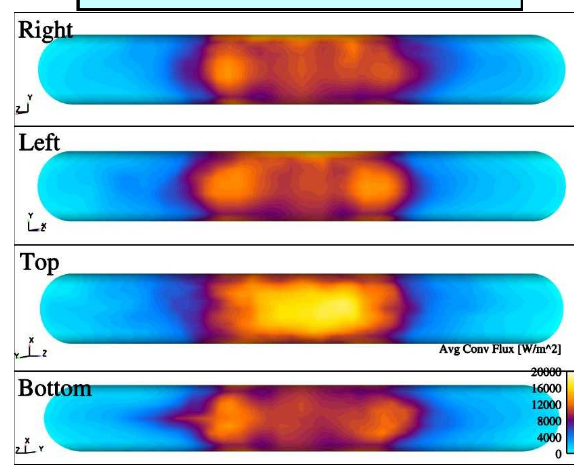
Radiative heat flux (incident)



Average temperature (left) and two views of the 900K isosurface

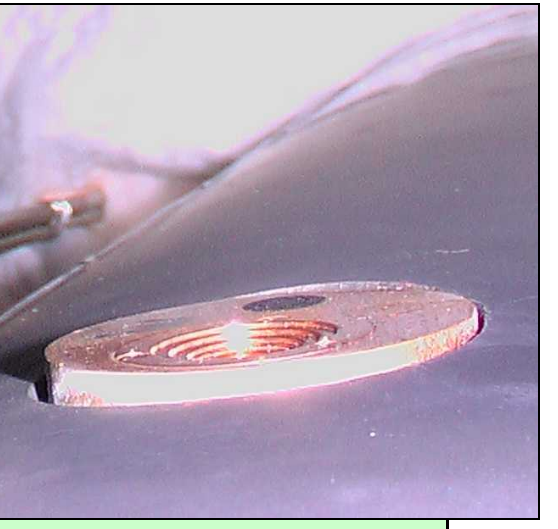


Convective heat transfer coefficient



Convective heat flux

Measurement of Radiative and Total Heat Fluxes



- Dual mode (radiative and total) heat flux gauges
  - **Medtherm Model 96-15T-15RP(ZnSe)-21745**
    - **Schmidt-Boelter heat flux gauges**
    - **The total gauge is mounted flush with the surface of the gauge body**
    - **The radiometer is recessed in the gauge body behind a zinc-selenide window (150º view angle)**

- Total heat fluxes are also estimated from the thermocouples on the surface of the calorimeter
  - **A 1-D inverse heat conduction methodology is employed to determine the heat flux**

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Measurement of Convective Heat Fluxes

- Convective heat flux is given by $q_{conv} = h\,(T_{gas} - T_{surface})$, where h is a convection heat transfer coefficient
- Estimate $T_{surface}$ from thermocouples in the calorimeter outer shell
- Measure T_{gas} using CARS
- Determine h from an empirical correlation
  - **Typical correlations have the form $Nu_x = h\,x / k = C\,Re_x^m\,Pr^n$, where C, m, and n are determined empirically**
  - **$Re_x = \rho V\,x / \mu$, where ρ and μ, like Pr and k, are properties of the gas**
    - **Determine V using PIV**
    - **Evaluate Re and Nu assuming properties of air at an appropriate temperature and pressure**

CARS
(Coherent Anti-Stokes Raman Scattering)

Outer wall of FRH

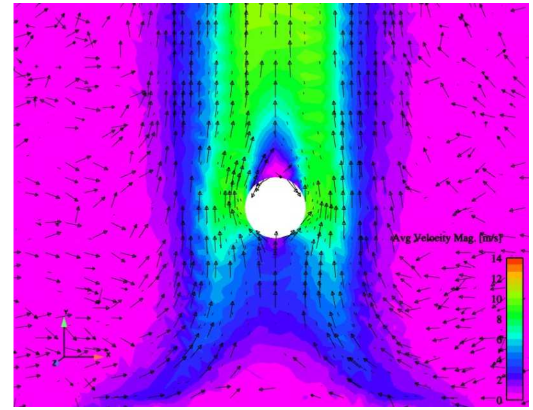
Optical access ports through the FRH wall

CARS laser

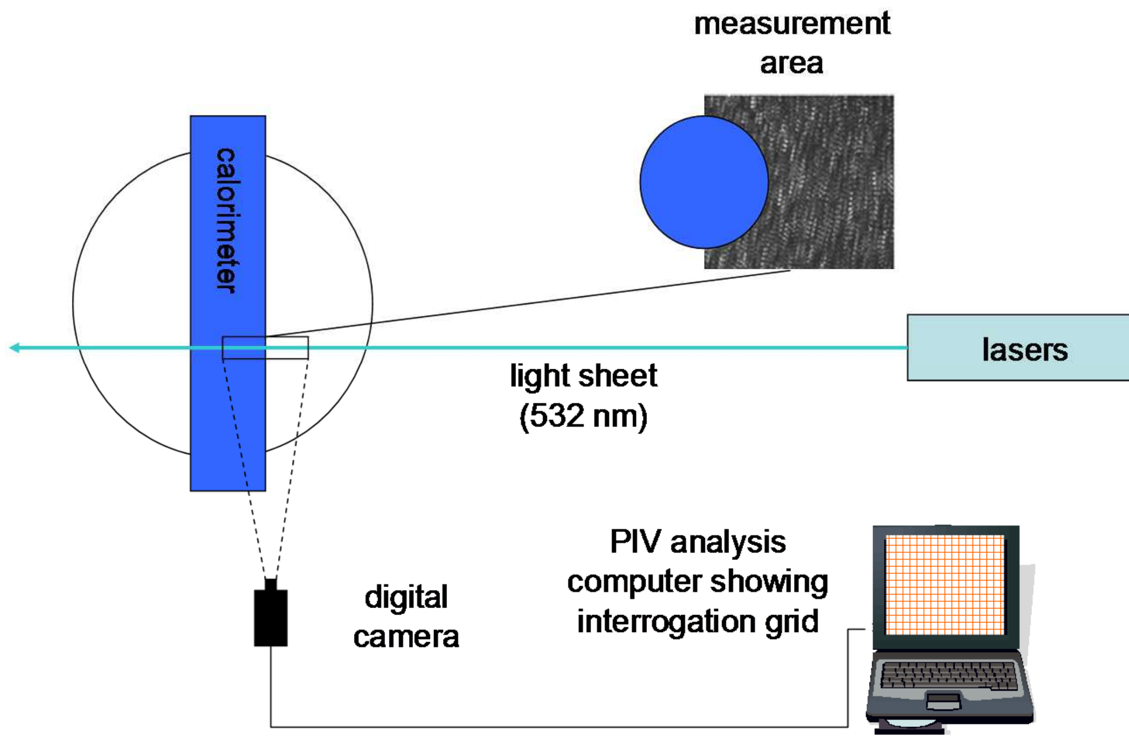
The gas temperature is determined from the spectral content of the CARS signal generated in an interrogation volume in which two frequency-tuned laser beams cross, exciting rotational-vibrational Raman transitions

PIV (Particle Image Velocimetry)

FUEGO – predicted velocity field



- A double-pulsed collinear laser sheet, generated by two coherent Nd:YAG lasers, illuminates particles suspended in a flow field
- An image pair is recorded on a CCD camera at a rate of up to 15 image pairs per second
- The velocity is inferred by cross-correlation of particle positions in subsequent frames of the image pair



Schematic of PIV system

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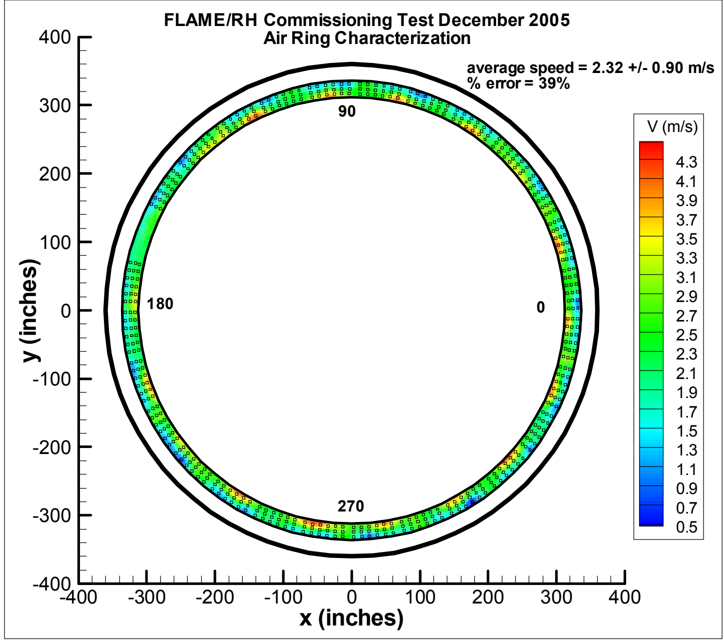
Quantify the experimental uncertainty

- **Cylindrical calorimeter fabrication and instrumentation**
  - **Sandia drawings**
  - **Material certifications**
  - **Inspected as-received parts**
  - **Thermocouple checks on receipt**
    - » Resistance (lead to lead, + to sheath, - to sheath (megger 200 volts, 1 s cycle, acceptance criteria > 100 MΩ)
    - » Water bath (10 TCs/test in a stirred chiller – 2°C and 90°C
    - » Acceptance criteria ±1°C to a calibrated TC)
  - **Dual heat flux gauge (Medtherm) checks on receipt**

- **Thermocouple placement on complex calorimeter**
  - **Per SOP and qualified technologist**
  - **Placement within ±0.0625 inches of punch mark**

- **Data Acquisition Systems (DAS) – FRH, PENLIGHT, and Cylindrical Calorimeter**
  - **All channel checked with calibrated Ectron**
  - **Acceptance criteria for thermocouples ±2°C**

Inlet Air Ring Uniformity



Quantify the experimental uncertainty (continued)

- **Pyromark® Paint Applied to calorimeter center section**
  - **Per manufacturer paint application and bake out schedule**

- **Emissivity field measurements**
  - ***Mean emissivity 0.86 ± 0.10 (total directional – cured Pyromark on 304SS - Figueroa 2005)***

- **Combustion Air Flow**
  - **FRH air source characterized at the inlet air ring and at the level of the pool**
  - **Velocity monitored with differential pressure gauges (ADM Model 880C)**
  - **39% standard error of inlet air ring velocity at 150000 cfm/blower**
  - **207% standard error of pool-level velocity at 150000 cfm/blower**

- **Fuel regression**
  - **Real-time, continuous measurements with calibrated Rosemount DP transducer**
  - **Uncertainty of 0.6% (contributors are pressure, time, and fuel SG)**

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Quantify the experimental uncertainty (continued)

- **TC Data Acquisition System Analysis (Nakos 2004)**
  - Apply to Type K, chromel-alumel, mineral-insulated metal-sheathed (MIMS) thermocouples
  - Typical results for **"normal"** environments (e.g., maximum of 300-400K) showed the total uncertainty to be about **±1% of the reading** in absolute temperature
  - In high temperature or high heat flux **"abnormal"** thermal environments, total uncertainties range up to **±2-3% of the reading** (maximum of 1300K)

- **MIMS Thermocouple Bias Errors (Figueroa 2005)**
  - Surface temperature measurement errors can vary from **1.5% to 6% at 1300K** (as compared to intrinsic thermocouple measurements). The large range is believed to be the results of significantly different radiation boundary conditions seen by the thermocouple (1.5% for TCs with embedded surrounding insulation, 6% for TCs on a hot surface in an open cavity that has the potential to radiate to a cold surface

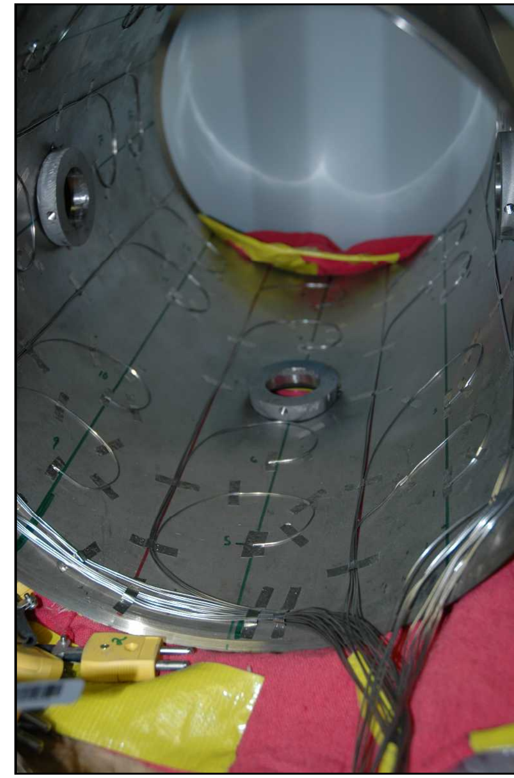
- **Uncertainty Analysis of Heat Flux Measurements Estimated Using a 1D Inverse Heat Conduction Program (Figueroa et al. 2005)**
  - **15-19% uncertainty** to 95% confidence at the highest flux, neglecting multidimensional effects

- **Estimates of Error Introduced When 1-D Inverse Heat Transfer Techniques Are Applied to Multi-D Problems (Lopez et al. 2000)**
  - **Maximum errors of 3%, 7%, and 18%** for a non-uniform flux applied to a surface covering 360°, 180°, and 90° of a cylinder, respectively.

Quantify the experimental uncertainty (continued)

- Uncertainty Analysis of Total Heat Flux Measurements Estimated Using a Schmidt-Boelter Heat Flux Gauge (Dual Medtherms) (Nakos 2005)
  - 12% uncertainty in incident flux
- Uncertainty Analysis of Radiative Heat Flux Measurements Estimated Using a Schmidt-Boelter Heat Flux Gauge (Dual Medtherms) (same approach as Nakos, 2005)
  - 11% uncertainty in incident flux
- The uncertainty in the Convective Heat Flux can be quite large when convection is small relative to radiation.
  - The uncertainty in the convective flux is ±43% when the radiative fraction is 0.67
  - The uncertainty in the convective flux is ±16% when the radiative fraction is 0.25
  - Note that in practical applications the convective heat flux is either a significant fraction of the total flux (yielding a smaller uncertainty) or it is simply not very important.

Fabrication of the Cylindrical Calorimeter



Cylindrical Calorimeter Instrumentation:

4 Medtherm heat flux gauges are installed at the midplane of the calorimeter, at angular positions 0º, 90º, 180º, and 270º in the calorimeter coordinate system

36 thermocouples are attached to the inner surface of the outer shell

Plumbing and wiring for the thermocouples and heat flux gauges are routed inside the calorimeter to one of the ends

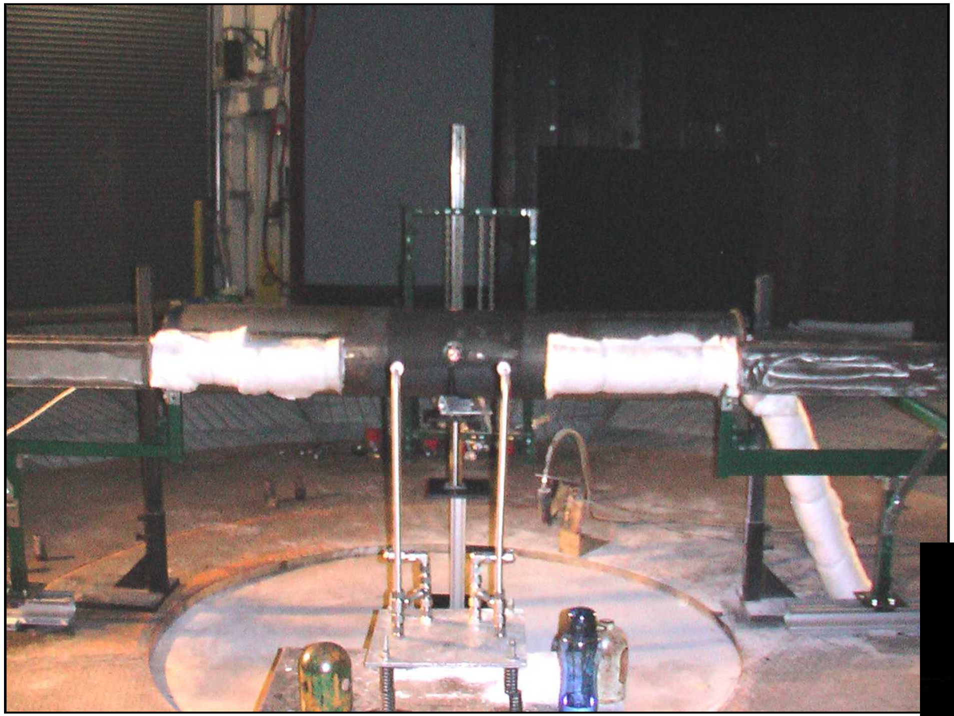
Test Setup and Conduct

•HFG results from nine methanol fire experiments are presented.

•Average initial and boundary conditions include: 1) 21±3°C wall temperature, 2) 19±3°C liquid fuel and ambient air temperature, 3) 0.82±0.01 atm ambient air pressure, and 4) 1.11±0.08 mm/min fuel regression rate with a corresponding mass flux of 0.015 kg/m^{2}s.

•The forced draft fan provided ~58 standard m^3/s of air into the cell.

•Steady-state fire durations were in the range of 10-30 minutes.



Location of calorimeter and HFGs

CARS

PIV

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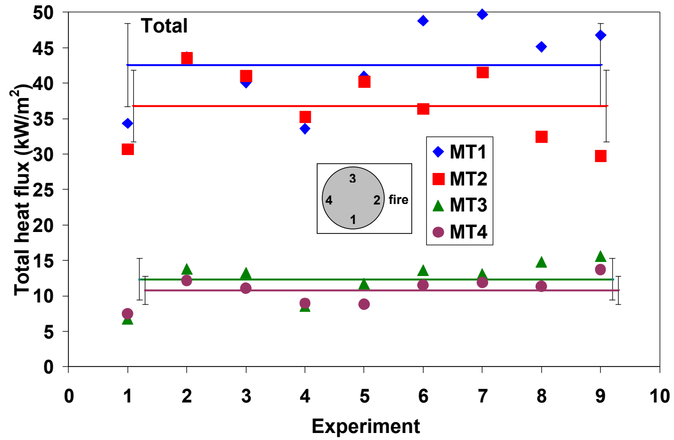
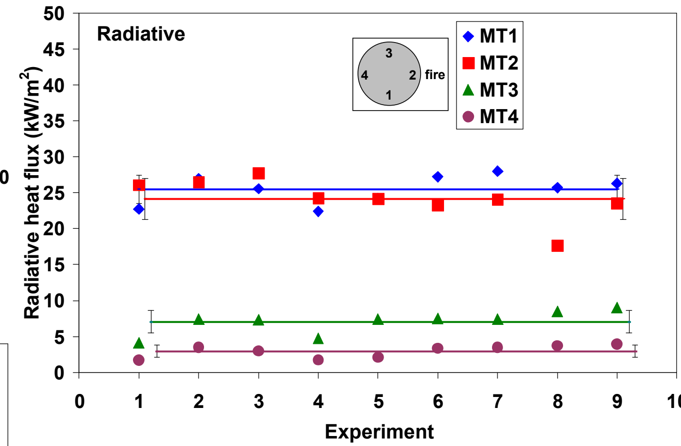
Average Steady-State Flux

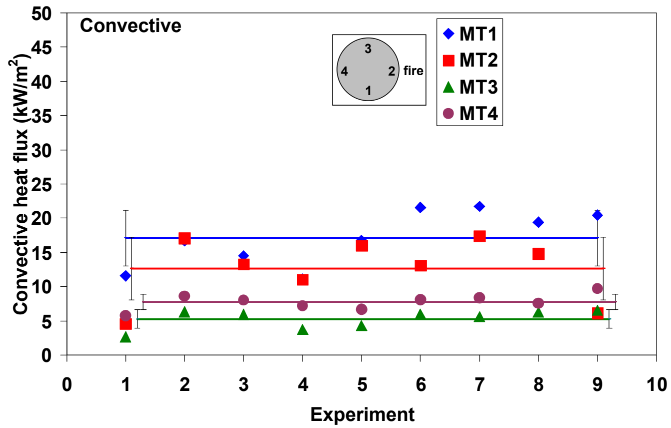
Larger total fluxes at MT1 and MT2 (facing the fire).

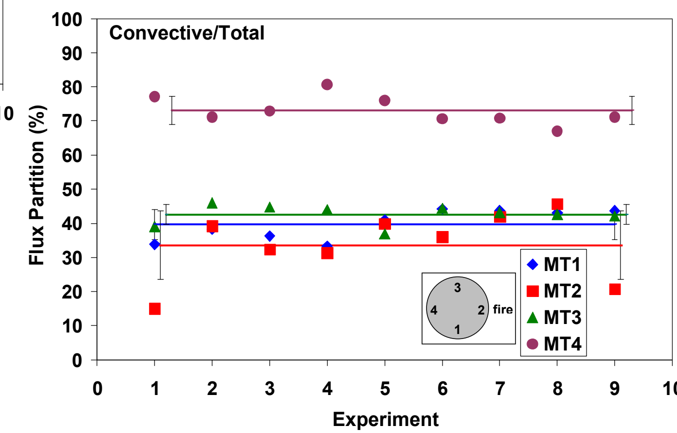
MT1-MT3: ~40%/60% partitioning of the heat flux into convective and radiative contributions.

MT4 (facing away from the fire): ~75%/25% convection/radiation partitioning.









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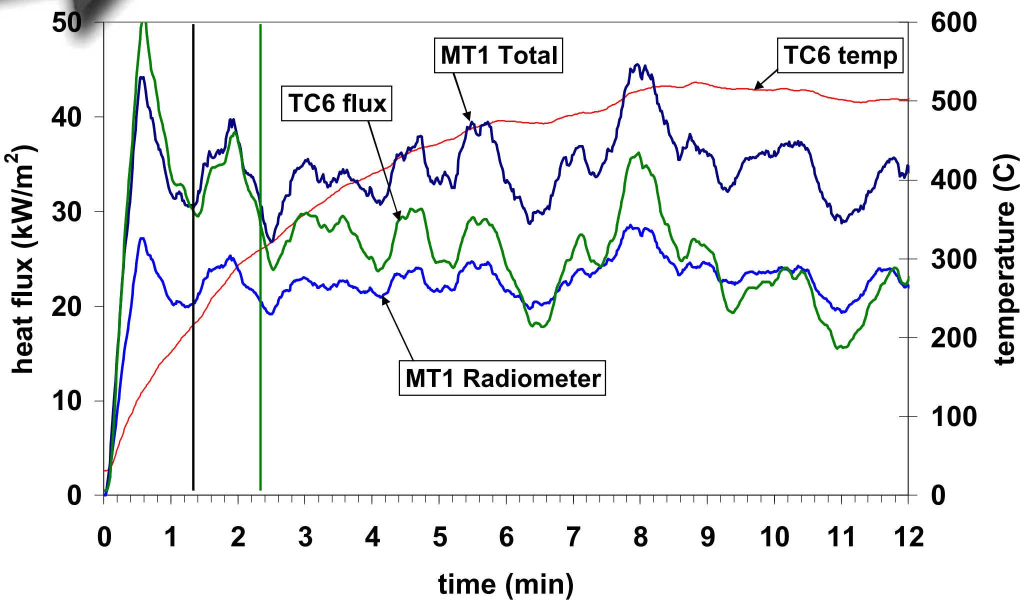
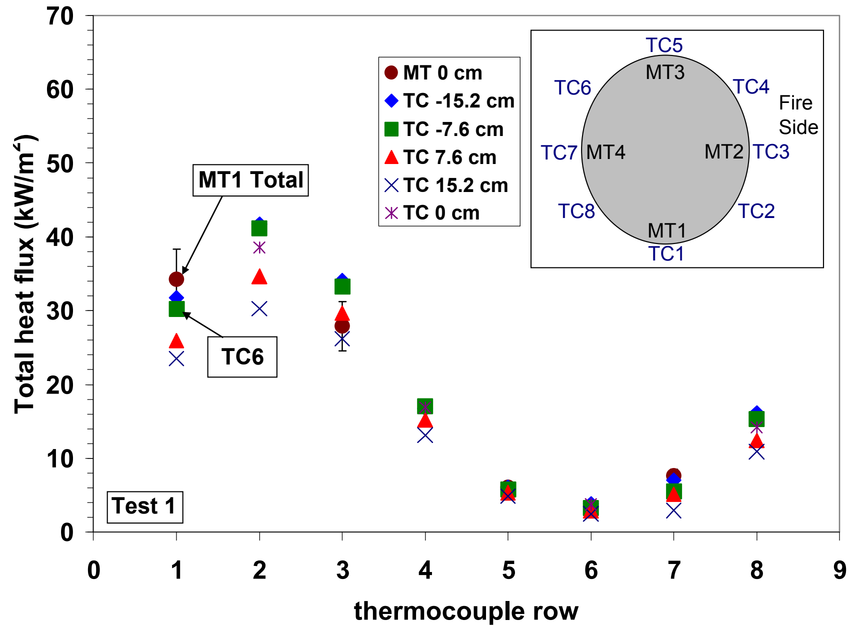
Flux Comparison: Thermopile vs. 1D Inverse Conduction



Thermopile to TC flux comparison



Asymmetric circumferential flux (Exp.#1 1-min average)

Initially the TC flux matches the *total* MT (water-cooled) flux.

Then, the TC flux trends to the *radiative* MT flux measurement as the calorimeter heats (TC6 temperature), reducing the convection.

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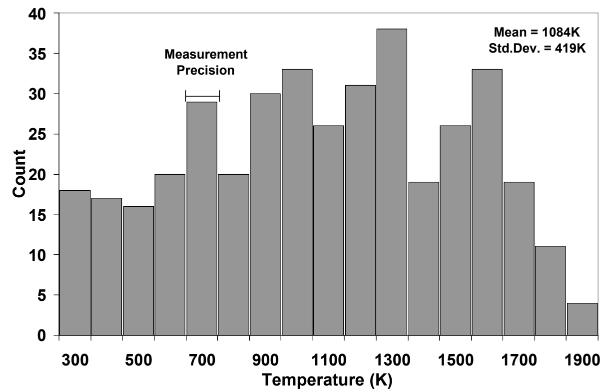
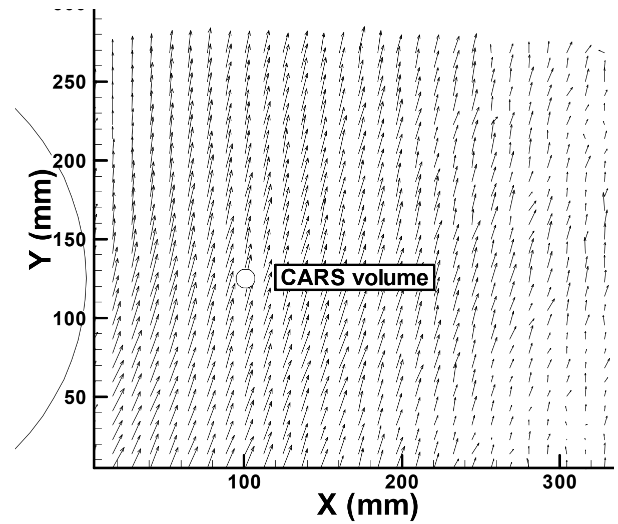
Experimentally Determined Local Convective Heat-Transfer Coefficient

$$h_{exp} = \frac{\dot{q}''_{conv}}{\left(T_s - T_\infty\right)}$$



CARS temperature histogram



PIV determined gas velocity

- **h_{exp}, *local* at sensor MT2 = ~16 W/m²-K**
- measured convective flux, $\dot{q}''_{conv}$ 12.1±4.5 kW/m²
- gauge surface temperature, T_s 323±3 K
- average CARS-measured gas temperature, T_∞ 1083±419 K

- engineering estimate using the Hilpert correlation

$$\overline{Nu}_D = \frac{\bar{h}\,D}{k} = C\,Re_D^m\,Pr^{1/3}$$

- **h = ~8 W/m²-K for the *surface-averaged* heat-transfer coefficient**

Summary

- Detailed measurements related to the partitioning of heat flux to an object in large-scale fully-turbulent methanol fires have been taken for the purpose of model validation.
- Care has been taken in the design of experiments to 1) ensure that convection is an important component and 2) data can be used to evaluate the uncertainty in numerical model prediction of both radiation and convection.
- Using methanol also eliminates soot as the primary radiative source, thus providing a data set that is based on gas band radiation only.
- Follows the recommendations for the design of validation-quality datasets
    - Measurements with estimation of experimental uncertainty of all initial and boundary conditions required as numerical simulation input.
- An extensive suite of hi-fidelity code validation simulations that include uncertainty quantification has recently been performed using the Sandia fire code Fuego*.
- The data sets (available on request) are unique in the first use of CARS, PIV, thermopiles, and thermocouples in the same experiment and conducted in a new large-scale fire research laboratory specifically designed to provide validation quality data.
- Future work will focus on extending the CARS and PIV measurements.

*Brown, A.L., Dowding, K.J., Nicolette, V.F., and Blanchat, T.K., "Fire Model Validation for Gas Temperatures and Radiative/Convective Partitioned Heat Flux," accepted to the 9th International Symposium on Fire Safety Science, 21-26 September, 2008, Karlsruhe, Germany.