A Thermal Precipitator for Fire Characterization Research

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Outline

- Motivation – Fire Characterization Research
- Background
- Design goals
- Modeling
- Testing & Hardware
- Results
- Conclusion
Fire Characterization Research
at NASA Glenn Research Center

- Most likely source of a fire on the International Space Station is overheating electronic equipment
- Early detection (before flame develops) allows rapid crew response
- Spacecraft fire safety is unique
  - No natural convection to concentrate smoke at ceiling
  - Smoke generated will disperse slowly through the cabin by forced convection caused by the ventilation flow
    - Approximately 10-15 cm/s but depends on location, stowage, etc.
ISS Destiny Smoke Detection Simulation-25% Soot

Low-gravity

Normal-gravity
Fire Characterization Research

• Next-generation space fire detectors will consist of
  • Aerosol sensors
  • Gas sensors

  } Appropriate alarm thresholds will minimize false alarms

• Multiple small, low-power sensors will allow distributed detectors and more rapid fire response
Fire Characterization Research

- Need: Characterize aerosols and gases produced by overheating common spacecraft materials
- A thermal precipitator was designed to collect smoke aerosol particles for microscopic analysis
- Information on particle morphology, size and agglomerate structure supplements other aerosol and gas data obtained in fire research
Fire Characterization Research

- Test smoke
  - Kapton, Teflon, circuit board, wire insulation, Nomex
  - 300° C to 640° C
  - $1 \times 10^5$ to $1 \times 10^6$ particles/cm$^3$
  - 40 to 70 mg/m$^3$
  - $100 \text{ nm} < d_p < 1000 \text{ nm}$
Fire Characterization Research

- Goal is to characterize smoke
- Verify a repeatable fire challenge for testing
  - Aerosol instruments
  - Gas sensors
  - Post-fire clean-up equipment
- Multiple NASA smoke test facilities
  - Slightly different burn methods
  - Check fuel preparation consistency
Thermophoresis

- Thermophoretic force, $F_{\text{th}}$, on a particle is the result of a temperature gradient established in the gas medium
  - The force is in the direction of decreasing temperature
- For small particles (large Knudsen number) thermophoresis is explained by kinetic theory of gases
- In the transition and continuum regimes, Navier Stokes equations with slip-corrected boundary conditions have been used
Thermophoresis

- The thermophoretic force on an aerosol particle can be expressed as (Brock, 1962)

\[
F_{th} = \frac{-6\pi\mu v d_p C_s \left( \frac{k_a}{k_p} + C_t Kn \right) \nabla T}{(1 + 3C_m Kn) \left( 1 + 2\frac{k_a}{k_p} + 2C_t Kn \right) T}
\]

- \(\mu\) = viscosity of air
- \(\nu\) = kinematic viscosity
- \(d_p\) = particle diameter
- \(k_p\) = particle thermal conductivity
- \(k_a\) = air thermal conductivity
- \(Kn = Knudsen number, 2\lambda / d_p\)
- \(\nabla T\) = Temperature gradient
- \(T\) = Absolute temperature of particle

\(C_t = 2.18, C_m = 1.14, C_s = 1.17, thermal exchange coefficients\) (Talbot et al., 1980)
Design

- Develop a portable device for sampling smoke aerosol particles for microscopy
- Collect particles on easily inserted substrates for microscopy
  - Scanning Electron Microscope (SEM) aluminum specimen mount
    - Hitachi stubs with threaded hole
  - Transmission Electron Microscope (TEM) grid
    - Attach to aluminum stub with carbon tape
Design

- Reduce aerosol flow from $\frac{1}{4}$" tubing inlet to very narrow gap
  - Laminar flow
- Highest possible temperature gradient achievable with minimal thermal management (power, size)
  - Thermoelectric coolers (TE)
Design

• Particle residence time in TP is controlled by
  • Flow rate
  • Height of gap
  • Length of body
  • Temperature gradient

• Multiphysics finite element model determined reasonable combination of these variables
  • Computational Fluid dynamics
  • Thermal
  • Particle trajectories
Modeling: CFD

- Spline function for contour of entrance region
- Body lengthened to increase residence time
- Gap height adjusted
- \(150 \text{ cm}^3/\text{min or less flow rate}\)
Modeling: Thermal

- Design iteration from model results
  - Increased area of constant thermal gradient
Modeling: Trajectories

- Particle trajectories based on combined physics in numerical model
  - Slip-corrected Stokes drag and thermophoretic force
  - Average value of particle thermal conductivity 0.19 W/m-K
  - Multiple particle sizes: 100 nm, 500 nm, 1000 nm
Modeling: Trajectories

- SEM stub locations
- Final flow rate
Hardware

- Thermoelectric (TE) coolers and Kapton heater provided temperature gradient
  - Gap height 1.25 mm
  - No direct temperature control, only $\Delta T$ of cooler
  - Efficiency of heat removal from the hot side of the TE cooler established the gradient
Thermal Design Iterations During Testing

- Permanent thermocouples on cold plate and heated plate
- Improve heat removal from TE cooler
  - Larger fin surface area & larger fan
- Increase contact conductance between stubs, TE coolers and heat sinks
- Add insulation
Testing

- Achieved 70° C temperature gradient with 8 to 10 minute warm-up time
  - Heated plate ~ 65° C
  - Cold plate ~ -5° C
- Sampled filtered air with TP for an hour
  - Verified no particles on stubs
- Verified PSL particle collection
  - 1.0, 0.67 µm and 100 nm
- Condensation issues during testing with PSL aerosol generation from aqueous solution
  - Smoke chamber dew point ranges from -9° to -18° C
Packaging

- Aluminum housing positions fan and directs air onto heatsink for heat removal
- Lid opens for access to SEM stubs
Wire Insulation 640° C

SEM stub 1

0.2 μm

0.5 μm

0.1 μm

4 μm

0.3 μm

1 μm

1 μm
Kapton 640°C

SEM stub

0.8 μm

2 μm

d_g = 225 nm
Kapton 640° C

SEM stub

2 μm

0.8 μm

0.5 μm

0.25 μm

1 μm
Teflon $640^\circ$ C

SEM stub

$1.7\mu m$

$0.4\mu m$

$0.2\mu m$

$d_g = 240 \text{ nm}$
Teflon 640° C

SEM stub

TEM grid

1.7 µm
0.4 µm
0.2 µm

2 µm

250 nm

20 nm
Conclusion

- Thermal precipitator designed, modeled and tested
- Successful particle collection
- Fire characterization research ongoing
  - Aerosol/gas kinetics
Acknowledgment: Daniel Gotti contributed to the mechanical design and did the CAD model for this project
Backup Slide: Thermoelectric Cooler

- Also known as Peltier cooler or heater
- Creates a heat flux between the junction of two different types of materials (N and P-type semiconductor pellets)
- Datasheet gives $\Delta T_{\text{max}}$ (between each side of cooler), cooling capacity, current and voltage restrictions

[Diagram of Thermoelectric Cooler]

Backup Slide

- Carbon tape strip placed in the direction of flow
- TEM and HRTEM grids are attached to carbon tape
Backup Slide