A Thermal Precipitator for Fire Characterization Research
Marit Meyer, NASA Glenn Research Center
Vicky Bryg, National Center for Space Exploration Research (NSCER), Microscopy
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

- 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 x 10⁵ to 1 x 10⁶ particles/cm³
  - 40 to 70 mg/m³
  - 100 nm < dₚ < 1000 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, $F_{th}$, 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)

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

\(\mu\) = viscosity of air
\(v\) = kinematic viscosity
\(d_p\) = particle diameter
\(k_p\) = particle thermal conductivity
\(k_a\) = air thermal conductivity
\(Kn = Knudsen number, 2\nu d_p\)
\(\nabla T\) = 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 ¼” 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 cm³/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

0.2 μm

0.5 μm

0.1 μm

4 μm

0.3 μm

1 μm

1 μm
Kapton $640^\circ$ C

SEM stub

$d_g = 225$ nm
Kapton 640° C
Teflon 640° C

SEM stub 2 μm

1.7 μm

0.4 μm

0.2 μm

d_g = 240 nm
Teflon 640° C

SEM stub

TEM grid
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

Backup Slide

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