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
- Multiple small, low-power sensors will allow distributed detectors and more rapid fire response
  
  Appropriate alarm thresholds will minimize false alarms
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
  - $300^\circ$ C to $640^\circ$ 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, $F_{th}$, 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 \( F_{th} \) (Brock, 1962)

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

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

\( C_t = 2.18, C_m = 1.14, C_s = 1.17, \text{ thermal exchange coefficients (Taibot et al., 1980)} \)
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 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

0.1 μm

0.5 μm

4 μm

0.3 μm

1 μm
Kapton 640° C

SEM stub

0.8 μm

2 μm

d_g = 225 nm
Kapton 640° C

SEM stub

0.8 μm

2 μm

0.5 μm

0.25 μm

1 μm
Teflon 640°C

1.7μm
0.4μm
0.2μm

SEM stub

2 μm

\(d_g = 240 \text{ nm}\)
Teflon $640^\circ$ C

SEM stub  

TEM grid

$1.7 \mu m$

$0.4 \mu m$

$0.2 \mu m$

$2 \mu m$

$250 \text{ nm}$

$20 \text{ nm}$
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

Backup Slide

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