RADIATIVE COOLING DEVICE USING NANOMATERIALS

INSTITUT FÜR THERMODYNAMIK

Owen Jarl

26.7.2019
OBJECTIVE

- Simulate a radiative cooling device that emits thermal radiation in the “sky window” wavelength (8-13 micron) while limiting absorbed solar radiation with the use of nanomaterials
- Cooling happens when the emitted radiation is greater than the absorbed radiation
- Hot / ambient temperatures cool directly to space (3 Kelvin)
- Benefits: Minimal to no electrical input for cooling
**Geometry**

- **Optical Layer**
- **Radiating Body**

Emitting Radiation at 8-13 microns

(Atmosphere does not absorb this wavelength well)

**Scattering and Absorption**

- Backward Scattering (Reflection)
- Forward Scattering

**Emission > Absorption = Cooling**
RADIATING BODY

- Definition: Any material that will emit radiation at certain wavelengths dependent on temperature
  - Every body above 0 Kelvin emits thermal radiation
- In the case of the simulation, the radiating body was assumed to be a black body
- In real life, an external temperature, or heat flux, will be applied to the radiating body
BLACK BODY

- Black body absorbs and emits the same amount of radiation (ideal)
- Planck’s Equation (UNITS: W/m^2 / micron)

\[ I_{\text{Black Body}}(T, \lambda) = \frac{2\pi hc^2}{n^2 \lambda^5 \left( e^{\frac{hc}{nkT\lambda}} - 1 \right)} \]

h = Planck’s Constant
k = Boltzmann’s Constant
T = Temperature
n = Refractive Index
c = Speed of light
Lambda = Wavelength
PLANCK’S LAW

- Temperature increases, higher radiation intensity at shorter wavelengths
- Temperature decreases, higher radiation intensity at longer wavelengths

GOAL IS TO EMIT INFRARED RADIATION (HEAT RADIATION) BETWEEN 8-13 MICRONS FROM THE RADIATING BODY
OPTICAL LAYER

- Optical layer is composed of ZnS (Zinc Sulfide) nanoparticles in HDPE (High Density Polyethylene)

- ZnS:
  - *Highly transmissive in the “sky window” (8-13 micron)*

- Other nanoparticles with fair properties for radiative cooling applications:
  - $TiO_2$, $SiO_2$, $HfO_2$
NANOMATERIALS

- Definition: Material consisting of nanoparticles
- Each nanomaterial has a different refractive index and volume fraction
REFRACTIVE INDEX

- Definition: How fast light can travel through a material
- Real and Imaginary parts of the refractive index
  - Real: Dispersion of wavelengths of light
    - Refractive index decreases as wavelength increases
  - Imaginary: Absorption in opaque materials
- Refractive index is about 2 for ZnS (Varies with wavelength)
NANOPARTICLES

- Nanoparticles determine scattering and absorption of electromagnetic waves
- Particle size and volume fraction influences scattering and absorption of wavelengths
  - *Larger particles scatter a larger band width of wavelengths*
SCATTERING

- Forward and Backward (Reflection)
- Determined by the real and imaginary refractive index
- The goal is to scatter small wavelengths that solar irradiance projects

**Figure 1:** Wavelength vs. Scattering Coefficient
ABSORPTION

- Based off of imaginary refractive index of the nanomaterial
- Based off of the real and imaginary refractive index of nanoparticles
- MATLAB function had high values for absorption
  - *This means no radiation was being transmitted through the optical layer*
  - Used average absorption coefficient (20 m^-1 @ 10.6 microns)

Figure 2: Wavelength vs. Absorption Coefficient
PROGRAMS USED

- MATLAB
  - *Scattering and Absorption functions*

- Ansys CFX
  - *Monte Carlo Radiation Method*
    - Define wavelengths being simulated
      - *Whole spectrum* (.2 - 1000 micron)
      - *Interested in* (8 – 13 micron)
    - Based on number of histories (5,000,000 histories)
SOLAR IRRADIATION

- Amount of electromagnetic radiation experienced, on average, from the sun
OTHER EQUATIONS

■ COOLING POWER EQUATION

\[ P_{\text{Cooling}} = P_{\text{emission from black body}} - P_{\text{absorbed solar irradiation}} - P_{\text{other heat losses}} \]

- (Other heat losses: Convection, or conduction, external factors)

■ Absorption + Transmission + Reflection = 1

- Applies to the waves traveling through the optical layer
RESULTS (Optical Analysis)

Figure 3: Total Incident Radiation in the Optical Layer when the Radiating Body was at Temperature 295 Kelvin

The optical properties (Scattering and Absorption) produce a non-uniform display of Incident Radiation
CONCLUSION

■ As particle size increases, scattering increases in small wavelengths
■ Total emitted irradiation flux between the wavelengths 8-13 micron is 82.13 Watts
  - *This value might be higher due to the average absorption coefficient*
  - *Value was calculated in Ansys Post Simulation*
■ As long as solar irradiation coming into the system is less than what is emitted there will be cooling
  - *This is determined by the properties of the nanomaterial*
FUTURE WORK / IMPROVEMENTS

- Adjust MATLAB code to simulate absorption accurately at each wavelength
- Couple optical analysis, thermal analysis, and solar irradiance analysis in Ansys CFX
- Obtain experimental values for real materials and use raw data in simulation
CHALLENGES

- Learning Ansys CFX, MATLAB, and Heat Transfer
  - *Steep learning curve with set backs*

- Coupling thermal and optical properties of the device in Ansys CFX
  - *This would simulate cooling effect*

- Obtaining raw data in papers and on the internet

- Getting a thermal analysis result
  - *Ran out of time*
CHALLENGES WITH ANSYS

- Having a quality mesh for radiation simulation
- Defining the Planck equation at the boundary
- Monte Carlo method was not working when the optical layer was a solid
  - *Simulate optical layer as a liquid with high viscosity*
- Keeping the optical layer at 0 Kelvin
  - *Not emitting any radiation*
  - *This also made the energy equation not valid; therefore, no thermal results*
RESOURCES


*Nanoparticle embedded double-layer coating for daytime radiative cooling*, Zhifeng Huang and Xiulin Ruan

*Radiation and Energetic Analysis of Nanofluid Based Volumetric Absorbers for Concentrated Solar Power*, Jan Rudolf Eggers, Eckart Matthias Lange, and Stephan Kabelac


*Wavelength Selective Cover for Sub-Ambient Passive Radiative Cooling*, Hannah Kim and Andrej Lenert

My German Summer
By: Owen Jarl
PLACES VISITED IN GERMANY

- Hannover
- Hamelin
- Hamburg
- Norderney
- Berlin
- Wolfenbüttel
PLACES VISITED IN EUROPE

- Amsterdam, Netherlands
DIFFERENCES (USA AND GERMANY)

- Public transportation is so easy and so common in Germany
- People walk everywhere in Germany and seem to have better relaxing habits (more outdoor activities)
- Three ingredients in beer
- Saying “Bon Appetite” before eating food
- Graffiti
- Smoking
- Knocking on the desk after a presentation
- Making food for celebration of a thesis being completed
THE GOOD EXPERIENCES

- Traveling is so easy around central Europe and in Germany
- Meeting new people that I could interact with everyday and not just meet once
- Learning who I am as an individual being on my own for so long
- Challenging myself in the institute
- Pommes und mayo <3
THE CHALLENGES

- Not having cell phone service or a car
- Nothing open on Sunday makes it harder to do things without planning ahead
- Paying to use the bathroom or to get water
- Keyboard on the computer made it hard to type in the institute
- Not being able to speak German
WHAT IS NEXT?

- Munich, Germany
- Innsbruck, Austria
- Salzburg, Austria
- Prague, Czech Republic
- Kraków, Poland
- Frankfurt, Germany

BACK TO MICHIGAN STATE TO FINISH THE LAST YEAR OF MY UNDERGRAD!
THANKS FOR EVERYTHING :)

![Image of the Nobel Peace Prize laureate statue in Oslo, Norway]