TFAWS Passive Thermal Paper Session

Thermal Systems Modeling of a Variable Emittance Coating for Human Spacecraft Applications

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Presented By

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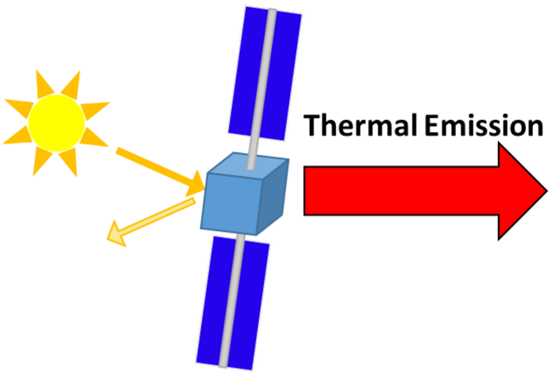
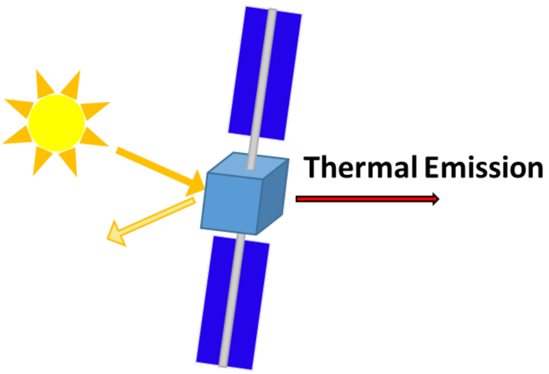
Outline

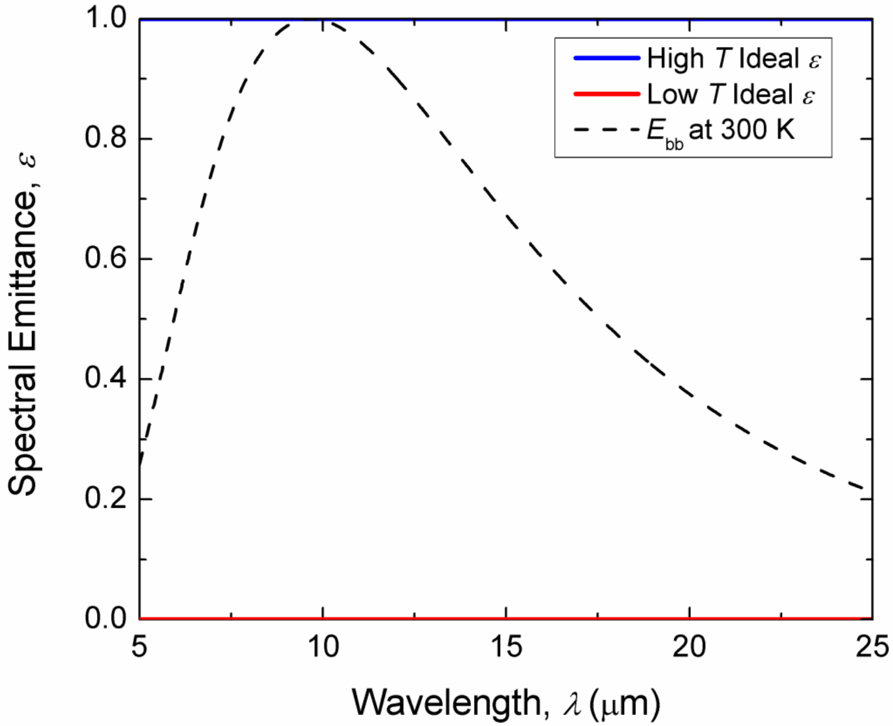
- Introduction
  - Motivation and background
  - Properties of vanadium dioxide (VO_2)
  - Variable emitter design and initial results
- Preliminary MATLAB modeling
  - Objectives
  - Representative spacecraft system definition
  - Modeling approach and cases considered
  - Model results
- Additional Geometries
  - Radial flow radiators
  - Bypass valve
- Comparison with Thermal Desktop
- Conclusions

High Temperature – High Heat Rejection



Low Temperature – Low Heat Rejection



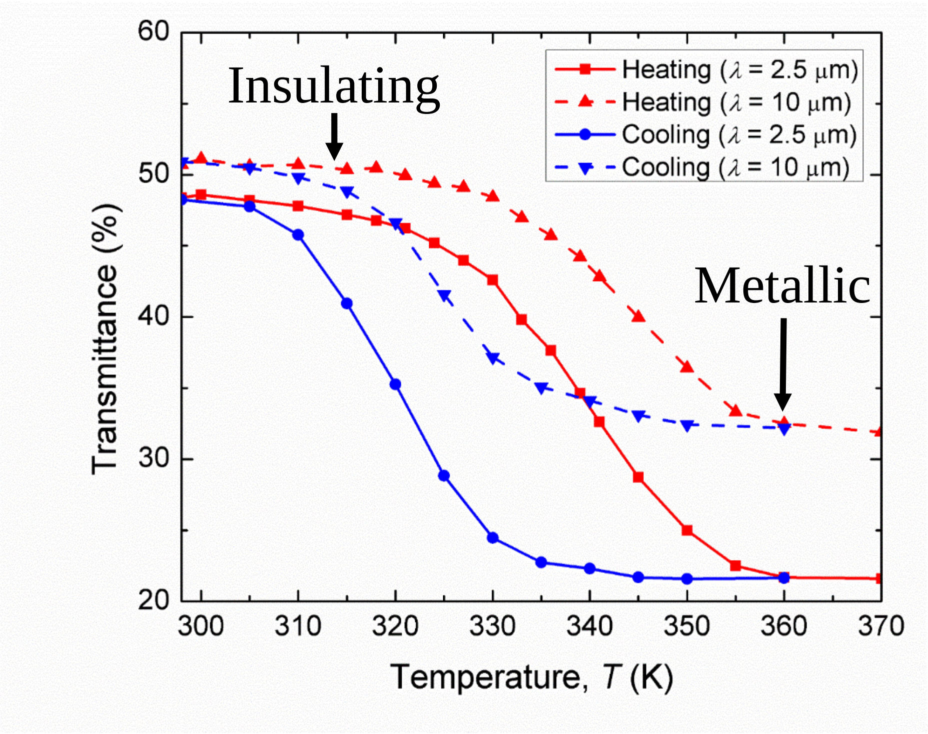


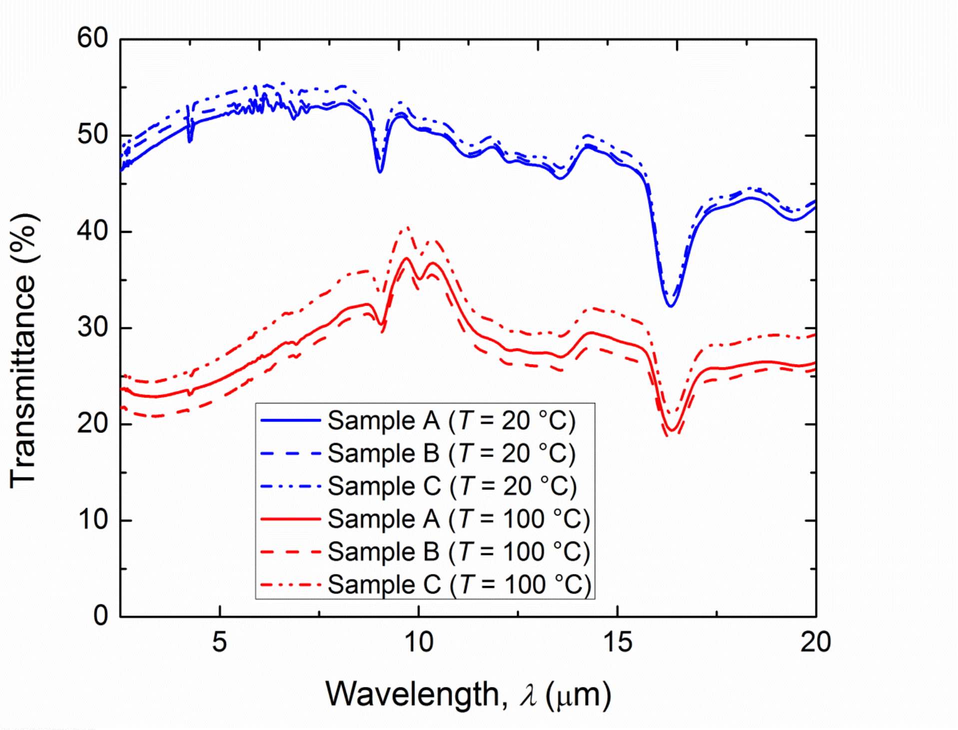
Ideal Broadband Emittance

- **High Temp: ε ≈ 1**
- **Low Temp: ε ≈ 0**

Background: Characteristics of VO_2

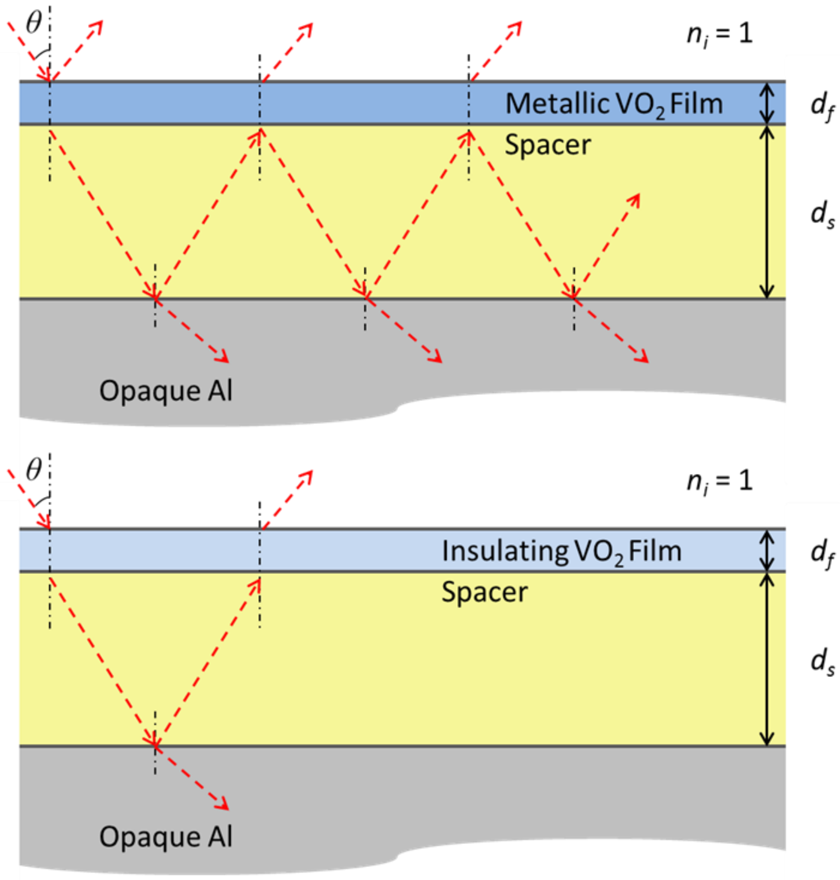
- VO_2 is an insulator-to-metal thermochromic material
- Changes phase at 341 K (68 ^{o}C)

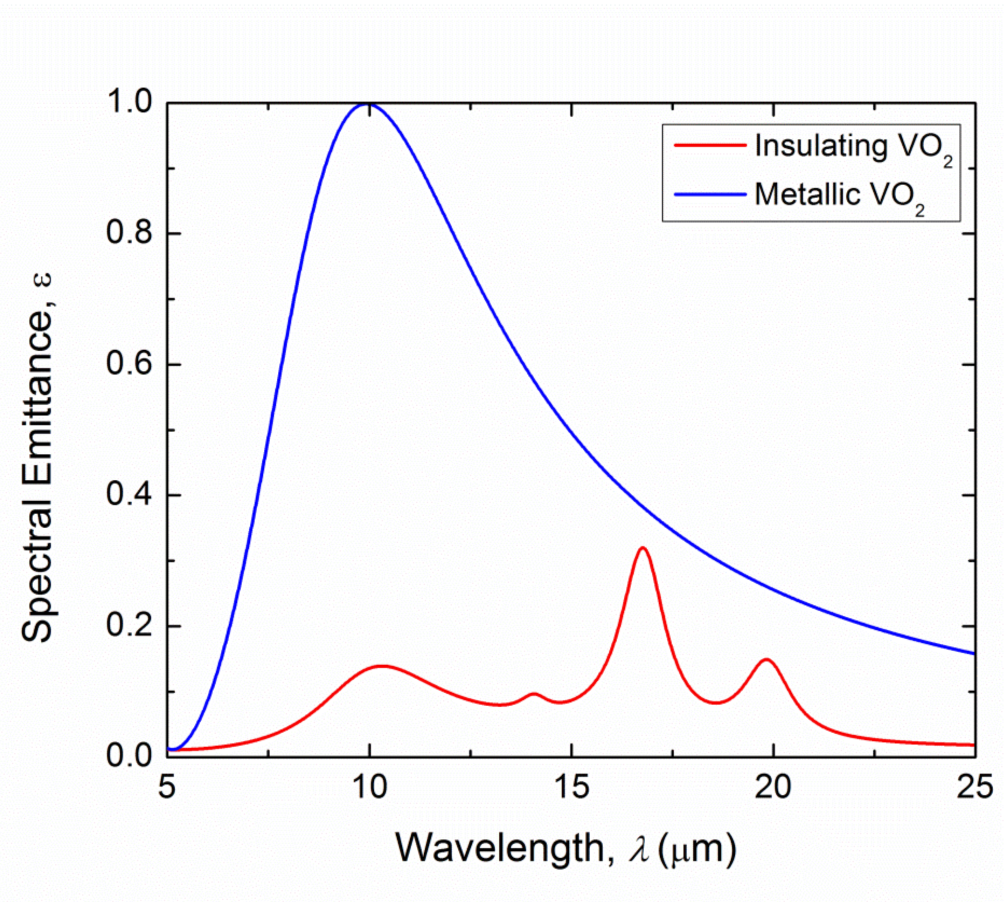




Taylor et al., Thin Solid Films, submitted

- Silicon is only 54% transparent in the mid-infrared
- Incorporate VO_2 in a multilayer structure to get variable ε

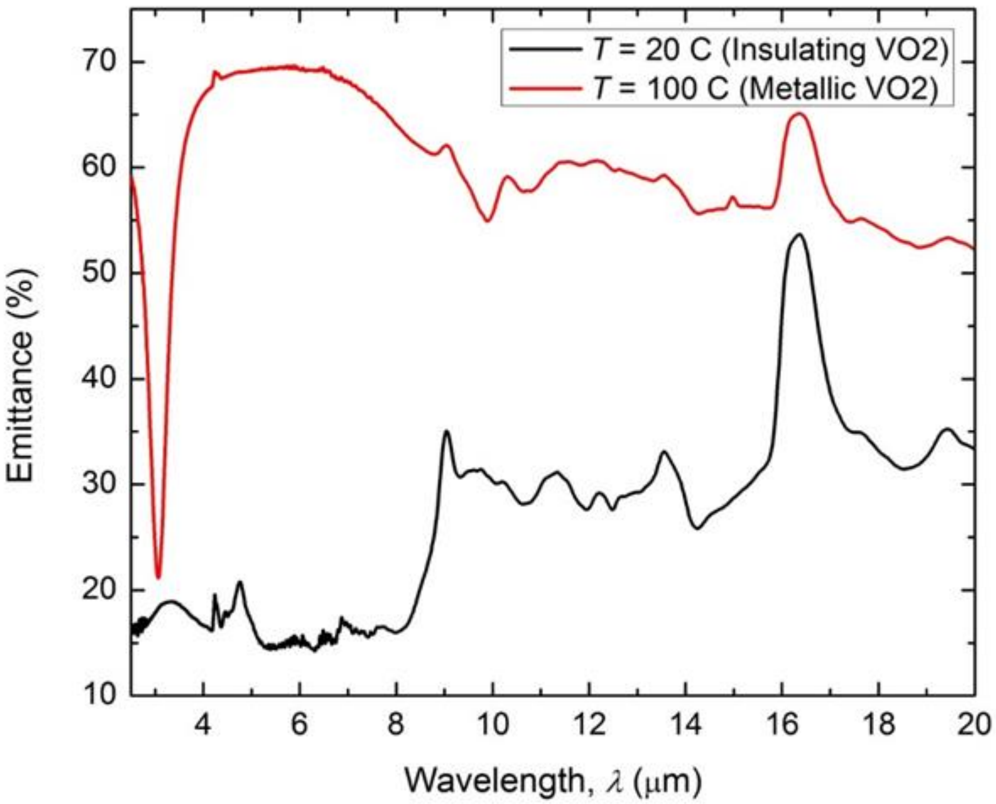




$d_f = 25$ nm
$d_s = 730$ nm

Taylor et al., J. Quant. Spectrosc. Radiat. Transfer, 197, 76-83 (2017)

Background: Initial Experimental Results



Presented as a poster at ICES2018

- Consistent results for the last 3 samples fabricated
- ~0.55 change in emissivity over short wavelengths
- ~0.30 change in emissivity over longer wavelengths

Objectives

<u>Modeling Objectives</u>:

1. Determine what **transition temperature range** is required for human spaceflight applications

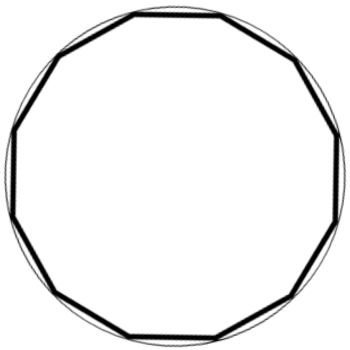
2. Determine the **minimum emittance change** required for the coating to have an appreciable turn down

3. Identify what **types of missions** would or would not benefit from variable emittance

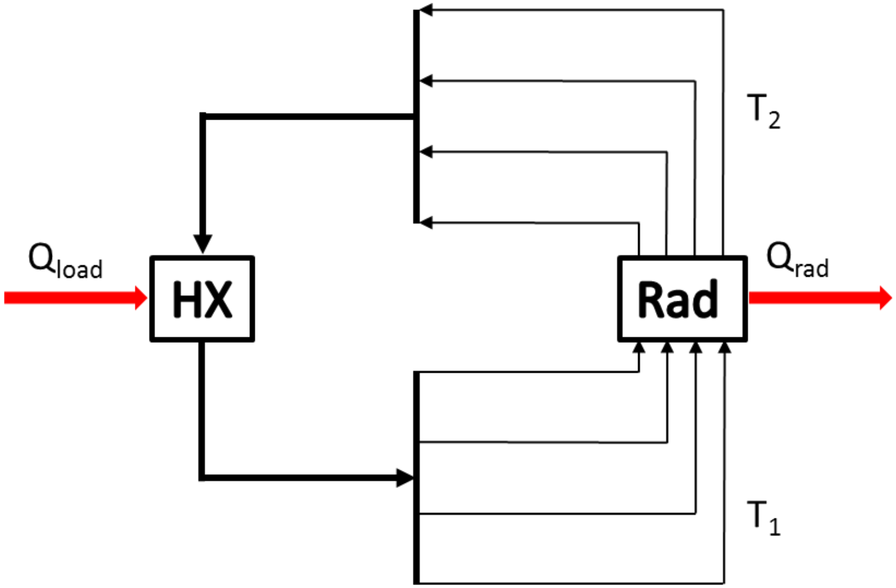
4. Identify which **radiator designs** seem to be the most effective when using a variable emissivity coating

Representative Spacecraft

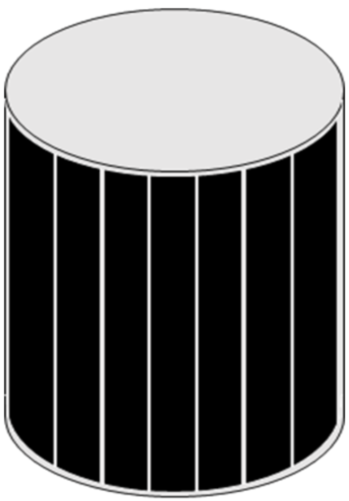
Top View

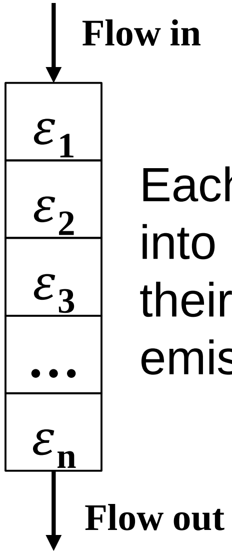


Body-mounted radiators that are discretized into N = 360 panels



Side View

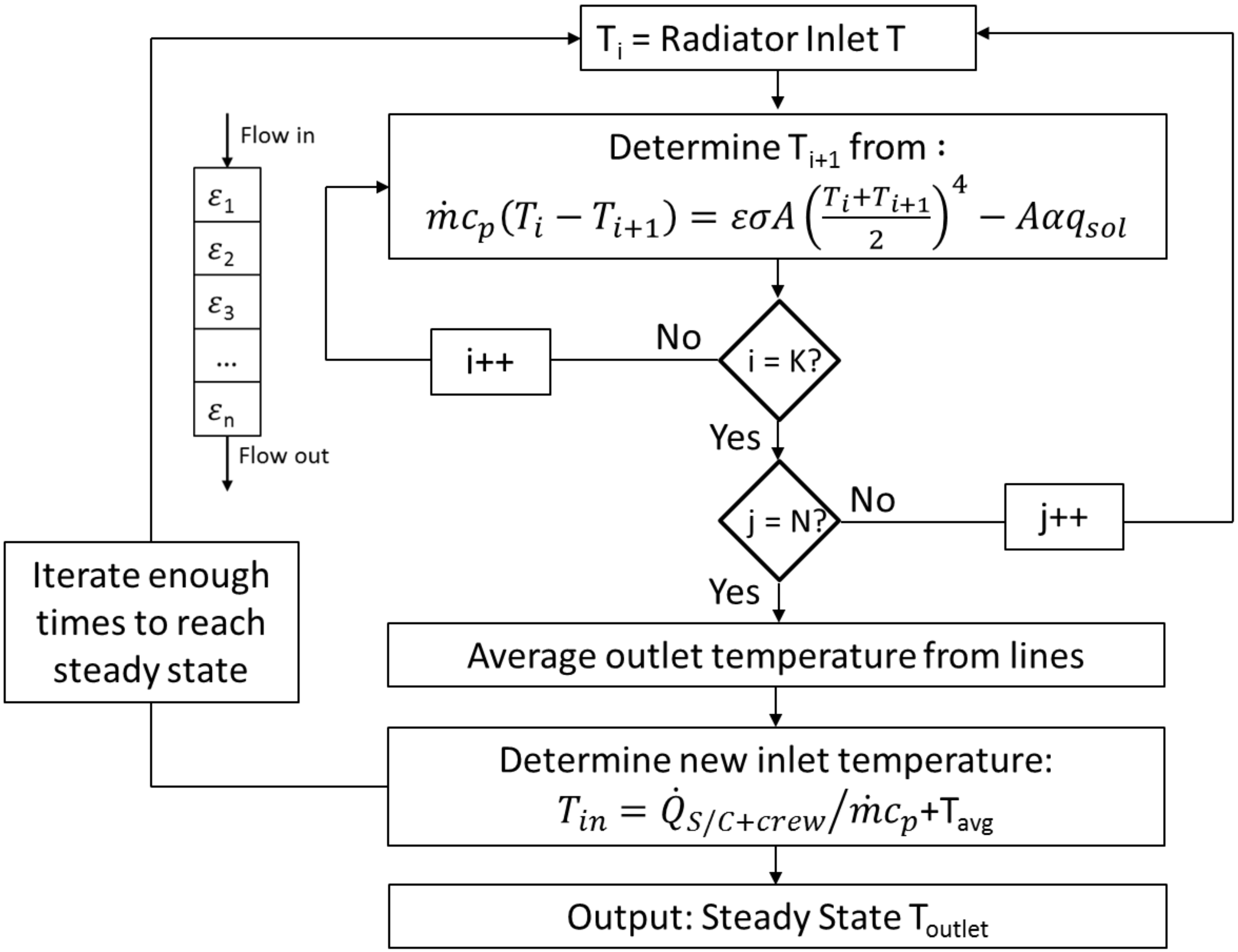


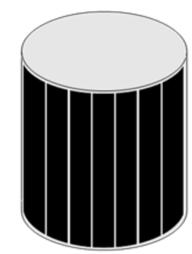


Each panel is discretized into K blocks, each with their own independent emissivity

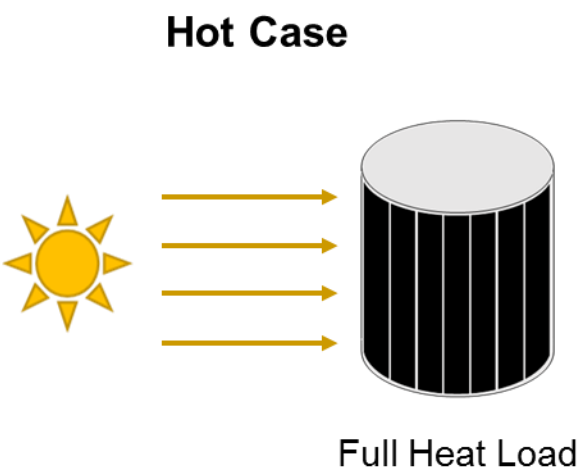
1. Fluid picks up heat from HX
2. Flow separates into 360 lines with equal flow rates
3. Heat is rejected by each separate fluid line/radiator panel
4. Flow is mixed to give average T_{outlet}

MATLAB Approach

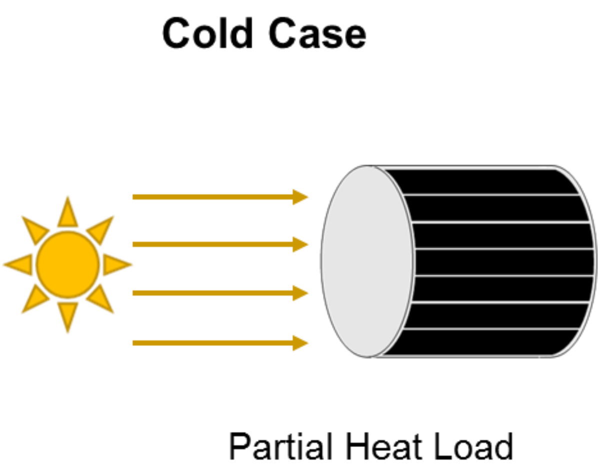




Initial Cases Considered



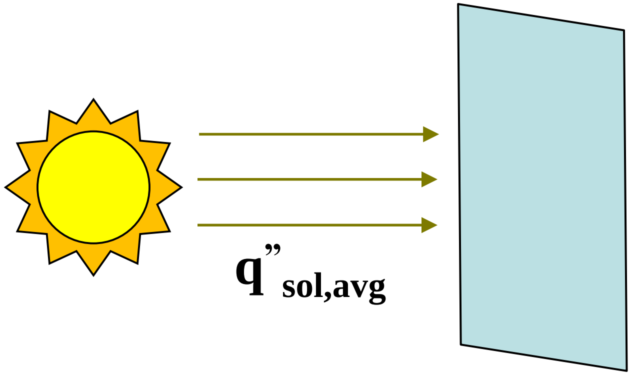
$Q_{FHL} = 8500\ W$



- **Requirement 1:** Average outlet temperature must be between 0 ºC and 10 ºC
- **Requirement 2:** The temperature of each radiator panel must be above -10 ºC

- Turndown percentage TD = lowest percentage of full load that can be reduced to while still meeting requirements

Radiator Area Sizing



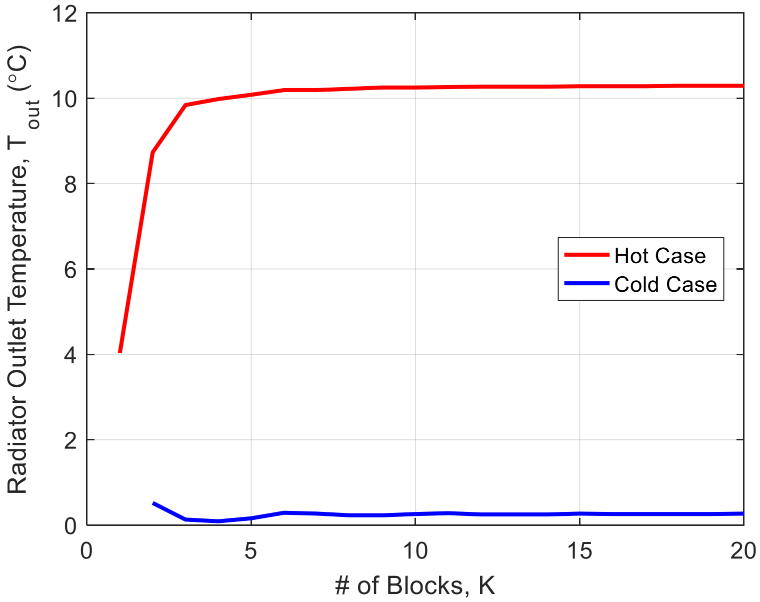
$$T_{Rad} = \frac{T_{in} - T_{out}}{2}$$

$$T_\infty = \left(\frac{1}{\sigma}\left(\frac{\alpha}{\varepsilon} q_{sol} + q_{IR}\right)\right)^{1/4}$$

$$A_{Rad} = Q_{load}/(\varepsilon\sigma(T_{Rad}^4 - T_\infty^4))$$

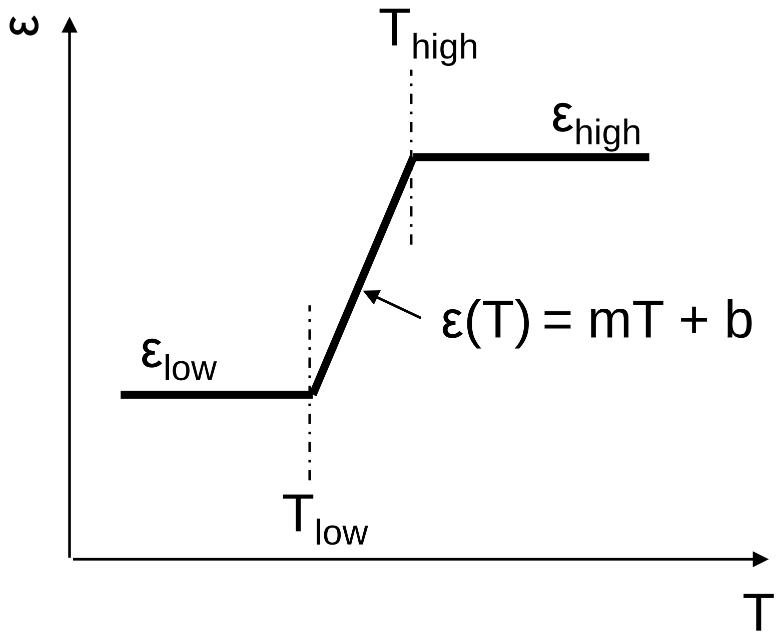
where $q_{sol} = 432.5\ W/m^2$

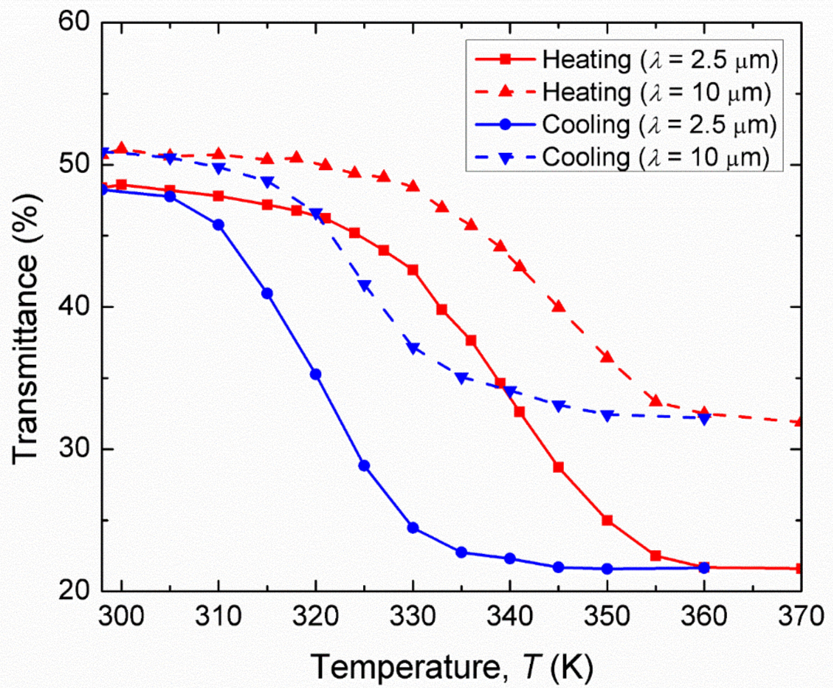
Panel Discretization



Results for both the hot case and cold case stop changing significantly after K = 10

Variable Emissivity Model



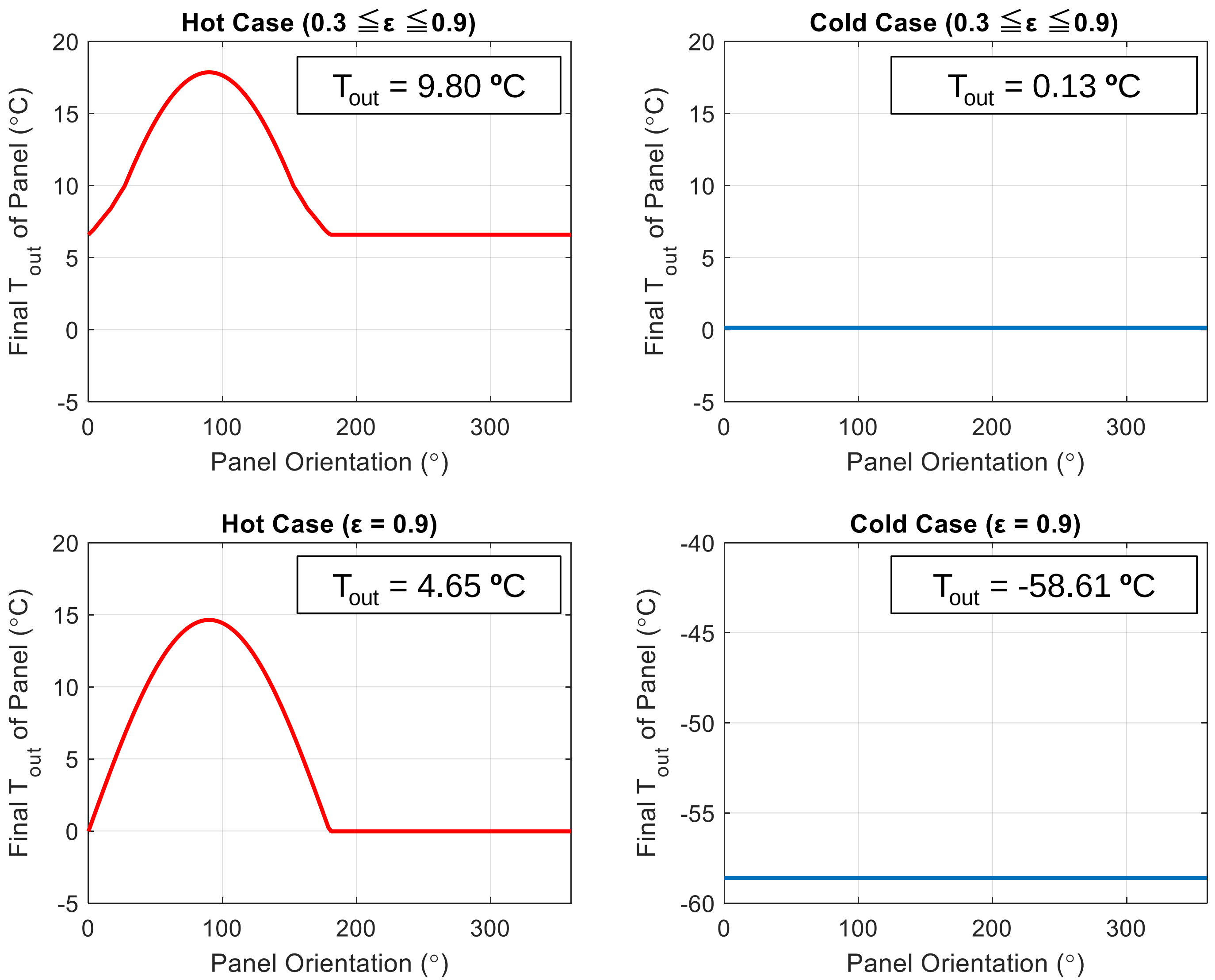


1. No hysteresis considered
2. ε_{low} can vary between 0.3 and 0.6
3. ε_{high} can vary between 0.6 and 0.9
4. T_{high} must be between 4 and 20 degrees higher than T_{low}

→ (2), (3), and (4) are based on fabrication limitations

Initial Results: Same Area

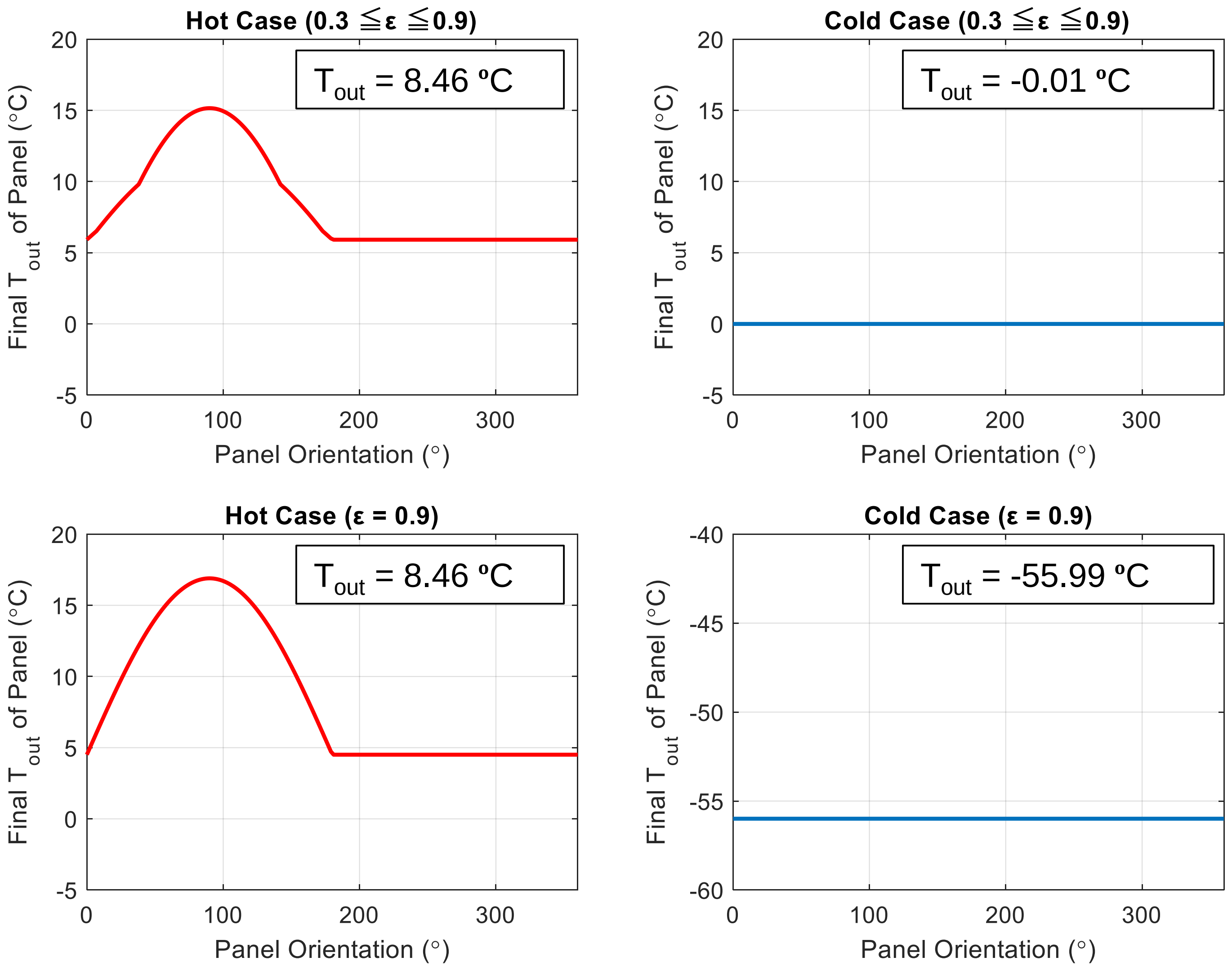
- $A = 28.8\ m^2$
- $T_{low} = 7\ ^oC$
- $T_{high} = 11\ ^oC$
- $T_{out,desired} = 4\ ^oC$
- Turndown = 40%



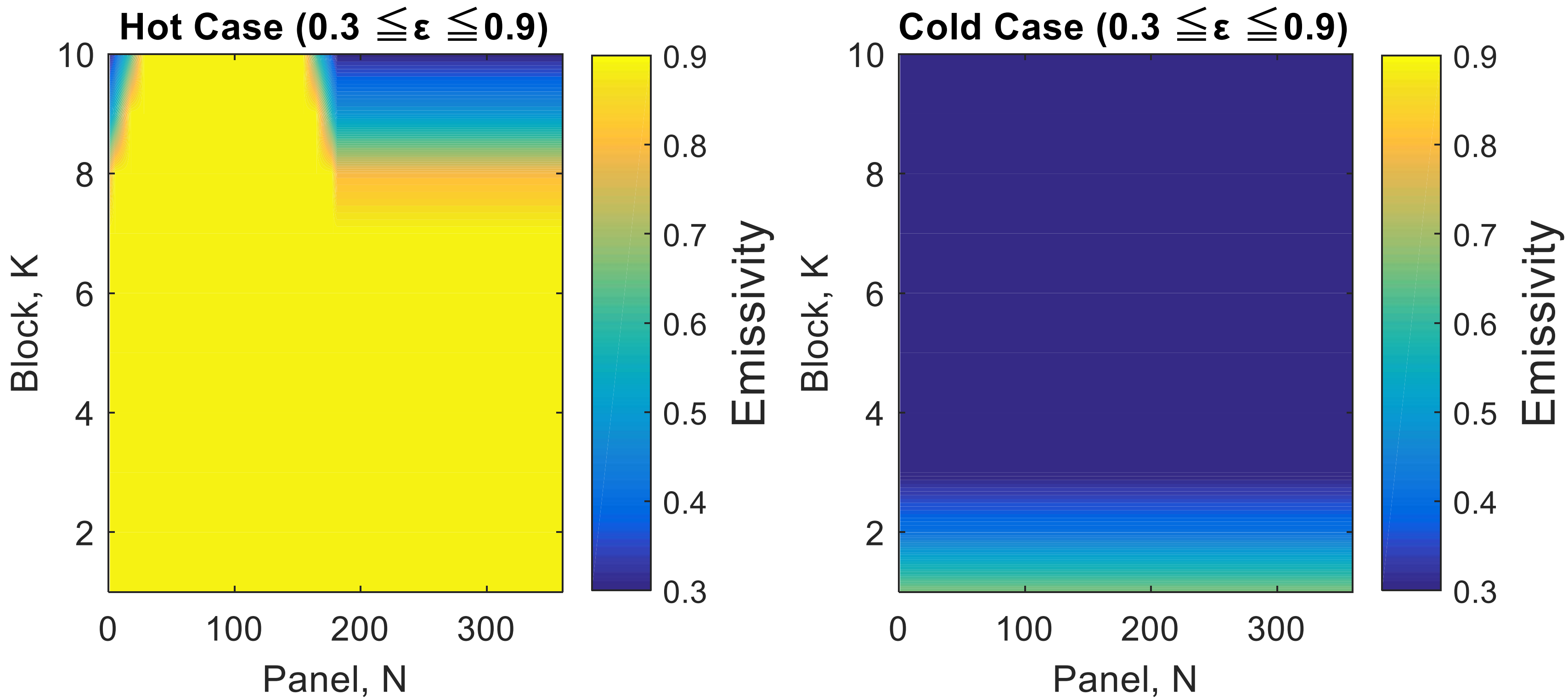
Initial Results: Same Outlet Temperature

- A_{static} = 27.8 m^2
- $A_{variable}$ = 32.2 m^2
- Mass ↑: 24 kg
- T_{low} = 7 ºC
- T_{high} = 12 ºC
- $T_{out,desired}$ = 8 ºC
- Turndown = 40%

- Study optimum tradeoff between increased mass and cold case turn down percentage

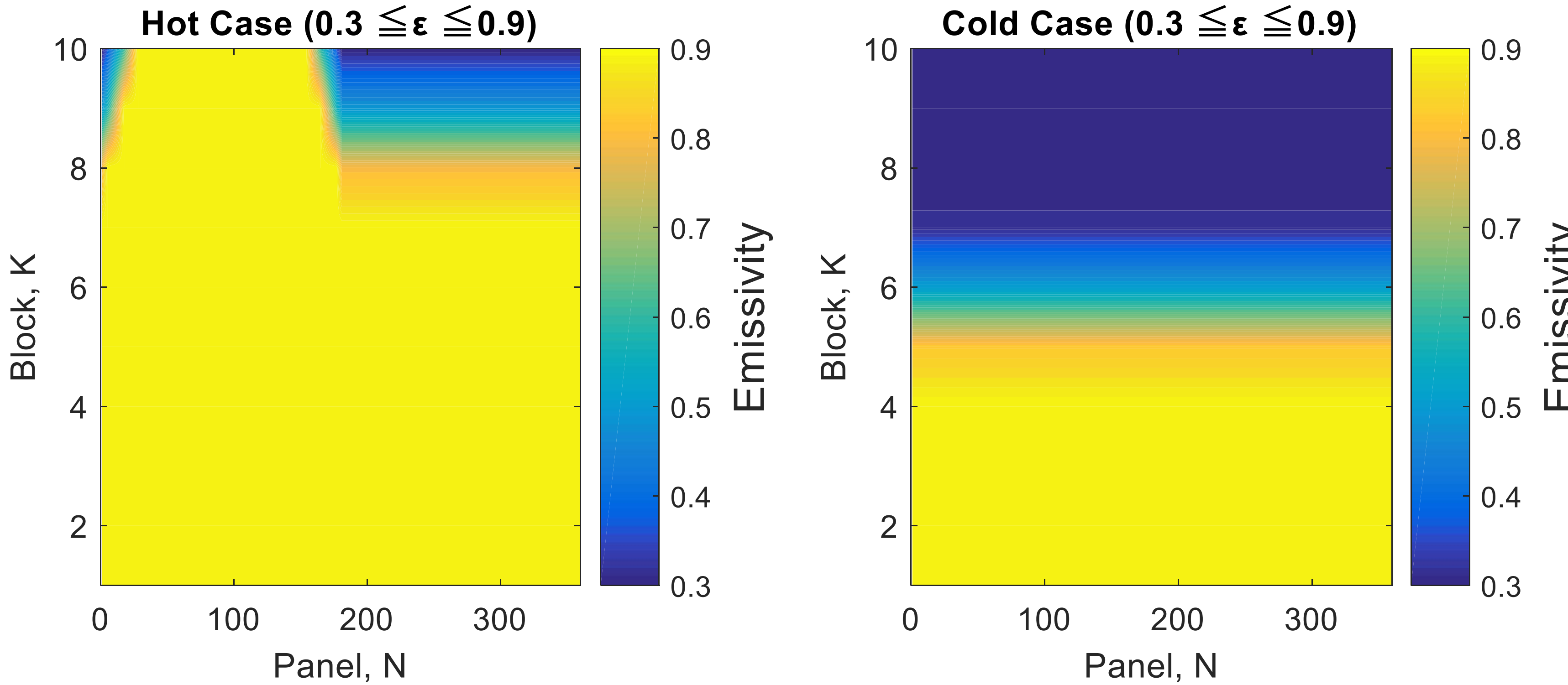


Emissivity Maps (Load = 40%)



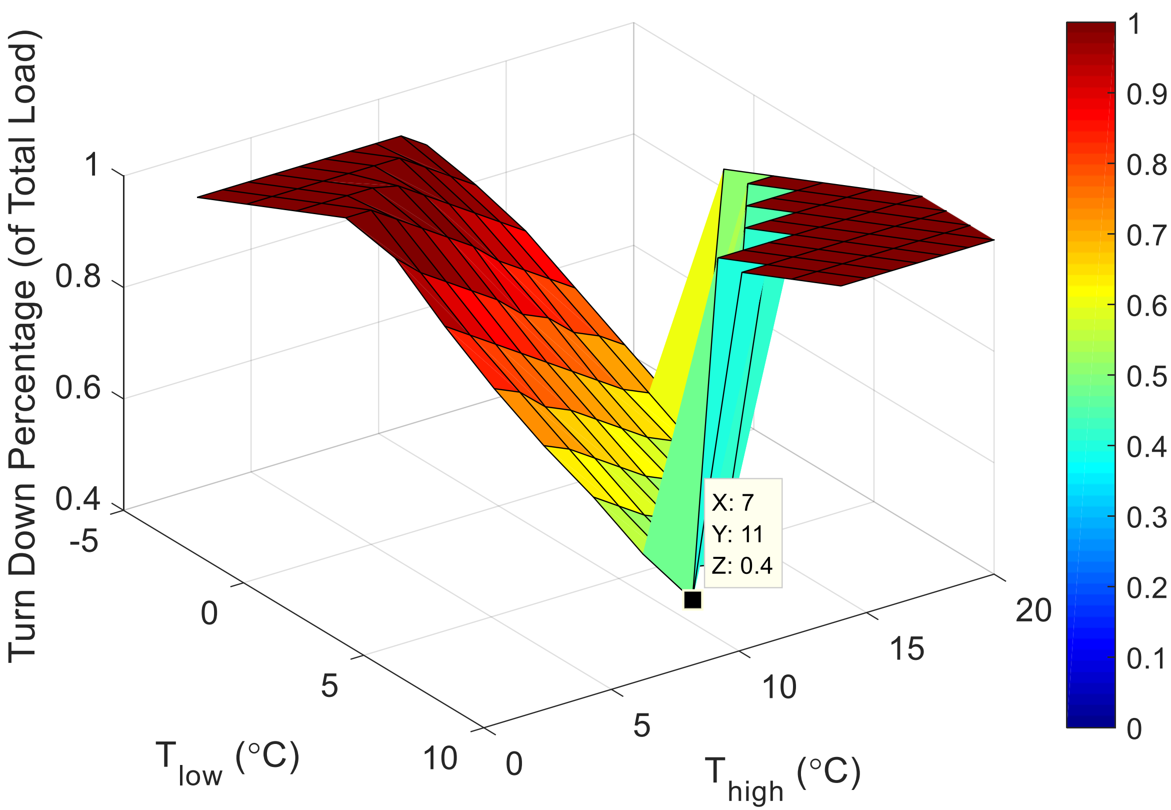
Optimized Case: Majority of blocks in hot case are ε = 0.90 and cold case has mainly ε = 0.30

Emissivity Maps (Load = 80%)



Intermediate Case: Cold case slowly changes from ε = 0.9 to ε = 0.30

Transition Range Optimization



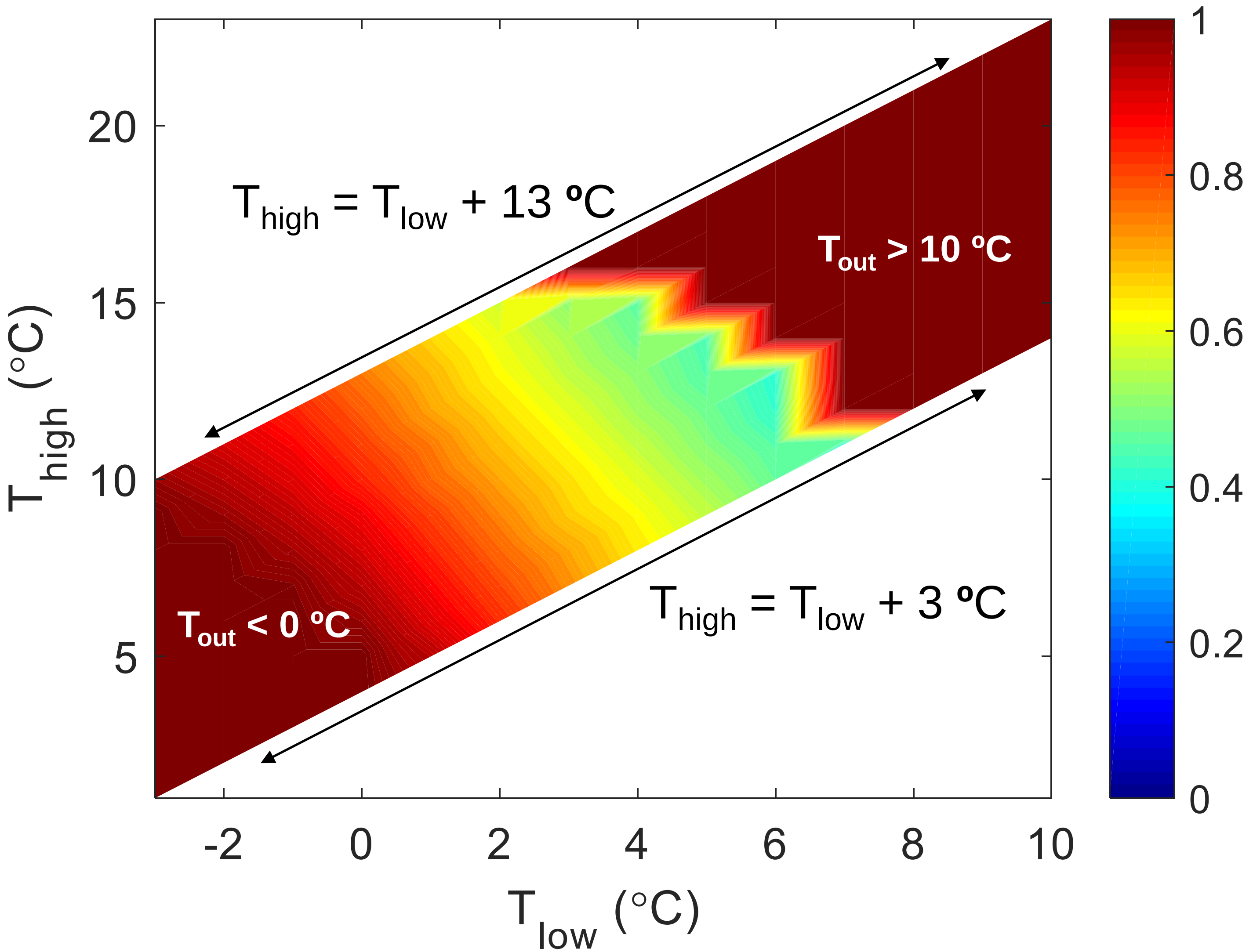
$\varepsilon_{low} = 0.30$

$\varepsilon_{high} = 0.90$

$A_{rad} = 28.8\ m^2$

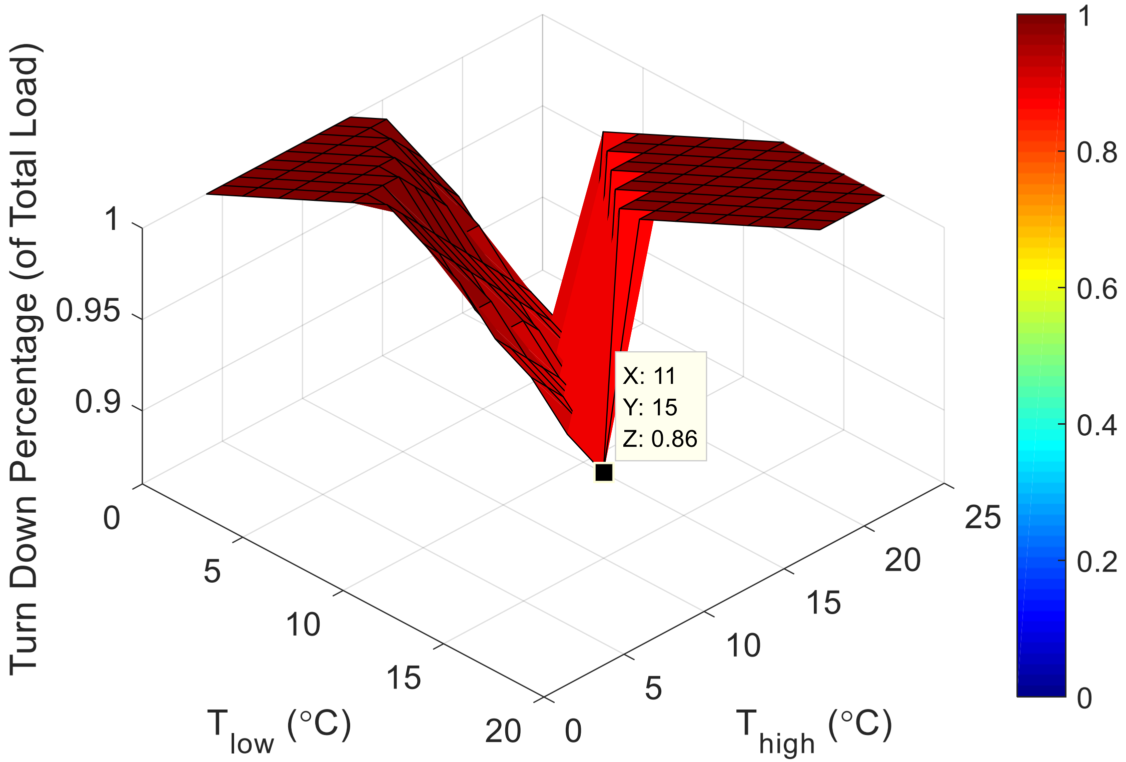
Maximum turn down percentage of 40% occurs when T_{low}= 7 °C and T_{high}= 11 °C

Transition Range Optimization



- Optimization ends due to T_{out} going out of bounds
- No cases with freezing as the exit condition

Transition Range Optimization



$\varepsilon_{low} = 0.60$

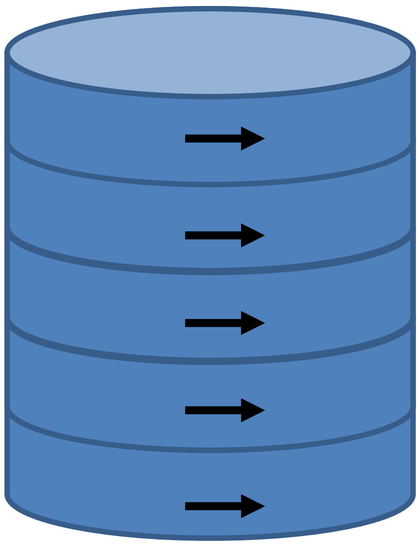
$\varepsilon_{high} = 0.90$

$A_{rad} = 28.8 \text{ m}^2$

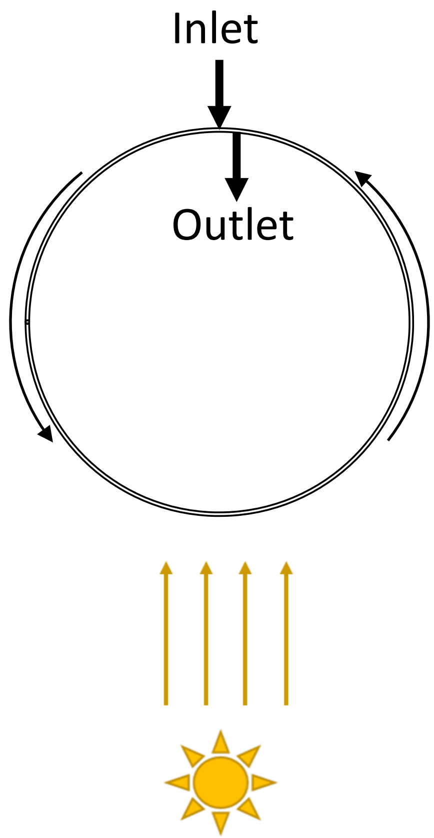
- Only 86% turn down percentage achieved → represents lower limit for emissivity change

Radial Radiator Model Set-up

Objective: Help improve turndown ratio by spreading the heat more evenly over the fluid lines



Five radial segments with fluid flow along the circumference of the cylinder body

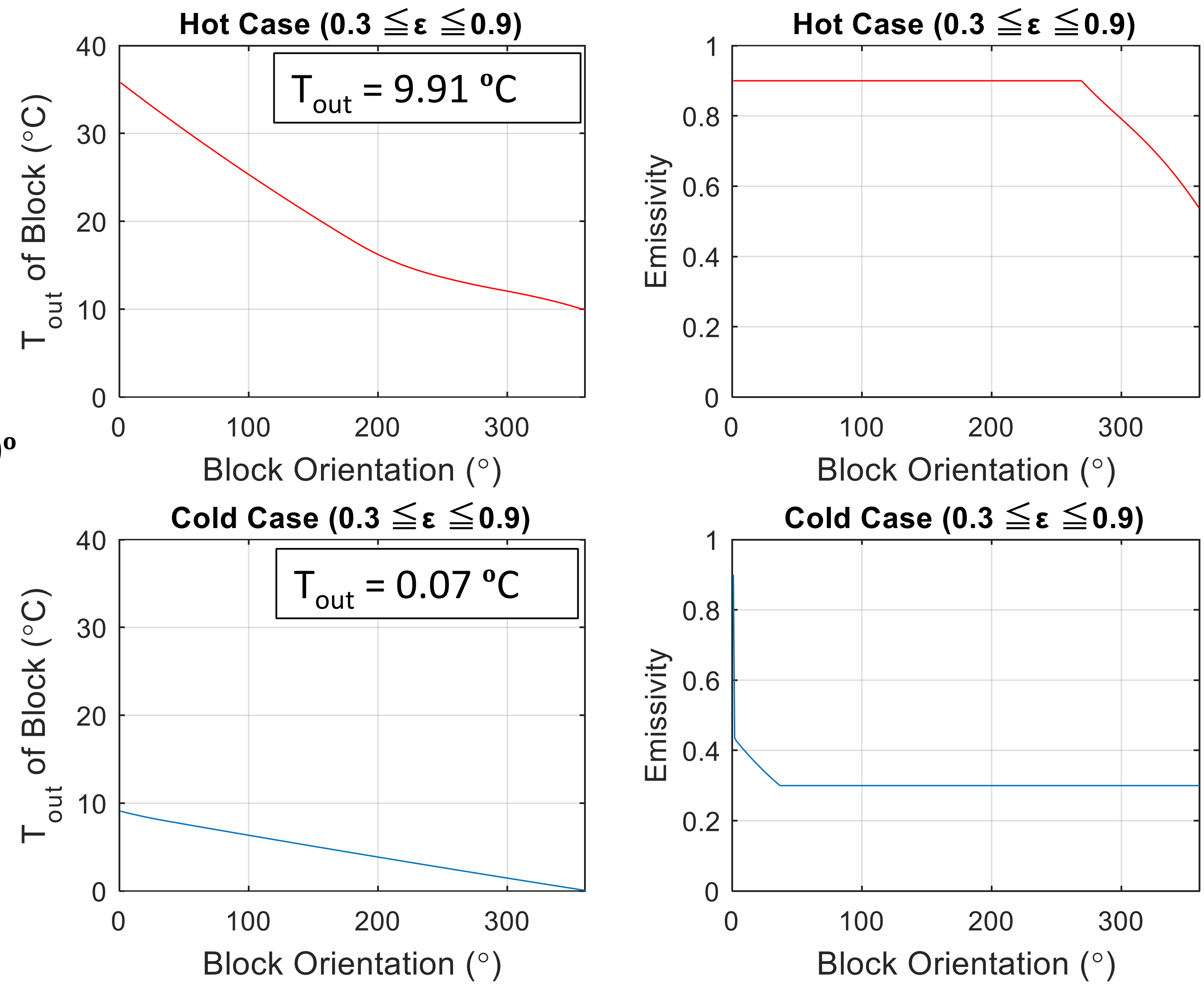


Direction of sunlight relative to inlet location is determined by pointing angle – in this orientation the angle is 270°

MATLAB implementation is similar to previous model where “blocks” are now discretized areas along the cylinder circumference and “panels” are the radial segments

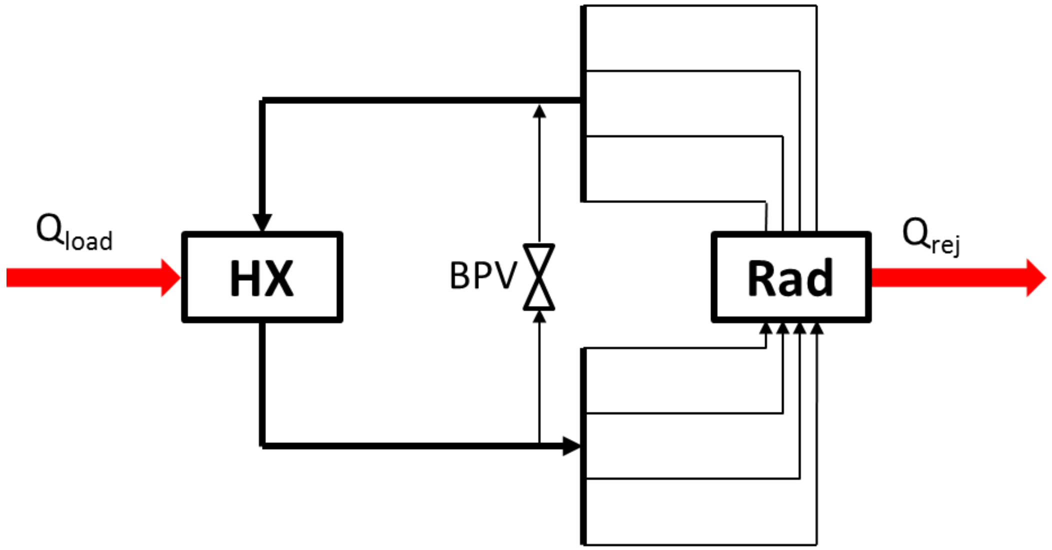
Radial Radiator Results

- $A = 28.8\ m^2$
- T_{low} = 8 ºC
- T_{high} = 13 ºC
- Turndown = 35%
- Pointing Angle = 180º



Bypass Valve Model Set-up

Objective: Improve the turndown by only flowing a portion of fluid through radiator, yielding higher average outlet temperature



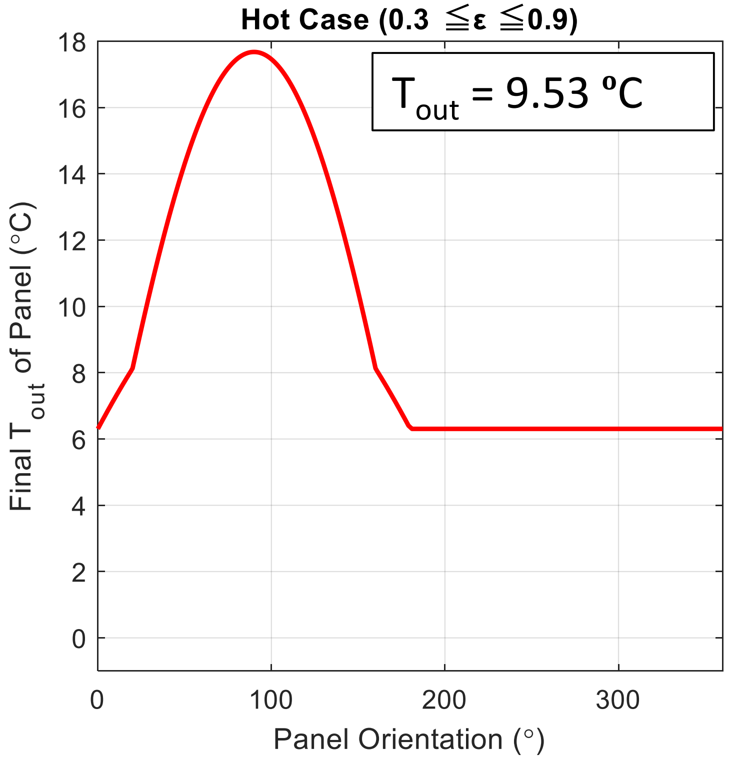
Implemented in the code by:

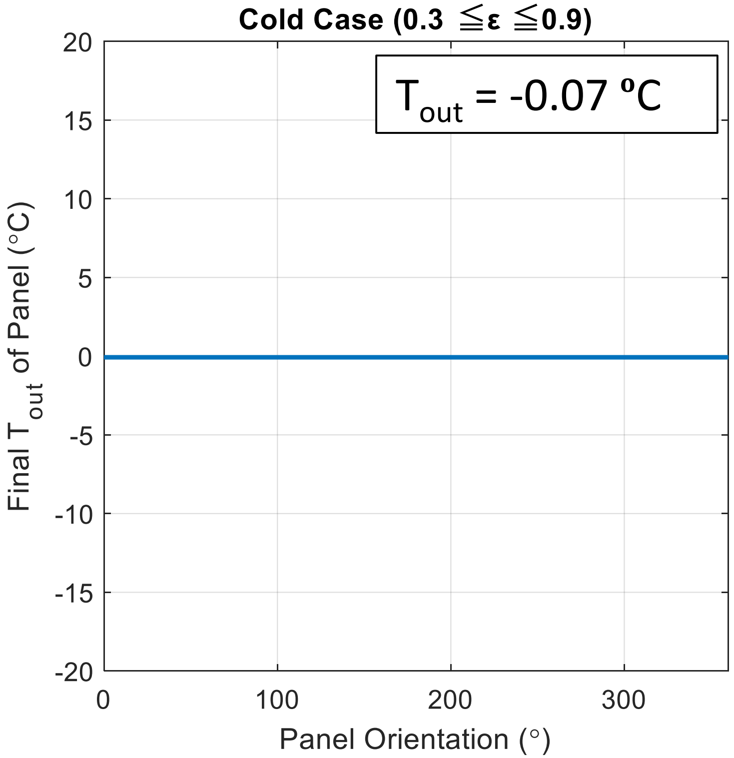
(1) Solving the radiator with (1 – BPR) percentage of mass flow

(2) Weighted average of the inlet temperature and the radiator exit temperature

$$T_{outlet} = T_{in} * BPR + T_{rad,avg\ out} * (1 - BPR)$$

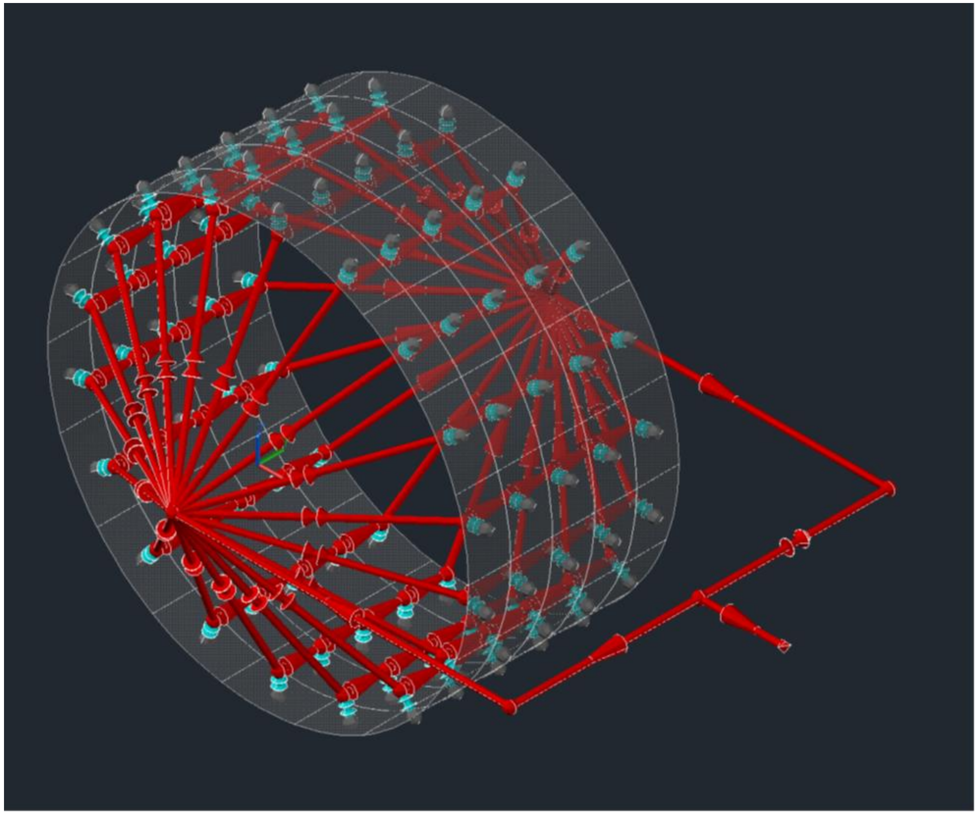
Bypass Valve Model Results





- Did not provide expected benefit
- Turn down was 50% rather than 40% with all else being equal
- Might be able to optimize to a better solution or change BPV configuration

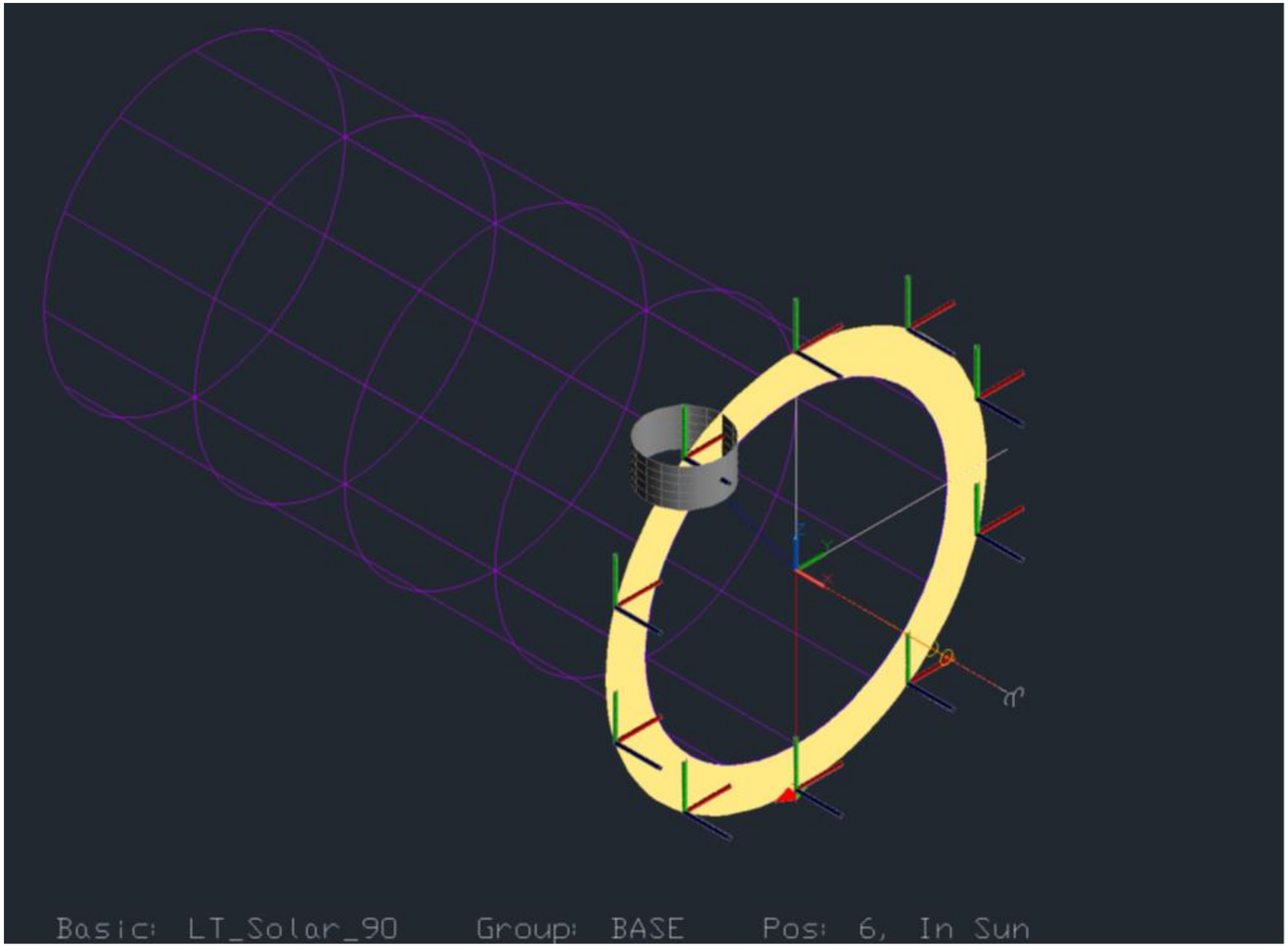
Thermal Desktop Model Set-up



S/C Heat Load	6000 W
Crew Heat Load	8500 W
Fluid	Water
Mass Flow Rate	600 lb/hr
Spacecraft Diameter	5 m
Rad Panel Length	1.8 m
Solar Absorptivity	0.15
IR Emissivity Range	0.3 to 0.9
Temperature	7 ºC to 13 ºC
Radiator Panels	18
Panel Blocks	5
UA considered	100 W/m^{2}K

- No conduction is assumed
- Mass flow is chosen from MATLAB to correlate with c_p

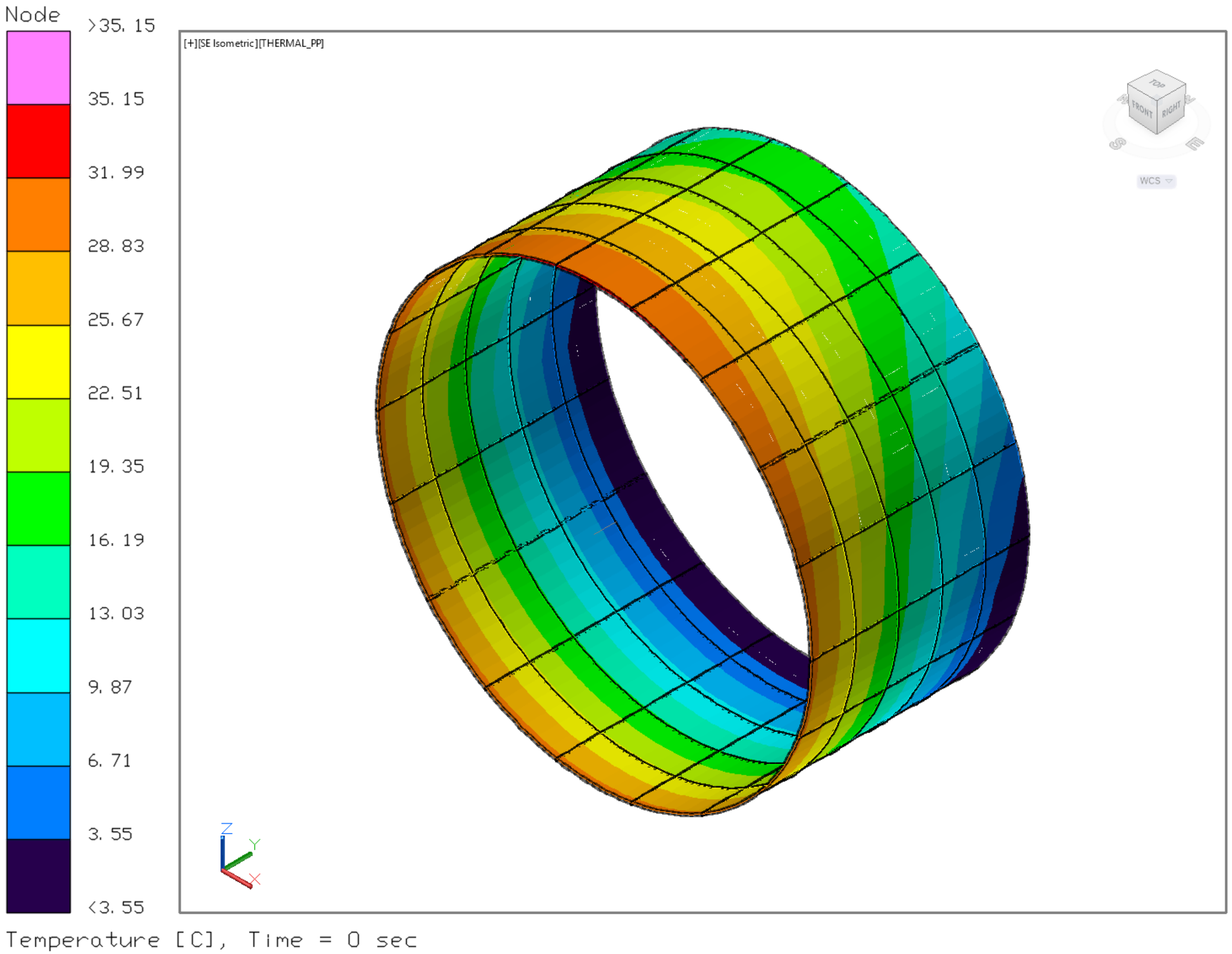
Thermal Desktop Case Construction



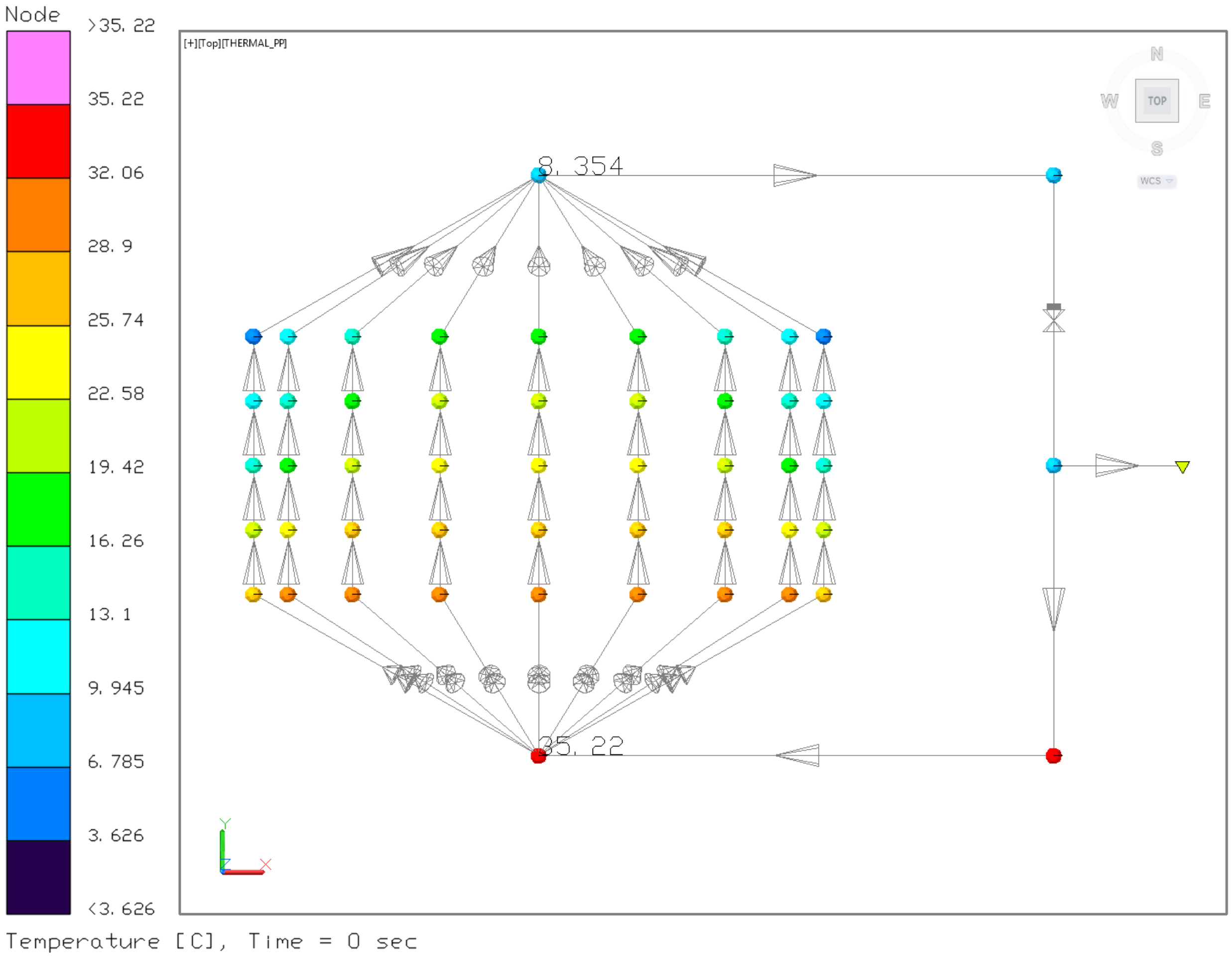
Hot Case Considered
Earth Orbit

Beta Angle	90°
Altitude	1680 km
Fluid	Water
Albedo	0
Planet IR	0
No Vehicle Rotation	

Thermal Desktop Results



Thermal Desktop Results



T_{in} = 35.22 ºC
T_{out} = 8.35 ºC

→ This agrees reasonably well with MATLAB results

→ Need to set up and run cold case

Conclusions

- Variable radiator runs hotter than static radiator
- Optimum transition range is approximately 7 ºC to 11 ºC
- 4 ºC radiator outlet temperature was very difficult to achieve → effectively no turn down
- Tradeoff between added radiator mass and minimum turn down percentage that can be reached
- Smaller width for transition temperature range is better
- Radial geometry radiator performs the best so far
- Radial radiator doesn’t seem to be as attitude dependent as we initially thought

Acknowledgements

- Thanks to Thomas Gross for help with the Thermal Desktop modeling
- Thanks to Rubik Sheth and EC6 for input on the MATLAB model
- This work is supported by a NASA Space Technology Research Fellowship (NNX16AM63H)

Questions?