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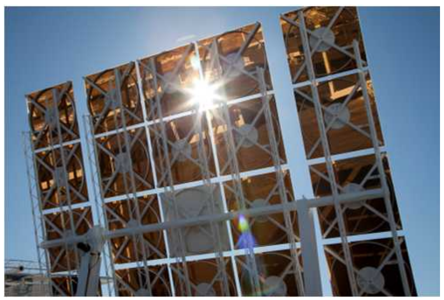

Meso- and Macro-Scale Fractal-Like Receiver Analysis

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Sandia National Laboratories

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Introduction

- Previously, Solar Two receiver has shown a thermal efficiency of up to 88% [1], but not continuously.
- The current SunShot initiative requires a thermal efficiency >90% [2] which has never been designed before.
- By manipulating the receiver geometry or adding special features, the view factors can be altered and the thermal efficiency could be increased by increasing the solar absorptivity and reducing radiative heat loss from the system.

Background

- A report by Garbrecht et al. showed that the use of pyramidal structures could reduce reflective loses by 1.3% [3].
  - Nonetheless, the main disadvantage of the pyramid structures are the hot spots created at the peaks of the structures due to stagnant flow conditions.
- Rocketdyne reported an initial evaluation in some star receiver geometry concepts in 1974 [4].
  - However, the thermal efficiency advantages of the receivers were not fully evaluated due to the complexity of the problem, at the time.

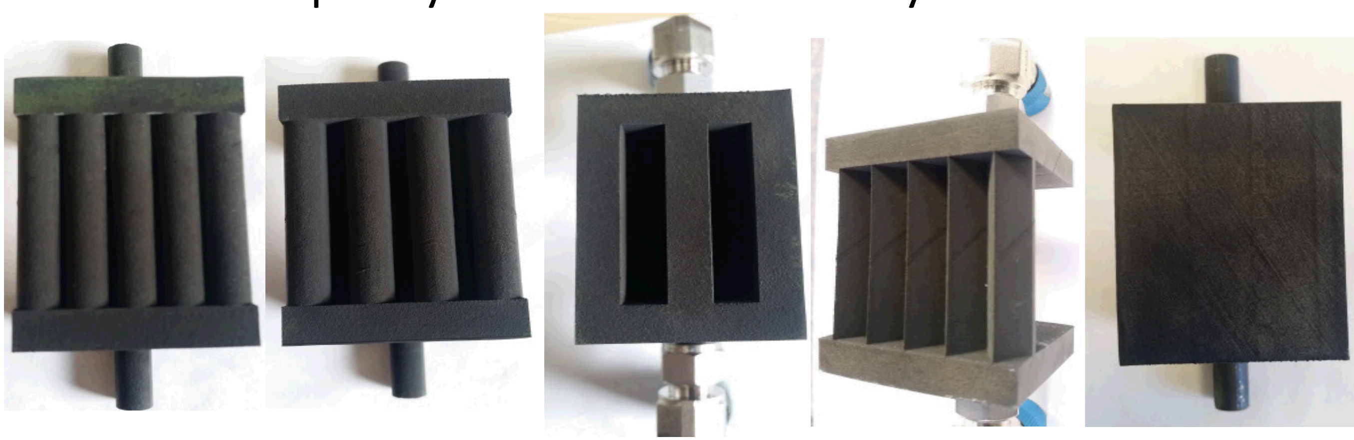
Background

- SNL has invented [5] several “light-trapping” receivers which take advantage of reduced view factors which could increase thermal efficiency of external direct receivers.
- These geometries have been analyzed analytically (ray-tracing models) and experimentally by Yellowhair et al. [6] to demonstrate an increase in solar absorptivity by creating a light trapping effect create multiple reflections.

Prototype fractal-like geometries (FLGs) fabricated with additive manufacturing using Inconel 718

Methodology

- These FLGs were redesigned to accommodate them for calorimetric tests at the NSTTF Solar furnace.
  - Parts were built of Inconel 718 metal by direct metal laser sintering.
  - Manifolds were added for the calorimetric tests.
  - The FLGs have an optical intercept of ~5 cm which matches the beam size from the solar furnace.
  - The FLGs were oxidized for 20 hours at 800° C in order to achieve an intrinsic absorptivity of ~0.9 and emissivity of ~0.8.

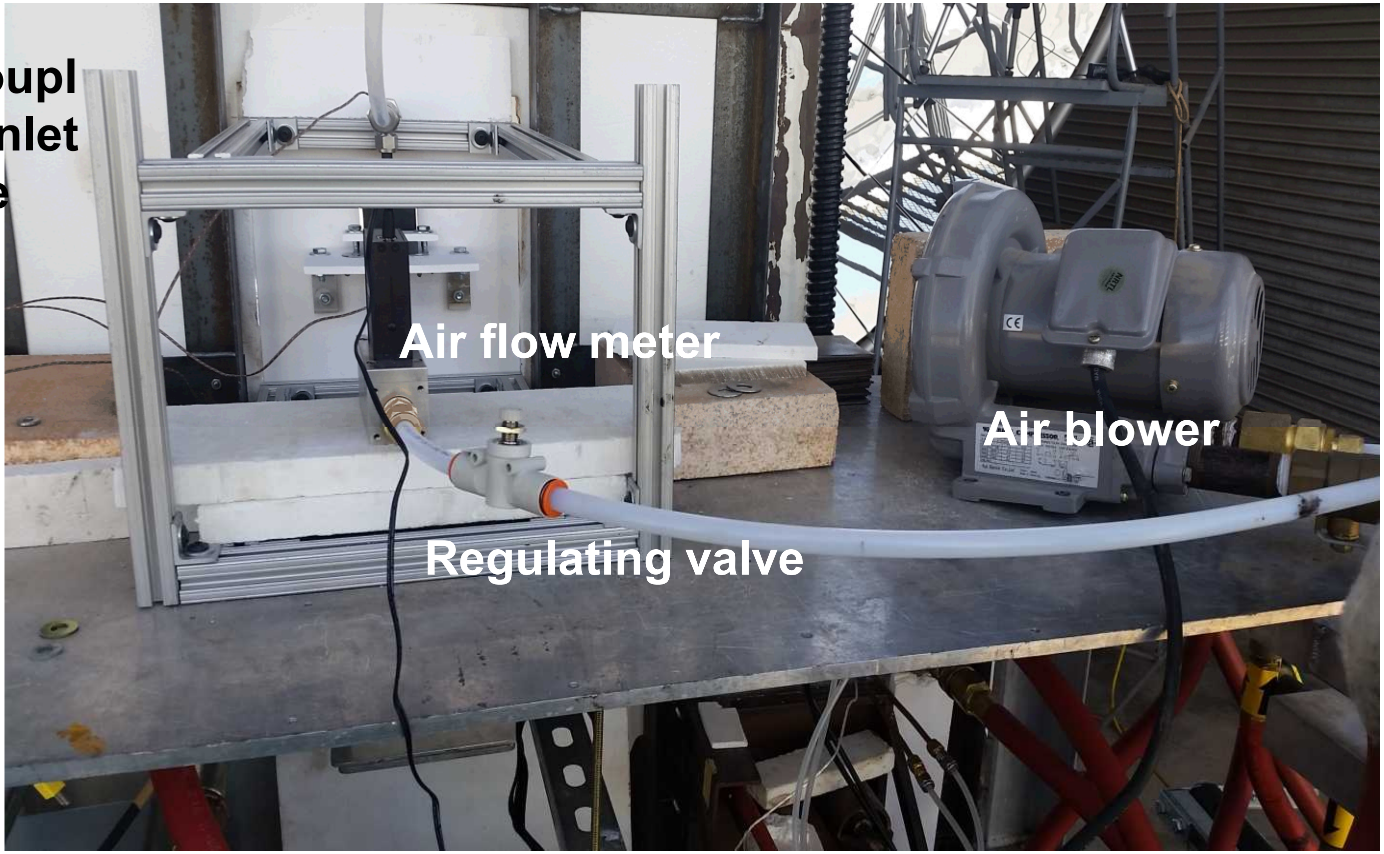


New FLGs with manifolds. From left to right: 0° offset cylinder tubes, 45° offset cylinder tubes, rectangular offset tubes, diamond tubes and flat plate

Calorimetric Test Loop

- The FLGs were connected to a test loop tested in the solar furnace to evaluate the thermal performance of the receivers.

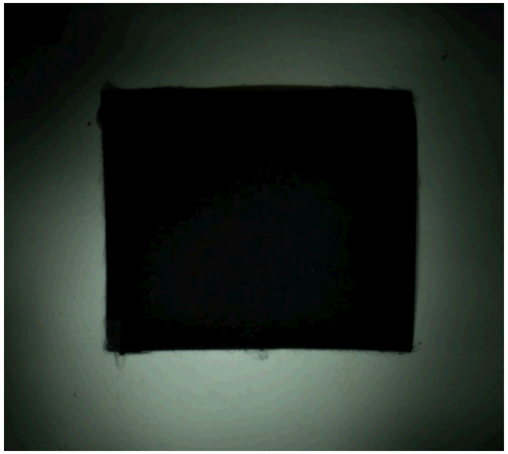
Thermocouples at the inlet and the outlet

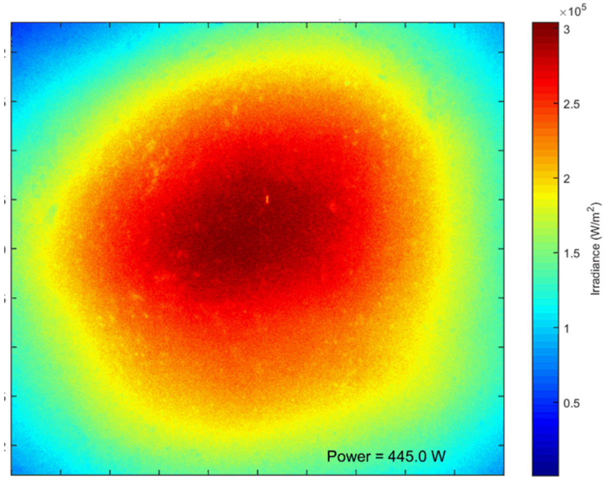


The complete test loop in the Solar Furnace

Calorimetric Test Loop

- The FLGs were placed at the focus of the dish concentrator while the test loop was running at the specified flow rate. The irradiance was applied on the part while the DNI, surface, inlet and outlet temperatures were recorded.
- Photographs were taken during the tests and were analyzed with the PHLUX tool [8] to generate the irradiance profiles of incident on the surface of the FLGs.





Incident heat flux on the FLGs ~30 W/cm^2

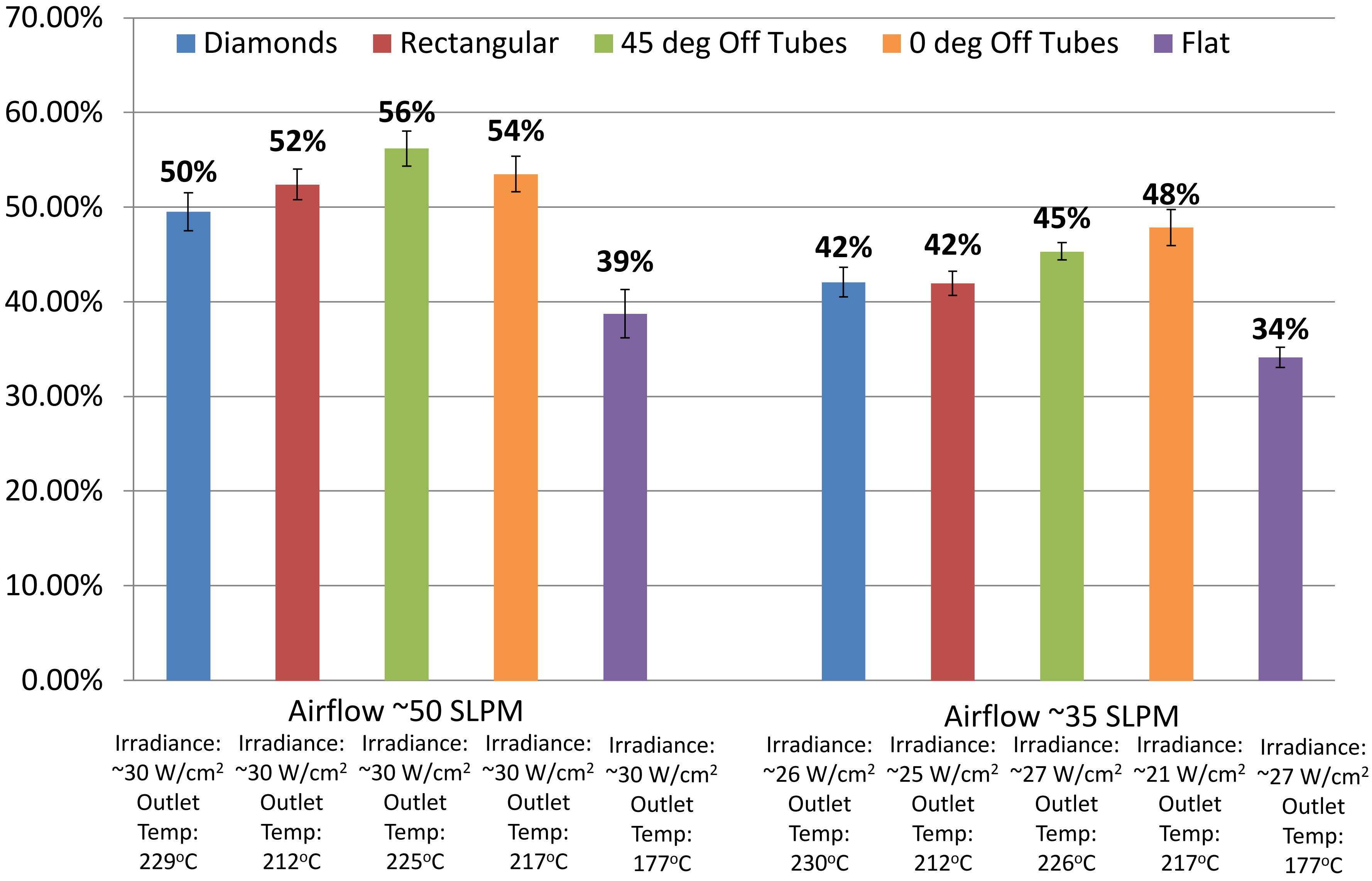
Thermal Performance

- The thermal efficiency of the FLGs is evaluated as:

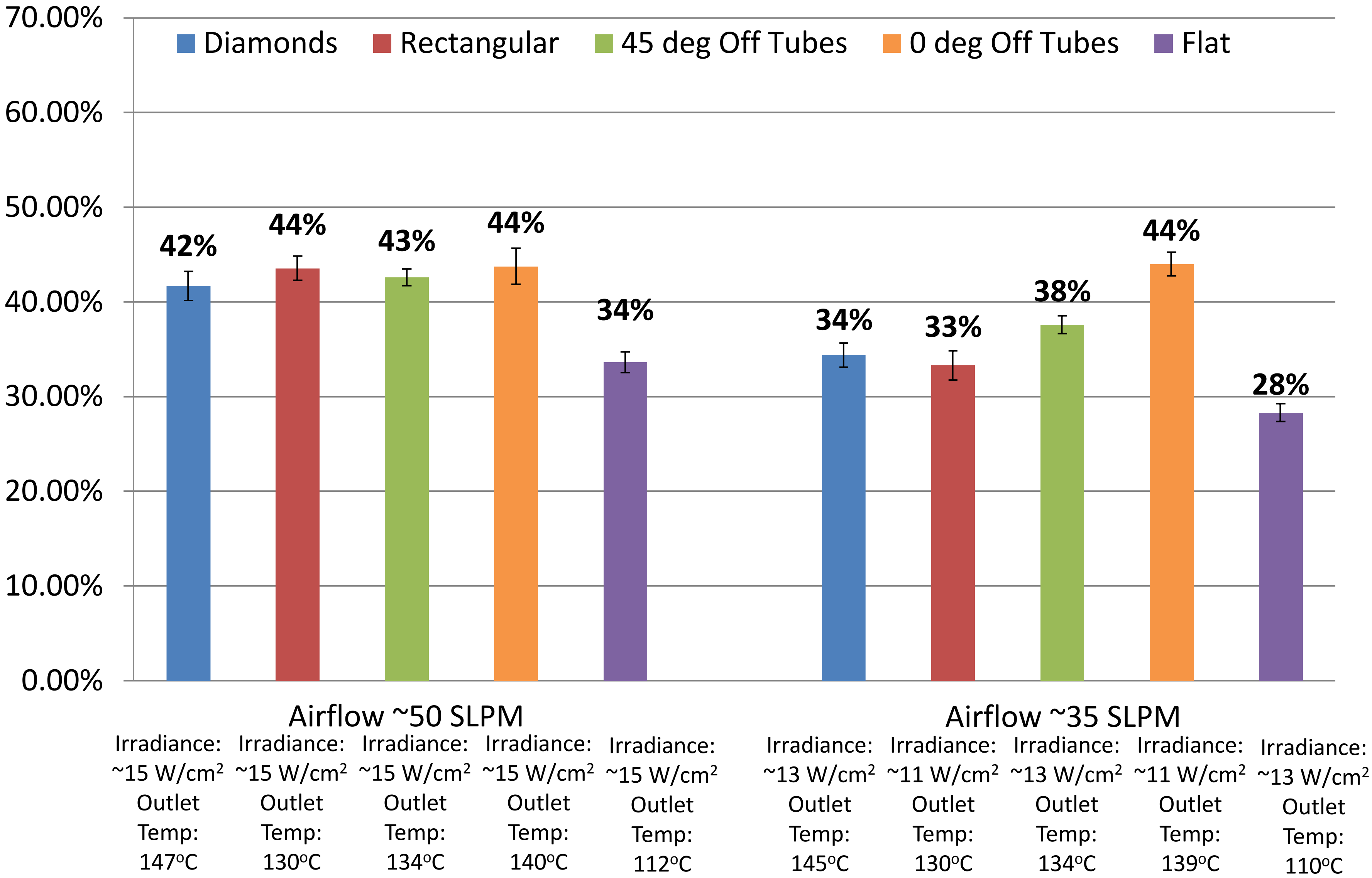
$$\eta = \frac{\dot{m} \int_{T_{in}}^{T_{out}} C_p(T)\,dT}{\dot{Q}_{in}}$$

- We compared the thermal performance of the FLGs in 4 different scenarios:
  - ~15 W/cm^2 irradiance and 50 SLPM air flow
  - ~30 W/cm^2 irradiance and 50 SLPM air flow
  - Equivalent irradiance and 35 SLPM air flow with similar target outlet temperature of first case
    - Range from ~11-13 W/cm^2
  - Equivalent irradiance and 35 SLPM air flow with similar target outlet temperature of second case
    - Range from ~21-26 W/cm^2

Thermal Performance



Thermal Performance

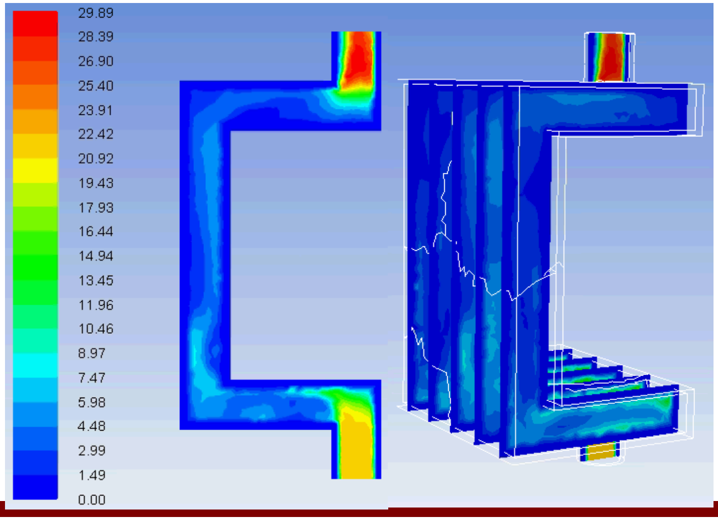


Conclusions

- In most instances the part with 0 degree offset tubes perform the best.
  - This results can be attributed to the flow dynamics inside the part and air being not a good heat transfer fluid.
- The impact of the light trapping effect is beneficial to increase the amount of heat going into the fluid.
  - Nonetheless since the surface area of the FLGs increased, the thermal losses also increase.

Computational Modeling

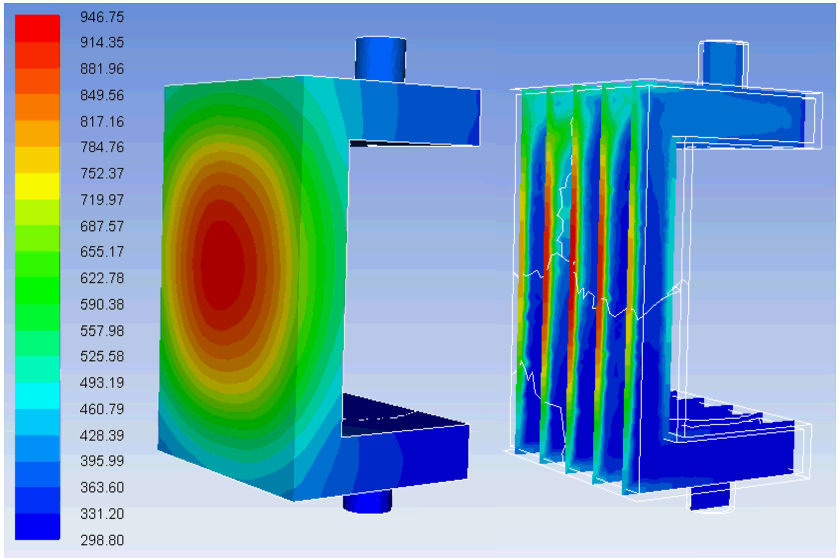
- Computational simulations were performed using ANSYS Fluent using the similar boundary conditions as the tests.
- These models provide a flexibility to analyze in detail the flow dynamics and the heat transfer across the FLGs.
- Validating these models using the test results, will give confidence to implement them to predict the thermal efficiencies of future designs.



Velocity contours of the air flow across the Flat Part

Computational Modeling

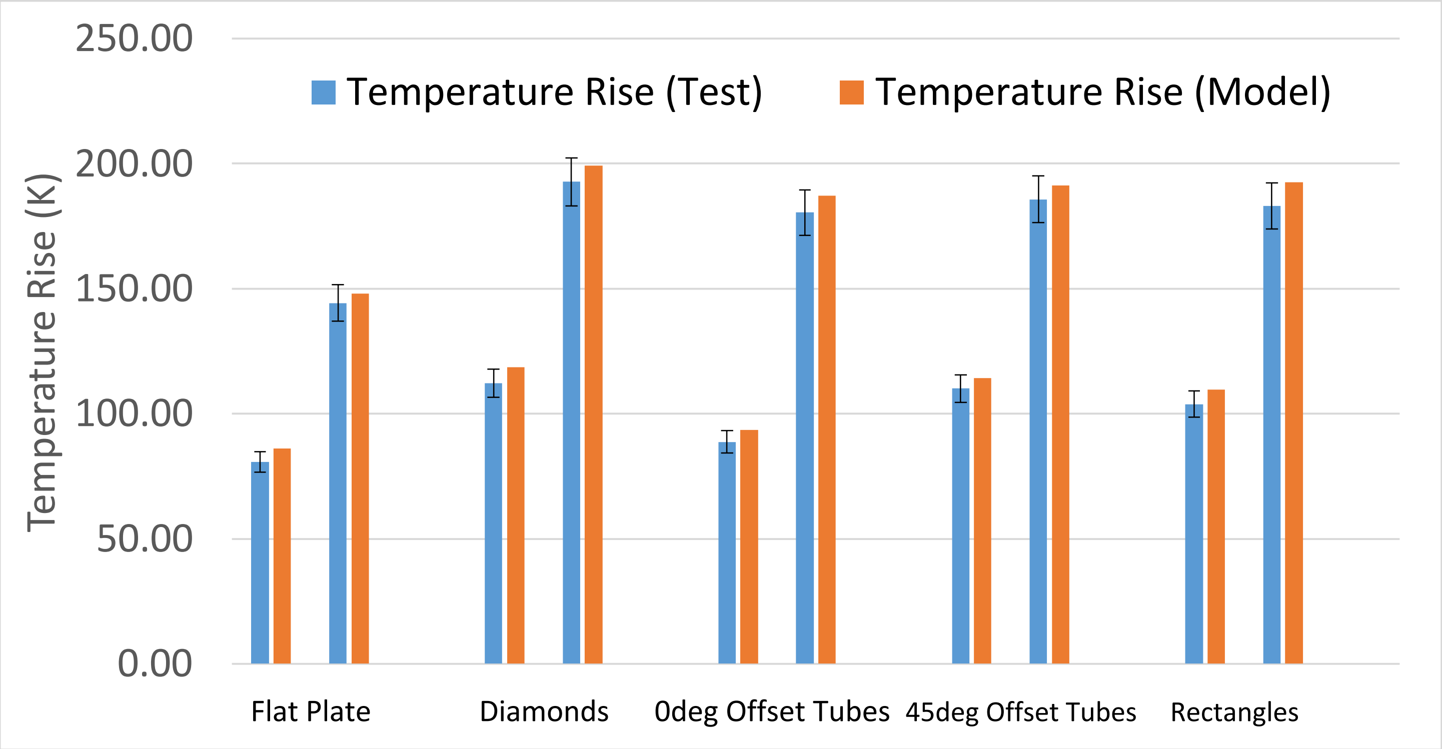
- Modeling Details
  - Materials
    - Atmospheric Air and Oxidized Inconel 718
  - k-ω Shear Stress Transport (SST) model
    - Good to accommodate a mesh with larger near-wall cells by handling Y+ values from 30 to 300.
  - Discrete Ordinates (D. O.) Radiation model
    - Used to solve the conjugate heat transfer throughout the FLGs



Temperature contours of the air flow across the Flat Part

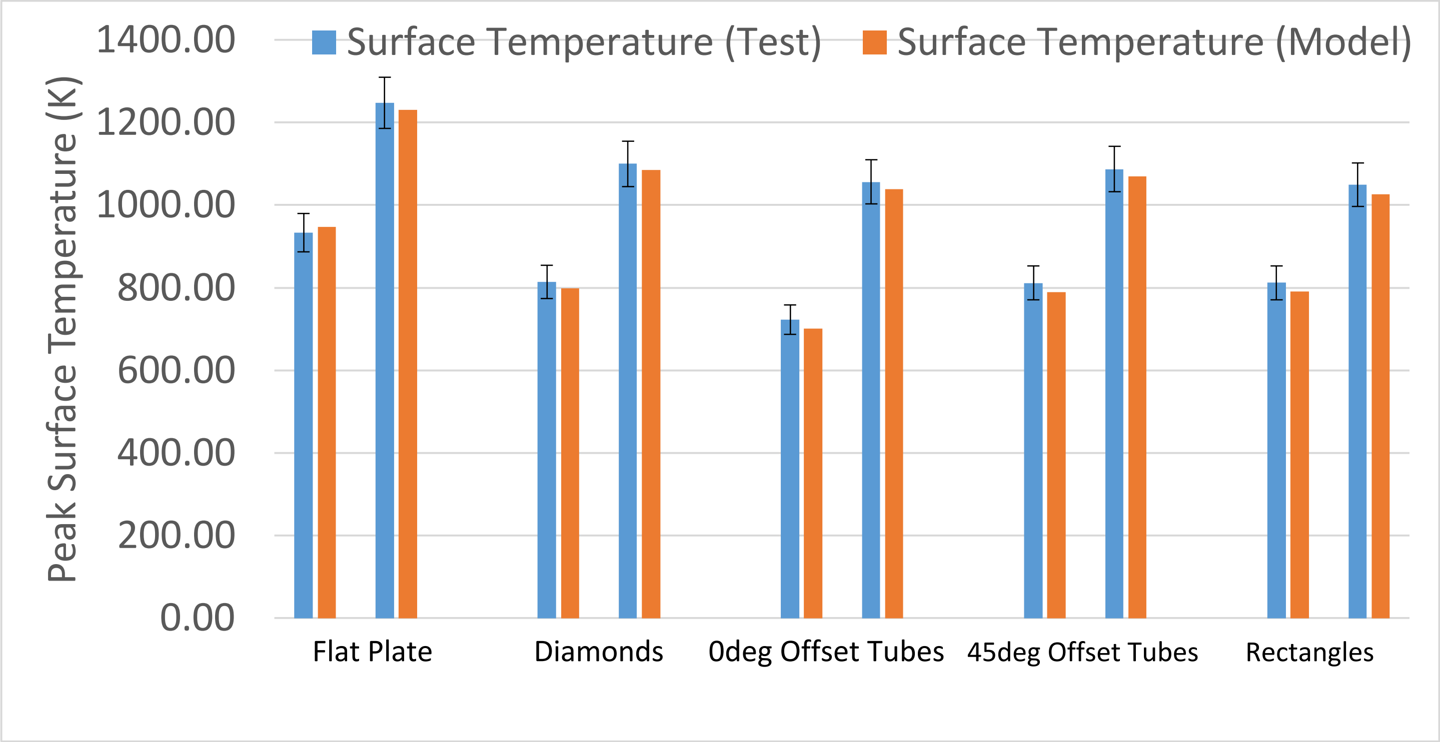
Model vs. Experiment Comparison

- Temperature increase in the models are compared to the measured temperature increase in the tests.
- The simulation values are observed to be within 5% of the measured values.



Model vs. Experiment Comparison

- Surface temperatures in the models are compared to the measured temperatures in the tests.
- The simulation values are observed to be within 5% of the measured values.



Conclusions

- It was observed that the meso-scale light-trapping features on the tubes have little impact on the thermal efficiency of the FLGs relative to conventional tubes
  - Nonetheless, we cannot say the same at a larger (macro) scale
- The computational models have been validated to study future geometry designs and patterns which could have a positive impact on the thermal efficiency at the small (meso) scale parts

MACRO-SCALE RECEIVERS

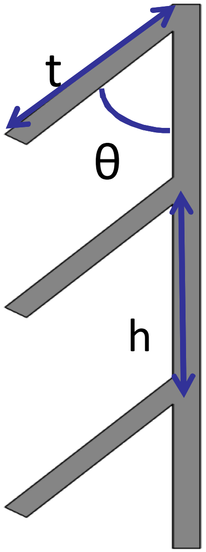
Background

- Maybe Josh can add something of what he did before?

Methodology

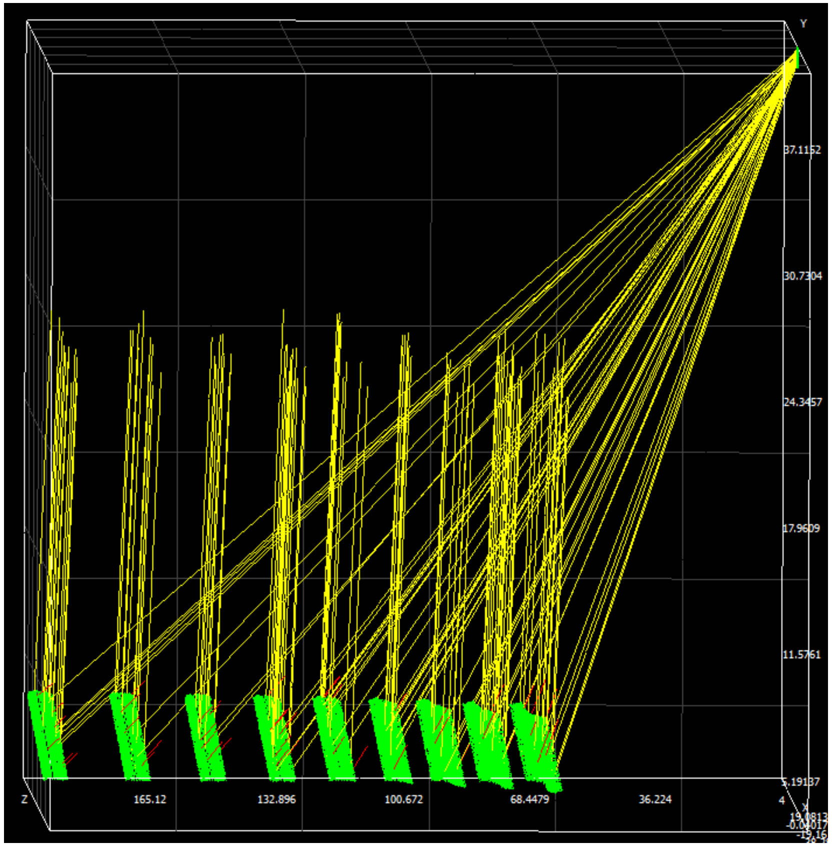
- The receiver with the best thermal efficiency was the one with angular fins.
- A parametric optimization was performed since there were 297 configurations containing 3 variables:
  - 9 angles [θ] (20-60 deg. by 5 deg. increments)
  - 11 number of tubes [nh] in the back panels (5-15 tubes)
  - 3 different number of fins [N] (3-5 fins)
- The number of tubes in the fins [nt] was calculated for an illuminated area (A) of 1 m^2

$$n_t = \frac{A}{2D^2N^2(n_h+1)} - \frac{n_h}{2}$$



Ray-Tracing Analyses

- Sol-Trace was used to perform the ray–tracing analyses



- Modeling Parameters
  - NSTTF Heliostat Field at Solar Noon during the summer solstice (Day 180)
  - Receiver Location 140 ft. level
- Optical Properties
  - Heliostats: 0.88 reflectivity
  - Receiver surface: 0.1 reflectivity
- Assumptions:
  - The receiver surface is perfectly oxidized to achieve the reflectivity
  - The receiver is modeled using flat surfaces instead of tubes.

Results

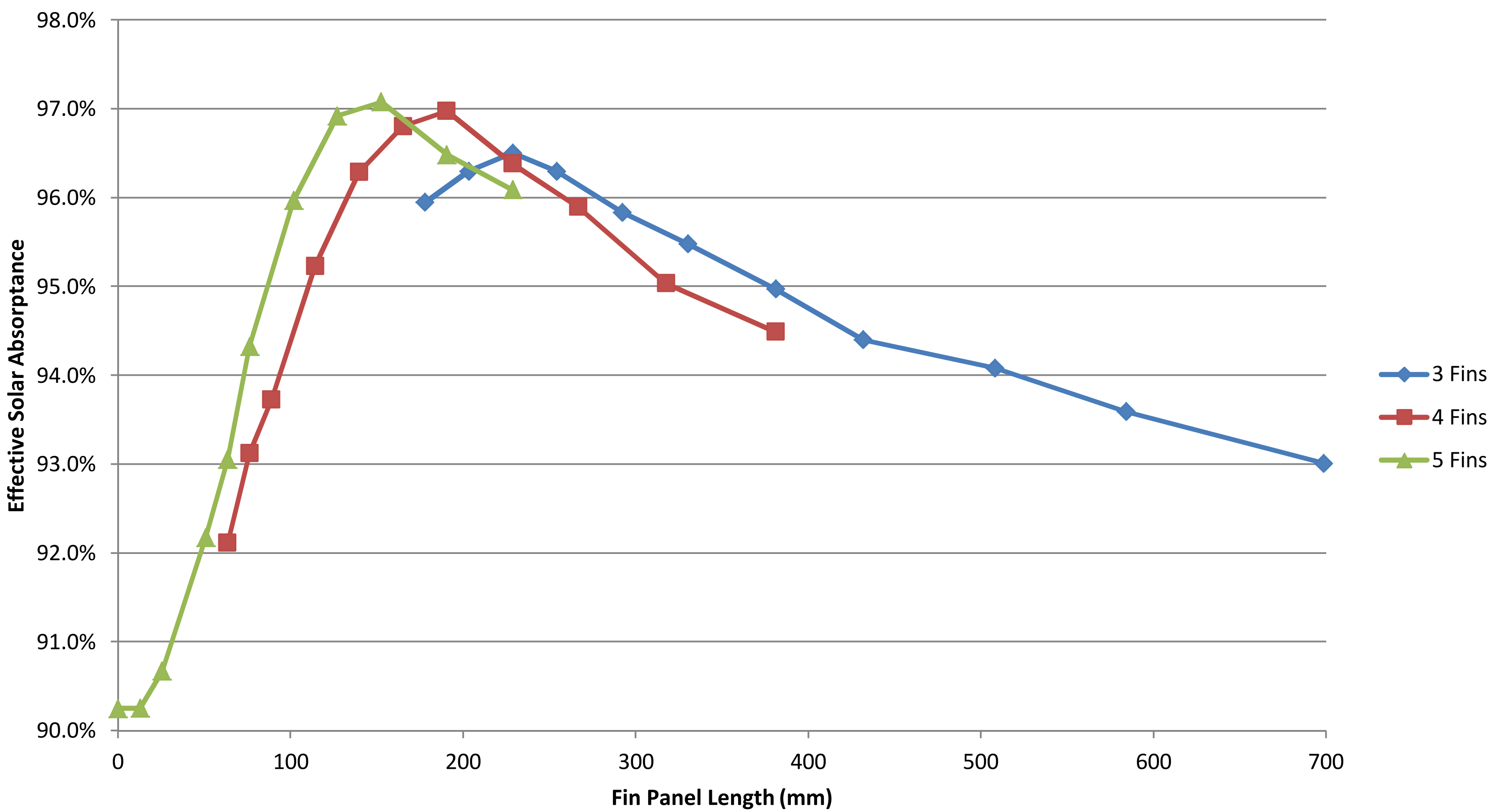
- The effective solar absorptance of every receiver configuration was measured by:

$$\alpha_{eff} = \frac{\dot{Q}_{abs}}{\dot{Q}_{in}}$$

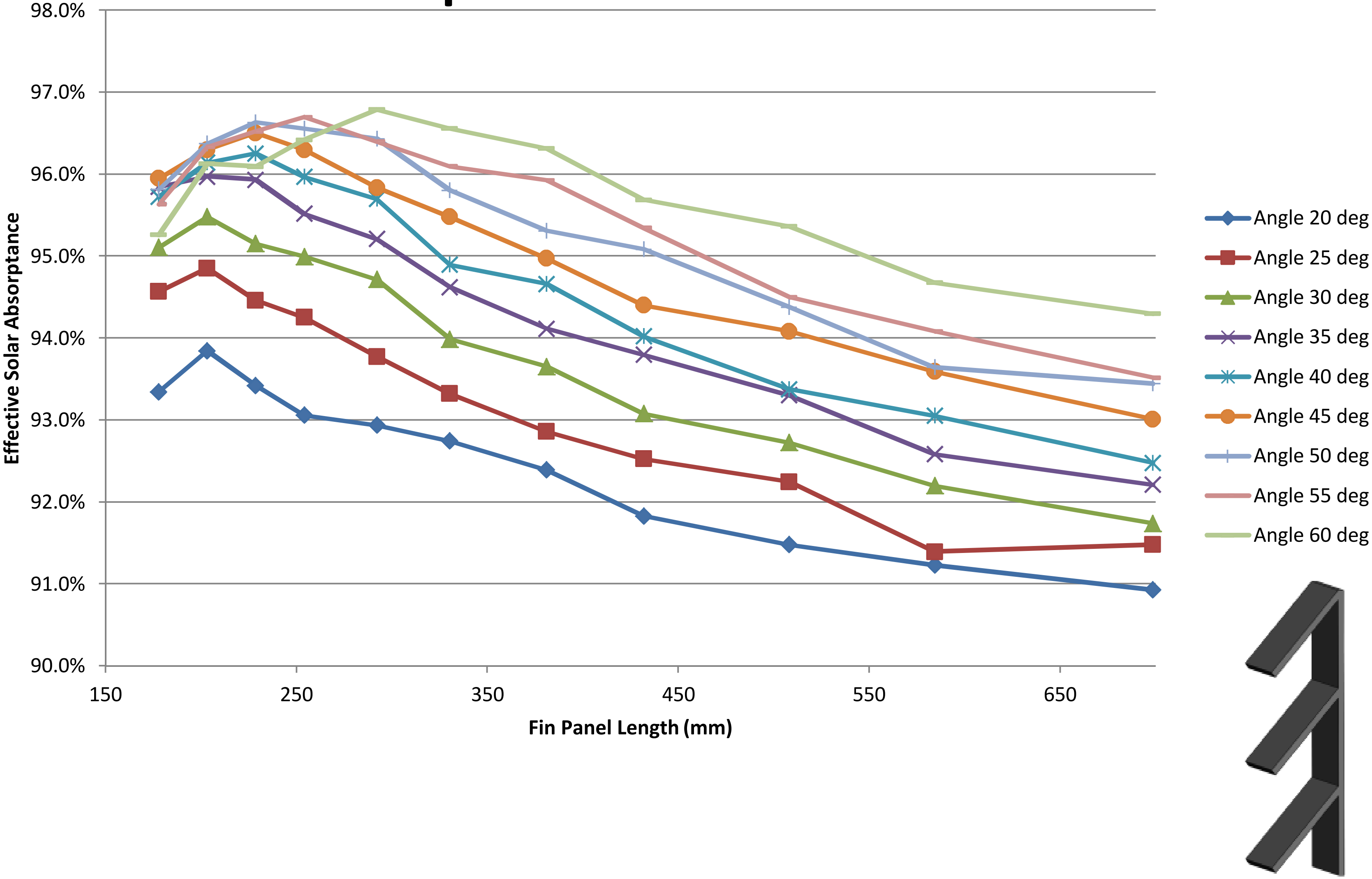
  Where $\dot{Q}_{abs}$ is the power absorbed by the receiver surface and $\dot{Q}_{in}$ is the incident power on the receiver surface.

- We were able to study several
  - The impact of varying the fin length and number of fins, on the effective solar absorptance.
  - The impact of varying the angle of the fin and number of fins, on the effective solar absorptance.

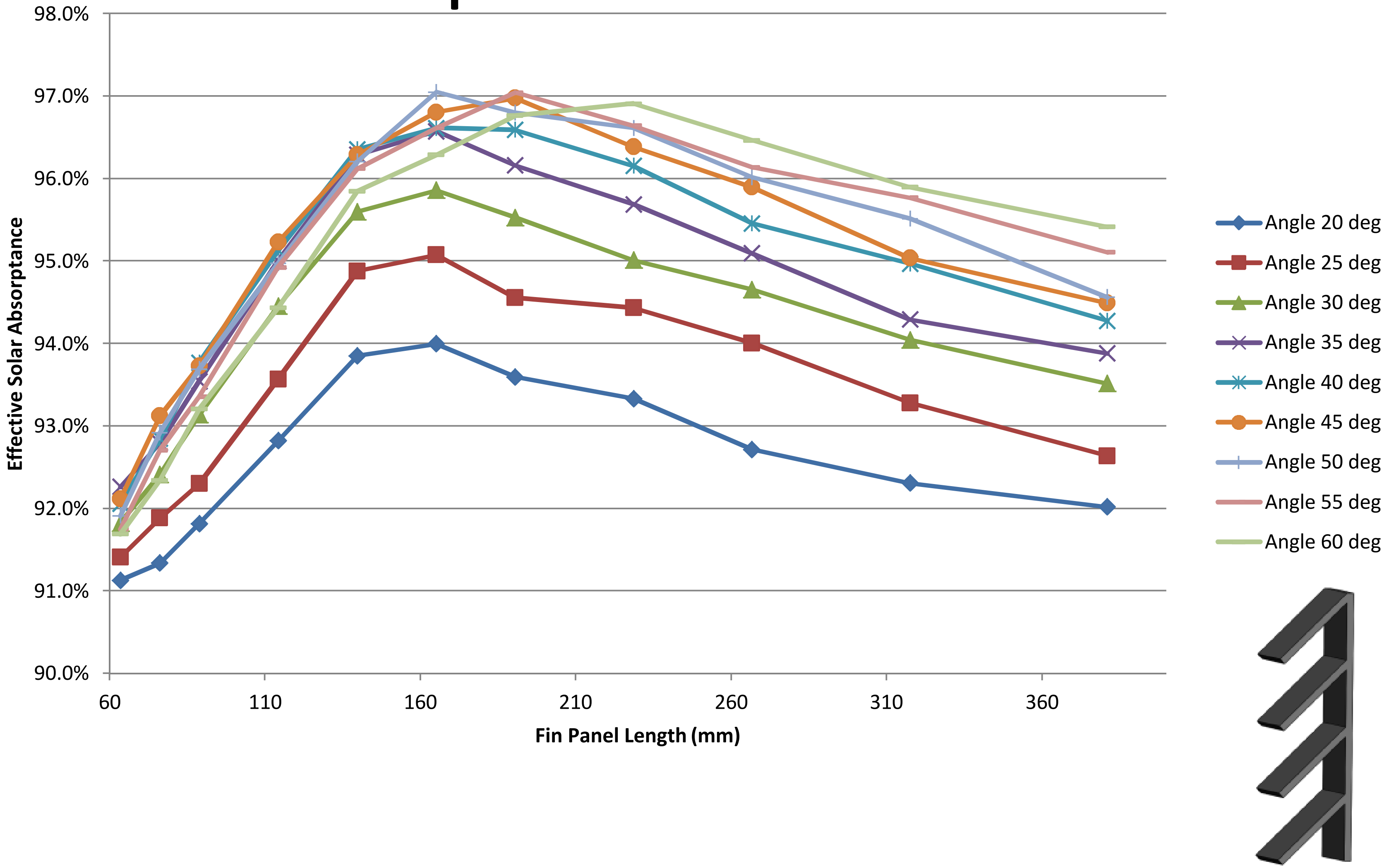
Impact of the variation of fin length and number of fins



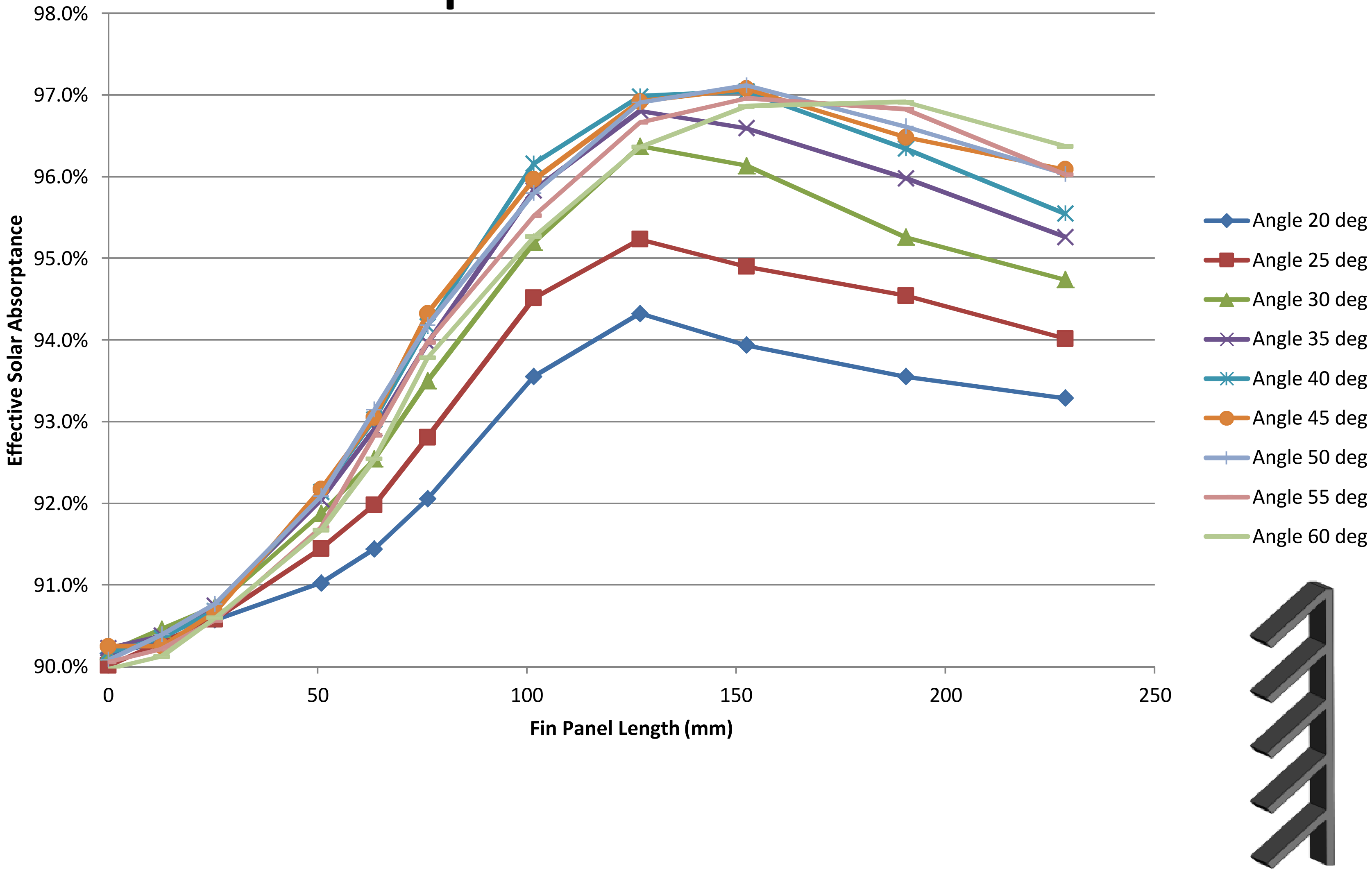
Impact of the variation of fin length and angle with respect to the back panel for N=3



Impact of the variation of fin length and angle with respect to the back panel for N=4



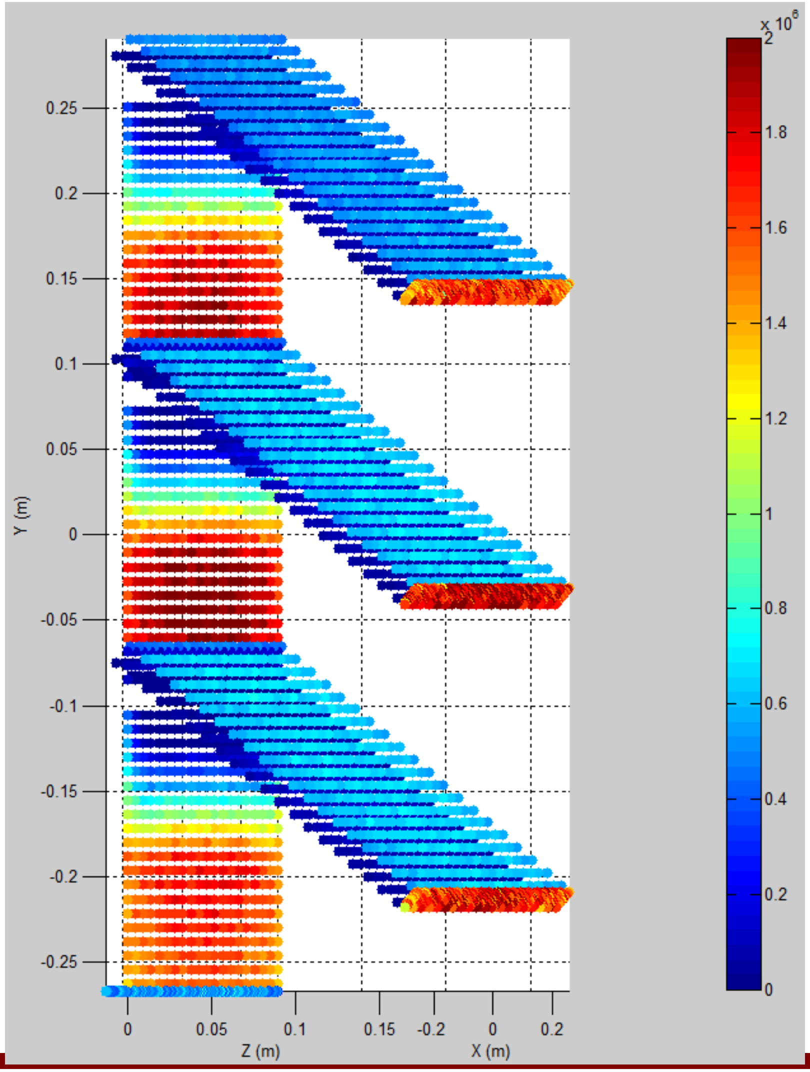
Impact of the variation of fin length and angle with respect to the back panel for N=5



Results

- 32 cases were found to have an effective solar absorptivity of ~97%
- We observed that the best configurations tend to have fin lengths between 150-200 mm long
- Angles of 45 and 50 degrees display the best effective solar absorptivity

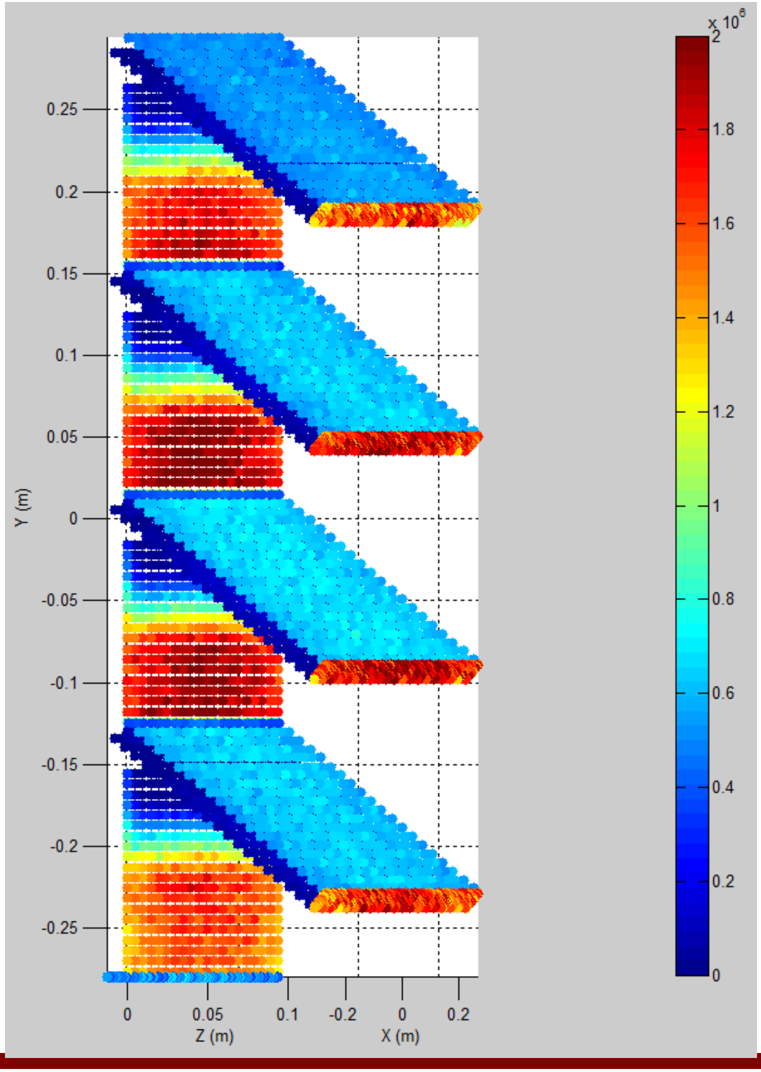
Best Configuration with 3 fins



Configuration:

- 13-1/2” tubes in the back panels (165.1 mm)
- 18-1/2” tubes in the fins panels (228.6 mm)
- Fin Angle: 50 deg
- Illuminated area: ~1 m^2

Best Configuration with 4 fins



Configuration:

- 10-1/2" tubes in the back panels (127 mm)
- 13-1/2" tubes in the fins panels (167.1 mm)
- Fin Angle: 50 deg
- Illuminated area: ~1 m^2

Best Configuration with 5 fins

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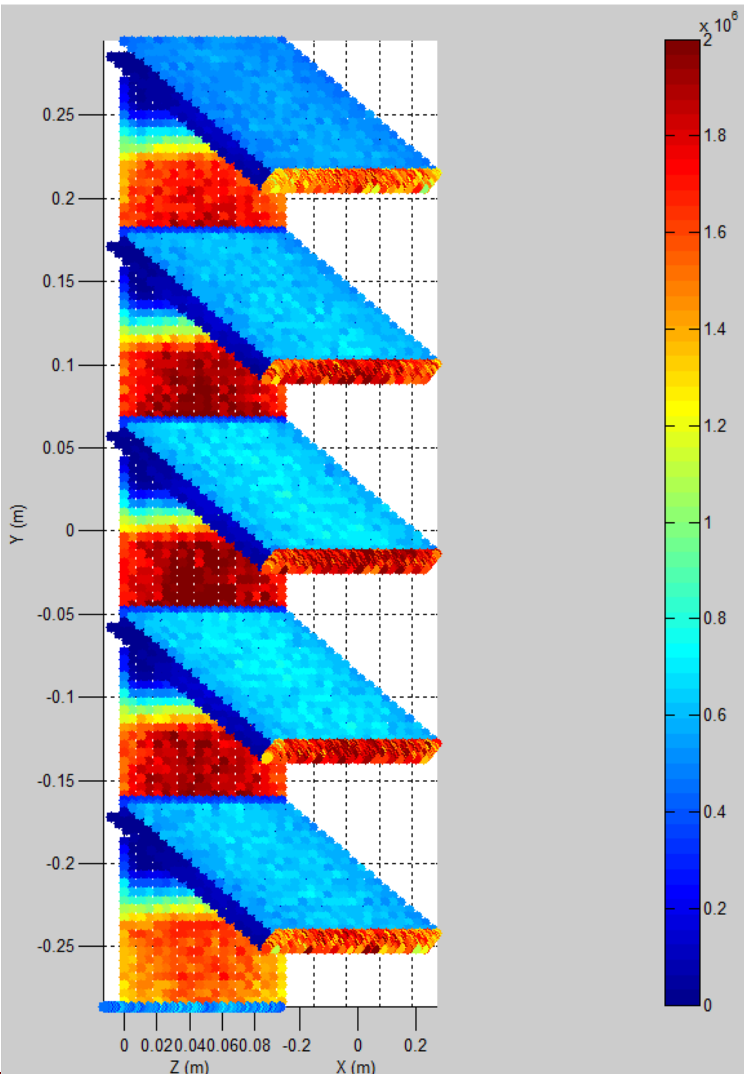

Configuration:

- 8-1/2" tubes in the back panels (101.6 mm)
- 10-1/2" tubes in the fins panels (127 mm)
- Fin Angle: 50 deg
- Illuminated area: ~1 m^2
- Optical Intercept:

Future Work

- We are planning to perform CFD studies on the chosen configurations using real tubes
- Experimenting with the different possible flow patterns to take advantage of the reduced view factors
- Repeat the ray-trace analyses and establish the peak fluxes on the surfaces

References

- [1] Pacheco, J. E., 2002, "Final Test and Evaluation Results from the Solar Two Project," SAND2002-0120, Sandia National Laboratories.
- [2] Energy, U. S. D. o., 2011, "SunShot Initiative."
- [3] Garbrecht, O., Al-Sibai, F., Kneer, R., and Wieghardt, K., 2013, "CFD-simulation of a new receiver design for a molten salt solar power tower," Solar Energy(90), pp. 94-106.
- [4] Friefield, J. M., and Friedman, J., 1974, "Technical Report No. 1: Solar Thermal Power Systems Baded on Optical Transmission,"Rocketdyne Division, Rockwell International.
- [5] "U.S. Patent Application 14535100, Filed Nov. 6, 2014, BLADED SOLAR THERMAL RECEIVERS FOR CONCENTRATING SOLAR POWER."
- [6] Yellowhair, J., Ho, C., Ortega, J., Andraka, C., 2015, " Testing and Optical Modeling of Novel Concentrating Solar Receiver Geometries to Increase Light Trapping and Effective Solar Absorptance", SPIE 2015 SPIE Optics + Photonics Conference San Diego, CA.