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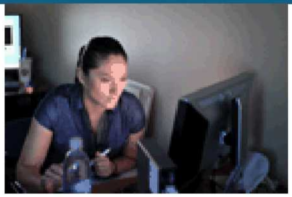
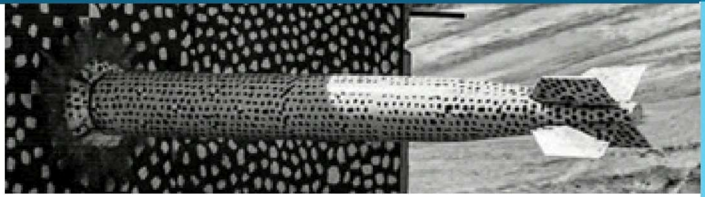
Optimizing a Falling Particle Receiver Geometry Using CFD Simulations to Maximize the Thermal Efficiency





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Presentation Outline

Background and Objectives

Computational Model

Optimization Approach

Optimized Geometry Evaluation

Conclusions

Falling Particle Receivers

Falling particle technology is a promising candidate to couple with next generation CSP systems

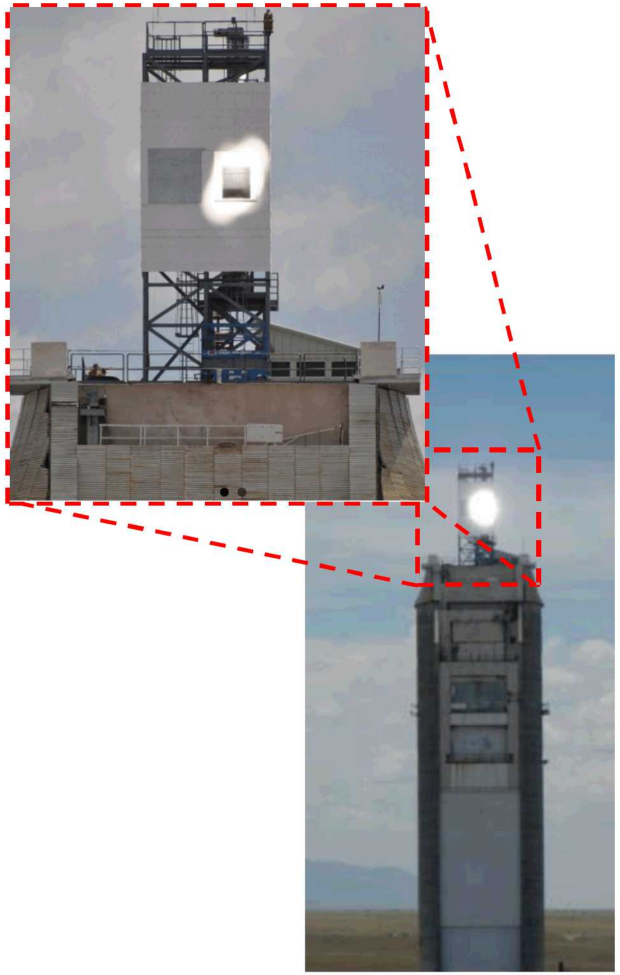
Falling particle receivers (FPRs) release a curtain of particles as the working fluid that are heated as they fall past the beam of concentrated solar radiation

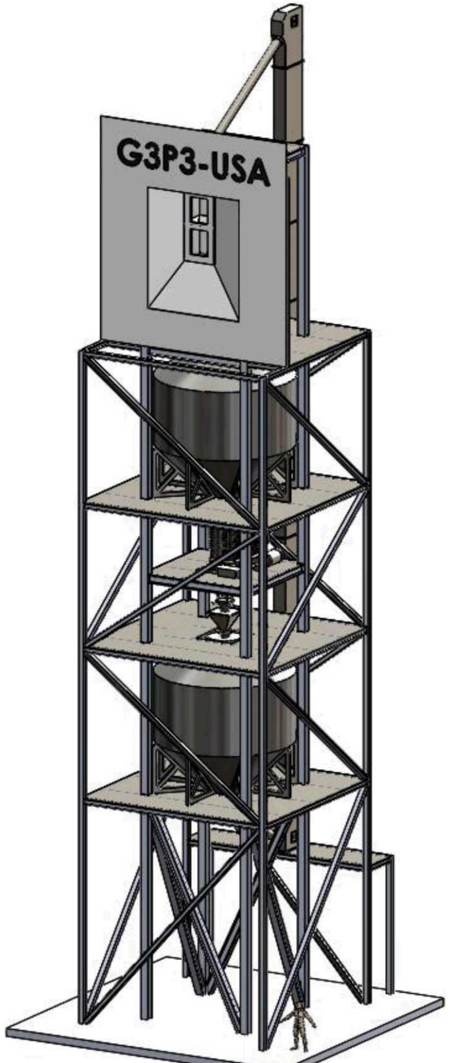
Advantages:

- Can achieve high particle temperatures
- High thermal efficiency
- Low cost transfer medium
- Efficient storage

The Generation 3 Particle Pilot Plant (G3P3) is the next realization of falling particle technology currently being designed at the NSTTF

NSTTF FPR test loop in 2018





G3P3 Concept

Advective Losses for Existing Receivers

A series of 26 on-sun experiments were performed using the NSTTF FPR test loop in 2018 to evaluate FPR thermal performance and validate thermal models

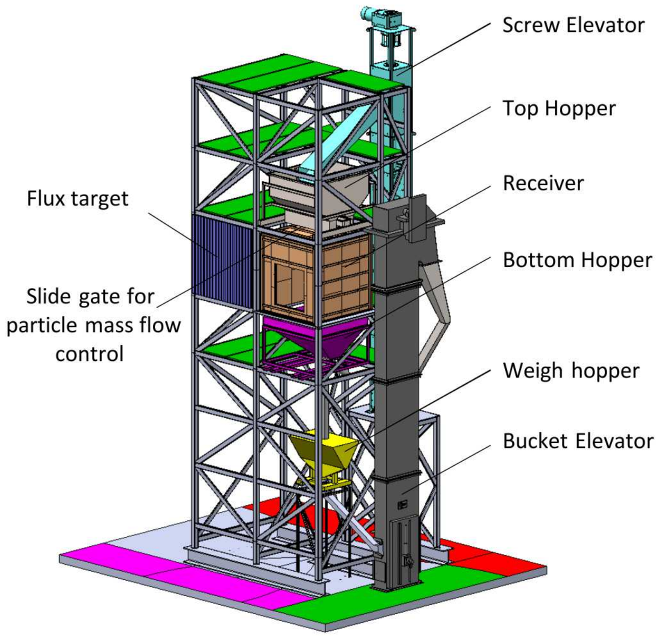
- A new particle mass flow rate measurement and control system had been implemented

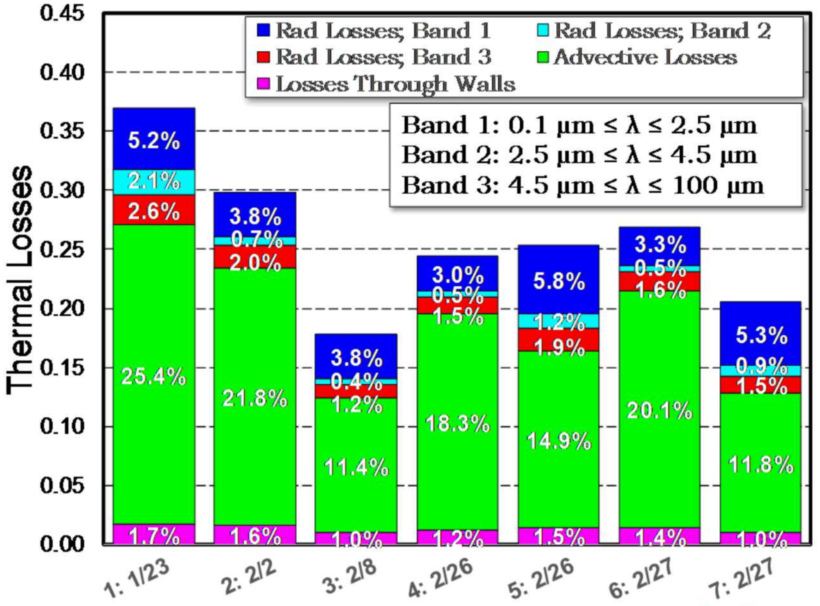
When compared with experiments, early CFD models of the receiver demonstrated that **advective losses were large** and **the efficiency of the receiver was sensitive to wind**

- Advective losses were also large in quiescent conditions

In designing the next generation receiver geometry, it is important to select a design that passively minimizes advective losses that depend on:

- The shape of the cavity
- The particle release location
- The particle temperatures
- The particle mass flow rate





[Mills (2018)]

Optimization Strategy

An optimization strategy was defined to identify a candidate geometry that passively minimizes advective losses

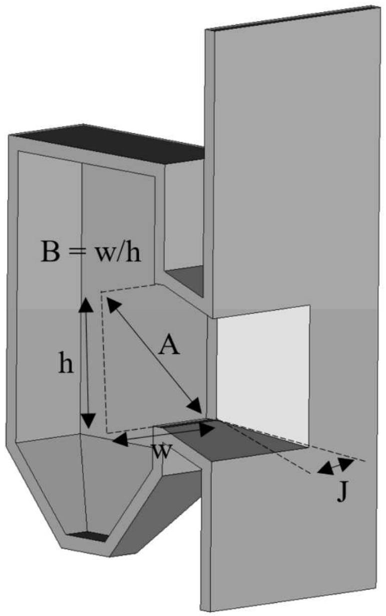
For nominal G3P3 conditions (q''_{irr} ≈ **1-2 MW/m^2**, $\dot{m}_{part}$ = **5-10 kg/s**, $T_{i,part}$ = **575°C**, ΔT_{part} = **200°C**), use the following optimization strategy to minimize advective losses in a design

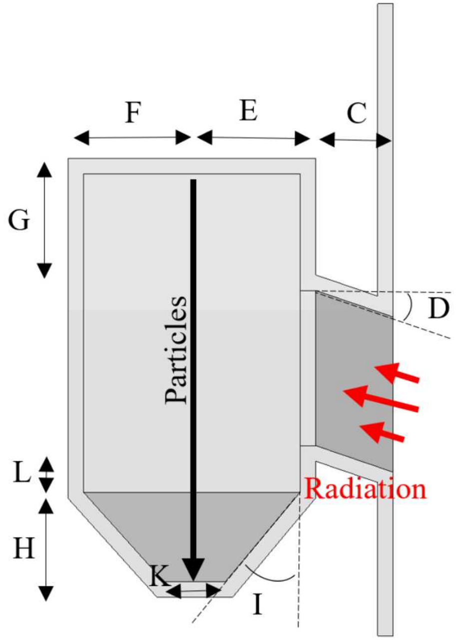
1. Starting with a candidate geometry, develop robust scripts to generate variations of that design
2. **Use Latin Hypercube sampling** to explore space of the variations
3. Use CFD to estimate the advective losses from those realizations
4. **Fit a surrogate model** to the results of those CFD simulations
5. **Use global optimization schemes** to find an optimized geometry from the surrogate model
6. Evaluate the final design in more rigorous CFD model to confirm its performance

1. Generating the Candidate Geometries

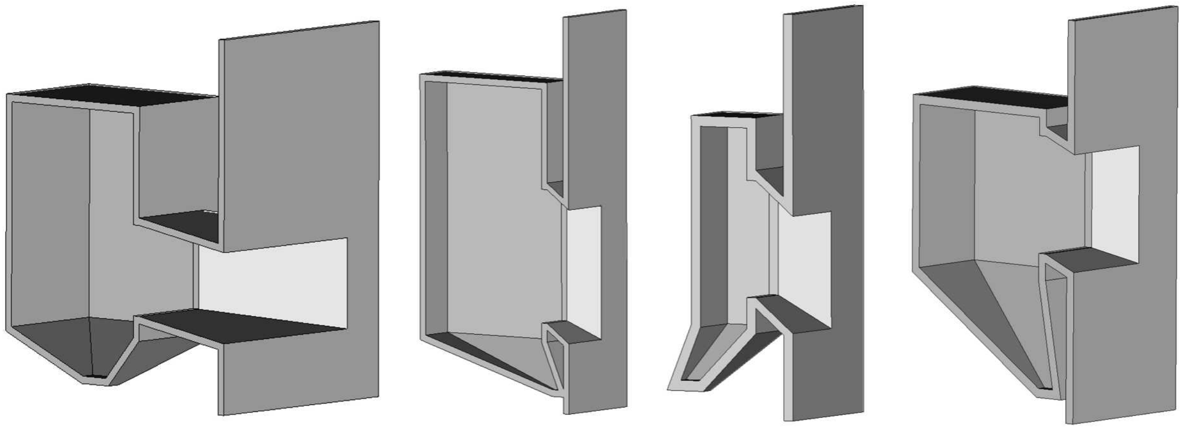
A conceptual FPR design was identified and 12 geometric parameters were defined that could vary to create a new geometry

Robust scripts were developed in using the meshing software Cubit to reliably generate and mesh candidate geometries





Item	Description
A	Aperture Area
B	Aperture Aspect Ratio
C	Tunnel Length
D	Tunnel Angle
E	Curtain Depth
F	Behind Curtain
G	Header
H	Hopper Depth
I	Hopper Angle
J	Width Multiplier
K	Hopper Exit Size
L	Below Aperture



The ranges for each geometric parameter were generally extended as far as possible without breaking the scripts

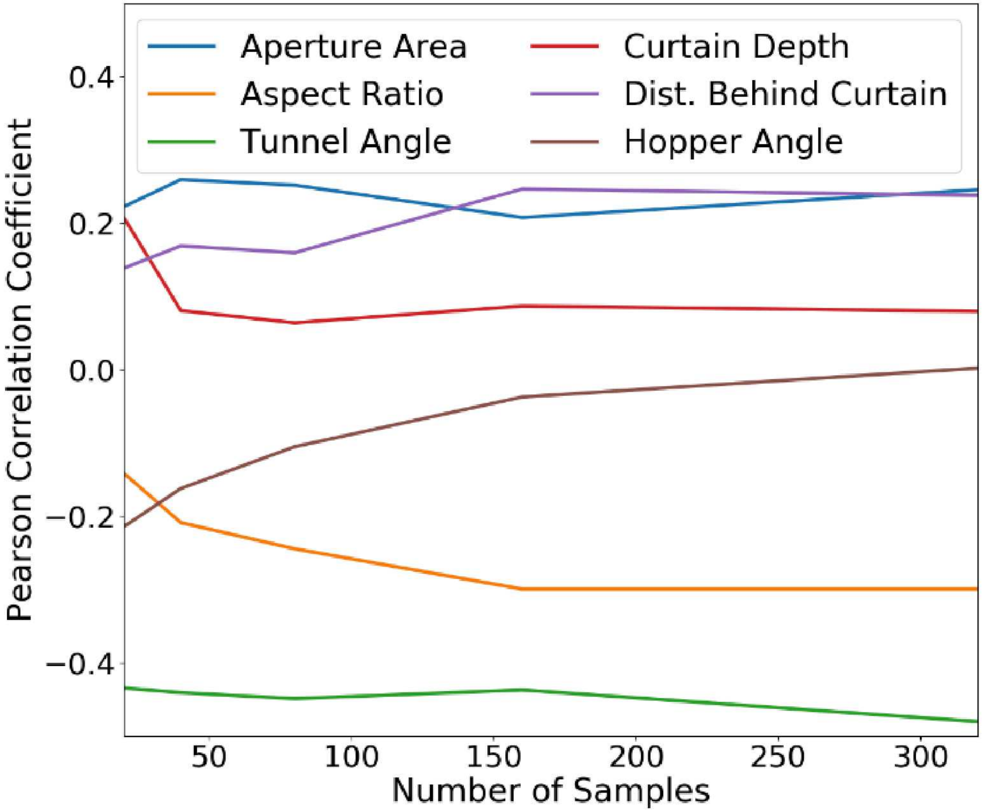
- Note that the geometries to the left are not using the same scale

2. Latin Hypercube Sampling Strategy

An incremental Latin Hypercube sample strategy was pursued to assure a sufficient number of realizations had been generated

- Pearson correlation coefficients converged for relevant parameters suggesting sufficient sampling
- A total of 320 realizations were ultimately simulated

Parameter Description	LHS Study Min.	LHS Study Max.
Aperture Area (m^2)	1.0	3.0
Aperture Aspect Ratio (-)	0.5	2.0
Tunnel Length (m)	0.2	2.0
Tunnel Angle (°)	5	60
Curtain Depth (m)	0.2	2.0
Behind Curtain (m)	0.1	2.0
Header (m)	0.25	2.0
Hopper Depth (m)	0.5	2.0
Hopper Angle (°)	-60	60
Width Multiplier (-)	1.1	1.3
Hopper Exit Size (m)	0.1	0.4
Below Aperture (m)	0.35	1.5
Avg. Irradiance (MW/m^2)	1.0	2.0



3. CFD Simulations of the Realizations

A Lagrangian-Eulerian model was developed in ANSYS Fluent® of particles falling through air in the receiver

Falling particles were released from 600 injection sites and coupled to the air through drag forces, heat transfer, and turbulent interactions

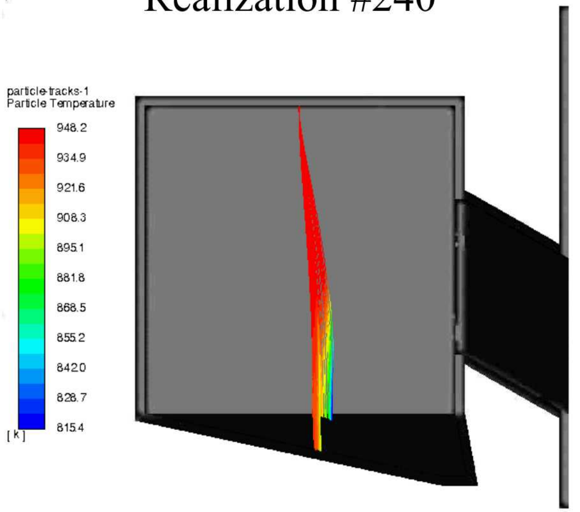
- Particles: CARBO Ceramic ACCUCAST ID with diameter of 350 μm

Steady-state simulations were performed

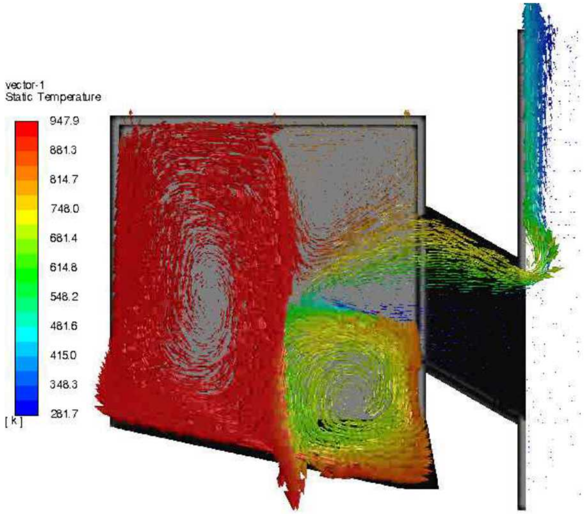
Unlike previous versions of this modeling approach, radiation was excluded from the analysis for minimize expense

- It was assumed that advective losses would be approximately the same without radiation is the receiver temperatures were similar

Realization #240



Particle curtain colored by temperature

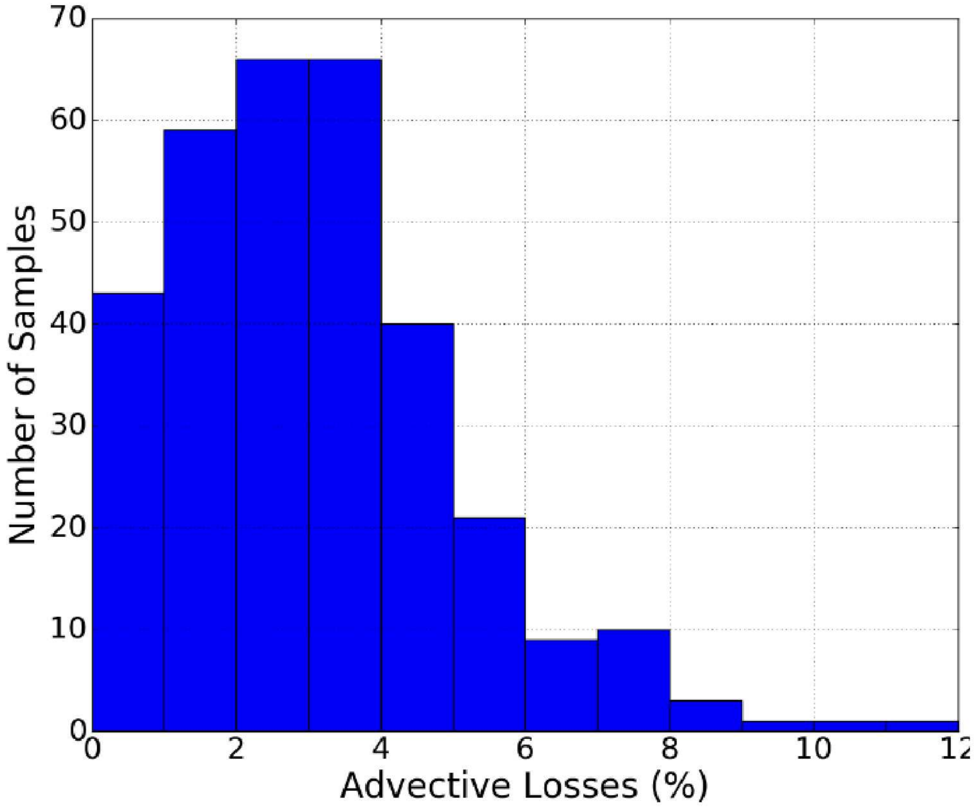


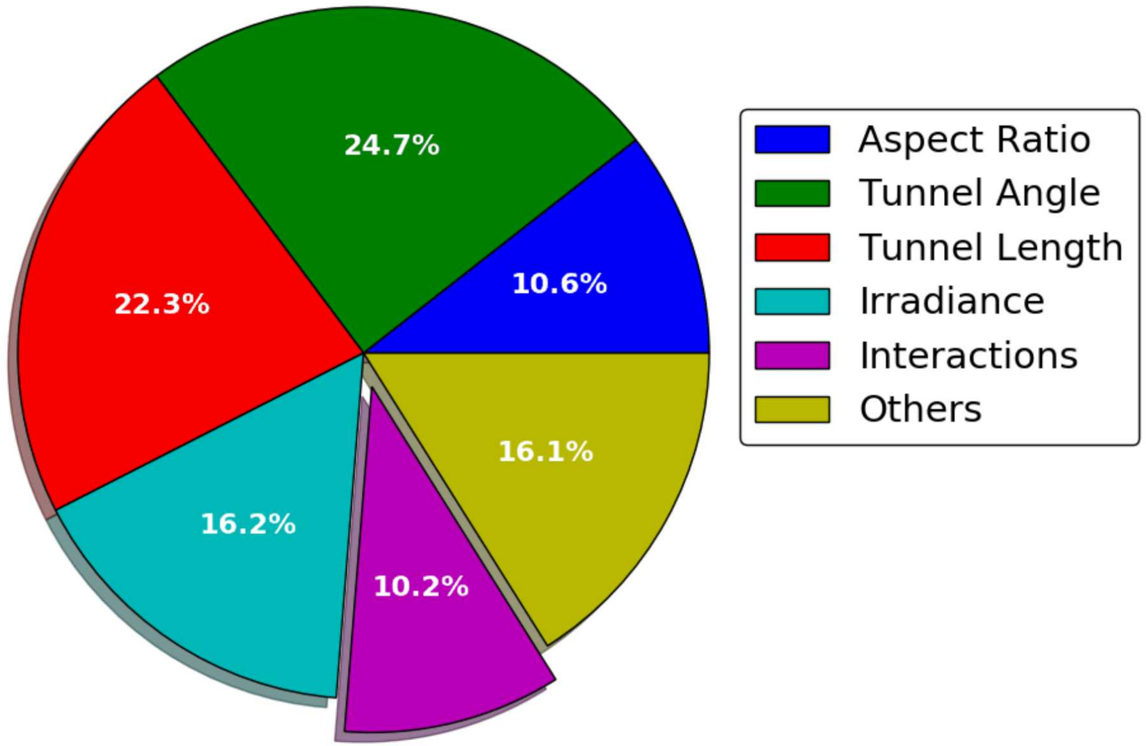
Air vectors colored by temperature

3. CFD Simulations of the Realizations (cont.)

The candidate geometry proved to be very robust with regards to advective losses with all geometries having less than 12% for all realizations

Sobol indices were computed from the realizations to identify the most important geometric parameters





4. Fitting a Surrogate Model to the Realizations

A linear polynomial model was used to fit the realizations as the surrogate

- A linear fit was used in order to be less susceptible to local nose but still capture global trends

Before optimization on the surrogate, the bounds over which the optimization was evaluated were narrowed to remove 'edge effects' and avoid obstructing the incident radiation

Parameter Description	Optimization Min.	Optimization Max.
Aperture Area (m^2)	1.5	2.8
Aperture Aspect Ratio (-)	0.995	1.005
Tunnel Length (m)	0.25	1.0
Tunnel Angle (°)	7.5	30
Curtain Depth (m)	0.2	1.9
Behind Curtain (m)	0.2	1.8
Header (m)	0.35	1.9
Hopper Depth (m)	0.5	1.8
Hopper Angle (°)	-30	30
Width Multiplier (-)	1.12	1.28
Hopper Exit Size (m)	0.12	0.38
Below Aperture (m)	0.35	1.5
Avg. Irradiance (MW/m^2)	1.5	2.0

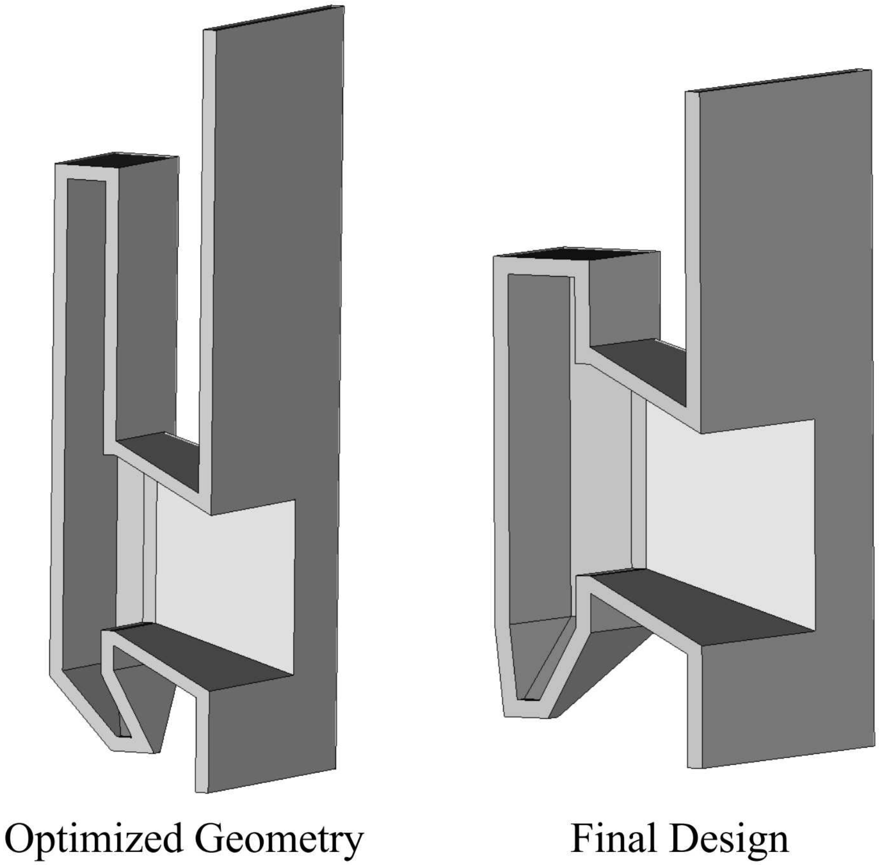
Held constant to minimize overheating from spillage

5. Optimize the surrogate model

A global, pattern-search optimization algorithm was used to find the optimal design from the surrogate

- Further modifications were made for practical considerations, but had a minimal effect on the advective losses predicted by the surrogate model
- From the Sobol indices, some changes had little to no effect

Parameter Description	Optimized Geometry	Final Design
Aperture Area (m^2)	1.5	1.5
Aperture Aspect Ratio (-)	1.00	1.0
Tunnel Length (m)	0.75	0.75
Tunnel Angle (°)	-30	**30**
Curtain Depth (m)	0.2	**0.3**
Behind Curtain (m)	0.2	**0.25**
Header (m)	1.9	**0.5**
Hopper Depth (m)	0.5	0.5
Hopper Angle (°)	-30	**30**
Width Multiplier (-)	1.28	**1.1**
Hopper Exit Size (m)	0.12	**0.15**
Below Aperture (m)	0.35	0.35
Advective Losses (%)	1.3%	1.7%



6. Complete CFD Evaluation

The final optimized design was finally evaluated in ANSYS Fluent® including radiative transport from the heliostat field.

A non-grey, discrete-ordinates model was applied

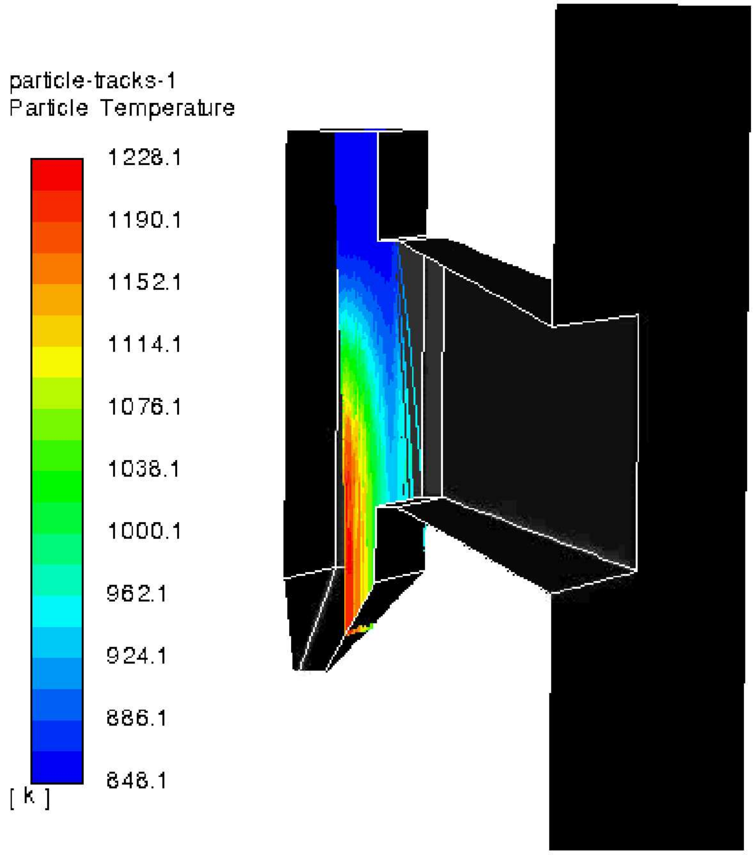
- Three wavelength bands (0.1 - 2.5 μm, 2.5 - 4.5 μm, 4.5 – 100 μm) were used in the DO model (1 band for solar radiation and 2 bands for thermal radiation)

Using G3P3 conditions:

- $q''_{irr} \approx$ **2.55 MW/m²**, $\dot{m}_{part}$ **= 9 kg/s**, $T_{i,part}$ **= 575°C**

The thermal efficiency of the receiver is used to evaluate the thermal performance:

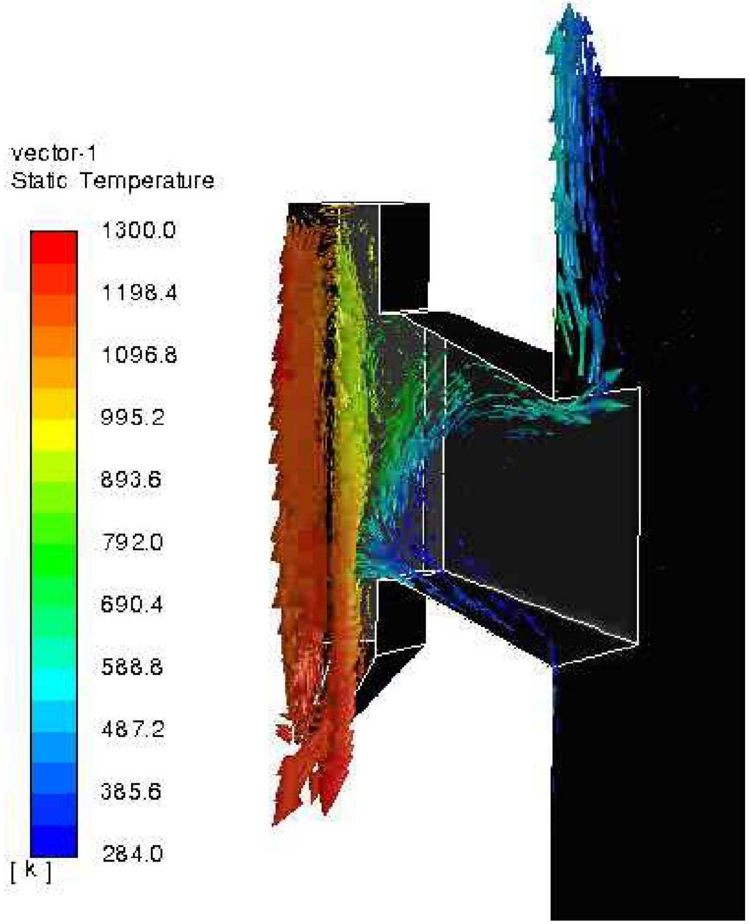
$$\eta_{th} = \frac{Q_{abs}}{Q_{in}} = \frac{\dot{m}\left(h_{out} - h_{in}\right)}{Q_{in}} = \frac{\dot{m}\int_{T_{in}}^{T_{out}} c_p\left(T\right)dT}{Q_{in}}$$

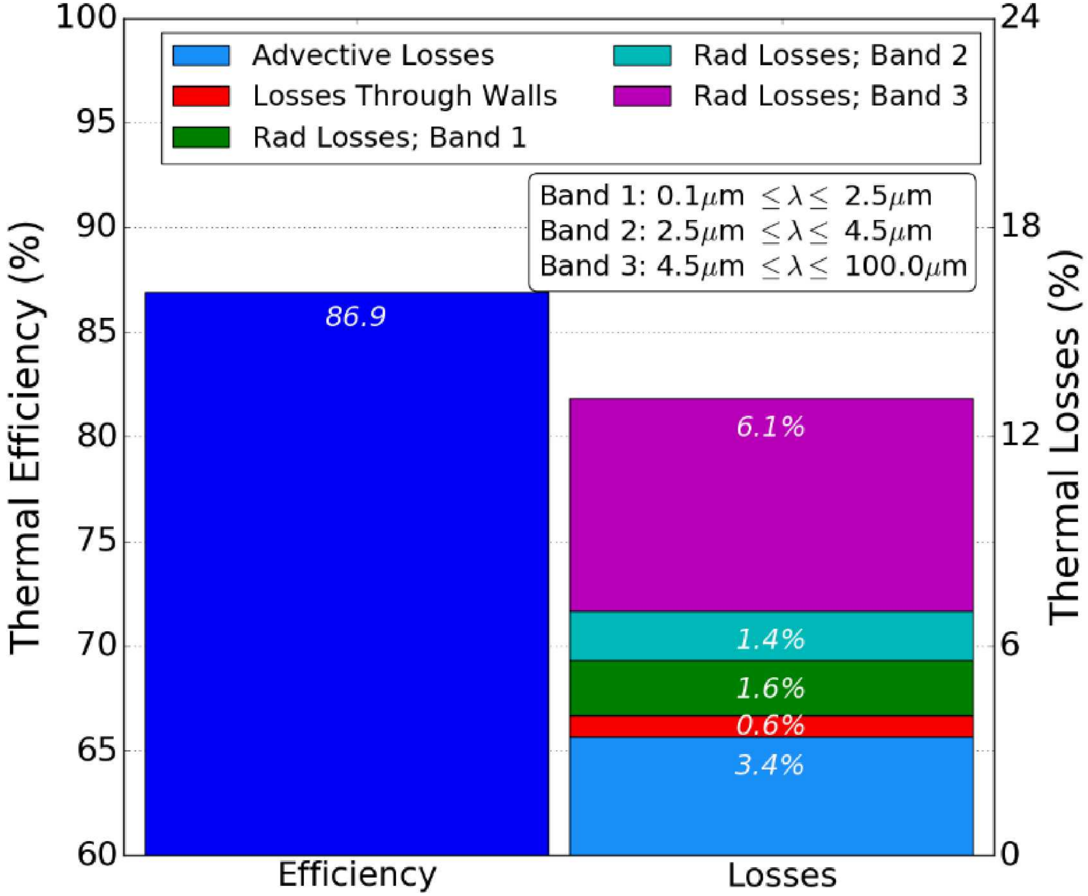


6. Complete CFD Evaluation (cont.)

The thermal efficiency of the receiver was **86.9%**

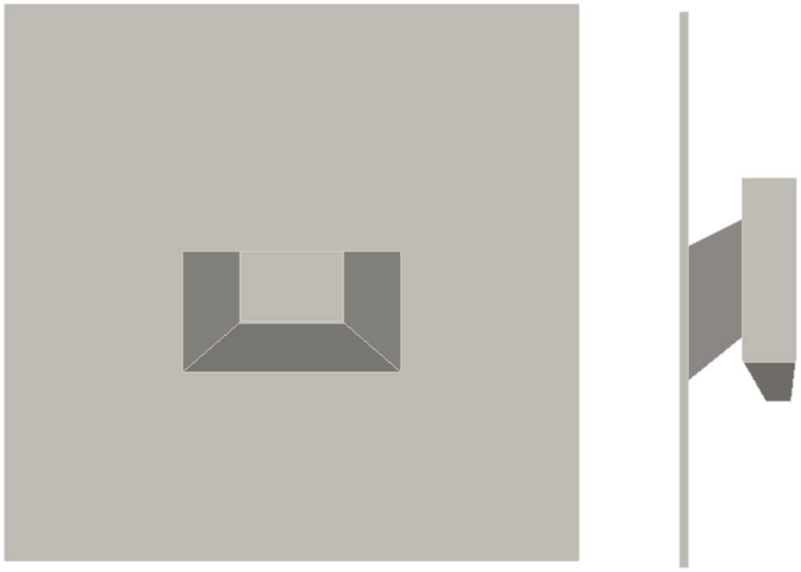
- Advective losses: 3.4%; total radiative losses: 9.1%, wall losses: 0.6%

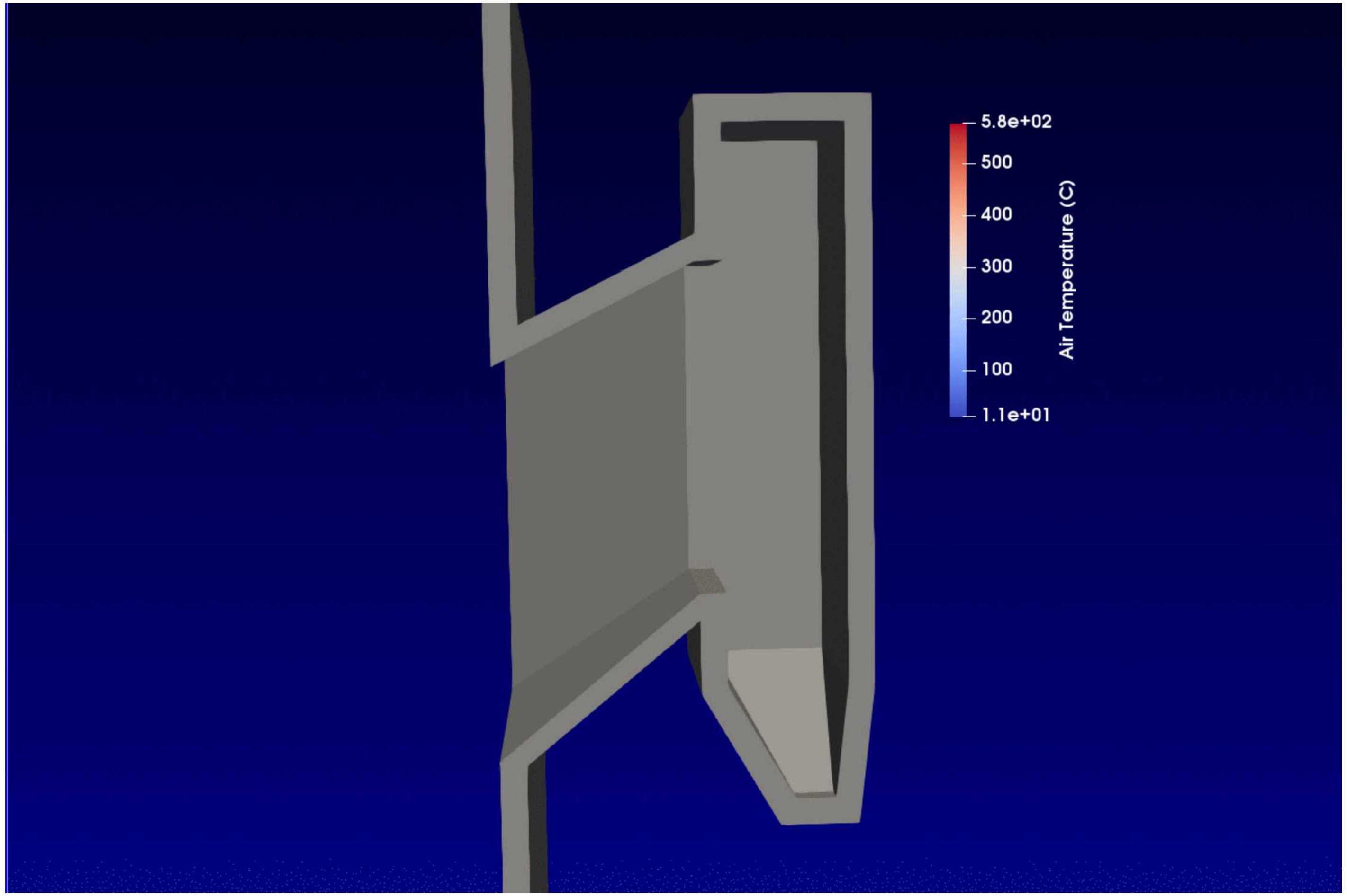




Transient evolution of the Flow

Using the SIERRA code suite, the transient evolution of the flow (excluding radiation) can be shown





Summary and Conclusions

An optimization scheme was utilized to develop a next generation falling particle receiver (FPR) for the G3P3 to minimize advective losses in quiescent conditions

An optimized geometry was found with predicted advective losses of only 1.3%

- The candidate initial geometry proved robust which enabled further geometric modifications for practical considerations
- A favorable internal flow in the cavity was found in the optimization that passively inhibited cold air from entering the receiver in quiescent conditions

More robust CFD models with radiative transport demonstrated that the simplified CFD models were sufficient to capture the advective flow in FPRs

Thank You!

Questions?