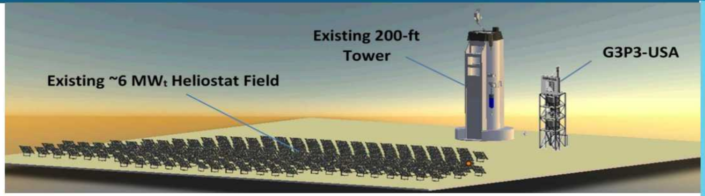
This paper describes objective technical results and analysis. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government.

SAND2019-10126C

EFFECT OF QUARTZ APERTURE COVERS ON THE FLUID DYNAMICS AND THERMAL EFFICIENCY OF FALLING PARTICLE RECEIVERS



Gen 3 Particle Pilot Plant (G3P3)

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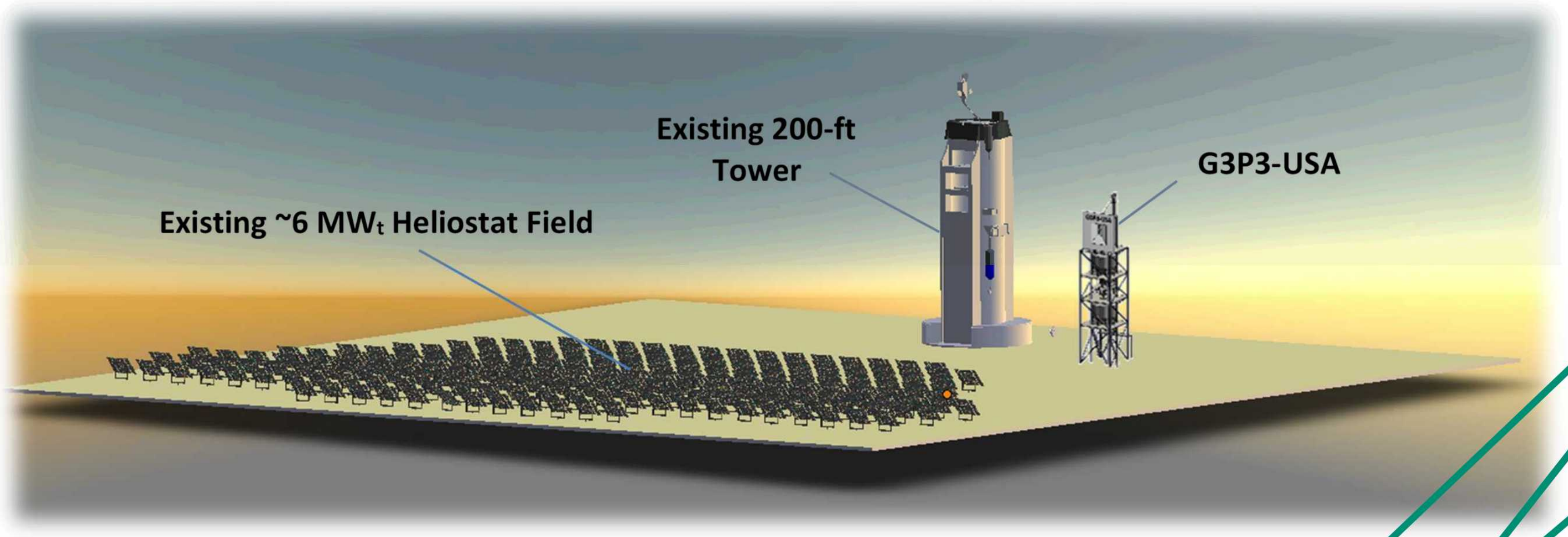
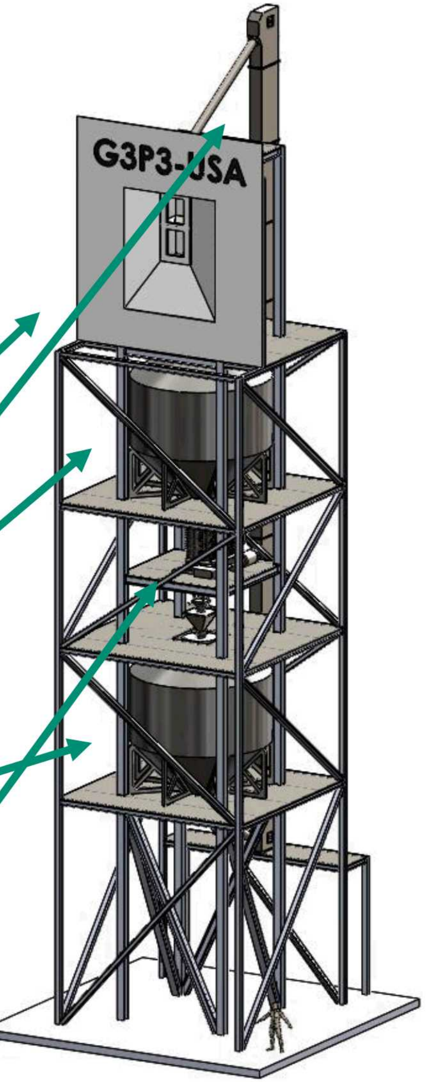
G3P3 Project



The Gen 3 Particle Pilot Plant (G3P3) is currently being designed for realization at the National Solar Thermal Test Facility. The plant uses small, sand-like ceramic particles as the heat transfer medium.

Project in-line components include:

- 1 MW_{th} cavity receiver
- Hot and cold storage bins
- Particle-to-supercritical CO_2 heat exchanger
- Particle handing system



G3P3 Project

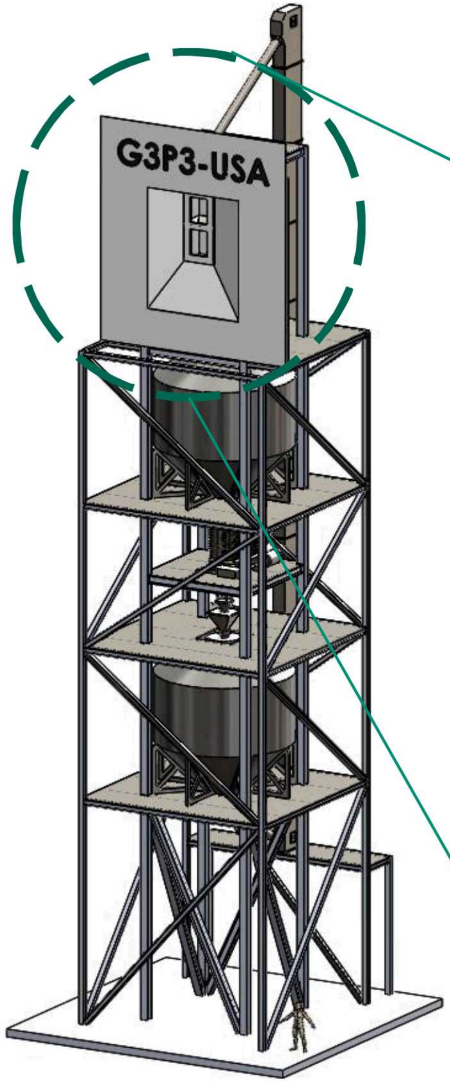
Falling particle receiver: a curtain of particles falls through the cavity

Potential to operate at higher temperatures:

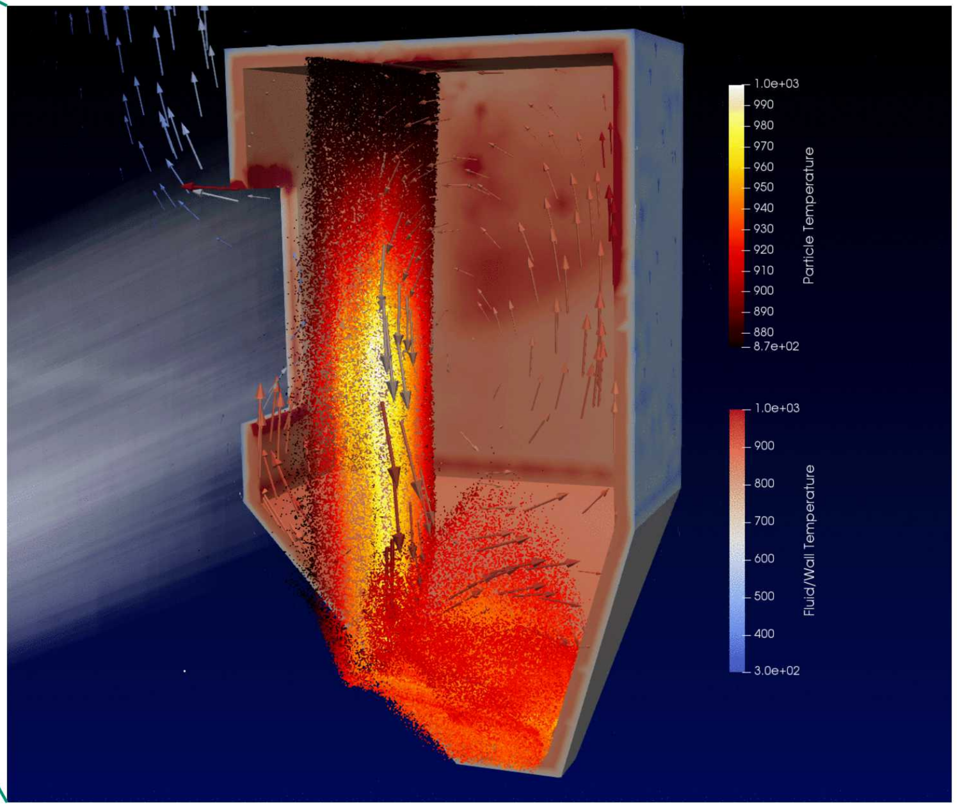
- Increasing the maximum potential power cycle efficiency
- Increases heat losses through the aperture

The dominant heat loss mechanism is hot air escaping out of the receiver aperture.

Question: Can **<u>quartz half-shell aperture covers</u>** decrease advective losses and increase receiver efficiency?



Example of a falling particle receiver geometry



Quartz half-shell aperture covers

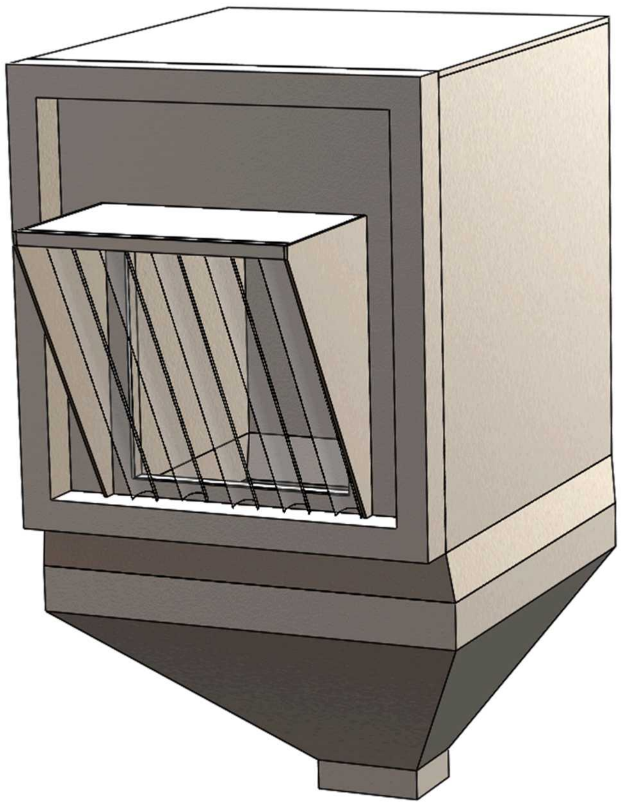
Fused quartz is
- Transparent to solar radiation
- Opaque to expected thermal emissions from receiver interior and particle curtain

Hypothesis: Quartz aperture covers may reduce radiative and advective losses while minimally reducing concentrated solar radiation entering the receiver.

Half-shells (2.5 mm thick with diameter 110 mm) are considered for their increased strength and potential for concentrating/light trapping over flat quartz panes.

Three cases are compared in this study (receiver geometry based on existing falling particle receiver at the National Solar Thermal Test Facility):
- Open aperture (no coverage)
- Partially covered aperture where adjacent half-shells have 110 mm spacing (half coverage)
- Fully covered aperture (full coverage)

'Half coverage' case



Falling particle receiver subdomain

Subdomain of receiver and surrounding air

- Turbulent fluid dynamics
- Motion of particle curtain
- Two-way turbulence interaction between particles and air
- Heat transfer due to radiation, convection, and conduction

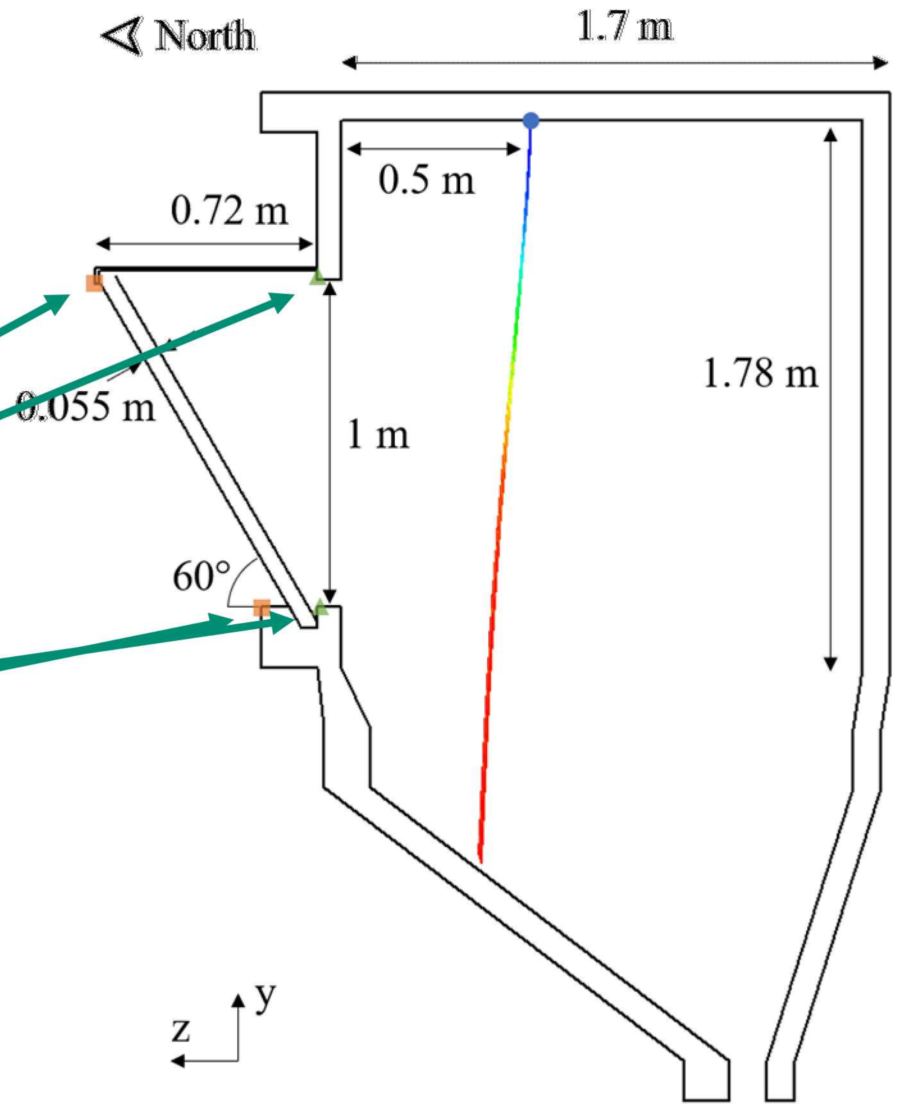
Compare cases based on:

- Advective, wall, and radiative losses
- Thermal efficiency

Two receiver 'control volumes' are used for evaluating losses and efficiency:

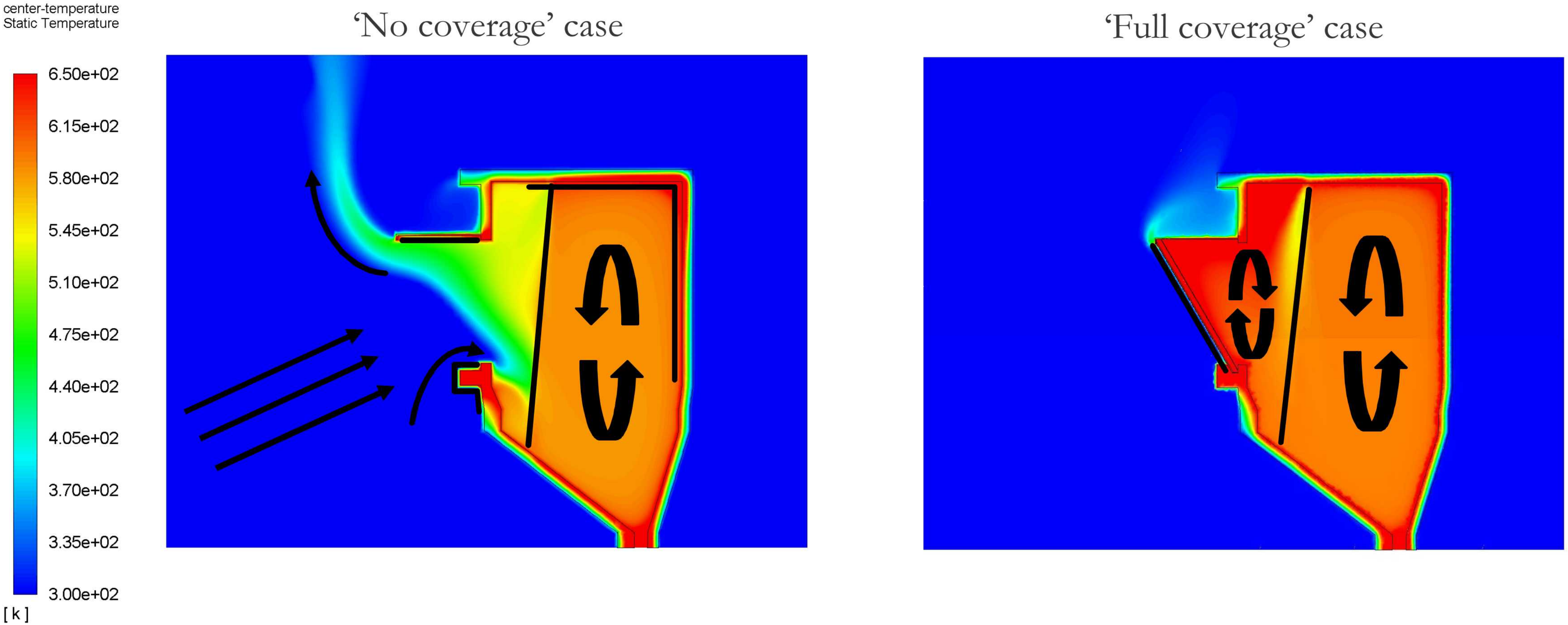
- Receiver aperture
- Hood aperture

Subdomain is idealized and does not predict full 3D receiver performance. Results should be viewed comparatively, not quantitatively.



Model Results: Temperature Contours

Observable phenomena: Particle and receiver wall heating (radiative exchange and losses; wall losses), air entrainment in particle curtain, insulated region of air behind the particle curtain, hot air plume rising from north edge of receiver (advective losses)



Model Results: Thermal Losses

Wall losses (shown in blue, stacked on the top)

- Do not appreciably change with coverage

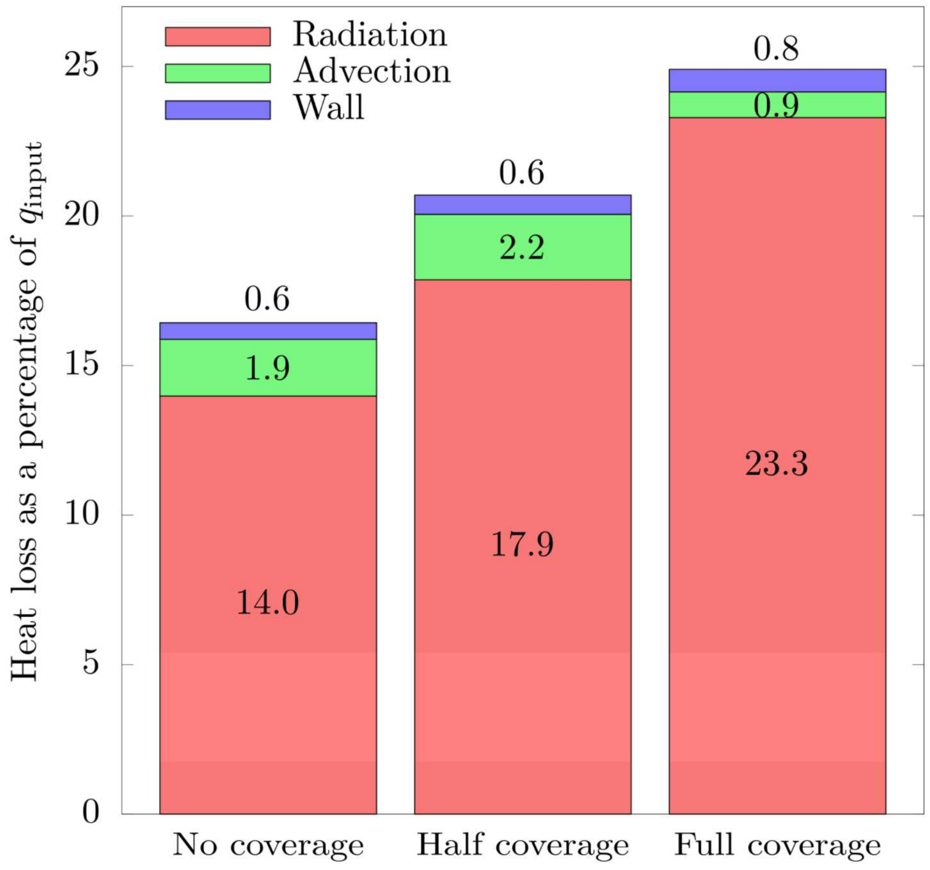
Advective losses (shown in green, stacked in the middle)

- Decrease for full coverage case, as expected, but not completely eliminated. Elevated quartz temperatures results in convective losses from the outward quartz faces.
- Increase for half coverage case, hot quartz appears to act as fins, transferring additional energy to the hot air leaving the receiver

Radiative losses (shown in red, stacked on the bottom)

- Increase with increase coverage

Question: Why are the radiative losses increasing? Are thermal emissions from the interior increasing due to the elevated temperature or is more concentrated solar radiation being reflected?



Model Results: Radiative Losses by Band

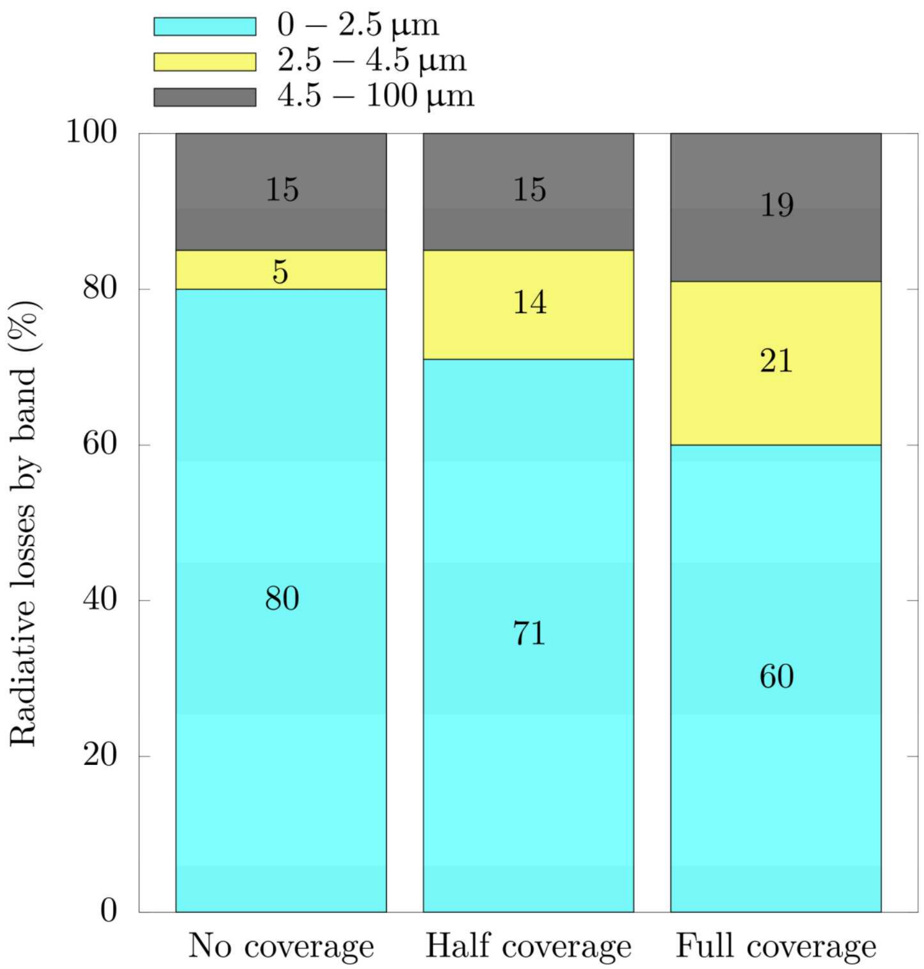
Radiative losses divided by band answer the question.

Radiative losses are dominated by reflection losses in short wavelength band (0–2.5 µm), shown in teal, stacked on the bottom.

However, longer wavelength band radiative losses increase with increasing coverage, thus increased radiative losses are due to:

- Increased thermal emissions (2.5–4.5 and 4.5–100 µm bands)
- Not due to increased reflections which would present in the 0–2.5 µm band.

This trend in radiative losses is not observed as strongly in losses leaving the receiver aperture (behind the quartz) but is observed in radiative losses leaving the hood aperture (in front of the quartz), thus can be mostly contributed to increased quartz emissions.

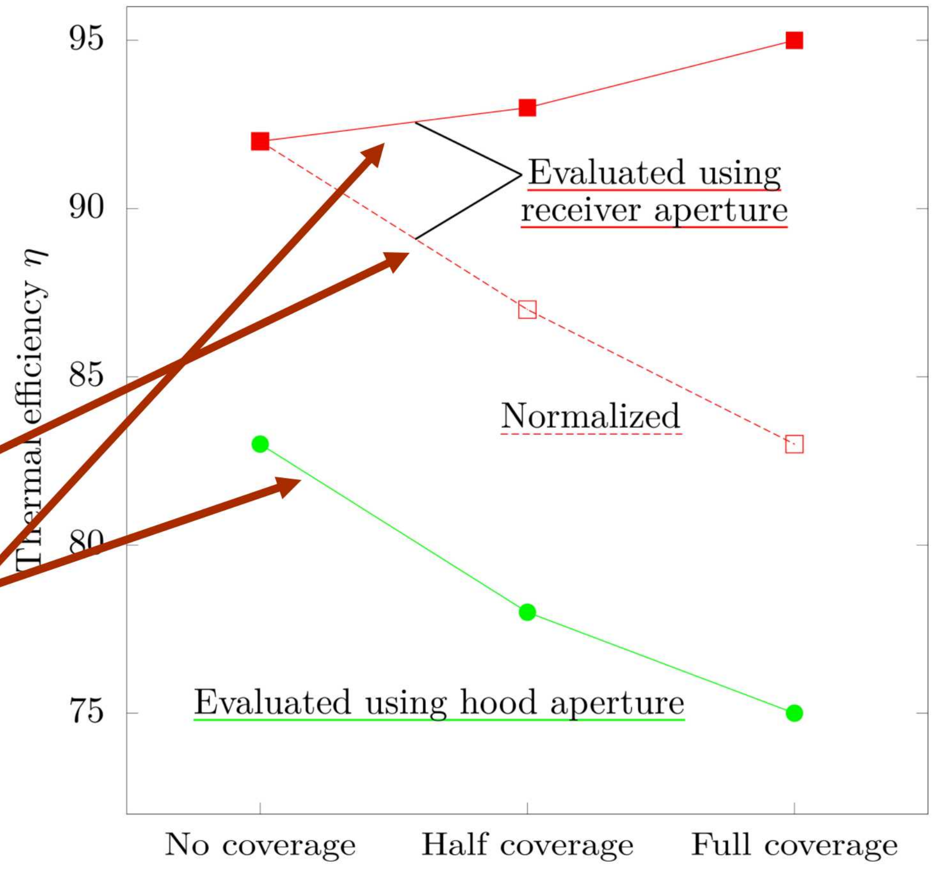


Model Results: Thermal Efficiency

Receiver thermal efficiency compares radiation entering the receiver to power absorbed by the particles

$$\eta = \frac{q_{\text{particles}}}{q_{\text{rad}}} \times 100\% \qquad q_{\text{particles}} = \int_{T_{\text{in}}}^{T_{\text{out}}} \dot{m} c_{\text{p}} \mathrm{d}T$$

Case	No coverage	Half coverage	Full coverage
q_{rad} hood aperture	111 kW	111 kW	111 kW
q_{rad} receiver aperture	100 kW	93 kW	87 kW
$q_{\text{particles}}$	92 kW	87 kW	83 kW



Model Results: Sensitivity to Quartz Absorptivity

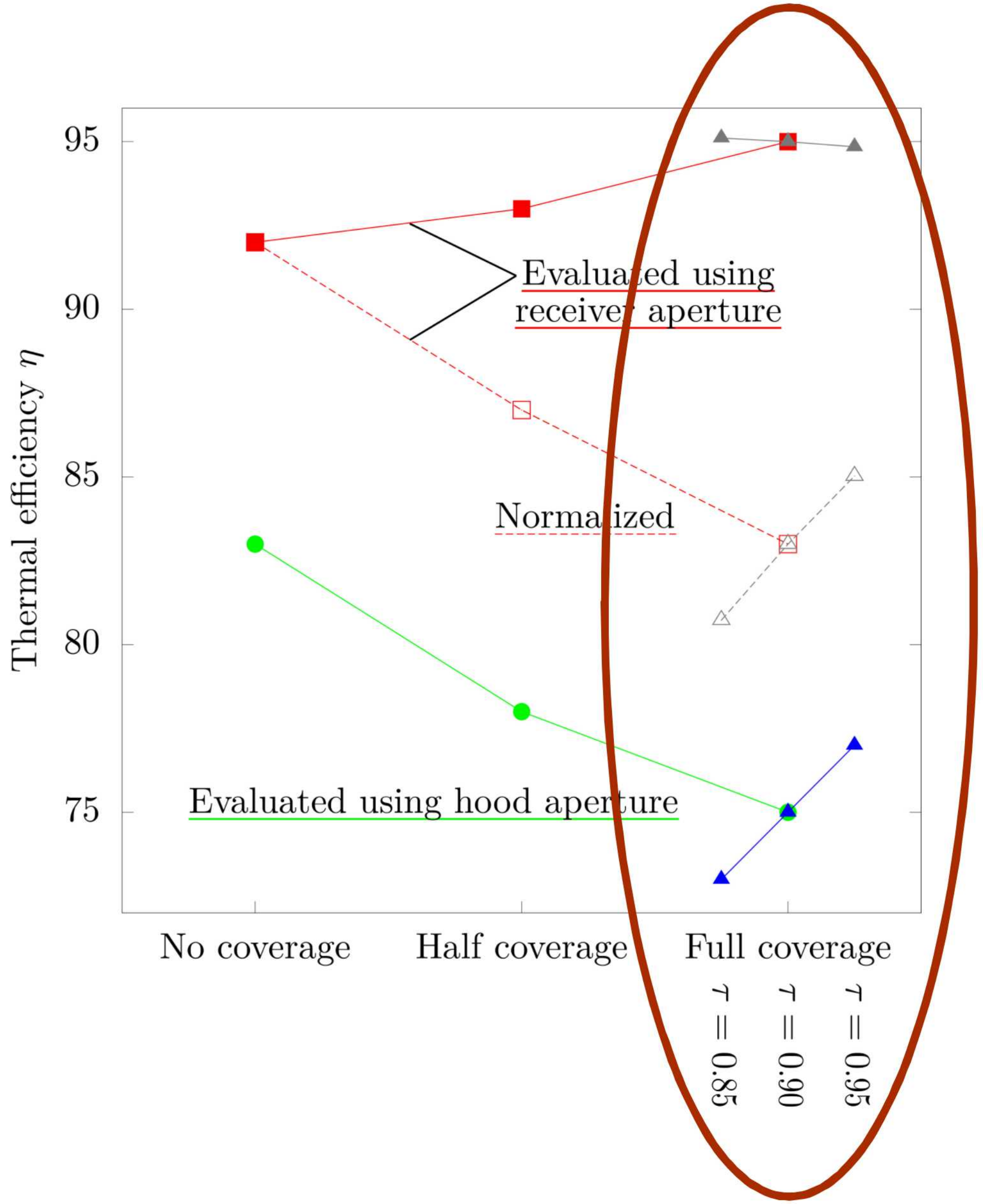
Quartz temperatures drive increased radiative losses and, in the half coverage case, increased advective losses.

Question: How sensitive are the results to quartz volumetric transmissivity?

Increased and decreased quartz volumetric transmissivity from the baseline of 90% in the solar band to 95% and 85%, respectively.

5% increase or decrease in volumetric transmissivity results in 2% increase or decrease in thermal efficiency.

Quartz volumetric transmissivity can vary by manufacturer, manufacturing technique, and also may vary due to 'prefiltering' of concentrated solar radiation through heliostat glass.



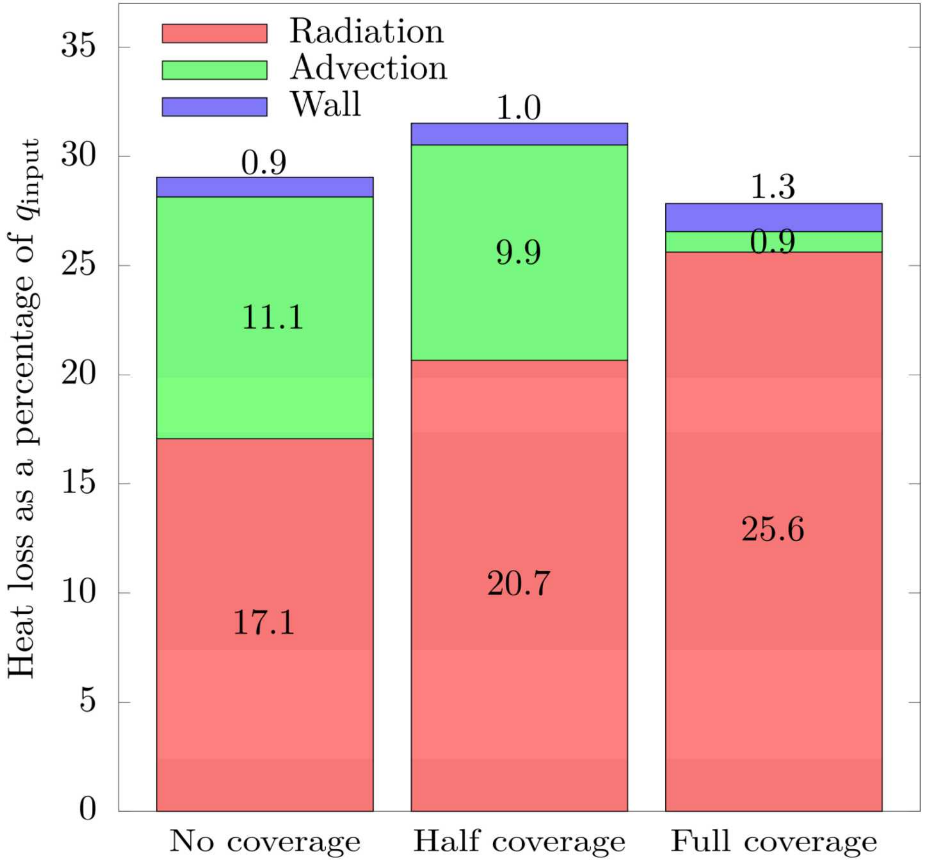
Model Results: Particle Inlet Temperature

Increasing particle inlet temperature from 227 to 600°C results in increased advective losses.

Full coverage case performance is comparable to the baseline no coverage case for $T_0 = 600$°C.

When advective losses increase, beneficial affect of a full coverage aperture cover outweighs the detrimental ones.

The beneficial effect of a full coverage aperture cover is expected to be magnified in the presence of wind which can further increase advective losses.



Evaluated using the hood aperture

Conclusions

Three affects observed with quartz half-shell aperture covers:

- Advective losses can increase or decrease with coverage
- Radiative losses increase with coverage → quartz half-shells act as a 'short circuit' for radiative losses
- Radiation entering the receiver decreases with coverage

Question: Can the one potential beneficial outcome (decreased advective losses) outweigh the two detrimental ones (increased radiative losses and decreased radiation entering the receiver)? Under what conditions could aperture covers have a net benefit?

Answer: Possibly when operating at higher temperatures and when subjected to wind which further increases advective losses.

Ongoing work:

- Modeling full 3D receiver geometry with quartz half-shell aperture covers to investigate wind effects
- Experimental investigation of quartz absorptivity of concentrated solar radiation
- Scale up challenges: what is the longest, feasible length scale?

Thank you

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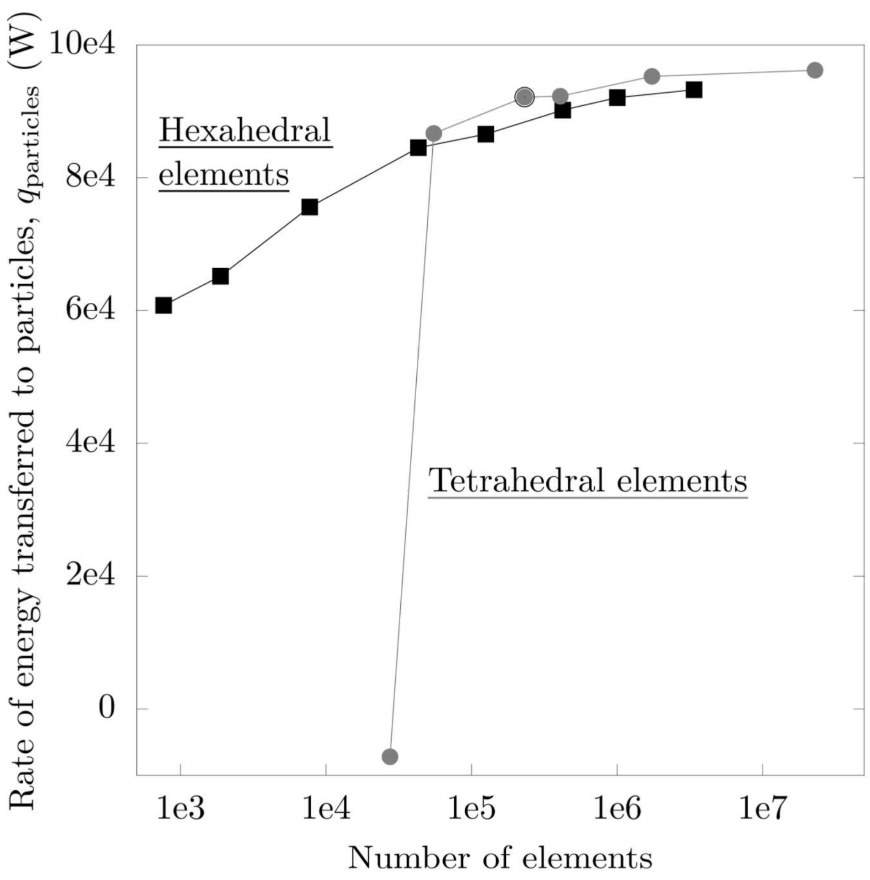
Mesh invariance study

No coverage case solved on meshes of both tetrahedral and hexahedral elements with varying number of elements.

The tetrahedral mesh has a sufficient number of elements that the results are reasonably independent of mesh size.

However, results from meshes with hexahedral vs tetrahedral elements do not agree.

Thus, results should be considered comparatively, and no quantitatively, given the discrepancy between results obtained using different meshes.



Material properties

PROPERTIES OF FUSED QUARTZ

Property	Value	Units
ρ	2200	kg m^{-3}
c_p	Piecewise-Linear Profile: 772@100°C 964@500°C 1052@900°C	J kg^{-1} K^{-1}
k	Piecewise-Linear Profile: 1.38@20°C 1.46@100°C 1.55@200°C 1.67@300°C 1.84@400°C 2.68@950°C	W m^{-1} K^{-1}
τ_λ	0.9 (λ=0-2.5 μm) 0.5 (λ=2.5-4.5 μm) 0.1 (λ=4.5-100 μm)	
n_λ	1.50 (λ=0-2.5 μm) 1.42 (λ=2.5-4.5 μm) 1.41 (λ=4.5-100 μm)	

PROPERTIES OF FIBERFRAX® DURABOARD® HD

Property	Value	Units
ρ	420	kg m^{-3}
c_p	1000	J kg^{-1} K^{-1}
k	Piecewise-Linear Profile: 0.075@204°C 0.1@427°C 0.14@649°C 0.19@871°C 0.22@982°C	W m^{-1} K^{-1}
$\alpha_\lambda/\varepsilon_\lambda$	0.1 (λ=0-2.5 μm) 0.4 (λ=2.5-4.5 μm) 0.8 (λ=4.5-100 μm)	

PROPERTIES OF CARBO ACCUCAST

Property	Value	Units
ρ	3550	kg m^{-3}
c_p	Piecewise-Linear Profile: 947@200°C 1073@400°C 1136@550°C	J kg^{-1} K^{-1}
ε	0.8	
scattering factor	0.3	
mean diameter	300	μm

Model physics

Turbulent flow of air modeled with the realizable k–ε turbulence model and Fluent's scalable wall functions, which has previously been used to model fluid dynamics of the entire NSTTF receiver with good agreement between experimental and numerical results [1].

Particles are modeled using the discrete phase model. They are injected from 30 sites, at 227°C with a downward velocity of 3 m s^{-1} at a total flow rate of 1 kg s^{-1}. Particle bouncing is neglected.

Radiative heat transfer modeled using non-grey discrete ordinate model with three bands. Receiver wall volumes are modeled as non-participating; air is modeled as non-absorbing and non-scattering with refractive index of unity; quartz half-shells are modeled as non-scattering, semi-transparent media. Incidence angle-dependent specular reflection is modeled at quartz–air interfaces using Snell's Law and the Fresnel equations.

East and west faces of the domain are modeled as symmetry boundaries.

For more information, please refer to the conference paper ES2019-3910 and/or ANSYS® Fluent® documentation.

[1] Siegel, N., Kolb, G., Kim, K., Rangaswamy, V., and Moujaes, S. *Proceedings of the 2007 ASME Energy Sustainability Conference*, Long Beach, CA USA. July 27–30, 2007.