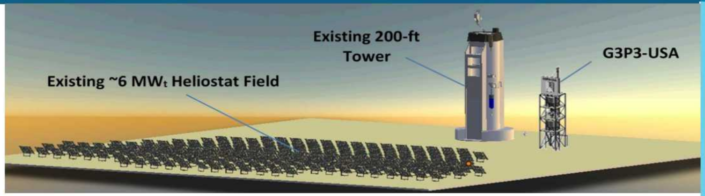
SAND2019-11398C

ACTIVE AIRFLOW FOR REDUCING ADVECTIVE AND PARTICLE LOSS IN FALLING PARTICLE RECEIVERS



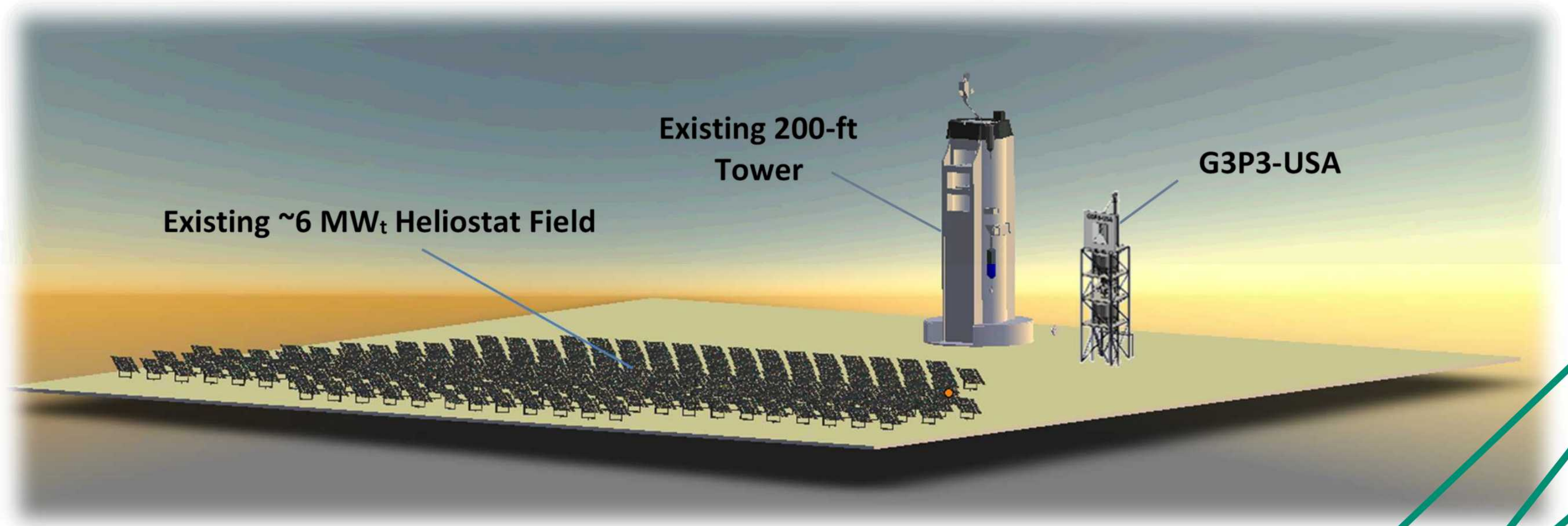
Gen 3 Particle Pilot Plant (G3P3)

Lindsey Yue, Reid Shaeffer, Brantley Mills, Clifford K. Ho

SOLAR ENERGY TECHNOLOGIES OFFICE
U.S. Department Of Energy

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

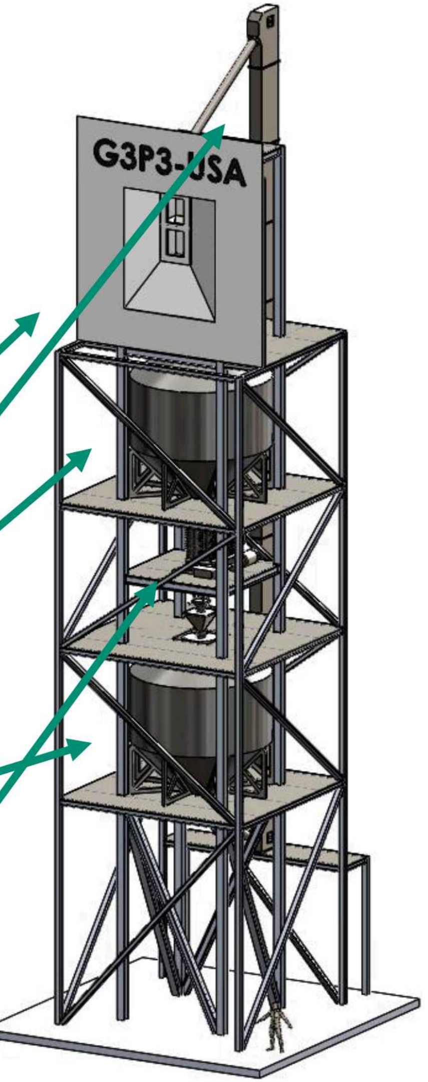
G3P3 Project



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

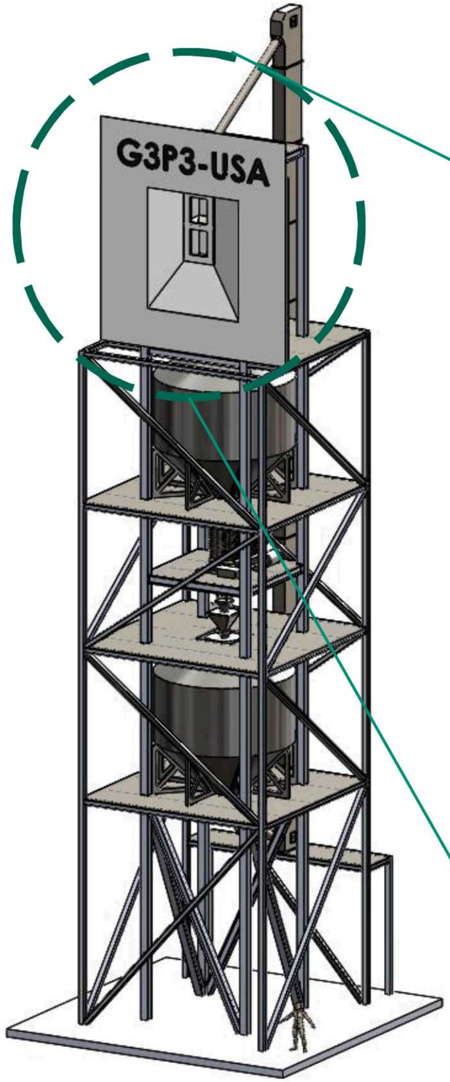
Falling particle receiver: a curtain of particles falls through the cavity

Potential to operate at higher temperatures:

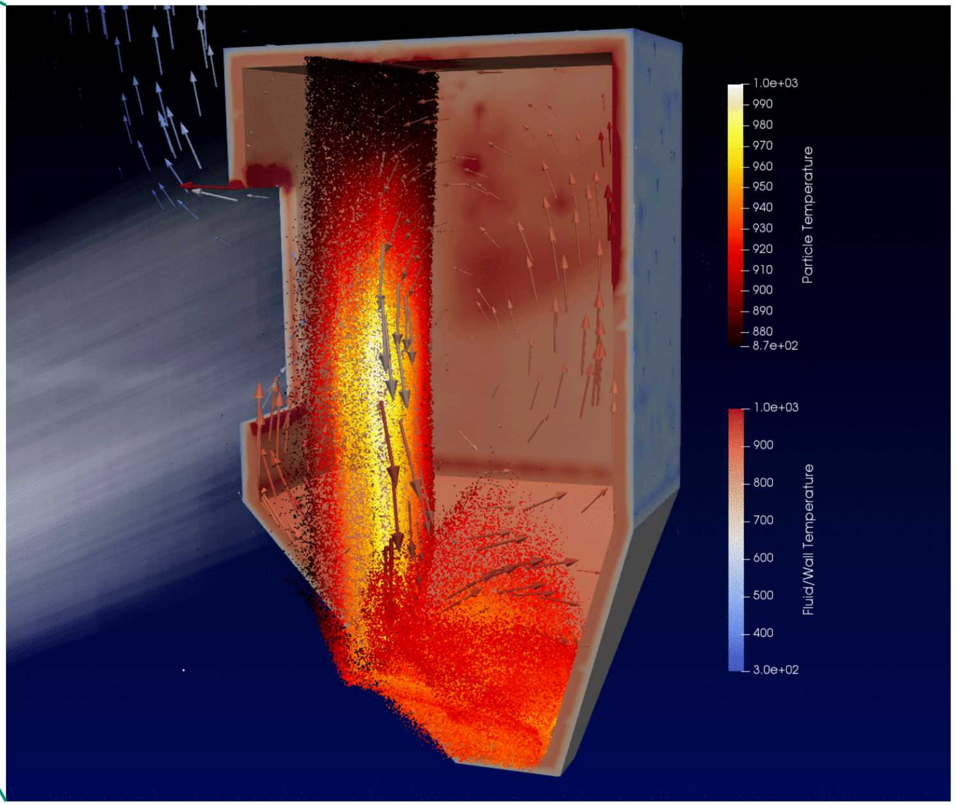
- Increasing the maximum potential power cycle efficiency
- Increases heat losses through the aperture

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

Question: Can **<u>active airflow methods</u>** decrease advective losses and increase receiver efficiency?



Example of a falling particle receiver geometry



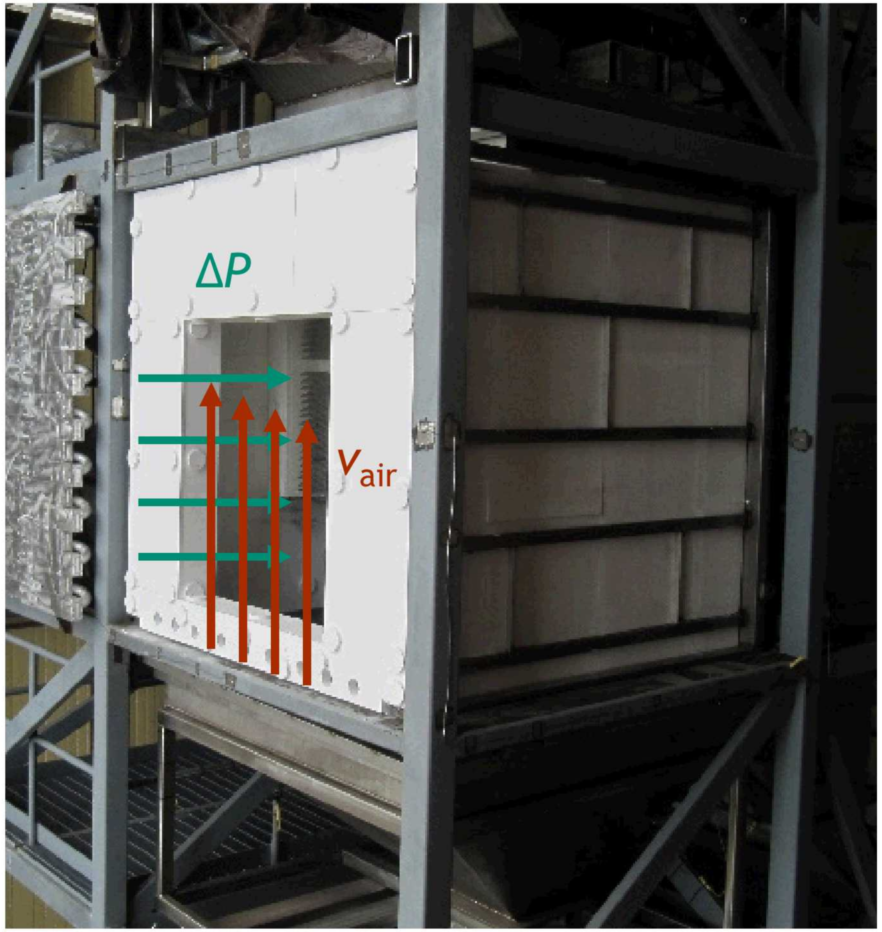
Active Airflow Methods

Hypothesis: Active airflow methods may reduce loss of hot air and particles from the open aperture

Active airflow configurations are investigated numerically for a receiver geometry based on an existing falling particle receiver at the National Solar Thermal Test Facility

Two active airflow configurations are considered:

- Once-through suction
  - Suction creates lower pressure within the cavity preventing loss of hot air and particles out of the aperture
  - Suction outlet location and air mass flow rate are investigated
- Air curtain
  - Air forced across the aperture creates a barrier preventing hot air and particles loss from the aperture
  - The direction and outlet velocity of two jets are parametrically varied
  - External wind direction and magnitude are also considered



Numerical Model

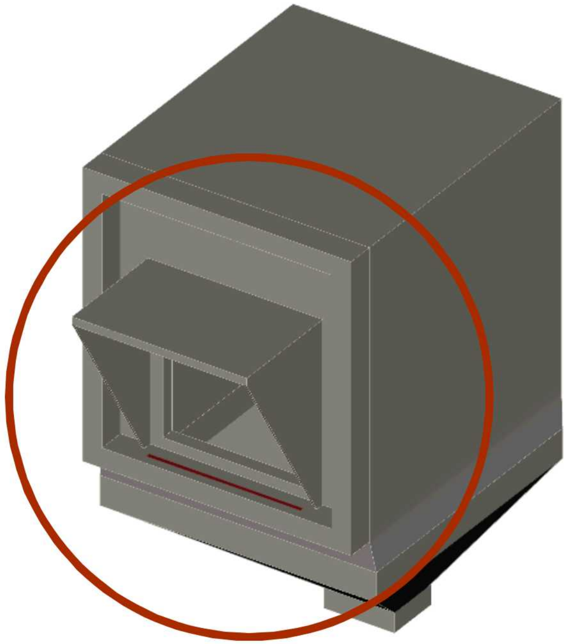
Numerical model:
- Turbulent fluid dynamics of air inside and surrounding the receiver
- Motion of particle curtain
- Two-way turbulence interaction between particles and air
- Heat transfer due to convection and conduction
- Radiation is only included in selected cases (all once-through suction cases and two air curtain cases) and omitted from the remainder due to computational expense
- Solved for steady state conditions

$$\eta = \frac{q_{\text{particles}}}{q_{\text{rad}}} \times 100\%$$

$$q_{\text{particles}} = \int_{T_{\text{in}}}^{T_{\text{out}}} \dot{m} c_{\text{p}} \mathrm{d}T$$

Cases are evaluated based on:
- **Thermal efficiency** for cases solved with radiative heat transfer (ratio of enthalpy transferred to the particles and radiation entering the aperture)
- Advective losses (net rate of enthalpy transfer across the aperture plane)

Geometries include a 0.72 m long **hood with sides**
- Preliminary simulations show the hood increases radiation entering the cavity and reduced advective losses
- Hood provides a location for an air jet in front of the aperture for the air curtain active airflow



Once-Through Suction Active Airflow

Subdomain geometry

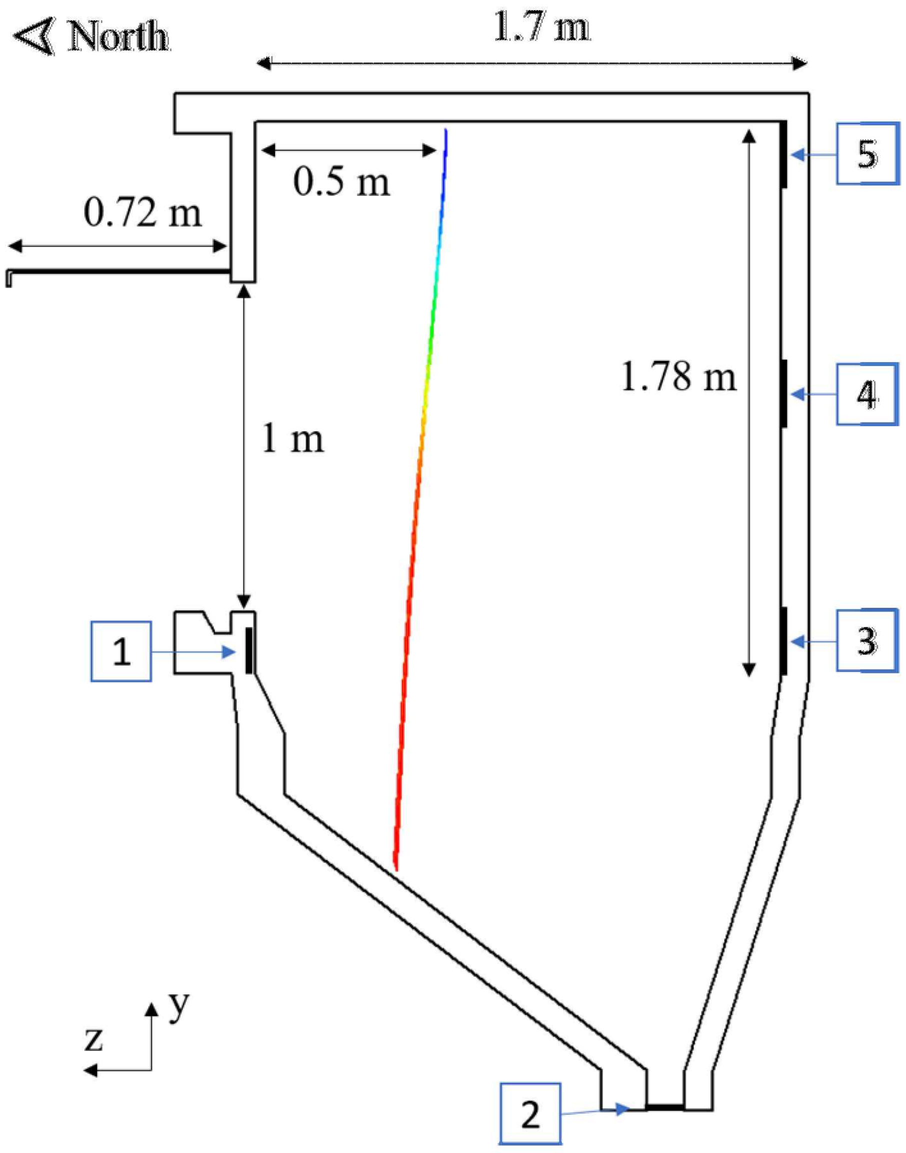
- 0.11 m in the east–west direction
- Symmetry boundary conditions on east and west faces
- 6 kg s^{-1} m^{-1} particle mass flow rate, initial temperature 575°C
- 0.85 MW m^{-2} flux entering the aperture (100 kW total power)

Outlet location investigation:

- Suction from five outlet locations is compared to baseline, no suction case
- 10 g s^{-1} suction rate for all cases

Suction rate investigation:

- Suction rate varied for best performing outlet location
- 2.5–50 g s^{-1} suction rate



Once-Through Suction Active Airflow

Suction introduces new energy loss pathway: advective loss due to enthalpy of air being removed by suction. Recovery of this thermal energy has the potential to be incorporated into the system to offset the energy loss, but that is not considered in this study.

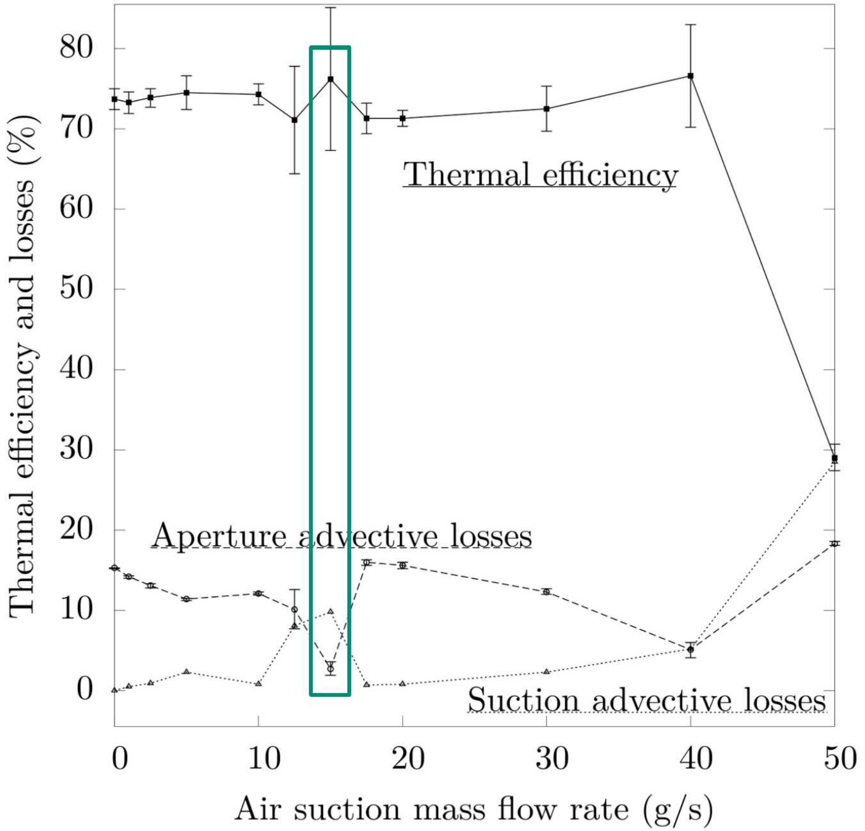
- **Back outlets (3–5)** increase advective loss from aperture
- **Front (1) and hopper (2)** outlets decrease advective loss from the aperture
- **Front outlet** has lowest advective loss due to suction and is the only case with increased efficiency over the baseline

Case	No suction	Back bottom	Back middle	Back top	Front bottom	Hopper
Advective loss from aperture	15.3%	16.1%	19.2%	18.0%	12.1%	13.7%
Advective loss due to suction	0%	7.0%	7.0%	8.0%	0.9%	7.5%
Receiver thermal efficiency	72.8%	66.2%	58.5%	62.0%	74.1%	65.8%

Once-Through Suction Active Airflow

Varied suction mass flow rate from 2.5 to 50 g s^{-1}. **15 g s^{-1}** resulted in highest efficiency of considered cases (η = 0.761 or +0.033 over the baseline case)

- Circulation in front of the curtain matches flow rate of entrained air, keeping more hot air in front of the particle curtain and counteracting buoyant forces
- 'Error bars' represent $\pm 2\sigma$ for oscillations in converged numerical solution around average values: numerical noise is larger than expected efficiency improvements

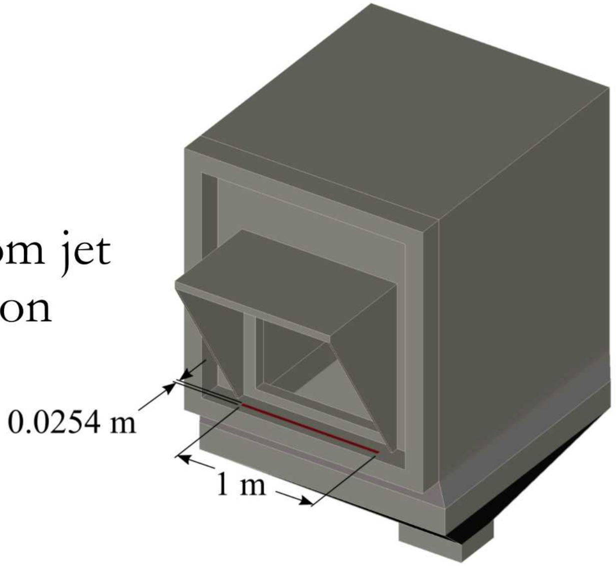


Results from 5 g s^{-1} case

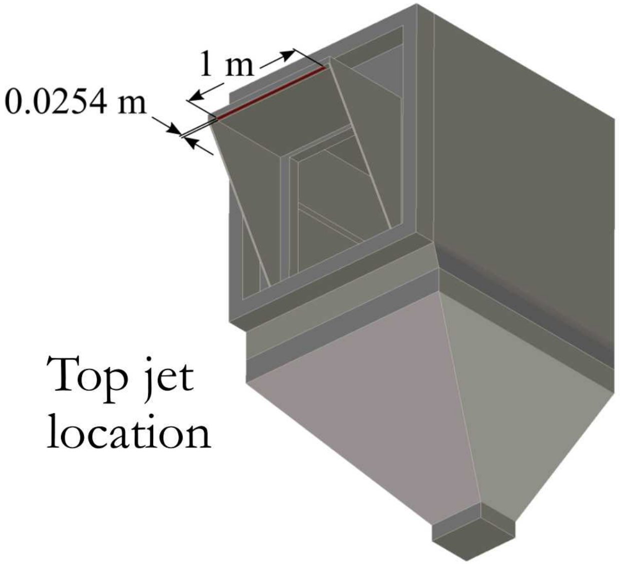
Air Curtain Active Airflow: 3 Parametric Studies

Parametric studies considering number of jets and jet location (Study 1) and jet velocity, jet direction, and wind (Study 2 and 3). Study 3 increases jet velocity. Latin hypercube sampling (LHS) is used to investigate parameter space.

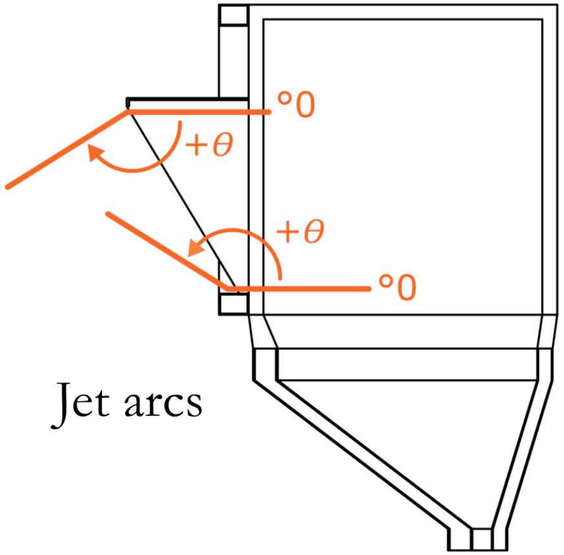
Bottom jet location



Top jet location



Jet arcs



Study	Number of jets	Jet arc	Jet velocity range	Jet temperature range	Wind directions	Wind speed range
1	2	15-165°	0-10 m s^{-1}	Fixed, 11°C	No wind	No wind
2	1	90-165°	7-12 m s^{-1}	11-600°C	N, NNW, NW	5-15 m s^{-1}
3	1	90-165°	12-30 m s^{-1}	11-600°C	N, NNW, NW	5-15 m s^{-1}

Air Curtain Active Airflow: Study 1

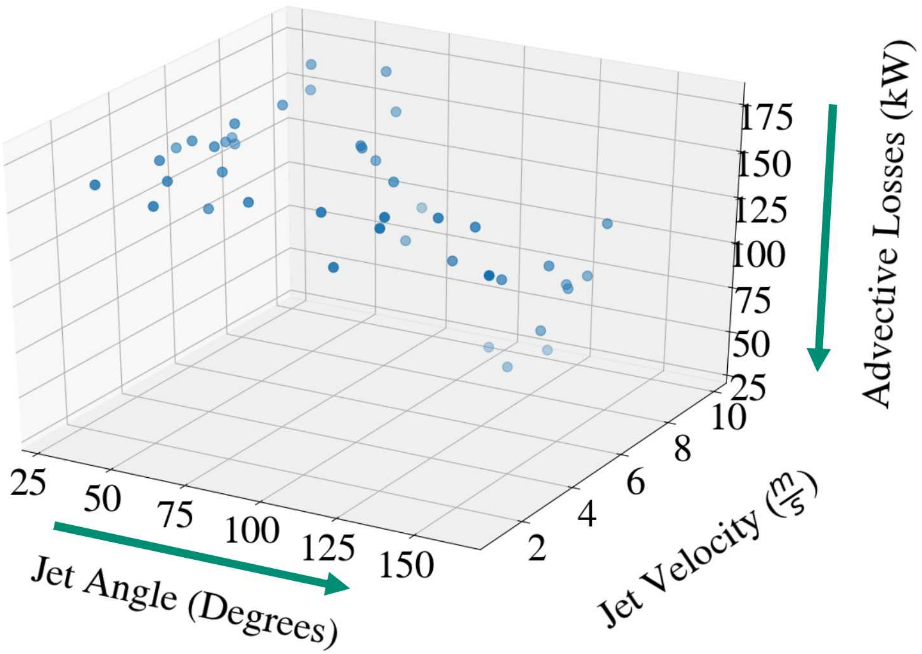
LHS was used to generate 50 combinations of jet settings.

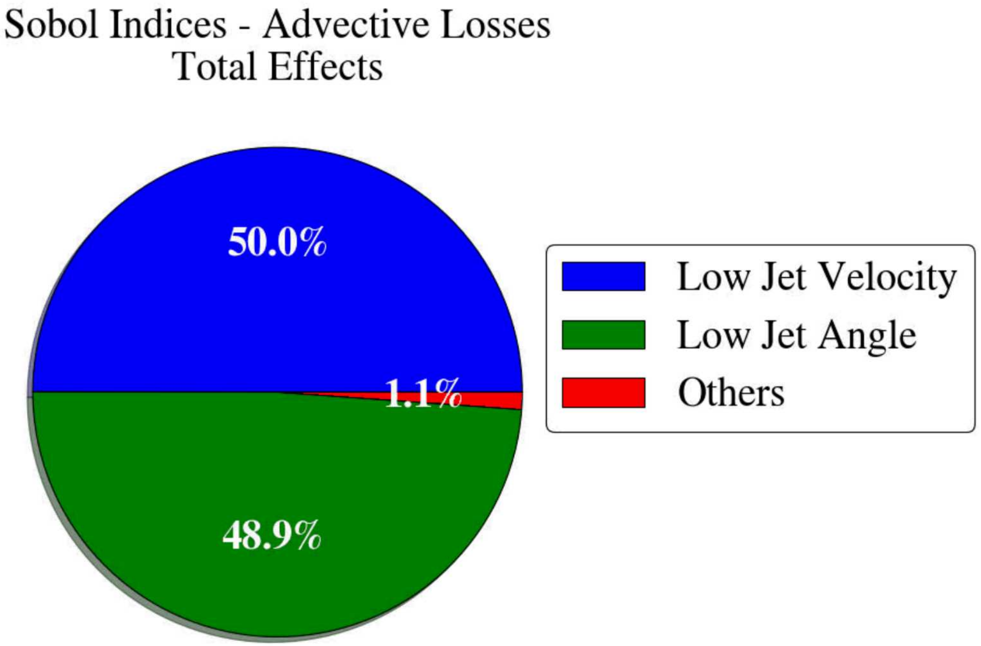
Cases solved with simplified model:
- Radiation omitted
- Particles introduced at elevated temperature (848K)
- Elevated temperature corresponds to average particle temperature observed in preliminary simulations with radiation
- Temperature gradients that drive buoyant effects are captured
- Promising configurations are then simulated including radiation

Best performing case simulated with full physics reduced advective losses from 21% in the baseline case to 2.8% and increased efficiency from 71% in the baseline case to 88%.

Cases with larger bottom jet angles (pointing slightly out of the aperture) have lower advective losses.

Statistical analysis shows Sobol indices for top jet angle and velocity are small (<1.1%). Thus, the top jet has little effect on advective losses and is removed from next studies.

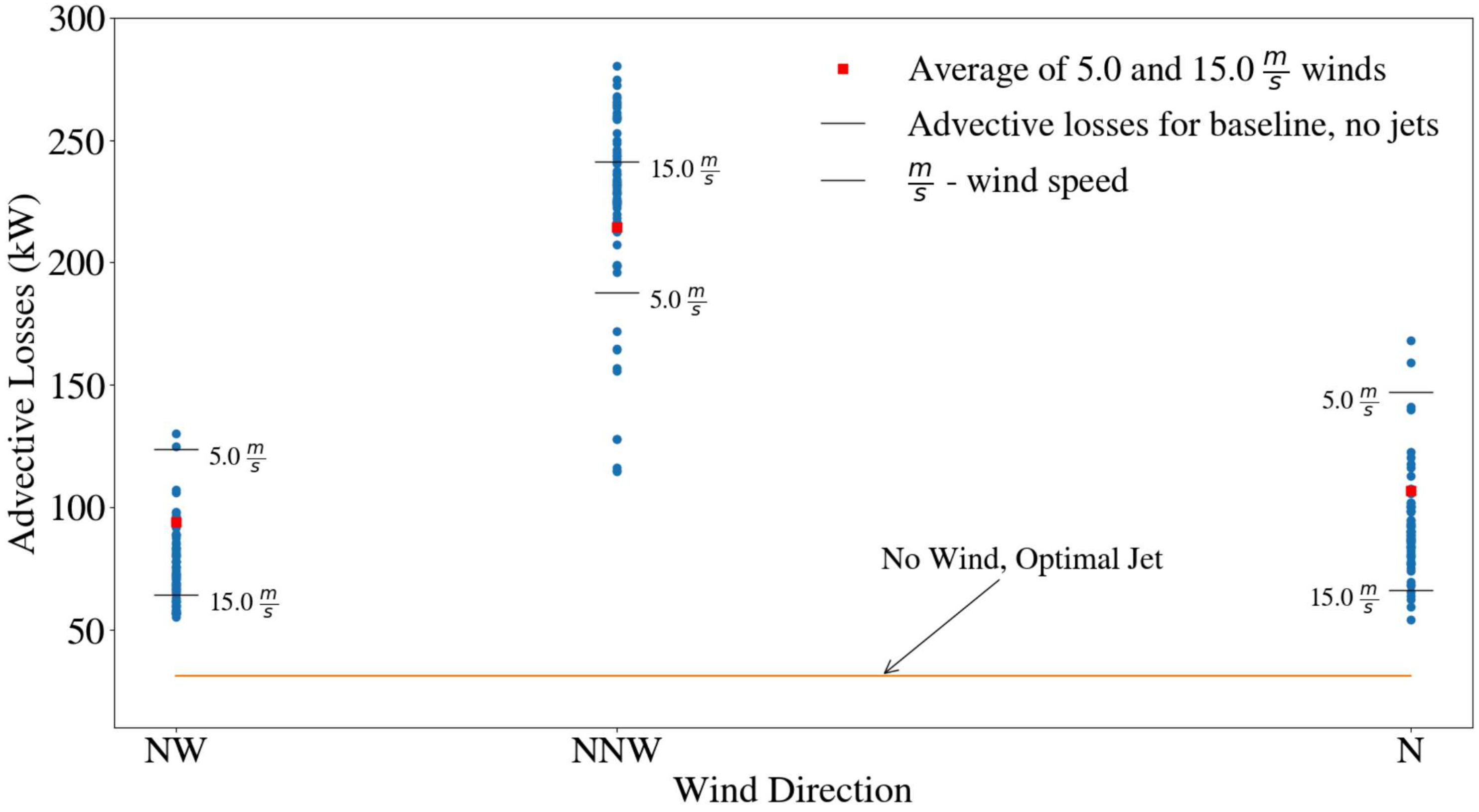


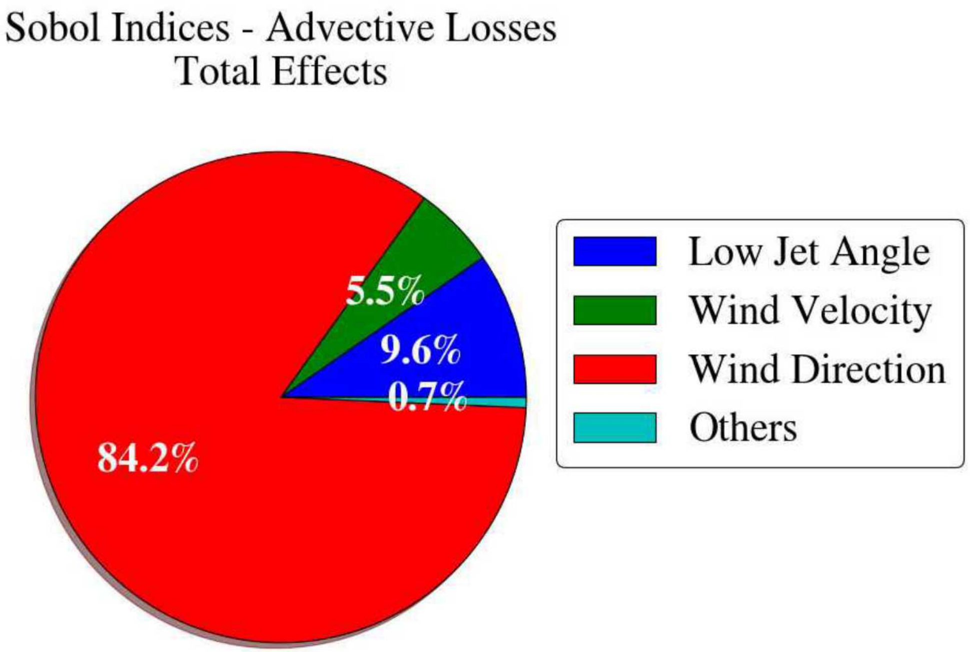


Air Curtain Active Airflow: Study 2

LHS was used to generate 210 combinations of bottom jet velocity, direction, and temperature and wind speed and direction.

- No cases maintain advective losses at optimal jet level (31 kW), some NNW wind cases have 10x larger losses
- Sobol indices for three jet parameters are small and advective loss most influenced by wind
- Jets are overwhelmed by wind for the considered ranges

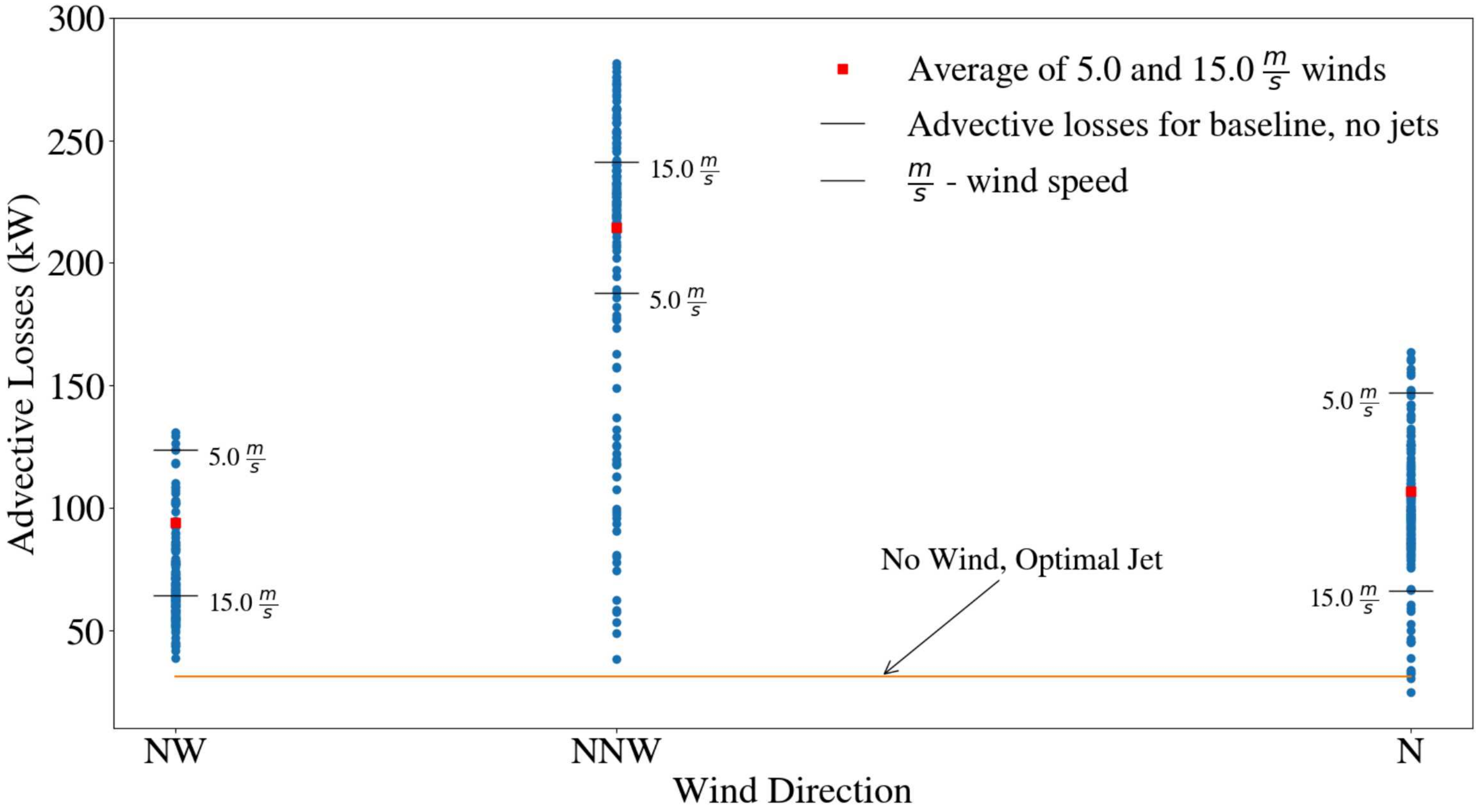


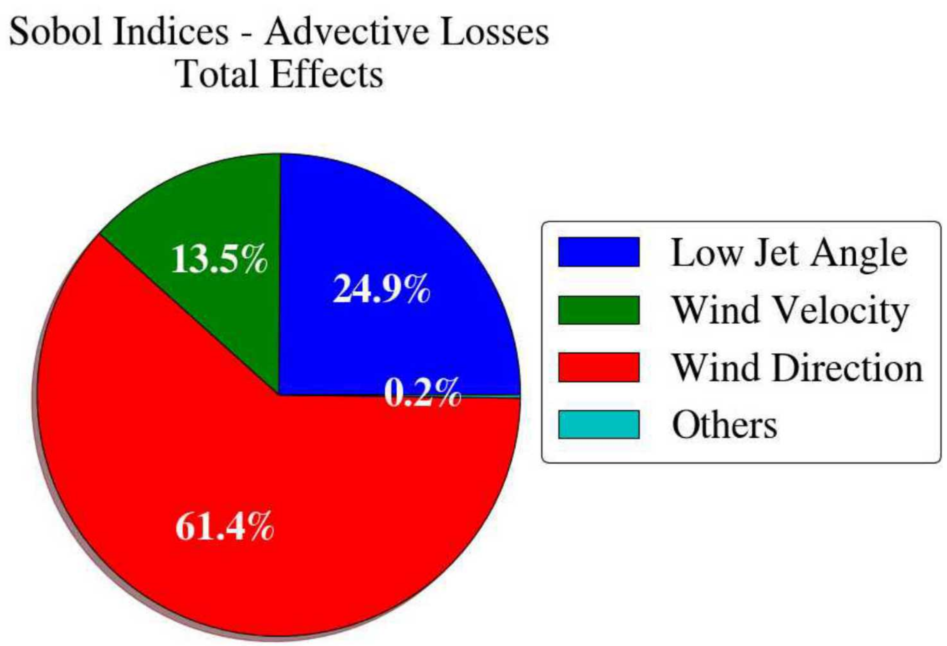


Air Curtain Active Airflow: Study 3

Increased jet velocity range, and LHS was used to generate 480 combinations of bottom jet velocity, direction, and temperature and wind speed and direction.

- Sobol indices for three jet parameters increased and advective losses were lower in most cases, but advective loss still most influenced by wind
- Sobol index for jet speed is still very small, suggesting jets are still overwhelmed by wind for the considered ranges

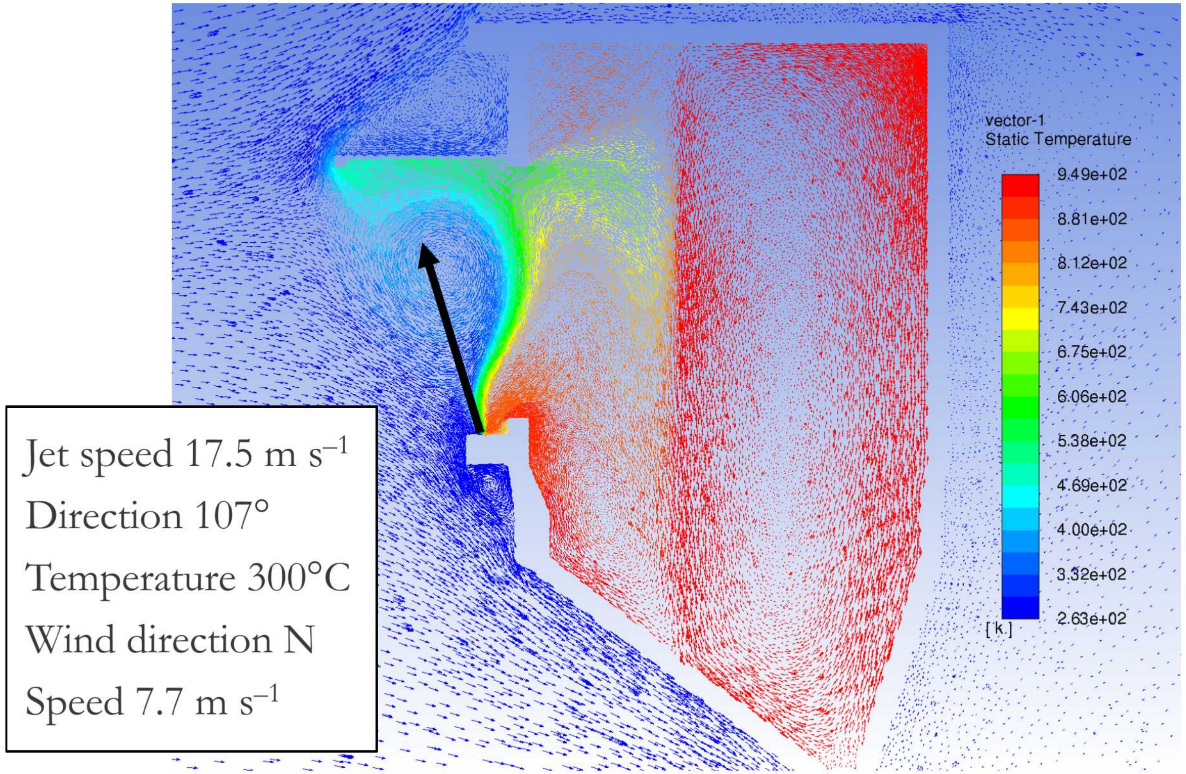


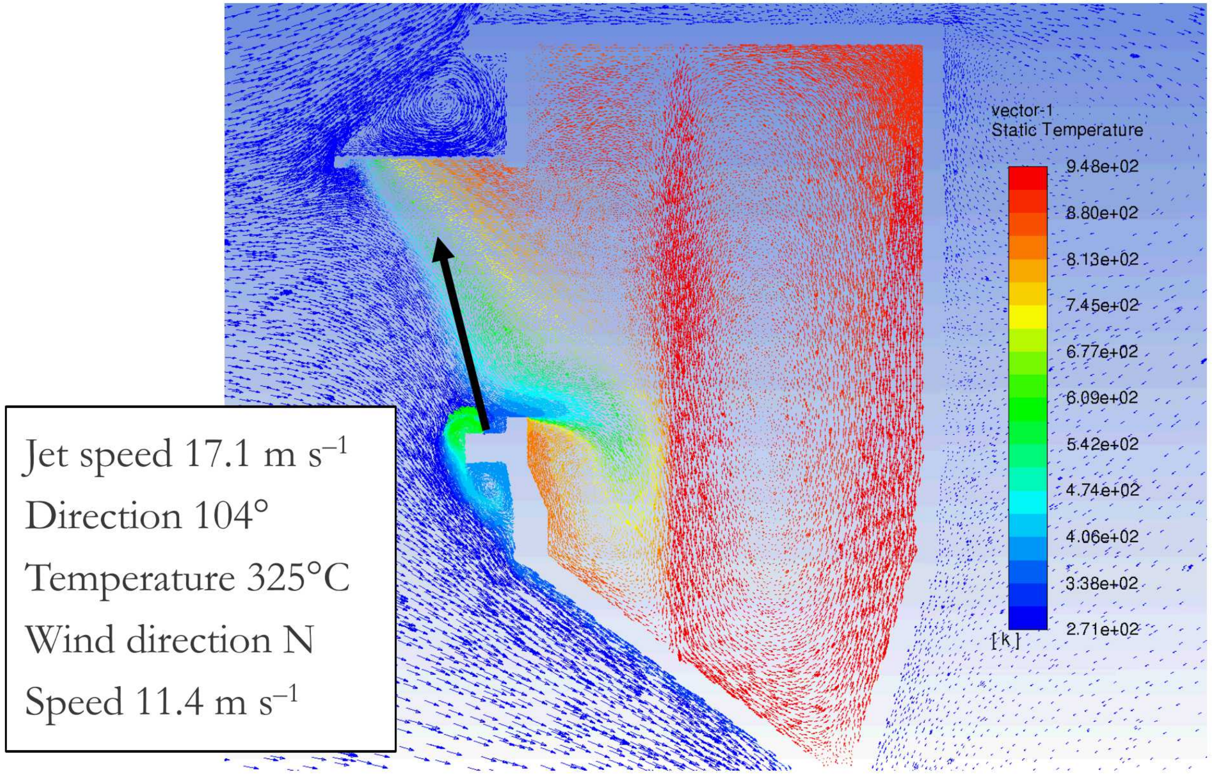


Air Curtain Active Airflow

How jets are overwhelmed: comparing two cases with similar jet parameters and wind direction

- In lower wind speed case (7.7 m s^{-1}, left plot), jet is pushed back into receiver, introducing lower temperature jet air into the receiver
- In higher wind speed case (11.4 m s^{-1}, right plot), jet is flipped forward and air curtain is not maintain, allowing advective losses to exit the aperture





Conclusions

Once-through suction

- In practice, conditions will not be uniform enough to achieve a balance of suction and entrained air circulation
- Any improvements are likely smaller than the numerical uncertainty and may not be observable in 1 MW_{th}-scale experiments

Air curtain

- One jet configuration greatly reduced advective loss under quiescent conditions
- No jet configurations performed equally well for varying wind conditions
- Further analysis of cost and parasitic energy penalty of implementing and operating an air curtain is warranted

Moving forward

- Both active airflow methods show potential for efficiency improvements, but may not be justified given the added complexity and cost of implementing an active airflow system
- Active airflow methods are tractable for a 1 MW_{th} cavity receiver with a 1 m square aperture, but questionably scalable when considering commercial scale receivers with 10–20 m square apertures or larger

Thank you

Cliff Ho, ckho@sandia.gov

This work was funded in part or whole by the U.S. Department of Energy Solar Energy Technologies Office under Award Number 34211

U.S Department of Energy Project Managers: Matthew Bauer, Vijay Rajgopal, and Shane Powers

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. 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.

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

For more information, please refer to the conference paper 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.