SOLAR ENERGY TECHNOLOGIES OFFICE
U.S. Department Of Energy

Characterization of Convective and Particle Losses in High-Temperature Particle Receivers

Presenter: Jesus Ortega

Presentation date: August 25th, 2026

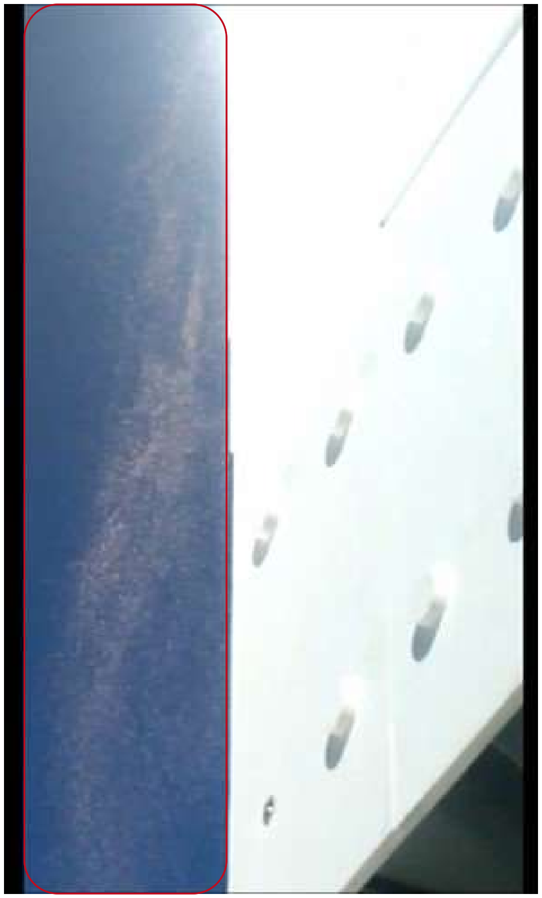
Contributors: SNL (Clifford Ho (PI), Andres Sanchez, Andrew Glen, Darielle Dexheimer, Sean Kinahan), University of New Mexico (Jesus Ortega, Guillermo Anaya, Peter Vorobieff, Gowtham Mohan), AirPhoton (Vanderlei Martins)

UNM MECHANICAL ENGINEERING

Sandia National Laboratories

Problem Statement

- Particles can escape from the open aperture of a falling particle receiver
  - Inhalation/pollution hazard
  - Loss of particle inventory
  - System efficiency losses
- Need to minimize both particle *and* convective heat losses
  - Can imaging of particles be used to estimate particle and convective heat losses?



Nov. 2, 2015
3/8" slot – free fall
330 micron CarboHSP 40-70
10-15 mph south wind
500 – 1000 suns

Project Objectives

1. Task 1: Develop imaging methods to characterize particle and heat losses emitted from the aperture of a high-temperature particle receiver
2. Task 2: Quantify particle emissions using standard air monitoring procedures and compare to OSHA and EPA standards

Project Objectives

1. Task 1: Develop imaging methods to characterize particle and heat losses emitted from the aperture of a high-temperature particle receiver
   - Develop a methodology which allows the processing of the images collected from the cameras used
   - Develop a post-processing technique that can calculate the mass and heat losses from the image sequences
   - Validate methodology using lab-scale testing
   - Apply methodology to on-sun tests and quantify particle and heat losses
     - This can be used to develop a strategy to minimize particle loss through the aperture

Equipment Used

- The IR camera will provide sets of temperature maps, or thermograms, which will provide an average temperature value of a region.
- The visible-light camera will provide sets of images which could be used to quantify the number of particle visible within a region.

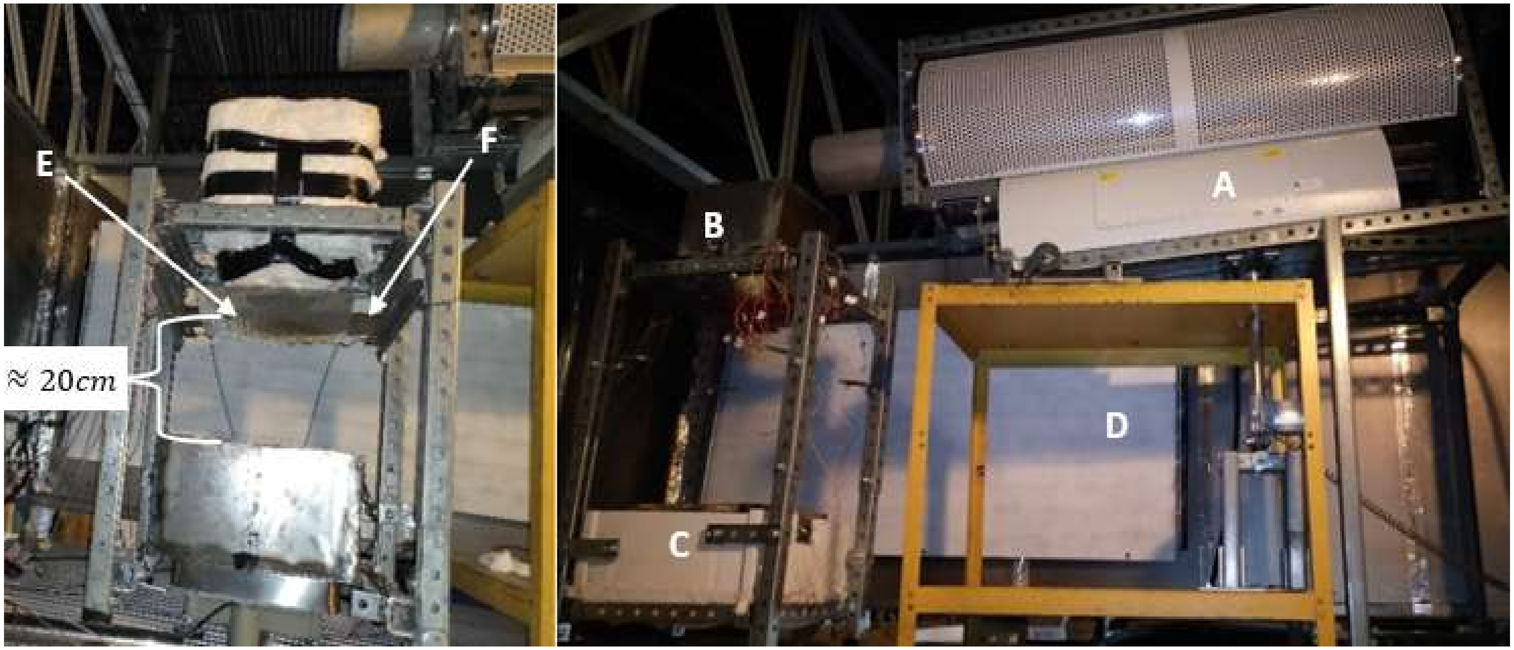
Infratec Image IR 8300
640 x 512 pixel resolution
Up to 300 fps

Nikon D3500
24 MP resolution
Up to 65 fpm

- Multiple methodologies were proposed and studied
  - Pixel temperature and plume opacity were found to be strongly correlated to particle temperature

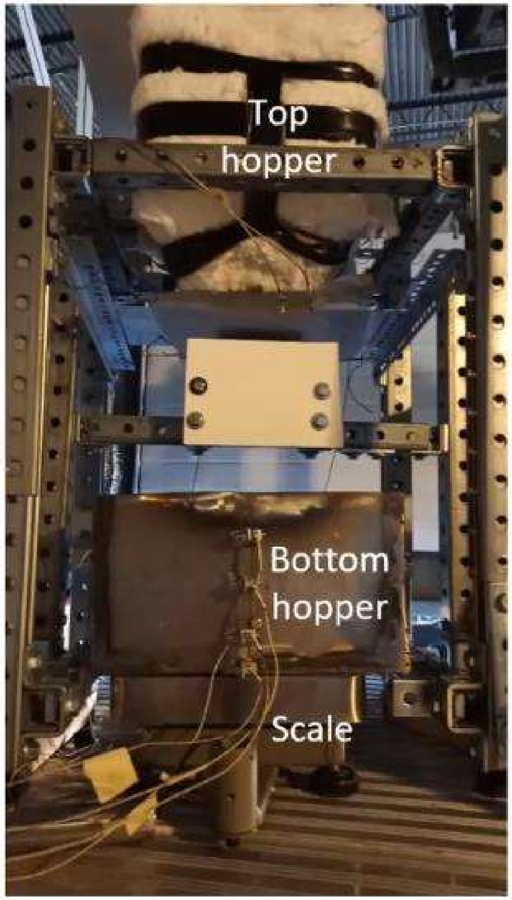
Experimental Setup (UNM)

- The components are the following: a) Actuated furnace. B) Top hopper. C) Bottom hopper. D) Cooled panel. E) Metallic mesh. F) Sliding gate. G) ImageIR8300 camera. H) Nikon D3500 camera.



Experimental Setup (UNM)

- 3 experiments were conducted on a lab-scale small particle receiver (SPR) at UNM
- ~3 kg of pre-heated particles (CarbHSP 40/70)
- Thermocouples located at the top and bottom hoppers recorded temperatures
- ±0.5 g resolution scale recorded weight change: mass flow rate

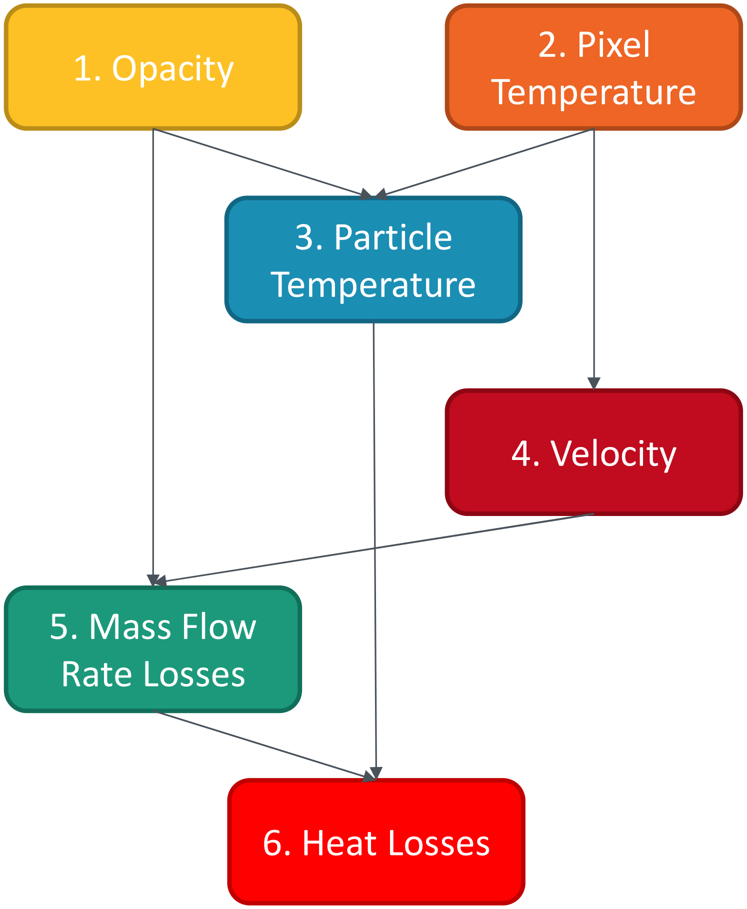


Small Particle Receiver (SPR)

Methodology Development

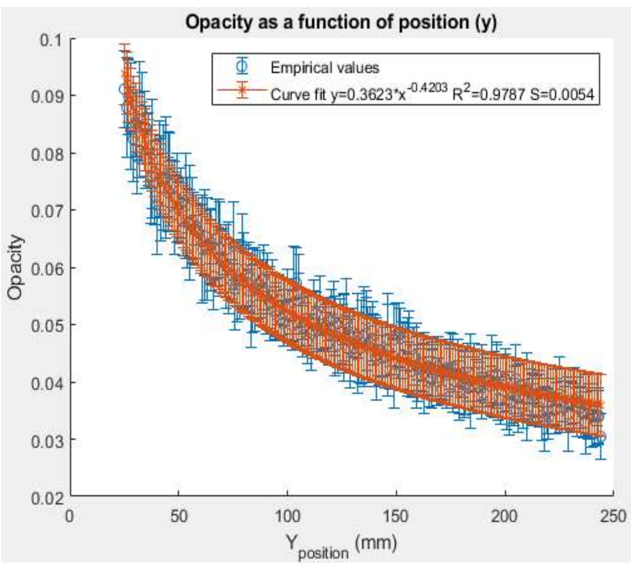
Methodology Development

- 6 major calculations must be completed:
  - The opacity of the curtain and plume can be obtained from the visible images
  - The pixel temperatures can be obtained from the thermograms
  - The particle temperature is a function of the pixel temperature and opacity
  - The velocity can be derived through PIV from the thermogram sets
  - The mass flow rate losses is a function of opacity and velocity
  - The heat losses is a function of mass flow rate losses and the particle temperature

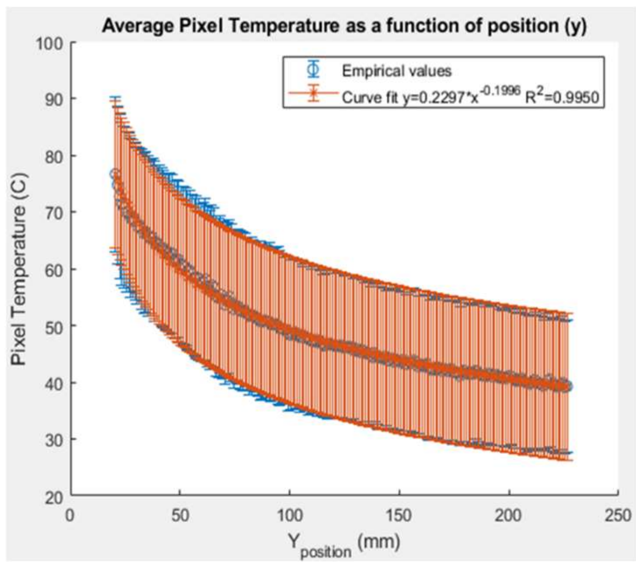


Particle Temperature Estimation

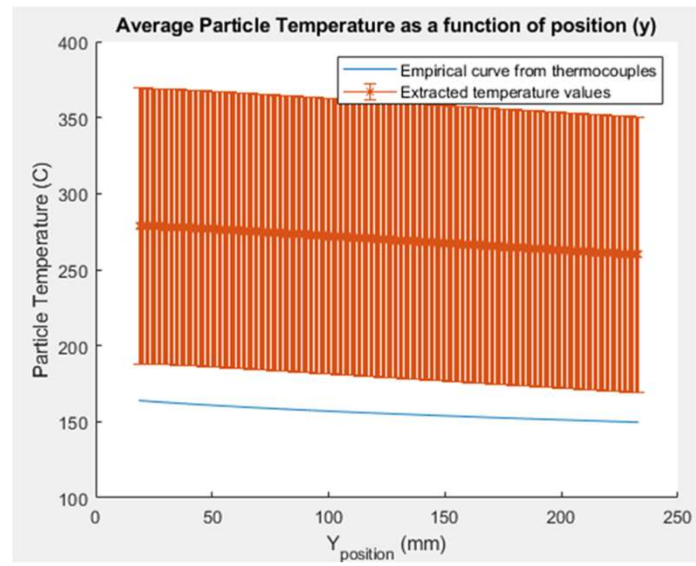
- Using the opacity and apparent temperature functions, the true particle temperature can be back calculated
- To validate our results, we compare the temperatures to the measured temperature values



+

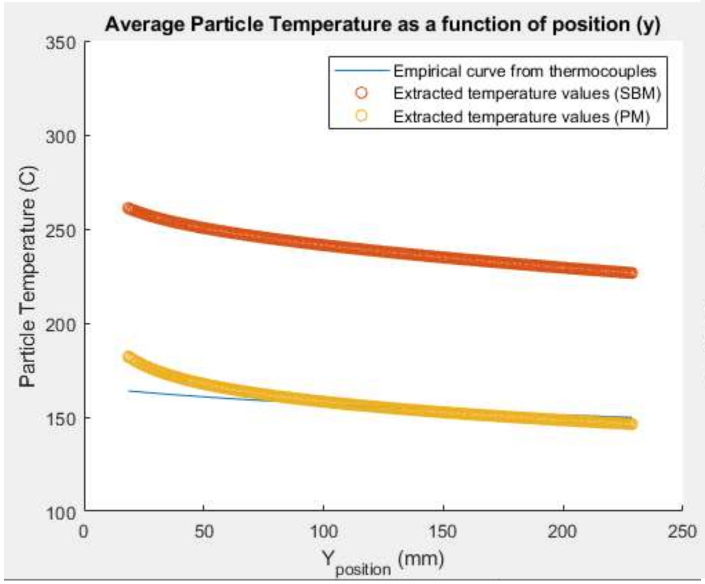


=

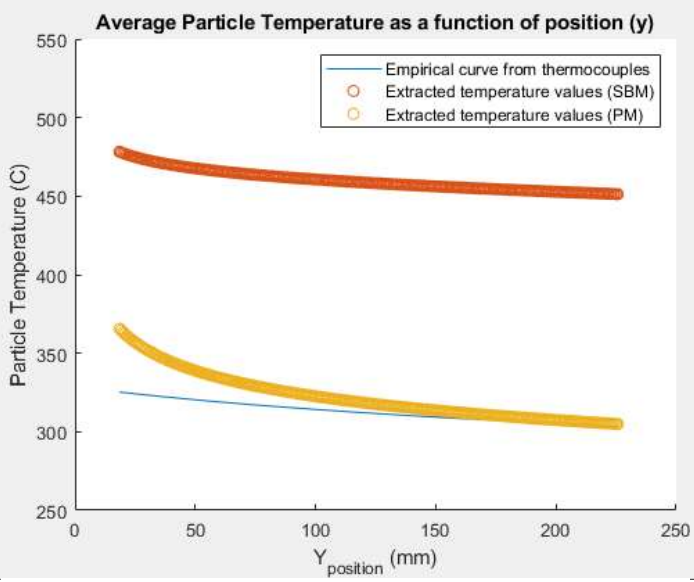


Particle Temperature Estimation

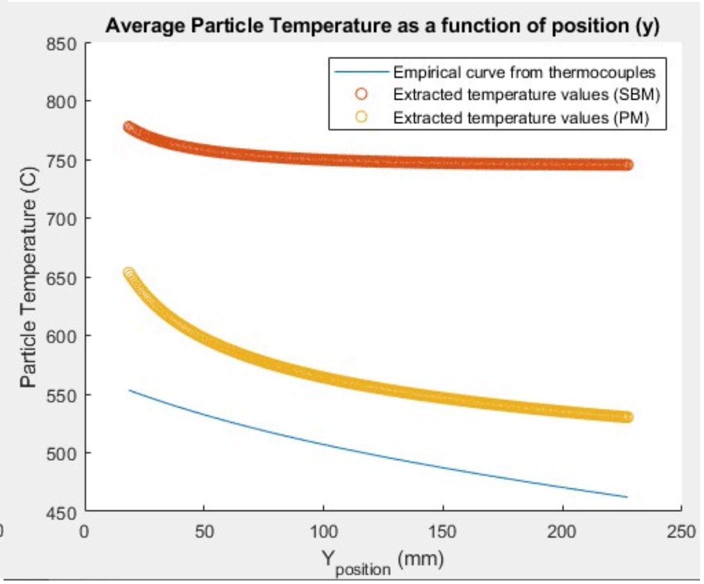
- Comparison of models used to extract the particle temperature against the empirical temperature curve



Particle preheat temperature of 200°C.



Particle preheat temperature of 450°C.



Particle preheat temperature of 700°C.

Particle Mass Flow Rate Estimation

- To estimate the plume mass flow rate, we must define the mass flow rate of the particles within the plume where ρ_b is the bulk density, A_c is the cross-sectional area of the flow, V_b is the bulk velocity of the flow

$$\dot{m}_b = \rho_b A_c V_b$$

- If we substitute the bulk density of the plume, and expand the equation where ρ_p is the particle density and φ is the volume fraction of the particles within the plume

$$\rho_b = \varphi\, \rho_p$$
$$\dot{m}_p = \varphi\, \rho_p\, w_c\, t_c\, V_b$$

- While we cannot directly measure the particle volume fraction, there are several indirect ways to find this value using the Modified Beer's Law

Particle Mass Flow Rate Estimation

- The modified Beer's Law is a modified version of this equation which was presented by Kim et al. and shows a correlation between opacity (ω), volume fraction (φ), particle diameter (d_p) and curtain thickness (t_c)

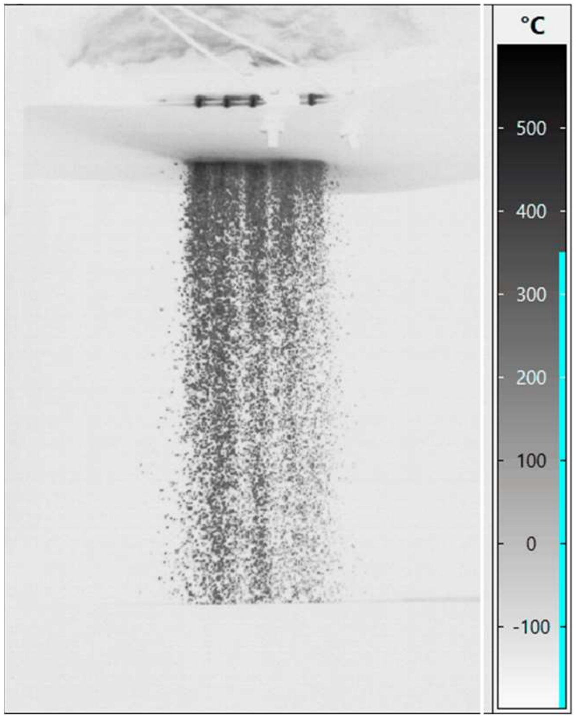
$$\omega = 1 - e^{-\frac{3\varphi\ {}_c}{2d_p}}$$

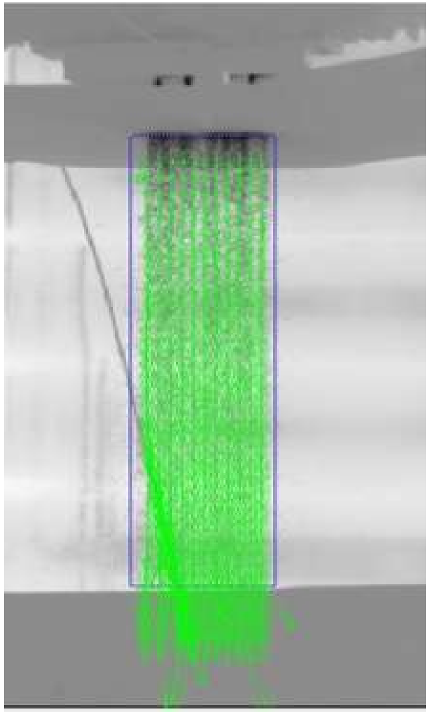
- Rewriting the mass flow rate equation, we end up with an equation which is a function of variables which are known or can be measured

$$\dot{m}_p = -\frac{2}{3}\, d_p\, \rho_p\, w_c\, V_b\, ln(1-\omega)$$

Particle Mass Flow Rate Estimation

- Particle Bulk Velocity
  - The particle velocity of the plume can be estimated using particle image velocimetry (PIV) analysis tools such as PIVlab
  - Taking the thermogram sets and processing them in PIVlab allows us to get a velocity vector field; hence obtaining an average velocity profile as a function of discharge position



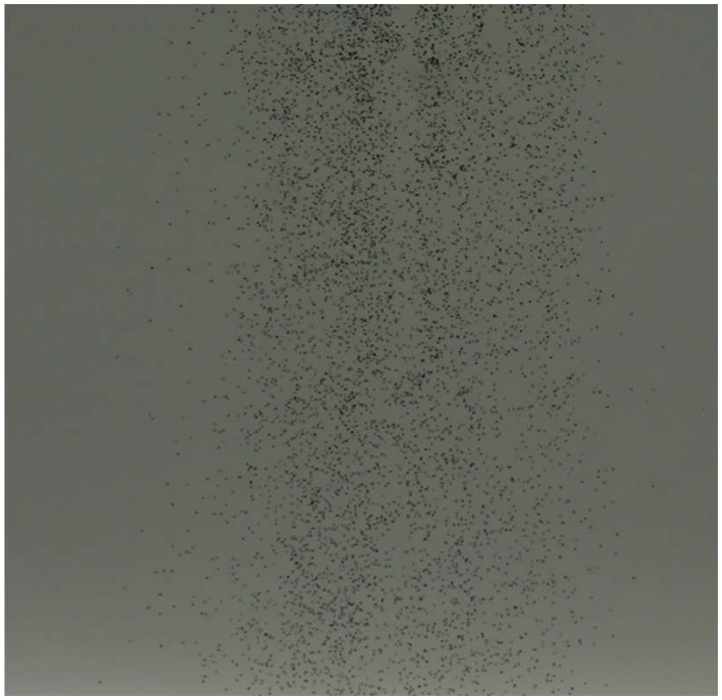


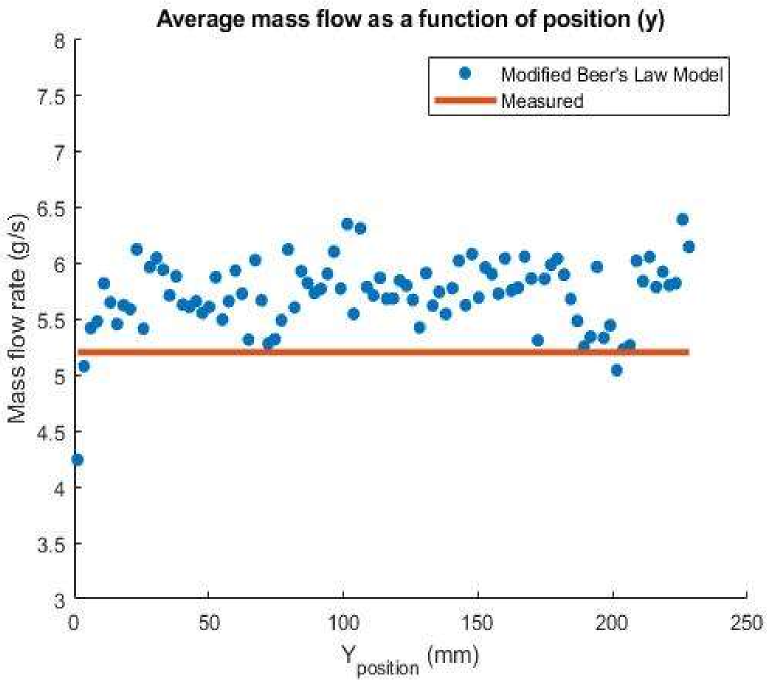
Lab-scale Testing: Average Particle Mass Flow Rate

- Applying the modified mass flow rate equation using the known and measured values we can determine an average mass flow rate for a curtain

$$\dot{m}_p = -\frac{2}{3}\, d_p\, \rho_p\, w_c\, V_b\, ln(1-\omega)$$

Mass flow rate estimated for a 5.2 g/s curtain





Particle Heat Flow Rate Estimation

- Calculating the particle mass flow rate, and knowing the particle temperature from the previous calculations, we can calculate the heat flow of the particles

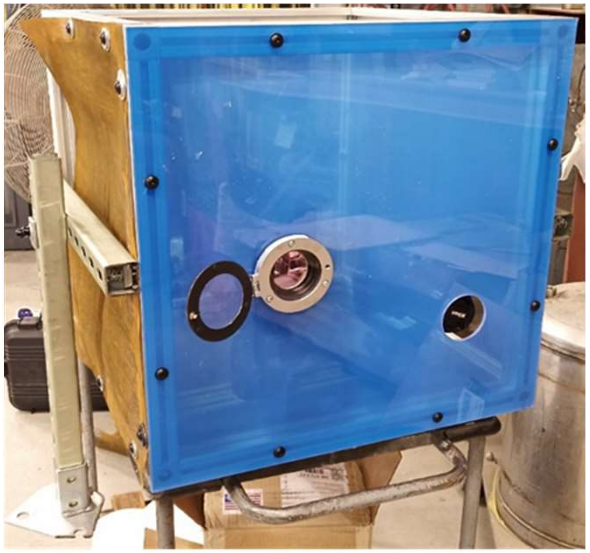
$$\dot{Q}_p = \dot{m}_p \int_{T_{amb}}^{T_p} Cp_p(T)dT$$

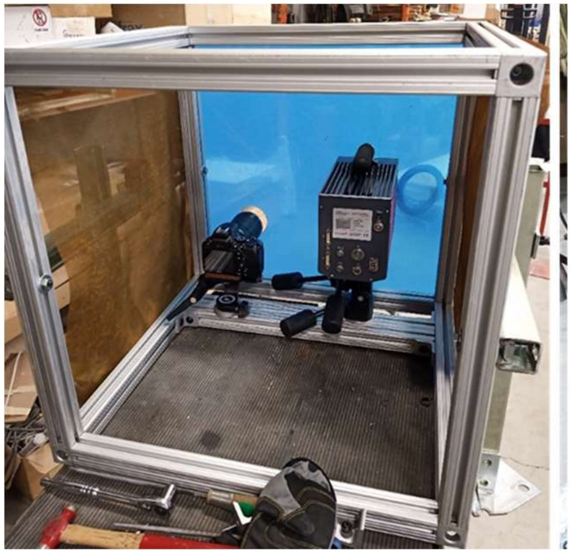
- Here the heat capacity of the particles (Cp_p) and ambient temperature (T_{amb}) are known quantities

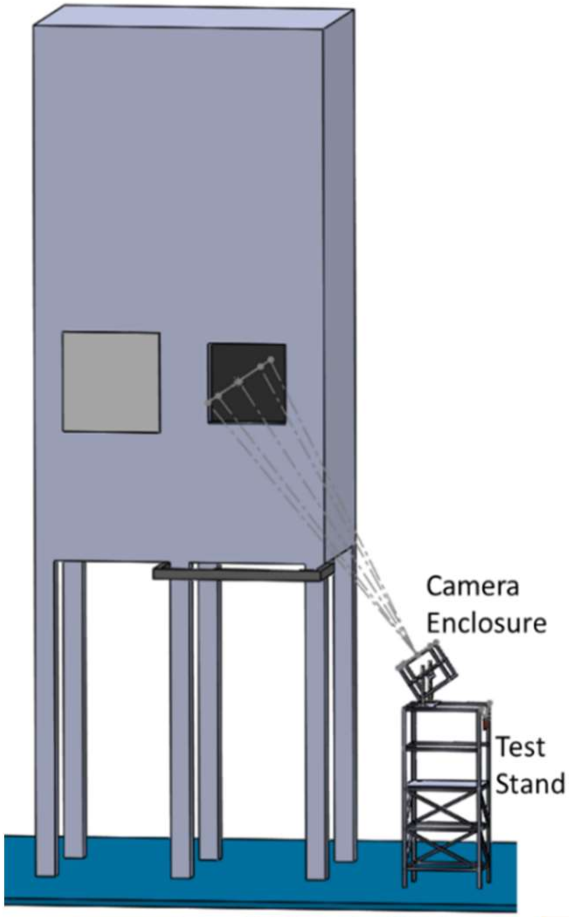
On-Sun Testing at Sandia

On-sun Testing Setup

- To protect the cameras from any hot particles damaging the cameras, we designed a camera enclosure which is mounted on a test stand 5 meters away from the aperture

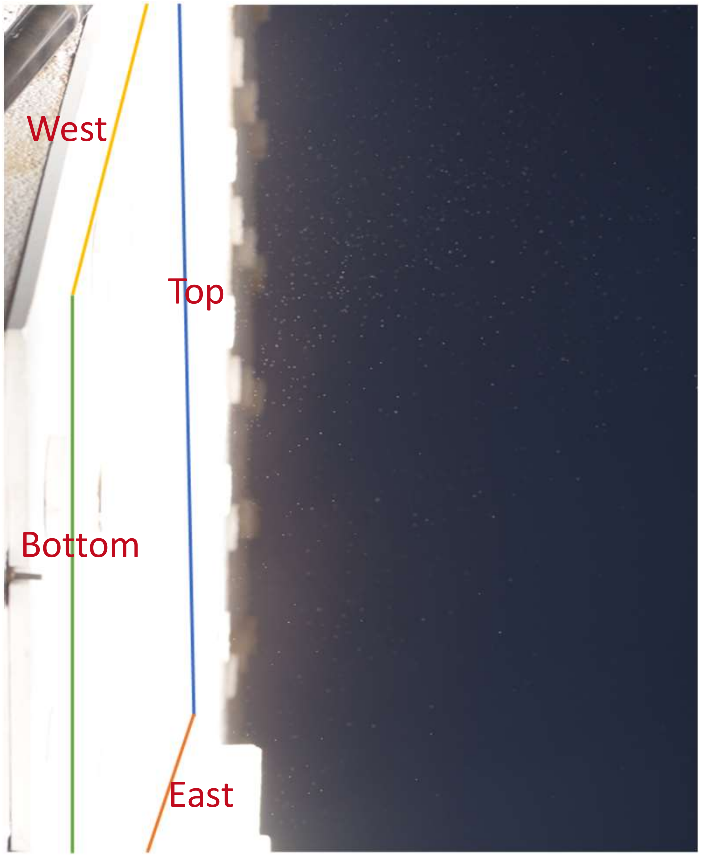






Filtering Images and Thermograms

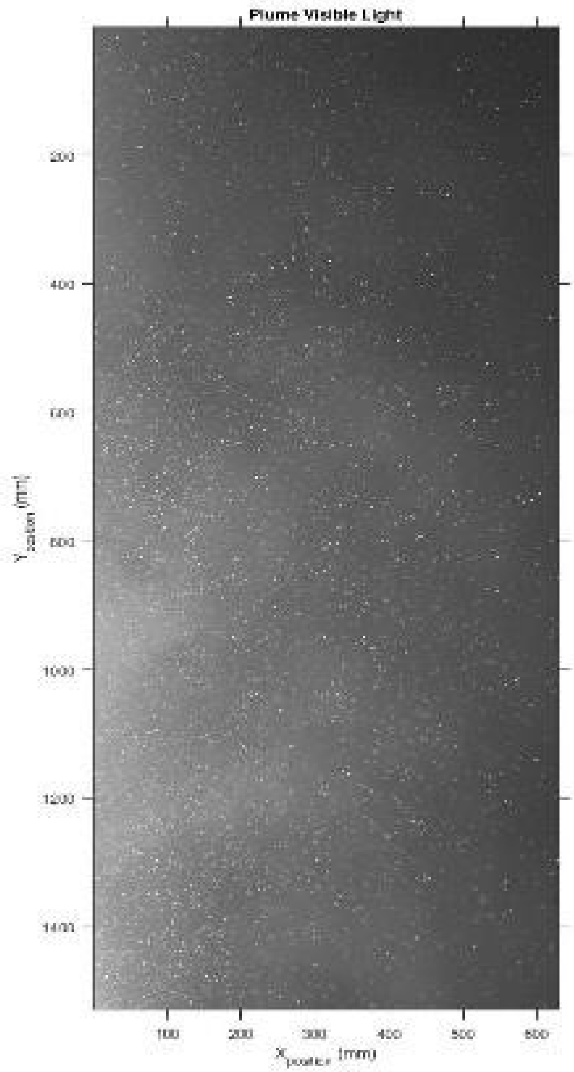
- To simplify the calculations, the image is adjusted so that the particle egress flow is to the positive side of the X-axis - to make calculations consistent for comparison
- The blue line denotes the top, the green line is the bottom, the orange line is the East side and the yellow line the West side of the FPR aperture

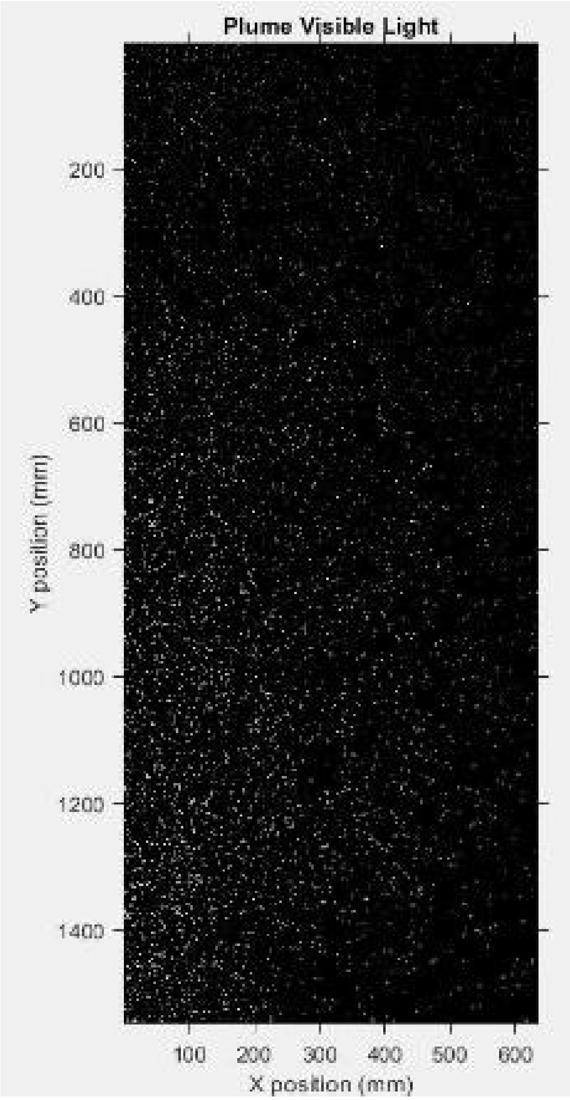


SOLAR ENERGY TECHNOLOGIES OFFICE
U.S. Department Of Energy

Filtering Images and Thermograms

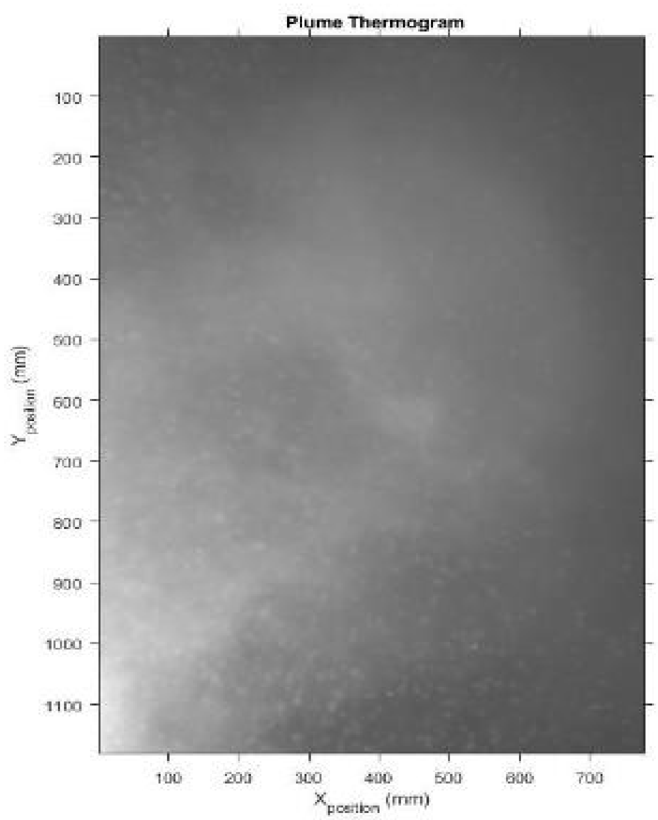
- A filtering technique was developed to ensure that any dust or clouds in the background were removed and only those pixels with particles were retained for the calculations

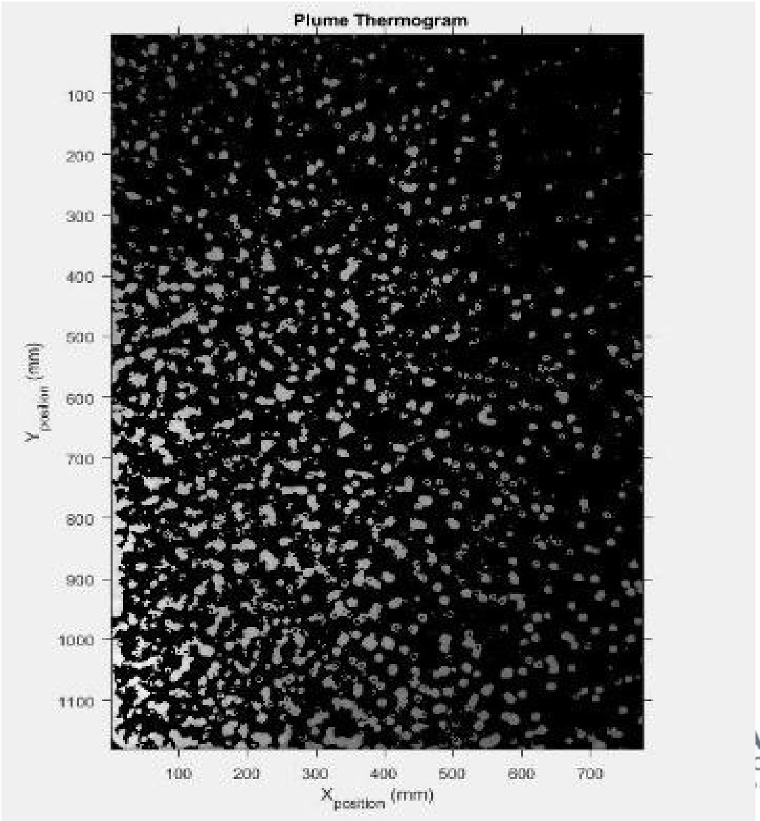




Filtering Images and Thermograms

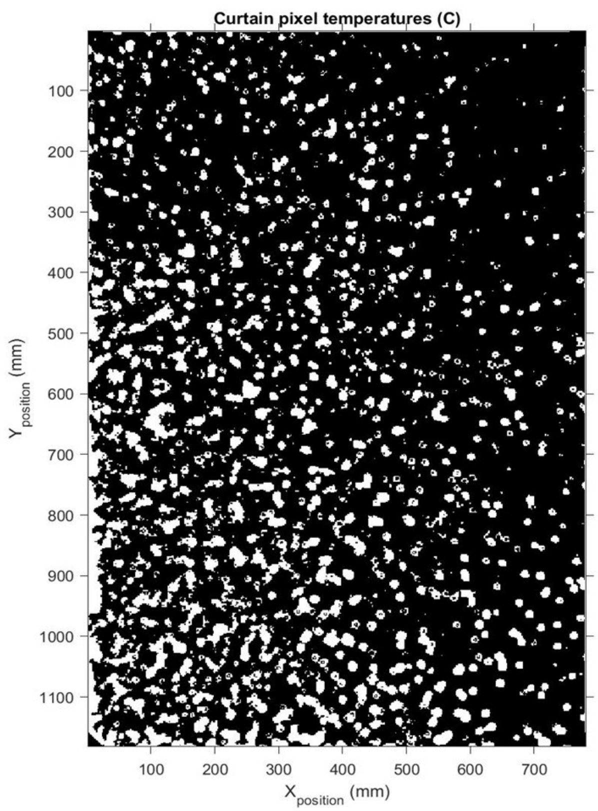
- In a similar fashion, the thermograms are left with the pixels with particles only and the rest is set to empty values

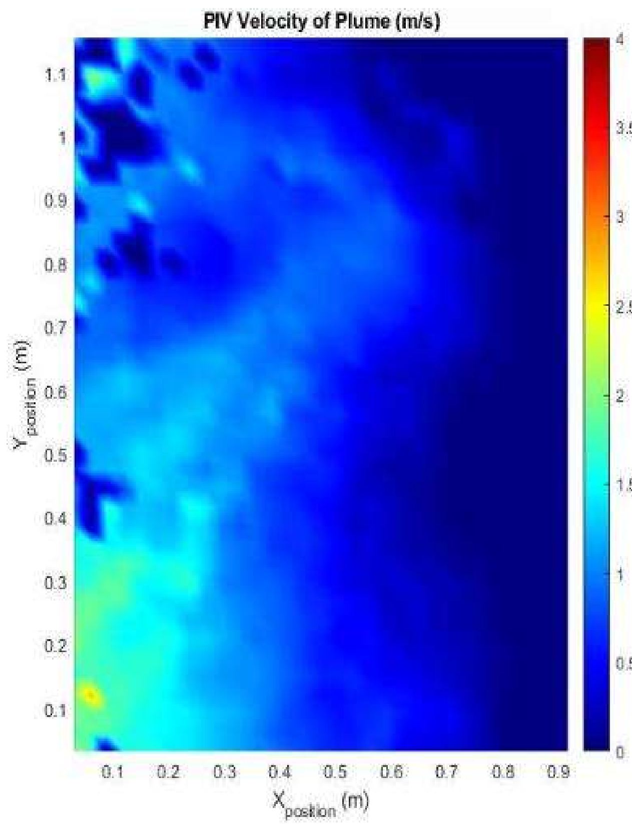




PIV Measurements

- Using the filtered thermogram sets, the average velocity of the plume can be estimated through PIVlab





On-sun Tests and Results

- The team collected data for multiple configurations of the FPR. Some changes were introduced into the code to adapt it to post-process the on-sun tests
- In this report, we will be presenting results for three different test cases from September 4th, 2020, November 3rd, 2020, and March 3rd, 2021
  - As mentioned before, 65 images and 36,000 thermograms (at 300 fps) correspond to a 2-minute data set

Test Date & Time	Input Power (kW)	Measured Particle Temperatures (°C)	Measured Efficiency (%)	Test Wind Conditions
9-4-20 10:59	420	Inlet:362 °C Outlet:408 °C	79-83 %	Wind due South (180°) 1.4 m/s
9-4-20 12:46	494	Inlet:528 °C Outlet:574 °C	67-69 %	Wind due Southwest (202°) 3.9 m/s
3-7-21 13:08	956	Inlet:679 °C Outlet:754 °C	55-59 %	Wind due Southwest (252°) 3.2 m/s

On-sun Tests and Results

- Since we are using the particles ejected as tracers to estimate the air egress rate from the cavity, to compute the air mass flow rate we can use:

$$\dot{m}_a = \rho_a(T_p)\, A\, V$$

- In a similar fashion, the heat losses due to the air egress can be estimated as:

$$\dot{Q}_a = \dot{m}_a \int_{T_{amb}}^{T_p} Cp_a(T)dT$$

- Which yields the total advective heat losses:

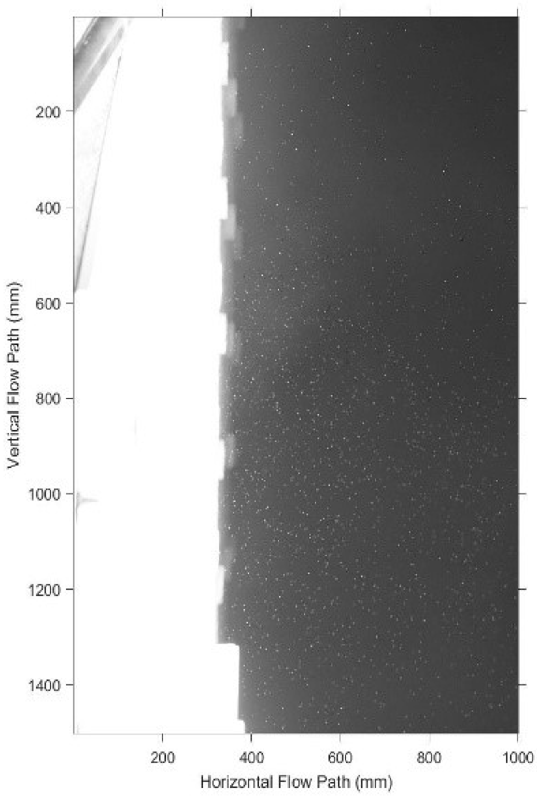
$$\dot{Q}_T = \dot{m}_p \int_{T_{amb}}^{T_p} Cp_p(T)dT + \dot{m}_a \int_{T_{amb}}^{T_p} Cp_a(T)dT$$

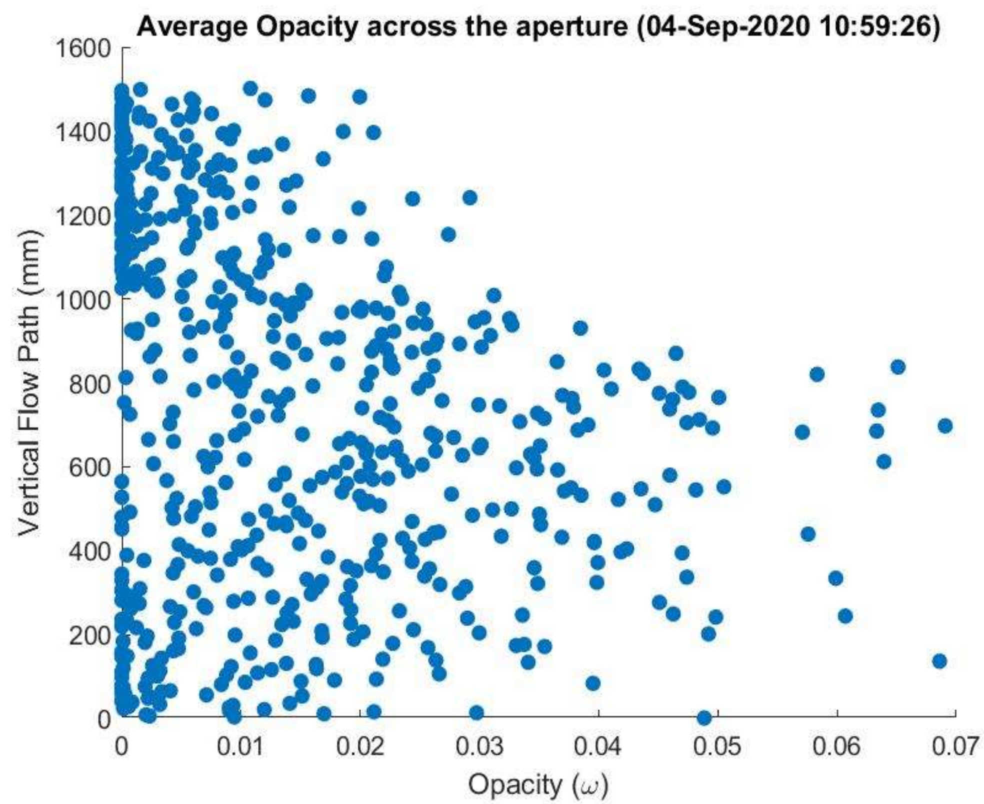
On-sun Tests and Results

- The opacity and pixel temperatures of the plume are extracted considering the first 100 mm outside of the aperture to neglect the effect of the wind outside of the cavity
- During the 2 minutes of data, the calculations are completed for specific cases which yield instantaneous values
- To capture the variations of heat and mass loss over time, a time series plot is generated which assumes that conditions do not change between captures

On-sun Tests and Results: Test 9/4/20 10:59 am

- The opacity of the plume

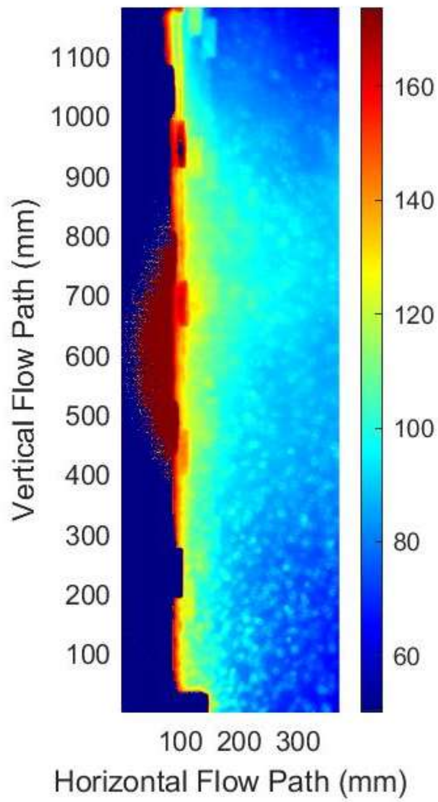


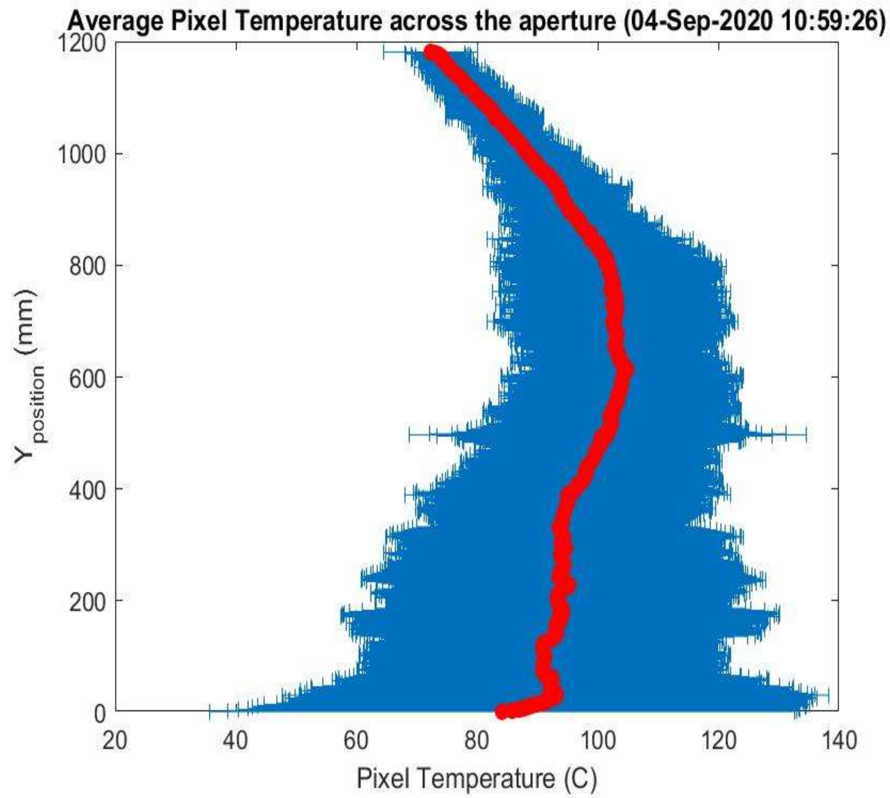


SOLAR ENERGY TECHNOLOGIES OFFICE
U.S. Department Of Energy

On-sun Tests and Results: Test 9/4/20 10:59 am

- The pixel temperature of the plume

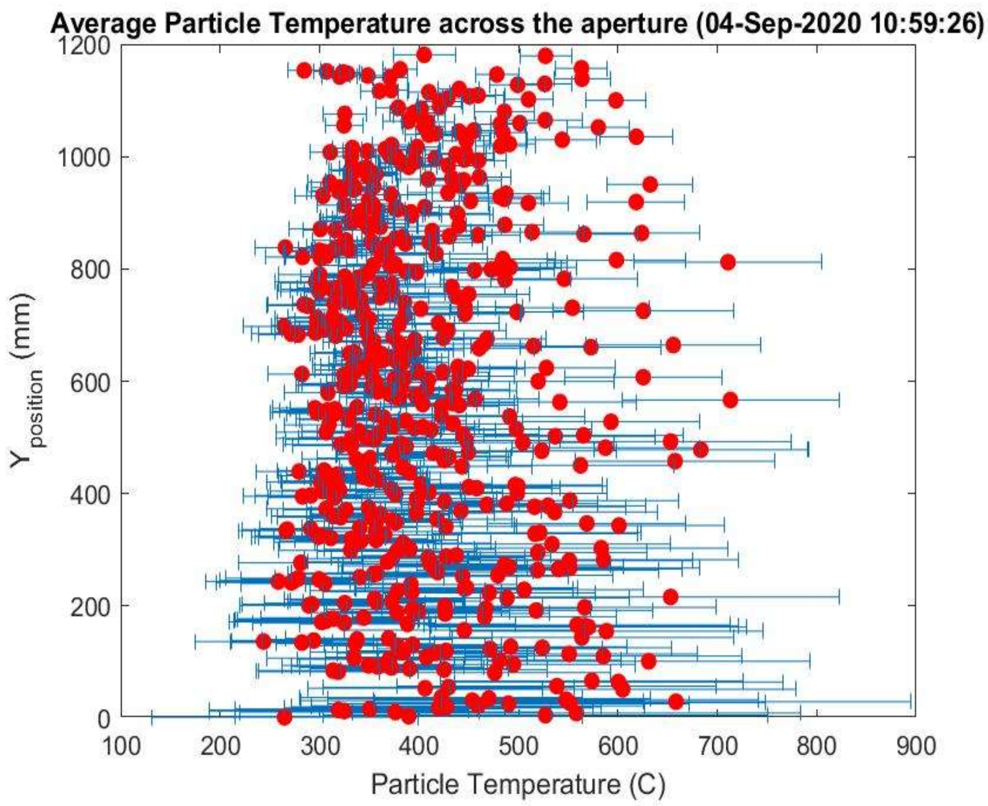




SOLAR ENERGY TECHNOLOGIES OFFICE
U.S. Department Of Energy

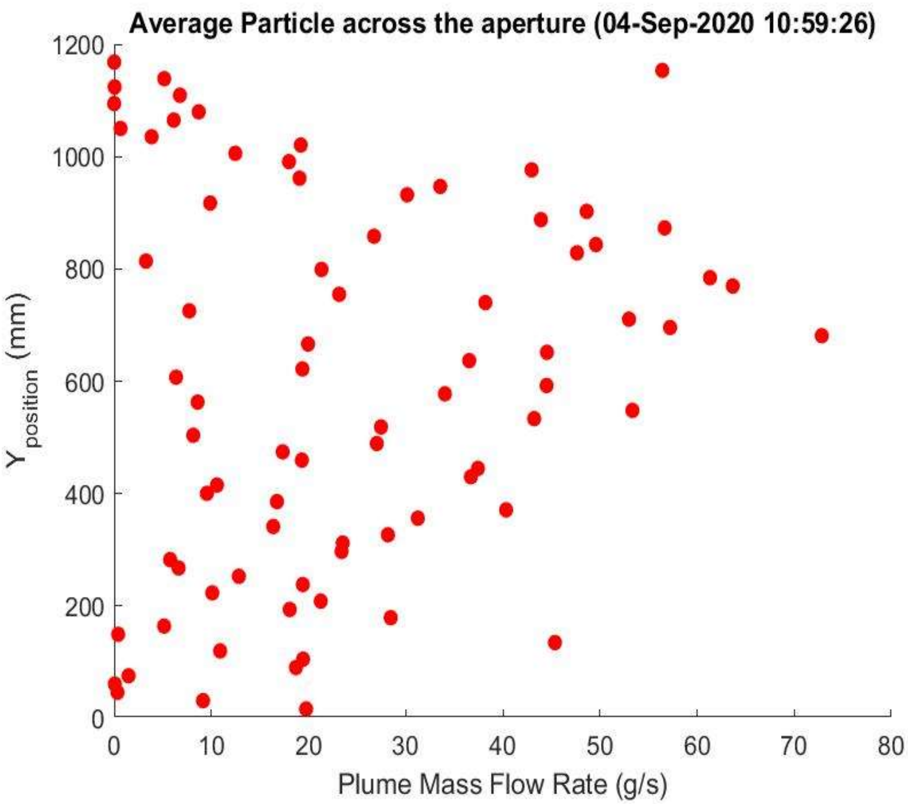
On-sun Tests and Results: Test 9/4/20 10:59 am

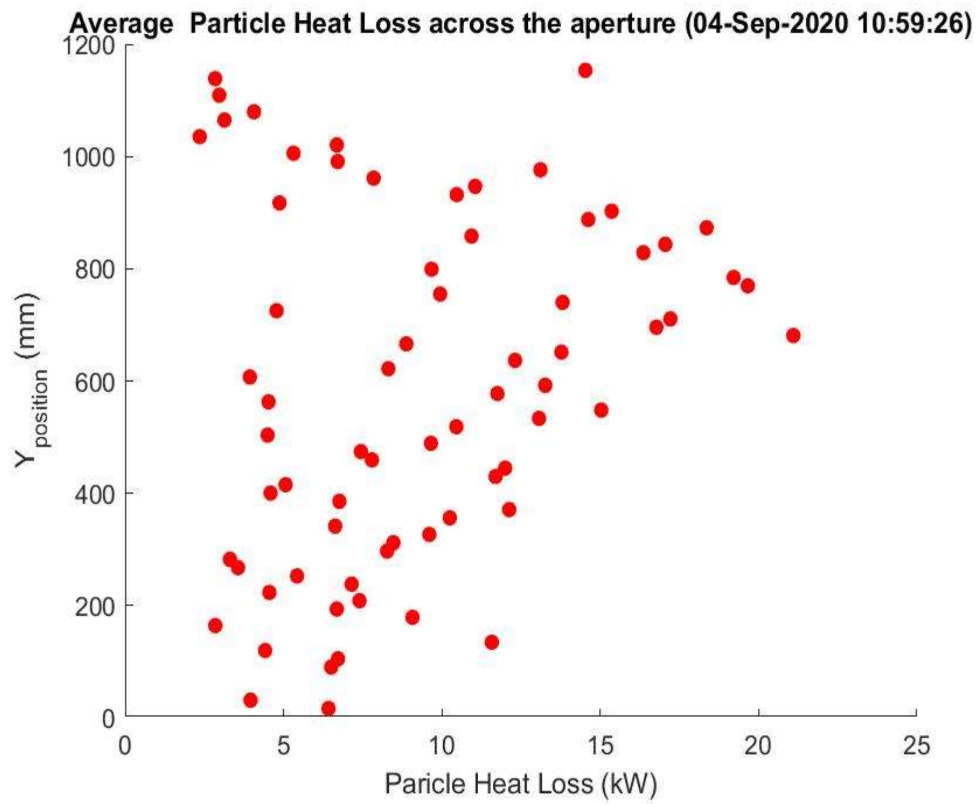
- The particle temperature of the plume calculated using the model developed



On-sun Tests and Results: Test 9/4/20 10:59 am

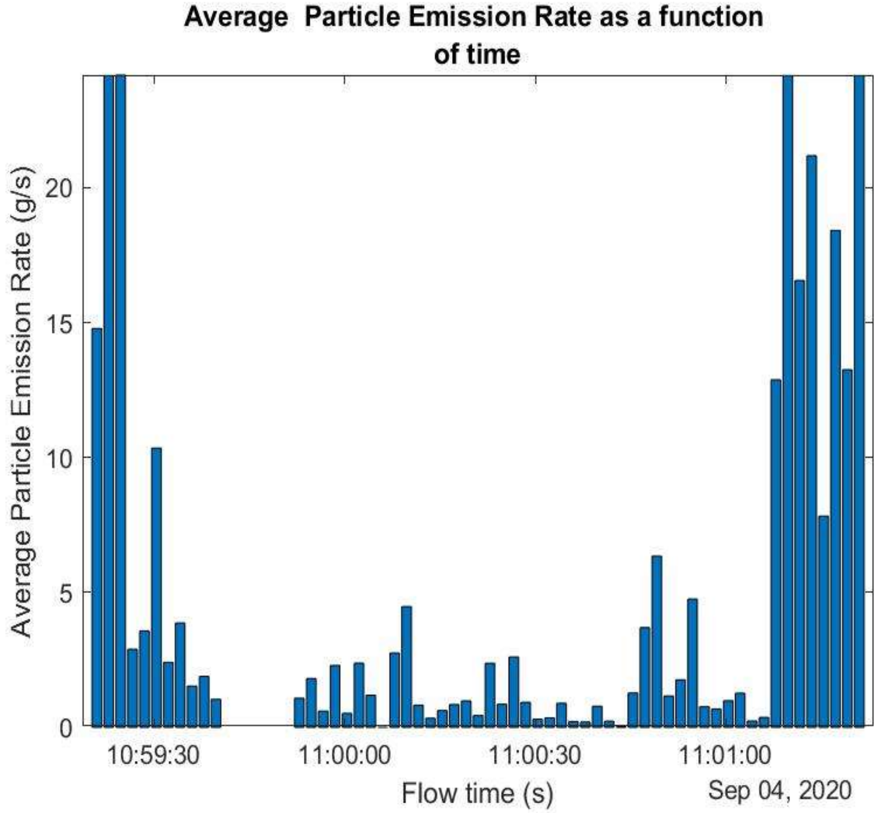
- Instantaneous particle egress and heat loss rates

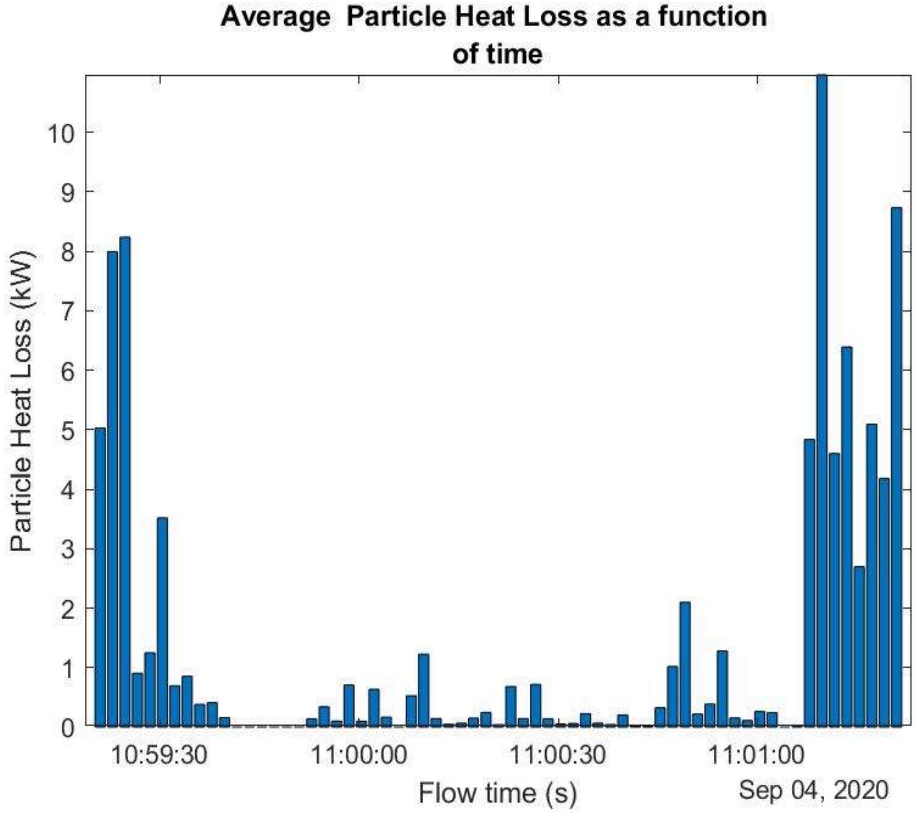




On-sun Tests and Results: Test 9/4/20 10:59 am

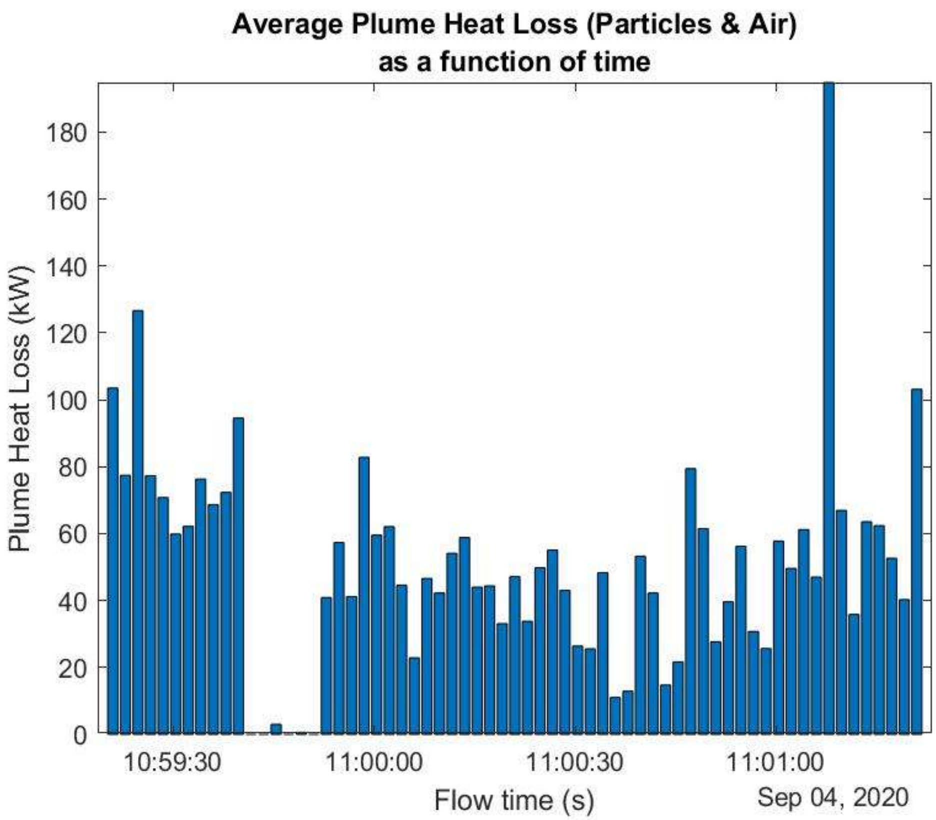
- Average particle egress and heat loss rates over the 2-minutes of data





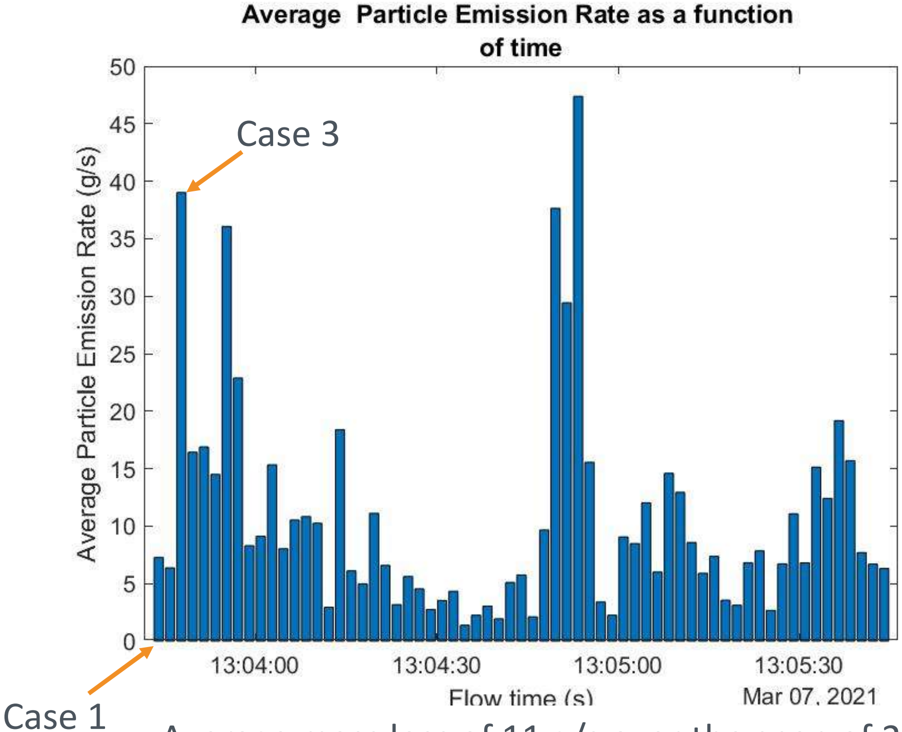
On-sun Tests and Results: Test 9/4/20 10:59 am

- Average total heat loss rates over the 2-minutes of data

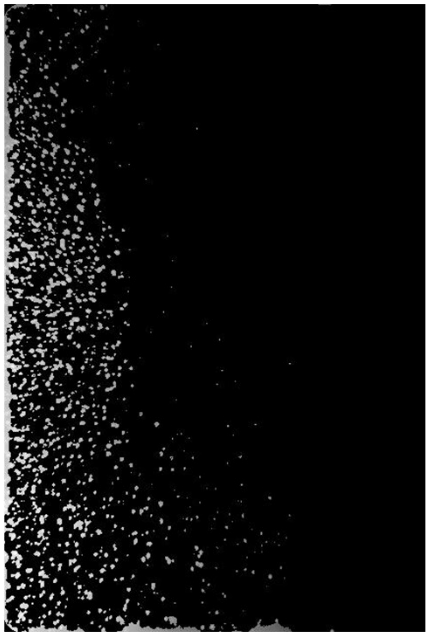


Closing remarks

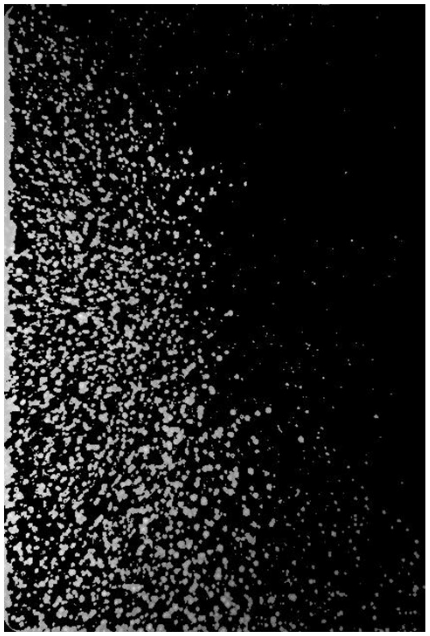
- We feel confident our imaging methodology is able to capture the fine dynamics of the particle plumes and we hope to continue reinforcing it



Average mass loss of 11 g/s over the span of 2 minutes; total mass loss 1.3 kg



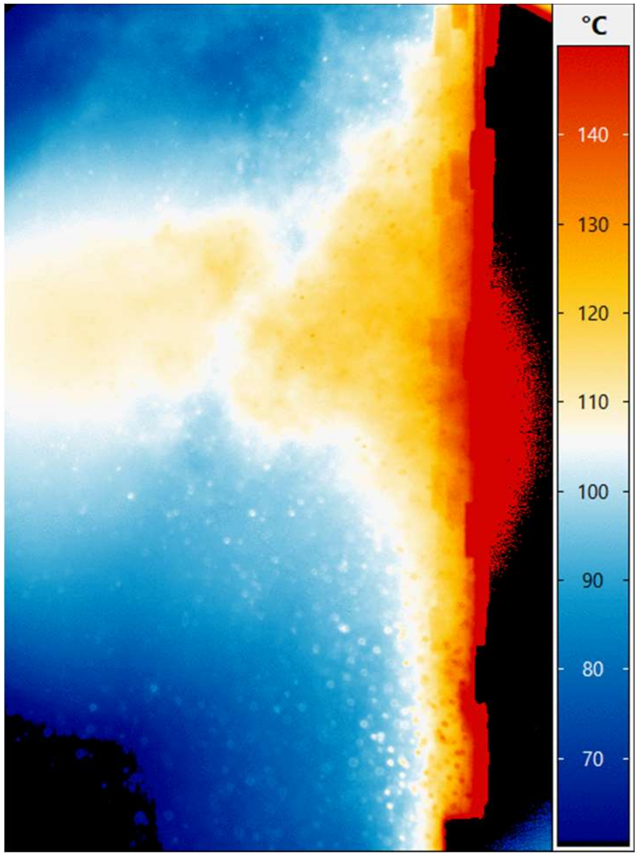
Case 1



Case 3

Closing remarks

- A design of experiments (DoE) matrix with 6 factors was developed
  - Average particle temperature (A)
  - Receiver mass flow rate (B)
  - Receiver flow configuration (C)
  - Heat flux level (D)
  - Wind speed (E)
  - Wind direction (F)
- The effects included the individual as well as compounded factors



Closing remarks

- There seems to be a direct positive correlation between average particle temperature and wind speed with particle egress rate
- However, particle temperature appears to be the most dominant factor affecting egress rate
  - Coupled with wind speed, the egress rate is further increased.

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	9.6435	2.9485	3.2706	0.0030	3.5828	15.7043
A	4.9017	2.4759	1.9798	0.0580	-0.1784	9.9818
B	-0.0013	2.0400	-0.0007	0.9995	-4.1870	4.1844
C	-0.7179	4.0029	-0.1793	0.8590	-8.9313	7.4955
D	-1.6738	3.5301	-0.4741	0.6392	-8.9169	5.5693
E	-0.0416	2.0697	-0.0201	0.9841	-4.2883	4.2052
F	0.1956	2.2643	0.0864	0.9318	-4.4503	4.8415
AB	1.1490	1.9137	0.6004	0.5532	-2.7776	5.0756
AC	2.0513	4.0507	0.5064	0.6167	-6.2600	10.3626
AD	-1.2283	3.4380	-0.3573	0.7237	-8.2825	5.8259
AE	3.1562	1.8824	1.6767	0.1051	-0.7061	7.0185
BF	2.9581	2.0175	1.4663	0.1541	-1.1814	7.0977
DE	-4.0475	2.0531	-1.9714	0.0590	-8.2602	0.1652
DF	0.2498	2.2938	0.1089	0.9141	-4.4566	4.9562
EF	-0.9262	1.8813	-0.4923	0.6265	-4.7863	2.9339

Publications

Full Author List	"Article Title"	Paper Number	Conference/ Proceedings Title	Conference Location	Dates
Jesus Ortega, Peter Vorobieff, Andrea Mammoli, Clifford Ho	Characterization of particle and heat losses of a lab-scale solid particle receiver.	-	APS Division of Fluid Dynamics Conference 2018	Atlanta, Georgia	November 18-20, 2018
Clifford Ho, Sean Kinahan, Jesus Ortega, Peter Vorobieff, Andrea Mammoli, Vanderlei Martins	Characterization of particle and heat losses from falling particle receivers.	ES2019-3826	ASME Energy and Sustainability Conference 2019	Bellevue, Washington	July 14-17th 2019
Clifford K. Ho and Christian Pattyn	Investigating Environmental Impacts of Particle Emissions from a High-Temperature Falling Particle Receiver	-	SolarPACES 2019	Daegu, South Korea	October 1 – 4, 2019
Guillermo Anaya, Jesus Ortega, Irma Vazquez, Adrian Cederberg, Peter Vorobieff, Clifford Ho	Velocity vector field extraction from high speed thermograms through particle image velocimetry tools.	-	APS Division of Fluid Dynamics Conference 2019	Seattle, Washington	November 23-26 2019
Jesus Ortega, Guillermo Anaya, Irma Vazquez, Adrian Cederberg, Peter Vorobieff, Clifford Ho	Particle temperature extraction from thermograms and mass flow measurements.	-	APS Division of Fluid Dynamics Conference 2019	Seattle, Washington	November 23-26 2019
Jesus Ortega, Guillermo Anaya, Peter Vorobieff	Bulk Velocity Extraction from Time-Resolved Thermogram Sequences through PIVlab	-	UNM STEM Symposium 2020	Albuquerque, NM	February 29, 2020
Jesus Ortega, Guillermo Anaya, Peter Vorobieff	Particle Curtain Temperature Estimation Using Imaging Methods	-	UNM STEM Symposium 2020	Albuquerque, NM	February 29, 2020
Jesus Ortega, Guillermo Anaya, Peter Vorobieff, Gowtham Mohan, Clifford Ho	Imaging Particle Temperatures and Curtain Opacities Using an IR Camera	ES2020-1688	ASME Energy and Sustainability Conference 2020	Virtual, Online	June 16-18, 2020
Ortega, J.D., C.K.Ho, G. Anaya, P. Vorobieff, G. Mohan	A Non-Intrusive Particle Temperature Measurement Methodology using Thermogram and Visible-light Image Sets	ES2021-63791	Proceedings of the ASME 2021 15th International Conference on Energy Sustainability	Virtual	June 16-18, 2021
Ortega, J.D., C.K.Ho, G. Anaya, P. Vorobieff, G. Mohan	Particle Plume Velocities Extracted from High-Speed Thermograms through Particle Image Velocimetry	ES2021-63336	Proceedings of the ASME 2021 15th International Conference on Energy Sustainability	Virtual	June 16-18, 2021
Glen, A., D. Dexheimer, A. Sanchez, C.K. Ho, S. China, F. Mei, N. Nahar	Near-Field and Far-Field Sampling of Aerosol Plumes to Evaluate Particulate Emission Rates from a Falling Particle Receiver During On-Sun Testing	ES2021-63466	Proceedings of the ASME 2021 15th International Conference on Energy Sustainability	Virtual	June 16-18, 2021

Thank you!

Jesus Ortega
University of New Mexico
jdortega4@unm.edu