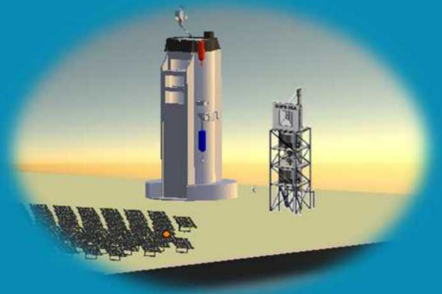
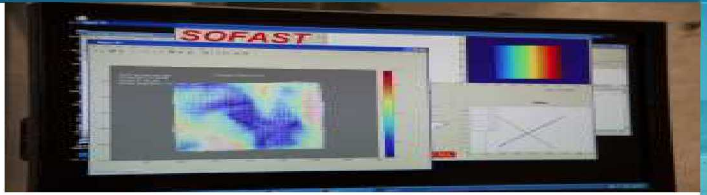
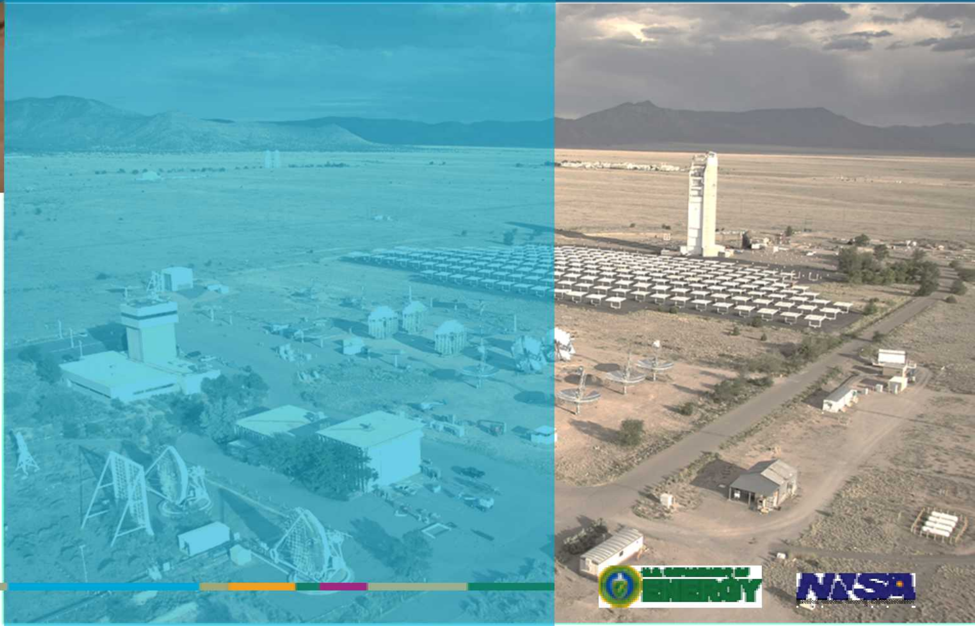
SAND2020-5675C

Testing and Simulations of Spatial and Temporal Temperature Variations in a Particle-Based Thermal Energy Storage Bin







ES2020-1660 Gen 3 Particle Pilot Plant (G3P3)

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Overview

- Introduction to G3P3
- Computational Model
- Validation Testing
- Results
- Conclusions and Next Steps

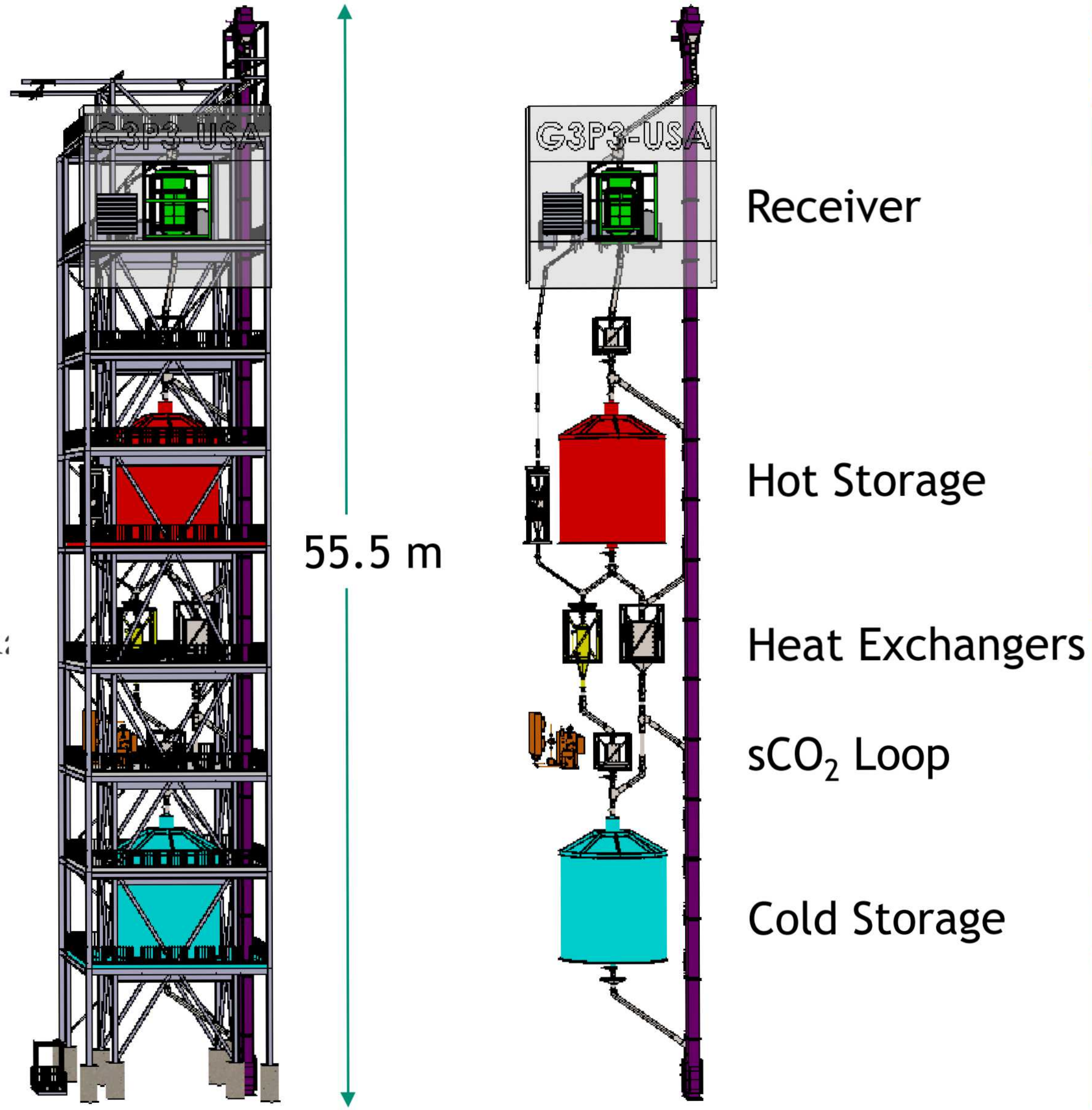
G3P3 and Hot Particle Storage

G3P3 1MW$_t$ pilot will be a vertically integrated falling particle receiver with 6MWh of thermal storage.

- ~163,000 kg
- ~77 m^3

Target particle inlet temperatures to hot storage bin will be ≤ 800º C and must be between 765-775º C upon outlet. Cold storage will have inlet temperatures ~600º C.

Storage tanks will be internally insulated to minimize therma stresses on metal shell and tower connections.

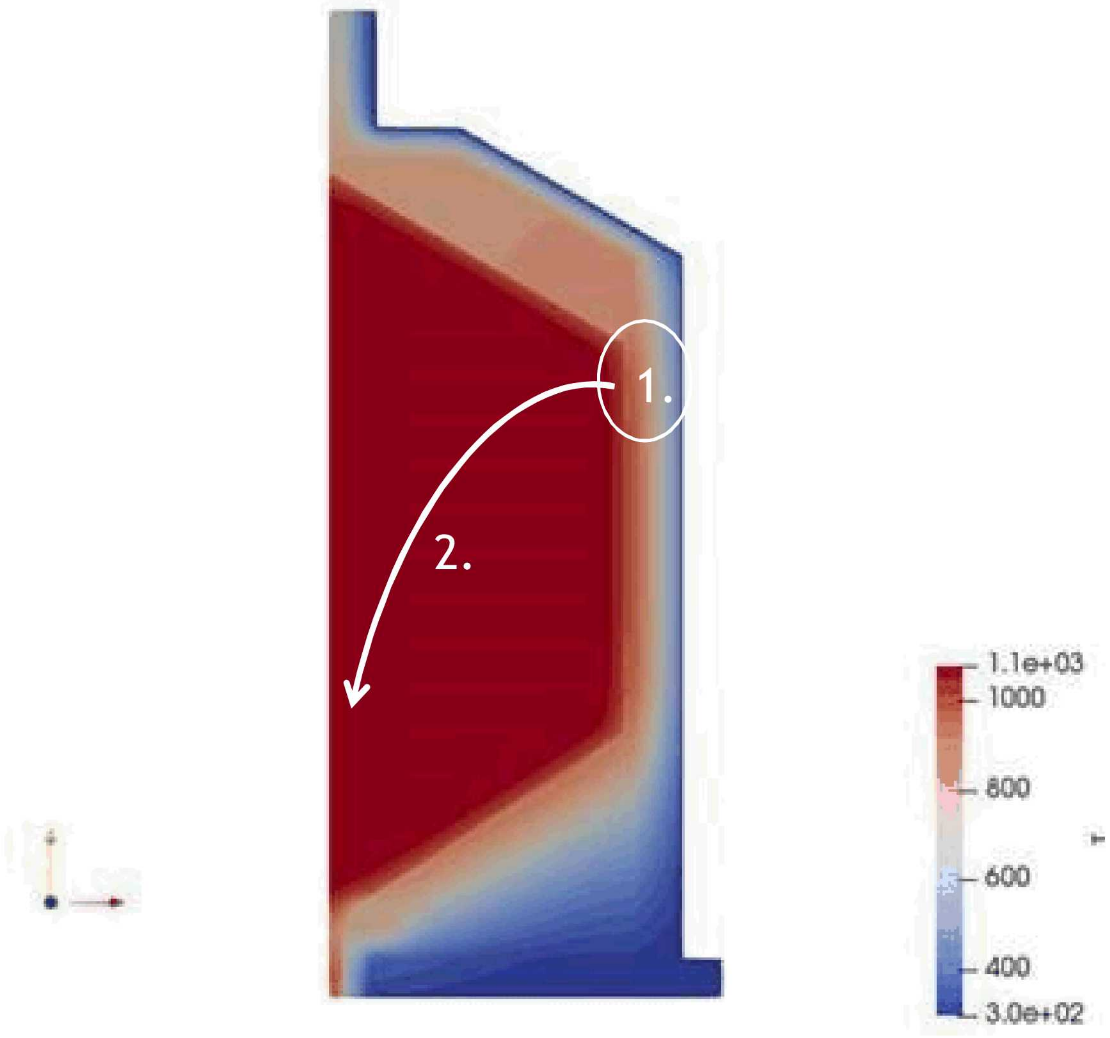


Project Objective

Determine the expected heat loss from particles as the bin discharges in funnel flow.

1. Particles give off heat to the refractory walls while in storage (ES2019-3903)
2. Particles flow away from the wall into the hot inner flow channel where they exchange heat with stagnant particles

Outlet temperature models must account for dynamics of funnel flow



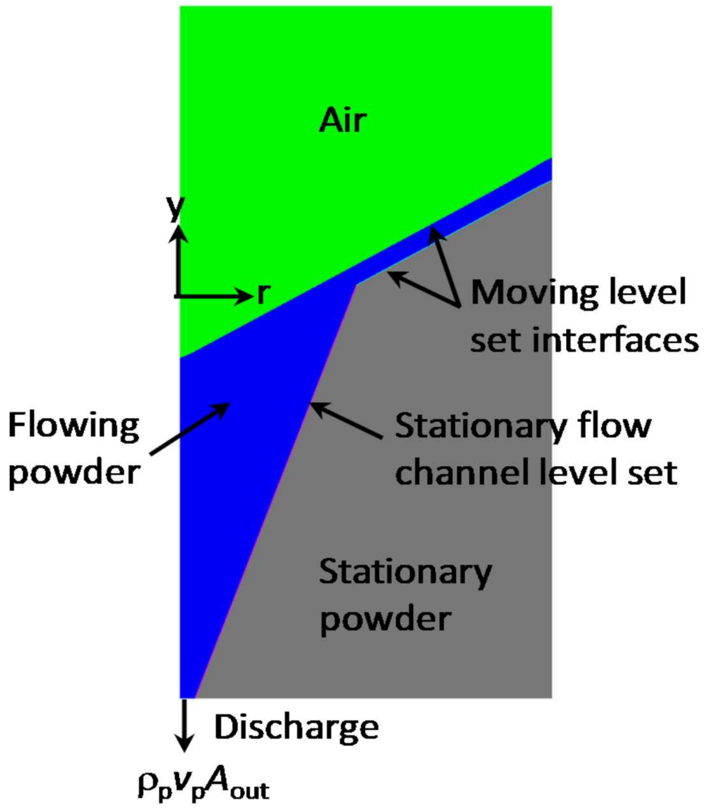
Computational Model for Flow and Energy Transport in Bin

The flowing particles are treated as a pseudo fluid

The particle region is decomposed as a flowing region (blue) in a funnel flow configuration, and a non-flowing, stationary particle region (grey), and the air-filled region above the particles (green).

The three regions are separated by level set interfaces with specified velocity to match the specified outflow of particles from the funnel flow region.

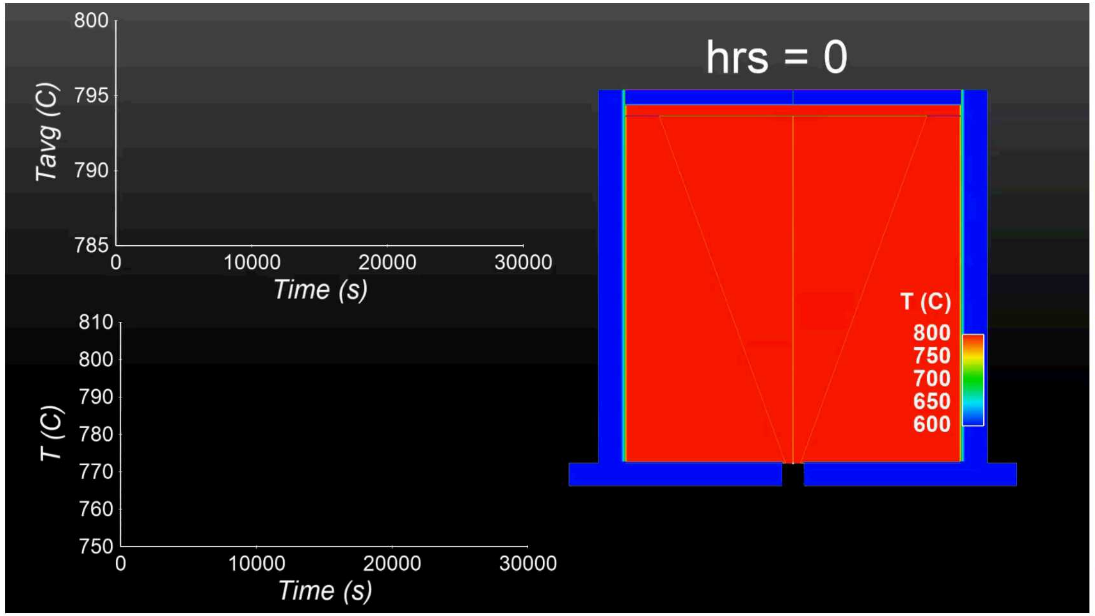
- air/particle interface set at the fixed "drawdown" angle, ~30°
- the interface between flow and nonflowing particles is defined along the flow channel angle and the drawdown angle.



Computational Model for Flow and Energy Transport in Bin

In a discharge simulation

- the two moving levels translate downward
- new layers of flowing particles are continuously exposed.
- particles flow through the drawdown channel and into the funnel region and out the discharge port.
- Energy transport in the flowing particles are via convection and conduction, by heat conduction in the stationary particle region, and from heat loss to the walls.



Energy transport is modeled via

- convection and conduction of the flowing particles
- heat conduction in the stationary particle region
- heat loss to the bin walls.
- radiation and convection from bin surfaces to ambient air

Heat transfer coefficient is determined by calibration with thermocouple readings measuring the time history of bin wall temperature.

Validation Testing – Objectives

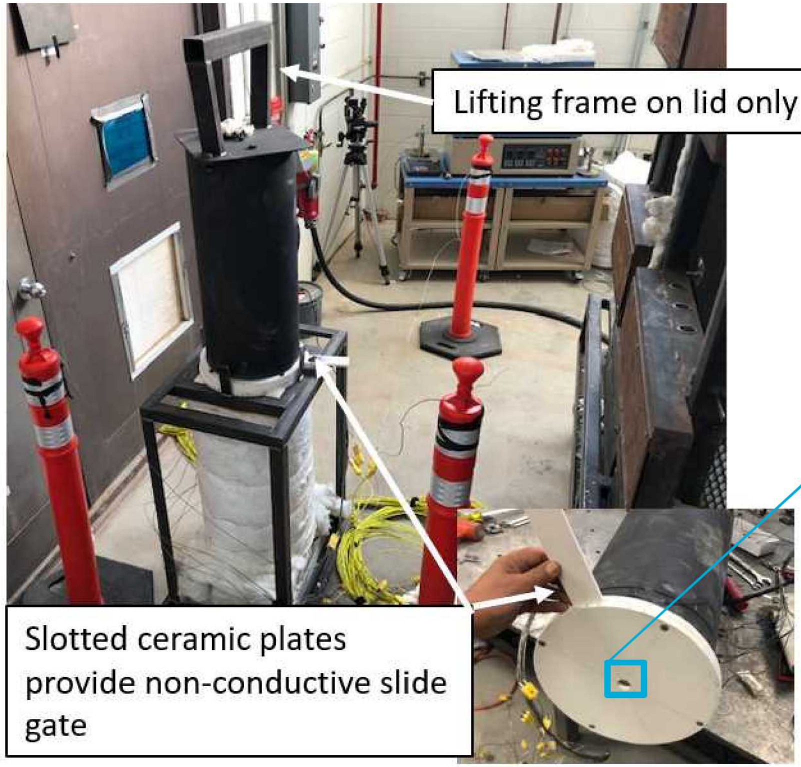
There were three test objectives intended to provide different parameters on which to evaluate the robustness of the model:

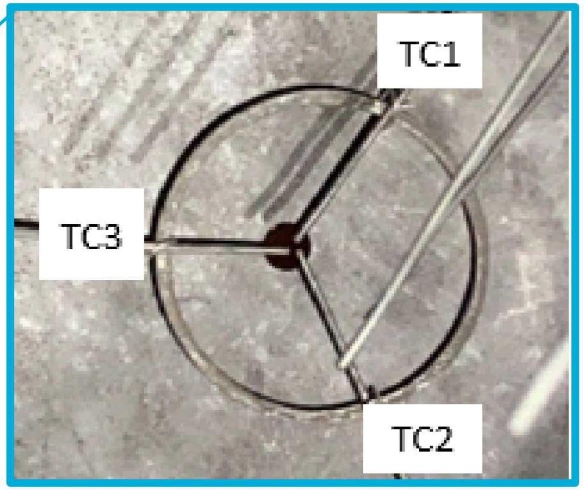
1. Characterize the salient features of the outlet temperature temporal variation
   - Measure outlet temperatures as bin discharges
   - Measure wall temperatures to understand boundary conditions
   - Measure center flow channel to understand mixing profile (not discussed herein)
2. Evaluate the models on varying geometric bin and particle formations
   - Full bin (67kg) – flow above and below the intersection of the flow channel and wall causing particles to initially start in mass flow and transition to funnel flow
   - Scaled bin geometry (29 kg) – maintains height to diameter ratio of G3P3. Particles are always in funnel flow (discussed in paper only)
3. Measure the significance of the amount of time particles are exposed to the upper surface
   - Parameterize outlet hole size to induce faster/slower flow rates (10-50 g/s)
   - Parameterize the amount of time particles are allowed to cool before flow commences (7.5 – 30 min.)
   - G3P3 discharge time is 6 hours, small bin test is 15-60 minutes.

Validation Testing –Procedure

Testing was performed on a small steel bin that could be heated in a furnace and allowed to discharge while logging data from thermocouples installed throughout the center flow channel, walls, and outlet.

- Particles heated inside bin to 800° C
- Thermocouple data was logged at 1 Hz.
- Heated bin was removed from the furnace and placed on a steel rack to cool.
- After a specified amount of time, the slide gate was pulled, and particles discharged into a lower catch bin.

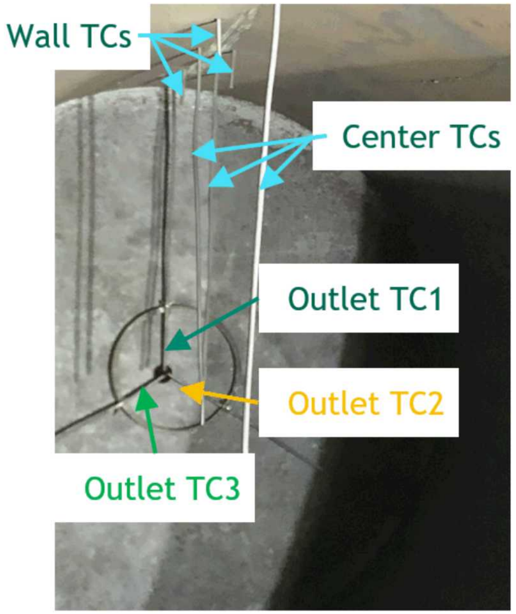




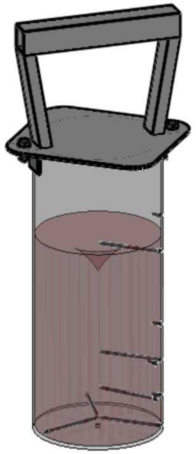
Test Parameters for Model Input

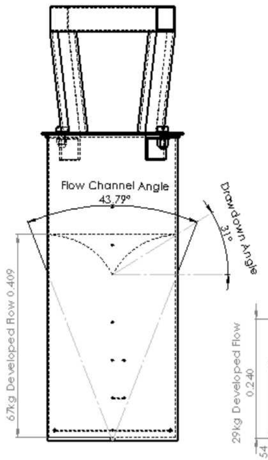
Variable	Full Bin	Partial Fill		
Initial Mass (kg)	67.1	29.0		
Final Mass (kg)	5.9	5.9		
Flow Rate (kg/s) min/max	0.02/.05	.01/.05		
Flow Time (s)	1150/3196	422/2333		
Cooling Time (s)		450	900	1800
Initial Temp - Start of Flow (° C)	792	787	777	719
Wall Temp at Start of Flow (° C)	495	524	478	338
Flow Rate (min/max)				

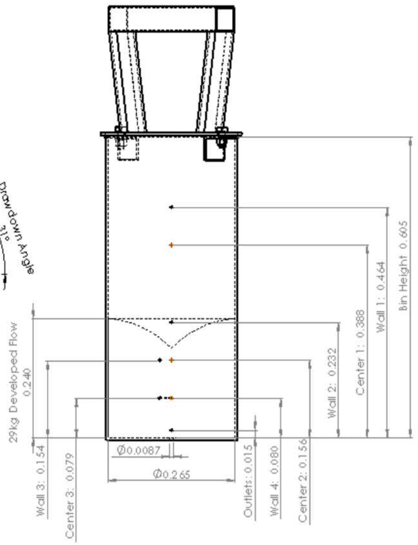
Initial fill of ~67 kg results in the peak of the repose heap being located at approximately top of bin



Inventory height where transition to funnel flow begins (left, middle)







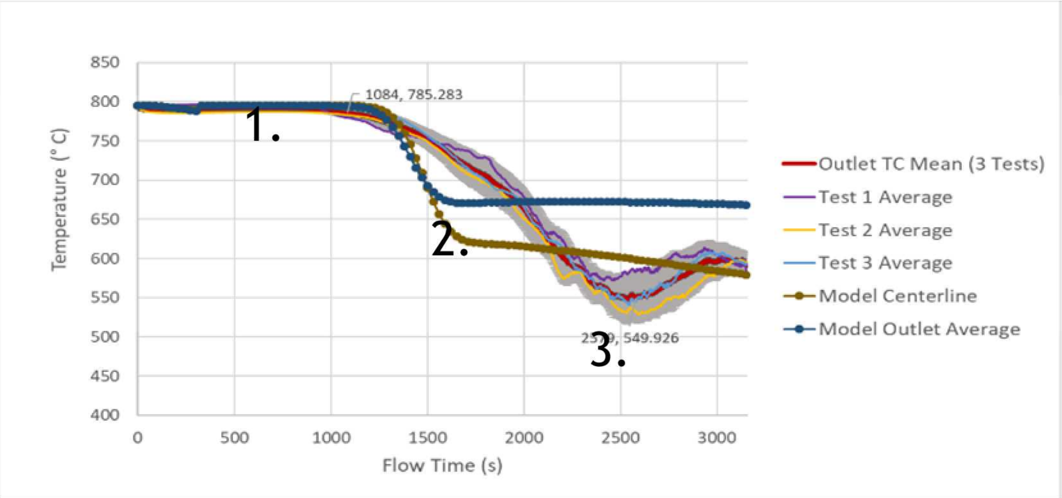
Partially full bin level with TC placement (right)

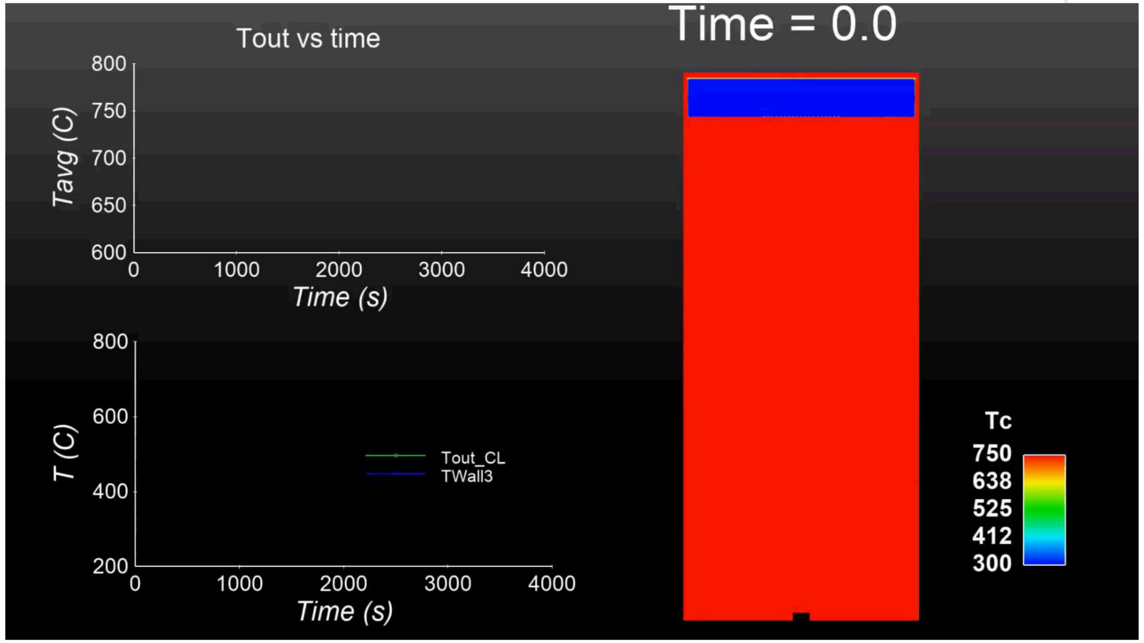
Results –Outlet Temperature Profile

The model of the small test bin captured some salient features of thermal transients in funnel flow.

1. Flat temperature region while the hot inner core discharges
2. Steep drop in temperatures as the cooler particles on the top surface and near the walls reach the outlet
3. Gradual cooling profile of mixed particles

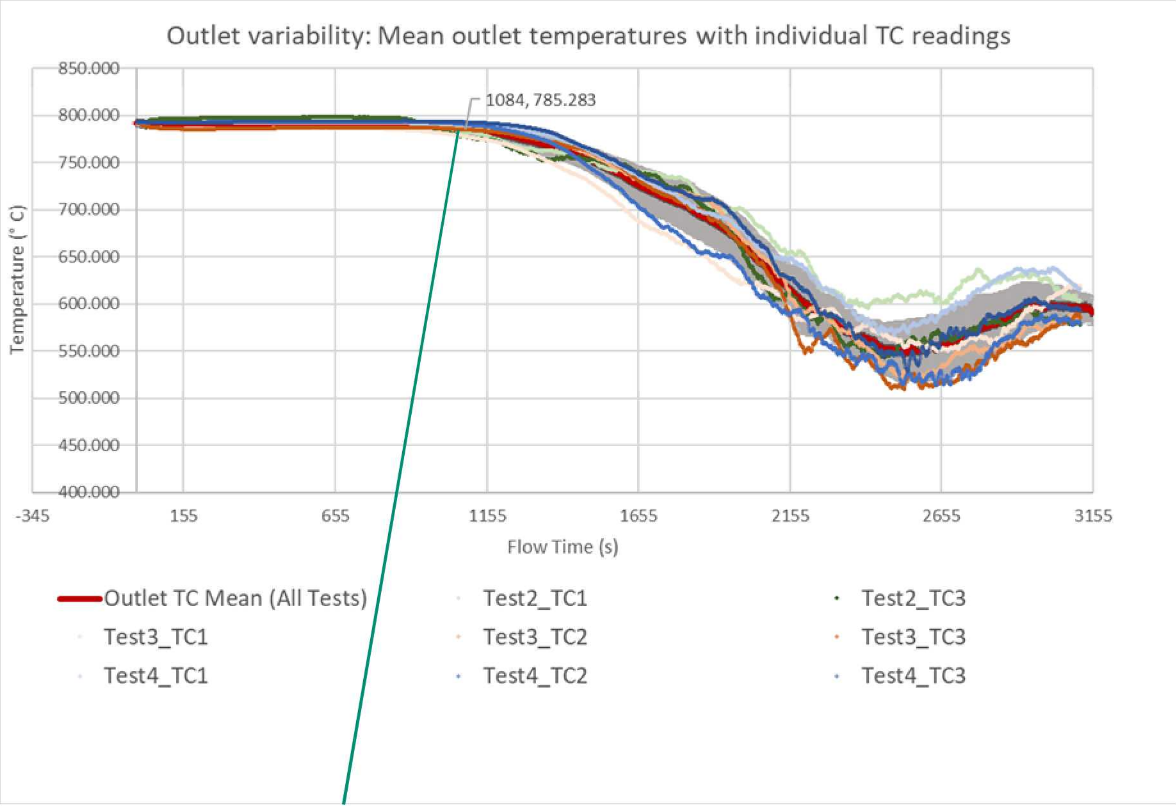
The main mode of cooling of the discharge stream is by convection of cold particles adjacent to the bin walls as they flow through the funnel.

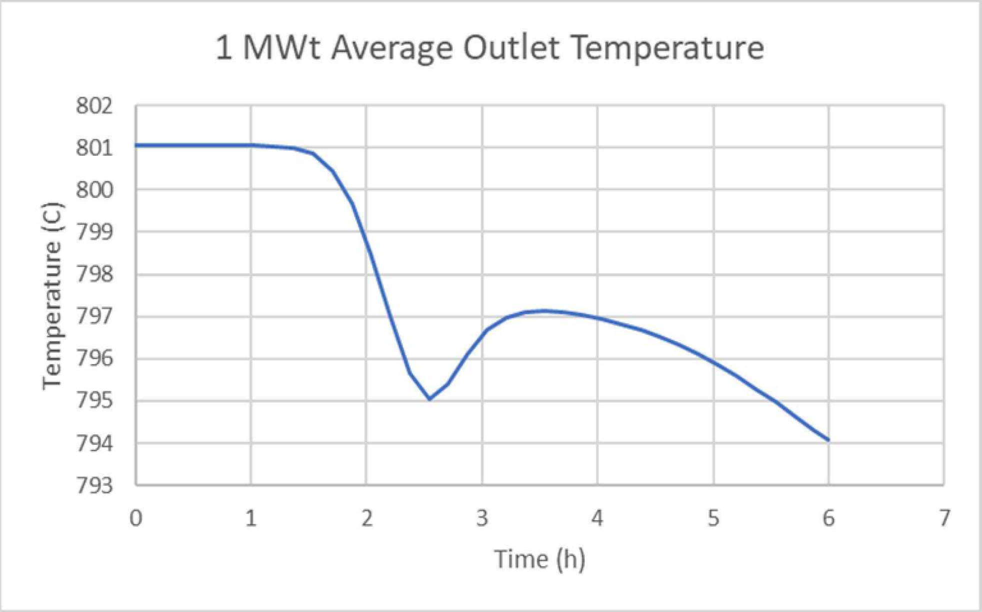




Results – Outlet temperature profile

A dip in temperature was observed in all runs of the 67 kg 19 g/s test series. This contour was also modeled in the 1 MWt bin (Figure 7) but did not appear in the any of the small bin models or partially filled (29 kg) tests.



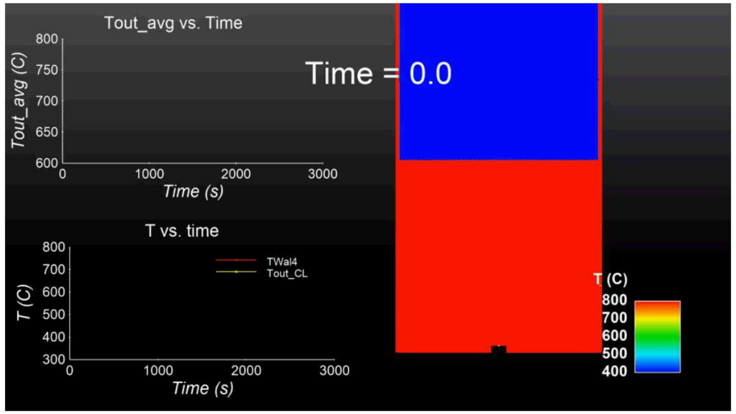


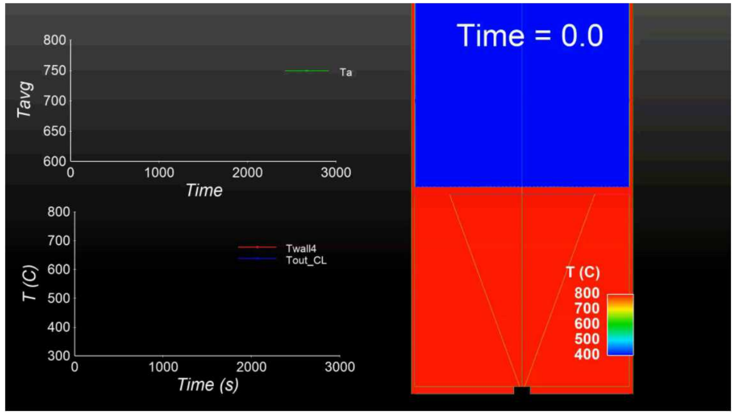
The decline in temperature corresponds to the point where the flow channel intersects the wall and funnel flow commences (right).

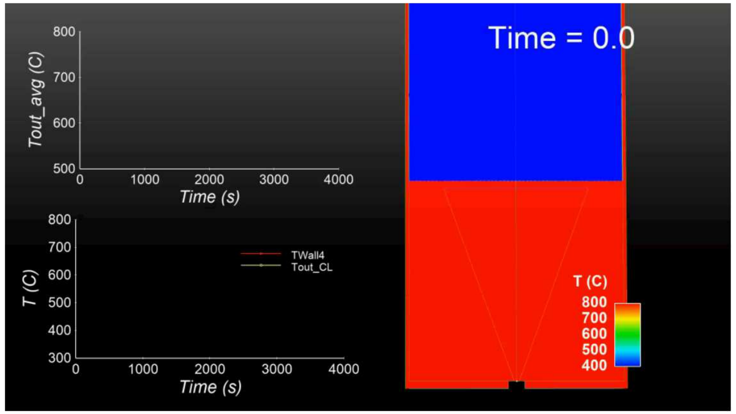
Results – Scaled bin with variable cooling times

The test was run again preserving the G3P3 height to diameter ratio to ensure the particles were always in funnel flow.

The particles were allowed to cool for increasing periods of time to evaluate the significance of wall boundary conditions on the final results.





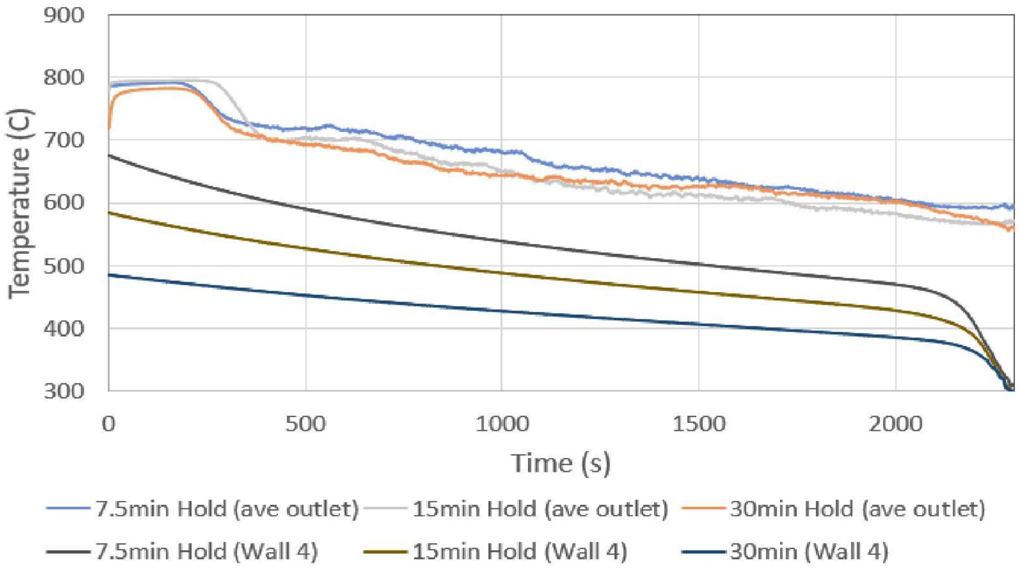


Results - Scaled bin with variable cooling times (cont.)

A test series was run with increasing hold times before commencing flow.

The three lower curves show wall temperatures at 7.5 and 15 minute and 30-minute hold times.

The resulting outlet temperatures for all three hold times overlap and do not parody the stratified wall temperatures indicating the initial temperature of the cool wall particles did not result in significantly lower outlet temperatures. This was also true for the full (67 kg) bin test series.



Conclusions

The level set modeling approach captured many of the salient features of the measured outlet temperature profile in the small test bin including:

- the nearly isothermal discharge of the central flow channel core
- the steep drop as coolest particles along the upper surface exit the bin

The apparent rise as hotter sub-surface particles begin to exit. The apparent rise may be related to the amount of time particles initially on the top surface are exposed.

Tests were run to evaluate the effect of cool particles mixing in the central flow channel. More significant cooling at the walls did not result in lower overall outlet temperatures during flow. The greatest variance seemed to come from measurement location across the outlet.

It is believed that convective air currents could have been present under the bin which would have caused additional cooling not captured in the model.

Next Steps

- Analyses of charging mode temperature gradients throughout the bottom hopper as it filled with particles
- Sensitivity studies on the flow channel and drawdown angle geometries

Acknowledgments

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Questions

Thank you!