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TESTING AND SIMULATIONS OF SPATIAL AND TEMPORAL TEMPERATURE VARIATIONS IN A PARTICLE-BASED THERMAL ENERGY STORAGE BIN

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ABSTRACT

The National Solar Thermal Test Facility (NSTTF) at Sandia National Laboratories is conducting research on a Generation 3 Particle Pilot Plant (G3P3) that uses falling sand-like particles as the heat transfer medium. The system will include a thermal energy storage (TES) bin with a capacity of 6 MWht¬ requiring ~120,000 kg of flowing particles. Testing and modeling were conducted to develop a validated modeling tool to understand temporal and spatial temperature distributions within the storage bin as it charges and discharges.

Flow and energy transport in funnel-flow was modeled using volume averaged conservation equations coupled with level set interface tracking equations that prescribe the dynamic geometry of particle flow within the storage bin. A thin layer of particles on top of the particle bed was allowed to flow toward the center and into the flow channel above the outlet.

Model results were validated using particle discharge temperatures taken from thermocouples mounted throughout a small steel bin. The model was then used to predict heat loss during charging, storing, and discharging operational modes at the G3P3 scale. Comparative results from the modeling and testing of the small bin indicate that the model captures many of the salient features of the transient particle outlet temperature over time.

Keywords: Particle Based Thermal Energy Storage, TES, G3P3, Bulk Solids Handling, NSTTF, Funnel Flow

1. INTRODUCTION

Research is being conducted at the National Solar Thermal Test Facility (NSTTF) at Sandia National Laboratories in Albuquerque, NM to design and de-risk a 1MWt concentrating solar tower for a Generation 3 Particle Pilot Plant (G3P3). Unlike conventional solar towers the G3P3 will use falling sand-like particles as the heat transfer and thermal storage medium. The bulk solids fall through the open aperture of the receiver where they are heated to ~800° C before falling into an insulated flat-bottomed storage bin sized for 6MWh thermal capacity with up to 10 hours of deferred storage. The storage bin has a flat-bottomed design that causes particles to flow away from the walls and into a central flow channel in a pattern called *funnel flow*, which differs from *mass flow* whereby all particles in the bin can move at the same downward velocity due to the steep hopper wall angles.

To meet the target efficiencies of the pilot system, approximately 120,000 kg of flowing particles with outlet temperatures ranging from 775-765° C are required to provide 6MWh$_t$ energy to the heat exchanger. Predicting the range of particle temperatures at the bin outlet computationally presents challenges related to the large volume of particles and to accurately rendering the dynamics and thermal transport of bulk solids during the charging and discharging operations of the bin. During discharge, the flat-bottom design of the G3P3 storage bin induces funnel flow which is a last in – first out configuration where particle motion only occurs along the top surface and in a central flow channel, and there is no vertical motion of particles along the walls. The self-insulating nature of the bulk particles keeps the inner core at stable temperatures near the initial maximum, while particles near the walls lose heat to the refractory layers before passing through the flow channel and exchanging heat with the surrounding stationary particle region.

2. COMPUTATIONAL MODEL

A series of modeling and testing was performed on a small (<70 kg) hot particle test bin at the NSTTF [1] to validate a model for particle flow and energy transport in the 1 MW$_t$ G3P3 thermal energy storage bin. Figure 1 depicts an axisymmetric model for flow and energy transport in a particle-filled bin. The flowing particles are treated as a pseudo fluid, and the flow and energy transport is modeled using conservation equations for flow and convective-diffusive energy transport through a pseudo porous medium in which the particle region is decomposed as a flowing region in a funnel flow configuration, and a non-flowing, stationary particle region, and the air-filled region above the particles. The three regions shown in Figure 1 are separated by level set interfaces with specified velocity to match the specified outflow of particles from the funnel flow region. The level sets separate the different fluid regions, allowing different physics and/or transport properties to be specified in each region. [2]

The upper level set is the air/particle interface, set at the fixed "drawdown" angle, ~30°, measured from horizontal. The lower level set is the interface between flow and nonflowing particles. It has one leg at the same drawdown angle as the upper level set, which intersects a fixed (non-moving) third level set comprising the flow channel, set at an angle of ~20° from vertical. The angles are determined by the internal friction properties of the particles which were measured empirically as a function of temperature and consolidating pressure.

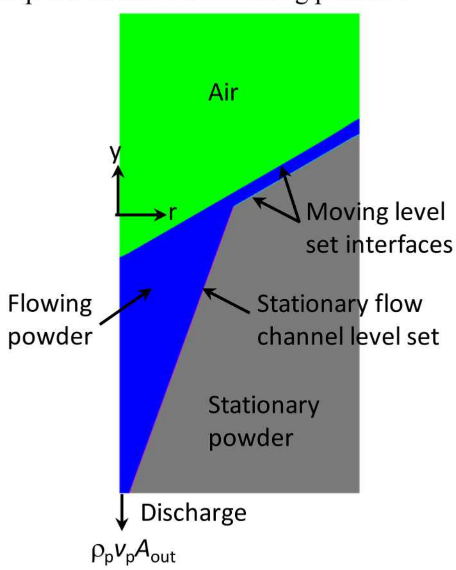

FIGURE 1: Axisymmetric particle bin model geometry

In a discharge simulation, the two moving levels translate downward at a rate determined to match the discharge rate of hot particles from the bin, thereby continually exposing new layers of flowing particles. The particles flows down the drawdown channel and into the funnel region, finally issuing out the discharge port. Energy transport in the flowing particles are via convection and conduction, and by heat conduction in the stationary particle region, and from heat loss to the stainless steel bin container (not shown). The bin loses heat by radiation and convection from its surface to a fixed ambient temperature. The heat transfer coefficient is determined by calibration with thermocouple readings measuring the time history of bin wall temperature. Heat loss from the upper surface of the particles is modeled similarly. 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.

3. VALIDATION TESTING

To build confidence in the 1 MW_t scale model, 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.

3.1 Test Methods

The small bin was constructed out of a 0.605 m long ANSI/ASME10 inch schedule 10 stainless steel pipe (0.265 m inner diameter, 4.2 mm wall thickness) with a 6.35 mm thick circular plate welded to the bottom and a second plate bolted to the top with a steel handle so that the bin could be lifted while hot via fork lift from the furnace. A slide gate was constructed out of two circular disks of RSLE board with a rectangular notch and bolted to the bottom of the bin. A rectangular wedge was inserted into the notch to cover the center outlet hole and obstruct flow (Figure 2).

The bin was instrumented with thermocouples, filled with particles, and placed in an electric furnace. Thermocouple leads were routed through a port in the furnace door. The furnace was initially set to 800° C and the particles were heated for several hours until all thermocouple readings stabilized near the set point. During the tests, thermocouple data was logged at 1 Hz. The heated bin was instantly removed from the furnace and placed on a steel rack. The furnace doors were reclosed and insulated to minimize radiant and convective heating of one side of the bin which was unavoidably in close proximity. After a targeted amount of time, the slide gate was pulled, and particles discharged into a lower catch bin.

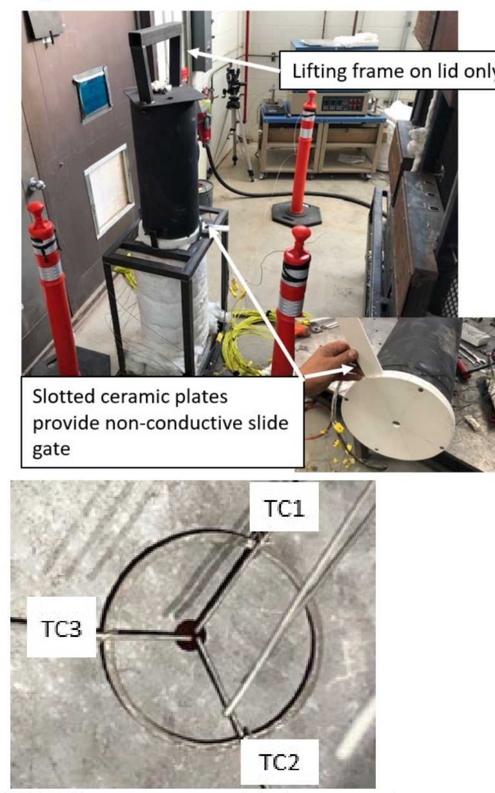

FIGURE 2: (Above) Test bin in test environment next to furnace with refractory RSLE bottom and slide gate and lifting frame connected only to lid. (Below) The location of outlet thermocouples over the 9 mm outlet hole.

The lower bin was wrapped in *Superwool* insulation. A second piece of *Superwool* was rested on the upper rim and sized to extend just above the hot bin cooling rack, where it was slightly compressed by the upper bin creating an insulated pathway through which the particles could flow from the upper to lower bin as shown in Figure 3. Thermocouples were mounted in the lower bin at intervals along the wall and central axis.

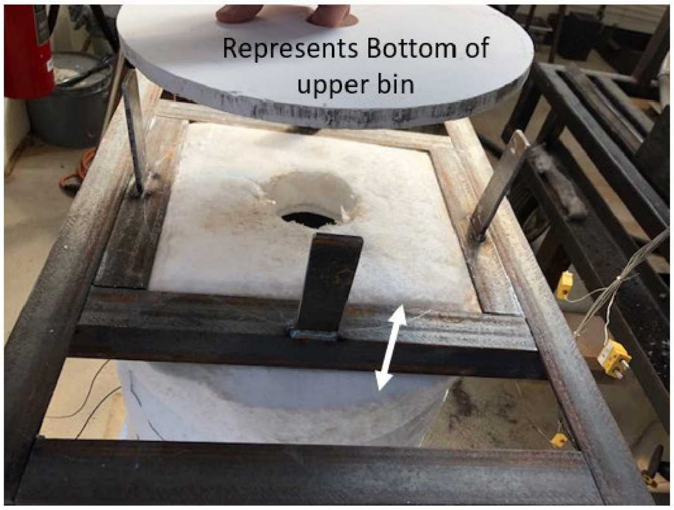

FIGURE 3. Insulated interface between the upper and lower bin.

FIGURE 4 shows the thermocouple locations inside the upper bin relative to the height of the particle bed at the start of developed flow for the respective fills. Outlet temperatures were measured 2 mm above the outlet hole inside the bin by taking the average of three thermocouples. Wall temperatures were also measured at intervals up the sidewalls of the bin. The lower bin was similarly instrumented.

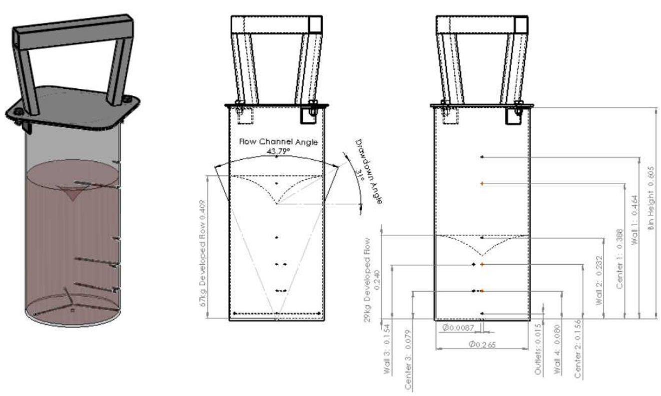

FIGURE 4: Left: design of hot particle test bin. Middle: height of particle bed at developed flow for high fill tests with flow channel angles and drawdown angles. Right: thermocouple placement and height of particle bed for low fill tests.

The model validation test was designed to evaluate the robustness of the model to predict outlet temperatures as a function of three factors:

1. The bin was allowed to cool in ambient air for between 3 and 30 minutes to induce the effect of increasing temperature gradients across the particle bed.
2. The flow rate was varied to examine outlet temperatures as a function of the amount of time particles are exposed to bin walls and air above the top surface.
3. The fill height in the bin was varied to examine outlet temperatures as a function of varying height to diameter ratios of the initial particle fill geometry.

In slow flowrate tests, the bin remained in open air for a minimal time (~5 minutes) and used full bins with smaller outlet holes to provide more time for temperature gradients to develop throughout the bin during flow. Fast flowrate tests were filled with fewer particles and left in ambient conditions for 7.5, 15, and 30 minute periods to produce larger wall temperature gradients and better isolate the effects of cooler wall particles mixing in the flow channels.

The high-fill tests were filled nearly to the top of the 0.605 m bin with an average mass of particles was 67 kg. The low-fill tests were filled with ~29 kg of particles which produced an initial particle bed height with the same height to diameter ratio of the G3P3 1 MW bin wherein the maximum height of the particle bed is still below the intersection of the wall and the flow channel – thus always in funnel flow.

The slow flowrate tests used a 9 mm outlet hole resulting in a flow rate of ~0.02 kg/s and took ~53 minutes to discharge 67 kg of particles. The slow flow rate was not tested with the low fill height. The fast flowrate tests used a 12 mm outlet hole for a flow rate of ~0.05 kg/s. It took ~19 minutes to discharge 67 kg of material and ~8 minutes to discharge 29 kg of material.

4. RESULTS AND DISCUSSION

The model of the small test bin represented some salient features of funnel flow as shown in FIGURE 4. There is a flat temperature region while the hot inner core discharges followed by a steep drop in temperatures as the cooler particles on the top surface and near the walls reach the outlet where after the outlet temperatures follow a monotonically decreasing heat loss profile.

The funnel flow temperature

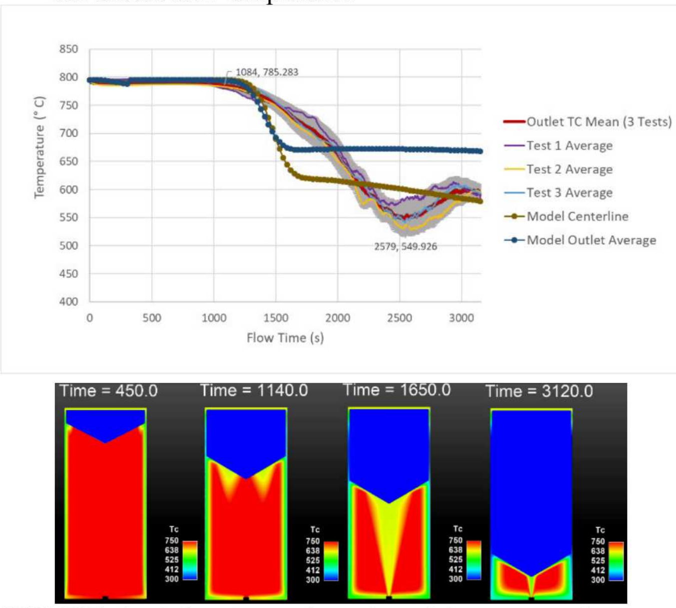

FIGURE 5: (Above) overlay of model output and average temperatures of three outlet thermocouples for three 67kg bin tests with 19 gps flowrate. Error bars are ± 1 standard deviation. (Below) contour plots from model at corresponding time steps. Model and test are for the bin with an insulated bottom.

The model results indicate significant sensitivity to the location at which the temperature is probed. This spread is also seen in the test data. Figure 6 shows an overlay of the model and measured outlet temperatures. The modeled temperatures are taken at the centerline (CL) and at the edge of the hole (edge). In an earlier test bin configuration, a test was run to verify the modeled gradient over the 9 mm outlet hole, a TC3 was bent slightly to remain very close to the edge of the hole. There may also be variability due to the relative heights of the TC. The data reflected in Figure 6 is from an earlier bin design that used no insulation under the steel bottom of the bin which may explain why the temperature drop was more severe.

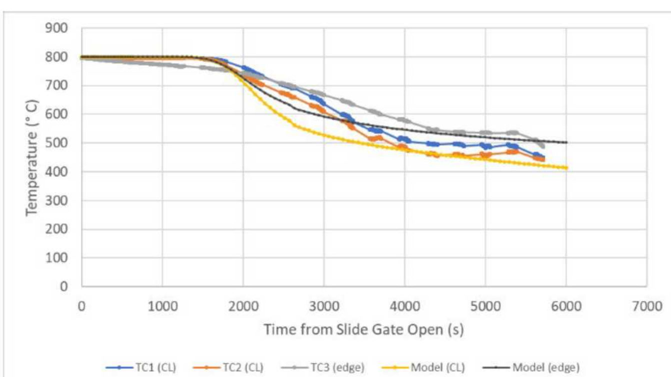

FIGURE 6: Overlay of modeled and measured outlet temperatures. Test data taken on earlier uninsulated bin design.

FIGURE 4 also shows a characteristic rise in temperature that was consistent throughout that test series. This contour was also modeled in the 1 MW_t bin (Figure 7) but did not appear in the any of the small bin models or partially filled (29 kg) tests.

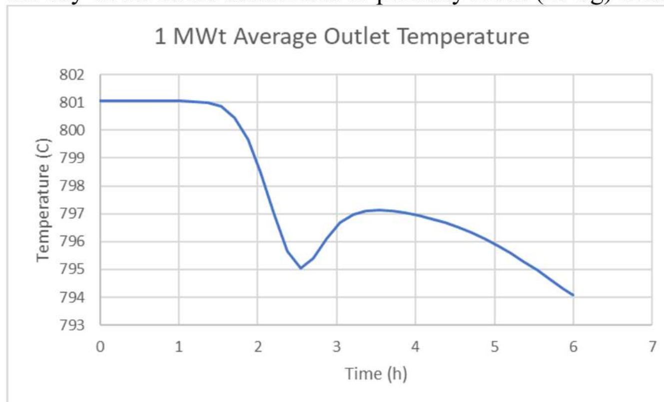

FIGURE 7: Level set model of 1 MW_t thermal energy storage bin.

The temperature rise was believed to be related particles initially on the upper surface and thus having maximum exposure times exiting the bin followed by subsequently exposed upper surfaces that had less time to release heat before entering the flow channel. Figure 8 illustrates the increased exposure of the initial top surface during flow. The bin begins to discharge in mass flow and the upper surface remains unchanged until a crater begins to form. The diameter of the crater gradually shrinks to a point and the upper surface moves into the flow channel. The timing of the steep temperature drop following the quasi-isothermal region in Figure 5 corresponds to the time at which the crater diameter converges to a point (Figure 8 right).

FIGURE 8: (left) initial height of high-fill test bin (mid) crater emerges and diameter shrinks with time (right) crater diameter converges to a point at the intersection of the flow channel and the wall.

During fully developed funnel flow, the temperature of the particles flowing out of the bin decreases as cooler particles on the upper surface near the wall flow into the central flow channel. The next phase of flow exhibits a partial rise in temperature which is believed to be caused by the discharge of warmer sub-surface particles.

To evaluate whether the wall temperature gradients were the primary cause, a test series was run with increasing hold times before commencing flow. Figure 9 captures the effects of increased gradients between center particles and the wall. The three lower curves were measured 12.7 mm from the inner pipe wall and indicate approximately 100° C of temperature drop for the 7.5 minute, 15 minute and 30 minute hold times respectively.

The resulting outlet temperatures do not parody the stratified wall temperatures indicating mixing occurs within the flow channel.

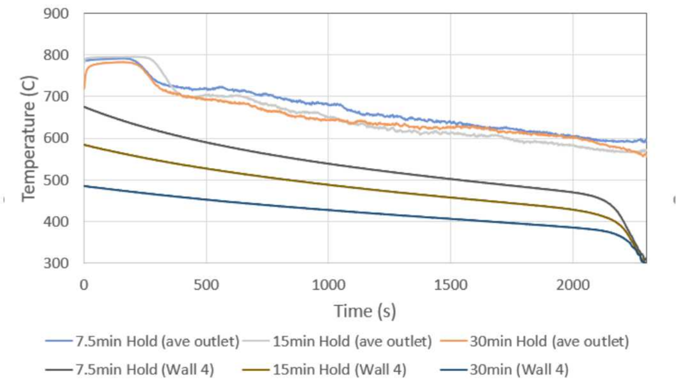

FIGURE 9: Average outlet and wall temperature gradients in 29 kg bin after 7.5, 15, and 30 minute hold times in ambient air before opening slide gate.

Model results for the 7.5 minute hold are shown in Figure 10. (Results from 15 and 30 minute hold times were unavailable at the time of writing.) The wall temperatures in the model were calibrated to match the measured 7.5 minute hold "Wall 4" temperature above. The model shows a drop of a similar magnitude and similar final temperatures on average. The magnitude of the initial drop in the centerline may not be reflected in the data due to sensitivities in TC placement or modeling error.

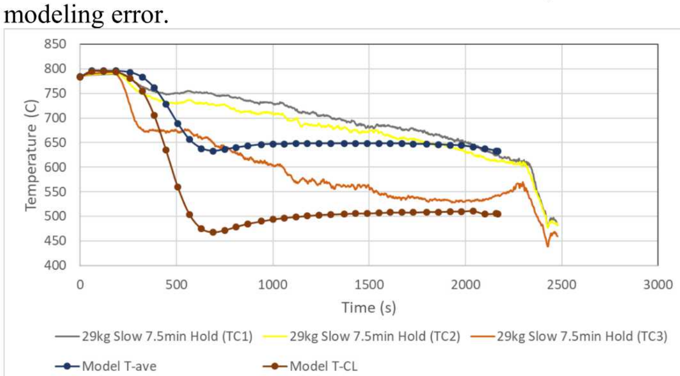

FIGURE 10: Outlet temperatures of the 29 kg 10 gps model and test.

To evaluate whether the geometric formation of the particle fill transitioning from mass flow to funnel flow, or the exposure time of the upper surface was influencing the rise in temperature, a subsequent test was run with a fast flowrate which preserved the mass flow to funnel flow transitional effects but did not provide for significant time on the upper surface relative to the test series in Figure 9. The results of the fast-flowrate, high-fill test are shown in Figure 11. Three phases can be identified: discharge of the core, mass flow, funnel flow with a characteristic rise near the end.

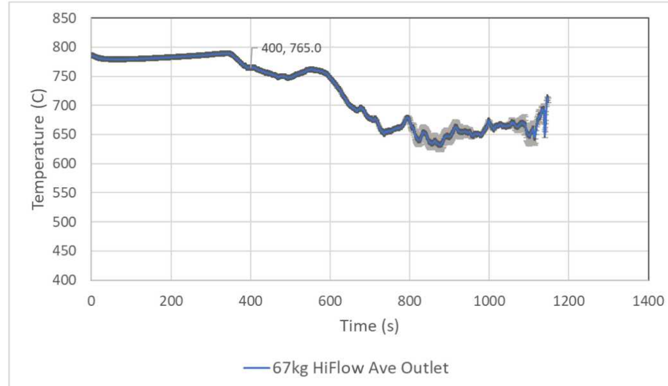

FIGURE 11: Average outlet temperatures from fast-flowrate, high fill tests. Fully developed flow was observed at ~400 seconds. Error bars are ± 1 standard deviation.

5. CONCLUSION

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 flow channel, the steep drop as upper surface particles exit the bin. Temperature profiles near the end of flow may be exhibiting a repeatable increase in temperatures as seen in many but not all model runs and tests. This rise may be related to the amount of time particles initially on the top surface are exposed to air. This level set model may be improved with more nuanced control of timing of particles along the upper surface though the current simplification of the upper surface at a fixed drawdown angle is a good approximation. More significant temperature gradients at the walls did not result in lower overall outlet temperatures during flow. Initial discharge temperatures of the bin core are not expected to cool significantly before funnel flow develops emphasizing the need to maintain particle temperatures exiting the receiver below the operating temperatures of the heat exchanger. A minimum temperature is expected as the upper surface discharges followed by a rise as insulated sublayers exit followed by a monotonic decrease as the entire system. Future work will include analyses of charging mode temperature gradients throughout the bottom hopper as it filled with particles and sensitivity studies on the flow channel and drawdown angle geometries.

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