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Particle Lift Challenges And Solutions For Solid Particle Receiver Systems

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ABSTRACT

Particle receiver systems require durable, reliable, and cost-effective particle transport equipment. These lifts are critical pieces of equipment to transport the particles from the heat exchanger back into the receiver. There are challenges that must be overcome with any particle lift device including high temperatures (800°C), particle load and friction, and erosion from particle contact. There are several options commercially available for particle systems including a screw-type vertical elevator, bucket lift vertical elevator, and skip-hoist-style bulk vertical lifts. Two of the elevator types (screw and bucket) have been tested at the National Solar Thermal Test Facility (NSTTF) at Sandia National Laboratories (SNL) in Albuquerque, NM. The two elevators are currently in operation on the 1 MW_{th} falling particle receiver at the Solar Tower. The screw-type elevator consists of a stationary internal screw with an outer casing that rotates about the screw. The frictional forces from the casing rotation drives the particles upward along the flights of the screw. The casing rotational velocity is variable which allows for mass flow rate control. Identified issues with the screw-type elevator include particle attrition, uneven loading at the inlet causes casing deflection, bearing deformation due to casing deformation, and motor stalling due to increased resistance on the casing. The bucket elevator is rated for temperatures up to 600 °C and consists of steel buckets and a steel drive chain capable of lifting particles at a rate of 8 kg/s. Identified issues with the bucket type elevator include discrete (non-continuous) discharge of the particles and a non-adjustable flow rate. A skip hoist type elevator has been studied previously and seems like the most viable option on a large scale (50-100MW_{th} power plant). Different control scenarios were explored with the variable frequency drive of the screw-type elevator to use it as a particle-flow control device. The objective was to maintain the feed hopper inventory at a constant value for steady flow of particles through the receiver. The mass flow rate was controlled based on feedback from measurements of particle level (mass) inside the top hopper.

1. INTRODUCTION

Particle receiver systems require a method to transport the particles from the bottom of the system back to the receiver for recirculation. A typical solid particle receiver consists of a top hopper residing above the receiver that introduces particle flow into the receiver. As the particles fall through the receiver, they are directly irradiated from the heliostat field radiation and fall into a bottom hopper (aka hot storage hopper) where they are either stored or can be sent through a heat exchanger for the power block. The particles are then sent to a cold storage hopper until they are required to pass through the receiver again. They are transported from the cold storage hopper back to the receiver top hopper with a particle lift device. There are several different types of particle lifting devices that can meet the requirements

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for a particle receiver system. The three main types include a screw-type vertical elevator, bucket lift vertical elevator, and skip-hoist-style bulk vertical lifts. Two of the elevator types (screw and bucket) have been tested at the National Solar Thermal Test Facility (NSTTF) at Sandia National Laboratories in Albuquerque, NM.

The test system at the NSTTF was a first of a kind, particle system with continuous particle flow capable of absorbing 1 MW_t from the heliostat field at the test site. The system is displayed in Figure 1 as a SolidWorks sketch. The previous experiments did not include a heat exchanger, but that is currently being installed into the system.

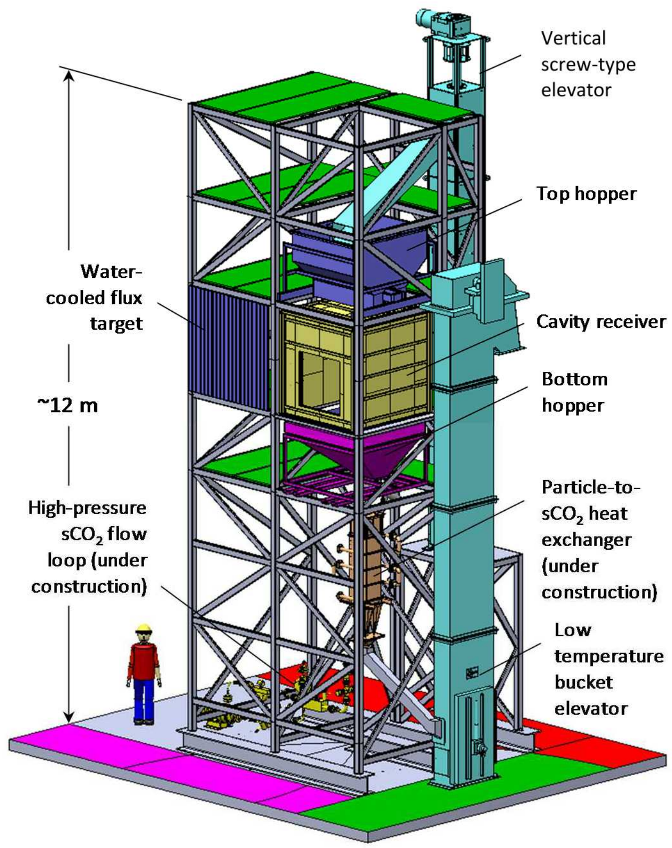

Figure 1. Sandia's Particle Test Loop (SPTL), situated on top of a 61 m (200 ft) tower, capable of recirculating particles at 1 – 10 kg/s at up to 800 °C with up to ~3 MW/m^2 of irradiance from a heliostat field at the National Solar Thermal Test Facility (NSTTF).

The experiments evaluated particle mass flow rates, operational characteristics of system components, and thermal efficiency. The system would flow particles from the top hopper, through the receiver, and into a bottom hopper. The particles were then diverted in two directions: to the screw-type elevator or the bucket elevator. The vertical screw-type elevator was utilized for a re-circulating mode providing multiple particle passes through the receiver to bring the system up to temperature. The bucket elevator was utilized to lift particles back up from ground level after mass flow rate was measured back into the screw-type elevator for transport to the top hopper. However, the bucket elevator was not insulated in this system to act as a heat sink as a heat exchanger was not present. The resulting system provided valuable information on the different particle lift devices commercially available. Key items measured or observed were: lift efficiency, operational issues, and possible control schemes to help control the particle flow through the system.

2. PARTICLE LIFT SYSTEMS

There are several options commercially available for particle systems including a screw-type vertical elevator, bucket lift vertical elevator, and skip-hoist-style bulk vertical lifts. Two of the systems (screw-type and bucket) were procured, installed, and tested at the NSTTF under on-sun testing conditions. The key design specifications and operational experience are described in this section.

2.1. Screw-Type Vertical Elevator

The screw-type elevator utilizing the Archimedes screw principle was chosen for the NSTTF system. The elevator has a center, stationary screw. A casing rotates about the screw causing upward forces on the particles. The rotating casing has outer insulation to reduce heat loss along the length of the elevator. This type of system is high temperature (800°C) and results in very little wear on the particles. Figure 2 shows a CAD model of the elevator that SNL tested. The drawing includes the lift tube (rotating casing causing particles to rise up the stationary screw), CB ring—centering bearing ring (keeps the rotating casing on-axis during operation), and the intake scoops (scoop the particles at the bottom of the elevator and forces them into the lift tube). The actual elevator includes external panels surrounding the support structure of the elevator to help keep the system weather tight and protect the insulation around the rotating lift tube.

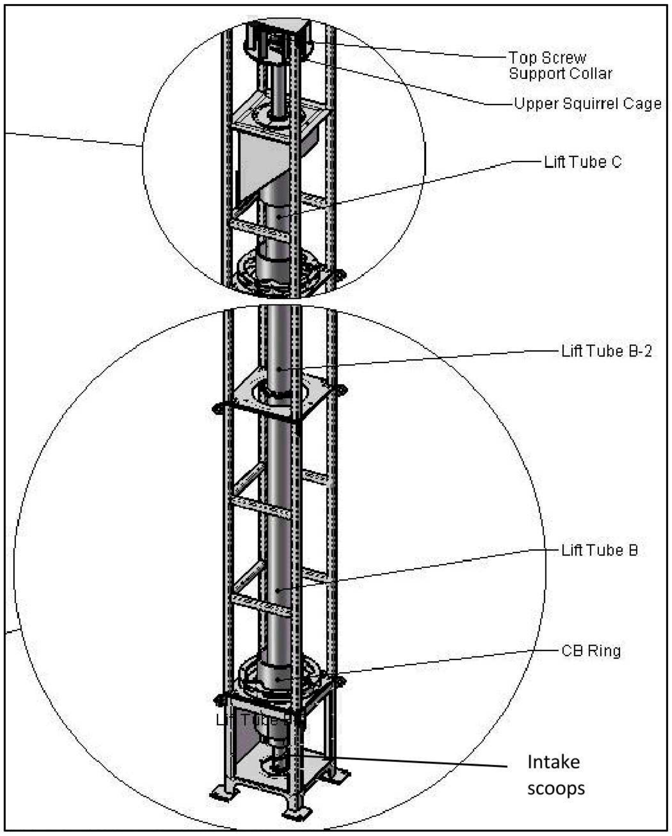

Figure 2. Screw-type elevator CAD representation exposing the internal components of the elevator

2.1.1. Design Specifications

The elevator had specific requirements to be utilized in the SNL particle system. This elevator needed a lift height of 7.62 m and a foot print of 0.88 m x 0.88 m to fit in the overall structure. A mass flow rate of 1-10 kg/s was required and designed for transporting ceramic particles in a 20/40 sieve size. A maximum particle temperature of 815°C needed to be transported and the elevator had to survive at these temperature conditions. The motor and drives were not specified and just needed to be powerful enough to provide enough rotation at low temperature and high temperature to transport particles at the required mass flow rate. The drive in this case was a variable frequency type drive with a NEMA4X enclosure, 25 hp, 460VAC, and 3 phase electrical requirement. The as-built elevator had all of these features and performed at the required conditions in most occasions.

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2.1.2. Operational Experience

This elevator has the most on-sun (heated) test hours of the two elevators currently present in the system. Several characteristics were measured and observed during the many operational hours. These items include lift efficiency, particle inlet loading conditions, and low-speed operation at high temperatures.

2.1.2.1 Lift Efficiency

The efficiency of the elevator was measured directly. The elevator was full loaded with particles and the current and voltage was measured on each phase wire of the elevator. The total power required to run the elevator is 18.5 kW and was calculated using these measure electrical values (30A and 460V measured on each wire), and a power factor of 0.87 (from motor technical sheet).

The elevator was then run at four frequencies to measure the mass flow rates at the different operational speeds of the elevator. The total power for each frequency setting was calculated by multiplying the mass flow rate by height of lift (7.62 m) and then by gravity (potential energy of the particles lifted). The resulting power values were divided by the power required to run the elevator. It is seen that the elevator gets more efficiency at higher mass flow rates, but is still an extremely low value.

Table 1. Screw-type elevator efficiency values at varying VFD frequencies

VFD Frequency (Hz)	Mass flow rate (kg/s)	Power (W)	Efficiency (%)
20	4.14	309.28	1.67
30	6.32	472.56	2.55
40	8.30	620.67	3.35
54	10.77	805.27	4.35

2.1.2.2 Particle inlet conditions to elevator

The elevator specifications required an equal flow of particles into the elevator inlet section. Due to the rotating nature of the elevator, the original design included a two-pipe ducting design for particle introduction into the hopper with particles being injected at the east and west side of the inlet with identical mass flow rates. This created a balanced load condition for the elevator during the initial testing of the elevator in on-sun conditions without a bucket elevator present in the system.

In the second phase of testing, the bucket elevator outlet particle flow needed to be fed back into the screw-type elevator inlet. This created a condition where the original two-pipe ducting still introduced particles on the east and west sides of the inlet space at identical flow rates, but also included the bucket elevator outlet ducting introducing another stream of particles on the west side of the inlet. The two-sided flow configuration for particle introduction into the inlet could not be met from the bucket elevator due to its geometric orientation to the screw-type elevator. To try and alleviate any potential issues, a wide duct was designed to help spread the particle flow across the entire west side of the inlet to avoid any localized particle mounding. This proved to be a flaw in the system and indicates a partial design flaw in screw-type elevators. In operational conditions, the bucket elevator flow added to the west side of the inlet forced the lift tube of the screw-type elevator to shift to the south-east in the elevator frame. The mechanical force of the extra particles on the west in addition to the other ducting introductions, in addition to the rotation/vibrations from operations, caused a deformation during operation and eventually led to a plastically deformed lift tube that is permanently biased to the south-east. The root cause for the deformation was believed to be a build up of particles in the inlet (with more on the west side) due to a mass flow rate greater than the design point of the elevator. However, the team did find that the screw-type elevator can account for slight deviations and still remain fairly balanced if the mass flow rate to the inlet of the elevator remained below the maximum design point of 10 kg/s. A secondary effect of this deformation was failure of two bearings at the middle, centering bearing of the elevator. The deformed lift tube, while normally is self-centering with a balanced load, was riding continuously on two of the south-east bearings of this particular centering ring (see Figure 3 for a CAD representation of the centering bearings). The continued off-balance vibrations, particles and dust penetrating the bearing surfaces, and constant contact with the tube resulted in failures of this bearing. These bearings were replaced multiple times with the same failure being identified. However, a failure has not been generated since applying a design condition of not introducing a mass flow rate of >10 kg/s into the inlet.

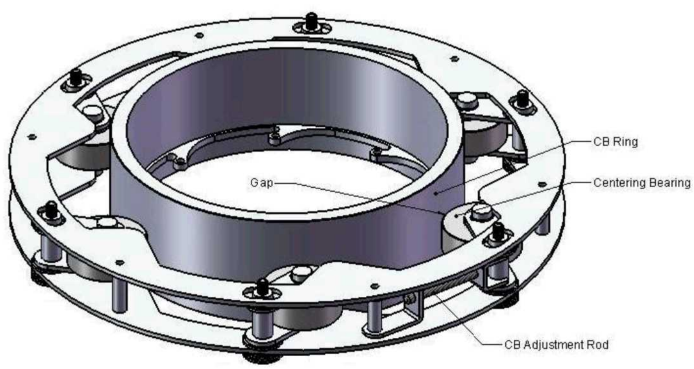

Figure 3. Centering bearing ring for the screw-type elevator, with bearings being shown

2.1.2.3 Thermal expansion issues

The design condition of withstanding 815°C requires the need to allow for growth in the elevator system itself. This particular screw-type elevator was designed to have the lift tube grow upwards towards the gear drive/motor to prevent any binding/buckling issues. However, during temperature operations above 300°C and low frequency conditions on the drive motor (resulting in a mass flow rate of 1-2 kg/s), the VFD would trip the motor out on over-current protection. The problem was narrowed down to be temperature related and no obstructions were observed at the top of the shaft where growth was supposed to occur. It is worth noting that the screw shaft was growing signifanctly (>2.54 cm) in the direction that it was expected to grow. However, the team believes that the internal casing and the scoops for the casing (see the scoops and inlet casing in Figure 4) were growing in a downward direction resulting in binding of the elevator. The binding is thought to have occurred due to packing of particles in the inlet (low mass flow rate out of the elevator, but high mass flow rate into the inlet of the elevator) and the downward growth of the scoops and inlet casing portions. Extensive experimentation was performed to resolve the issue and ultimately the solution was to run the motor at full speed if possible (if the mass flow rate of 10 kg/s can be allowed) which results in no motor trips due to lack of particle build up in the elevator inlet.

Figure 4. Inlet of screw-type elevator

2.2. Bucket Elevator

The bucket elevator is a simple device that has a series of buckets (sized for desired mass flow rate) mounted to a chain that runs the entire height of the elevator. The chain is connected to a gear drive and motor that forces the chain to rotate within the bucket elevator casing. As the chain rotates, the buckets are forced through the particulate media at the inlet of the elevator and are filled. They rise to the top of the elevator and as they are rotated past the apex of the rotational motion, the particles are dumped out of the elevator through some ducting. A bucket elevator can be built for high temperatures by using metal chain (with expansion joints built in) and providing some standoff between the hot chain/gears with the drive system. These types of elevators are common in the mining industry. One design issue could be that you are limited to a smaller range for mass flow rates due to a fixed bucket size.

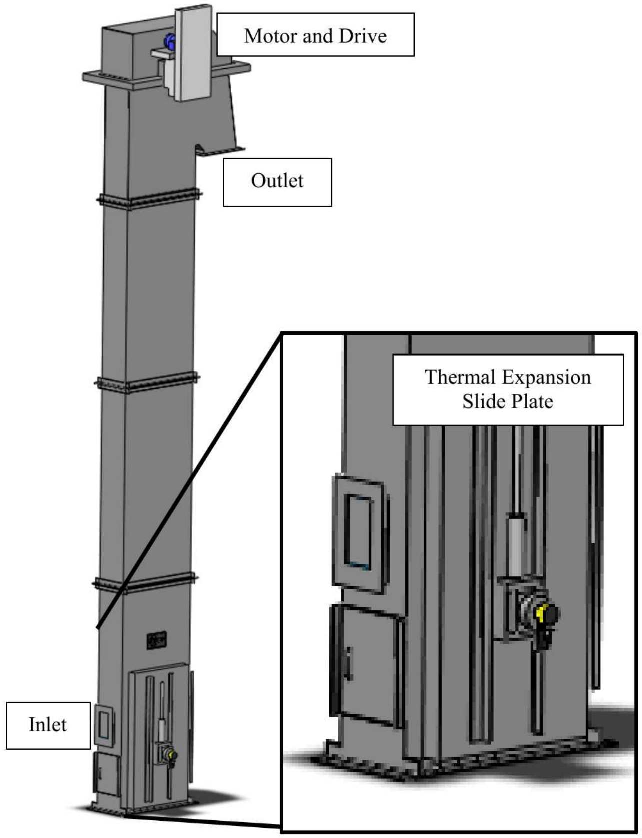

Figure 5. Bucket elevator CAD figure with dimensions on inlet

2.2.1. Design Specifications

The design requirements for this particle lift were based on the use as a secondary lift in the original particle system seen in Figure 1. The lift would transport particles after they are put in a mass flow rate hopper (in place of the heat exchanger in Figure 1) back into the screw-type elevator for transport back into the top hopper. The initial intent was a requirement for getting ground level particles back into the top hopper. To meet this condition several specifications were required. The discharge height must be 7.9 m (close to the screw-type lift requirement) and operate with a duty of 5000 kg of particles at temperature once to twice a week for months of testing. The elevator must handle 400-600°C particle temperatures at a mass flow rate of 0.5-1.0 kg/s. The design would be most compatible with particles from CARBO called Accucast ID-50 with a mean diameter of 280 microns. The motor specification must meet the required mass flow rate and was determined to be a 19 HP motor.

2.2.2. Operational Experience

The bucket elevator was tested in conditions with particle temperatures up to 600°C. It was utilized in a batch mode process and the operation had to be cognizant of the over-loading of the inlet hopper for the screw-type elevator issue. The elevator operated with particle temperatures from ambient up to 600°C. The efficiency of the lift and operational experience are presented.

2.2.2.1 Lift Efficiency

The bucket elevator was tested for efficiency similar to the screw-type elevator. The elevator was full loaded with particles and the current and voltage was measured on each phase wire of the elevator. The total power required to run the elevator is 3.1 kW and was calculated using these measure electrical values (4.6-4.75A and 280V measured on each wire), and a power factor of 0.8 (from motor technical sheet).

The bucket elevator mass flow rate was measured to be much higher than specifications at 6 kg/s. This made it much higher performing than anticipated. The potential energy from the particles lifted to 8.2 m height at a 6 kg/s flow rate results in 483 W. The bucket lift efficiency is 15.5%.

2.2.2.2 Thermal Expansion Slide Plate

The elevator installation was straightforward except for the expansion plate at the bottom of the elevator called the take-up slide plate. This plate is responsible for allowing adjustment to the chain to allow for thermal growth of the chain during high temperature operations. The plate is clamped to the outside of the elevator inlet and is oriented with the shaft near the center. It is only clamped down with enough force to keep particles from spilling out, but allow the slide plate to move. The shaft sits in a slot on the elevator sides that will allow movement up or down. A spring is used to tension the shaft to keep it in place, but can be compressed or expanded to allow the shaft to move in the slot. As the elevator heats up, the spring is expanded to allow the chain to grow and the shaft to shift downwards. There are two adjustments on the plate and spring. The first is to make sure that particles cannot escape from the inlet through the plate connection by clamping down the plate to the frame. The second is to adjust the compression on spring by torqueing a nut against the spring. Figure 6 shows the take-up slide plate and the clamps for the bucket elevator.

The clamps are press-fit with hand force against the plate and then tightened down by the two nuts on the clamp. This clamp does not have to be extremely tight against the plate, but needs to be loose enough to allow vertical movement of the plate. The spring can be compressed completely by torqueing the adjustment nut. The nut needs to compress the spring enough to allow for spring expansion when the chain grows, but not all the way otherwise the spring force and the chain growth counteract one another.

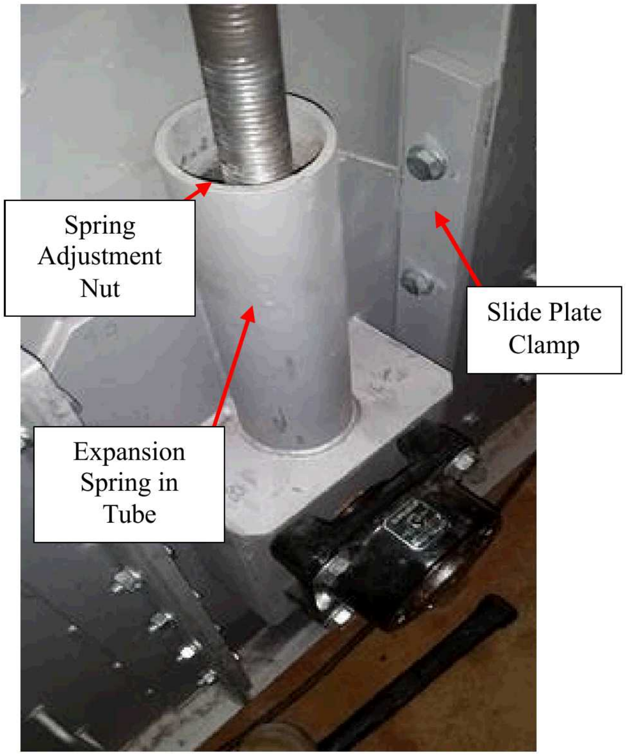

Figure 6. Take-up slide plate on the bucket elevator

2.2.2.3 Elevator Bracing

The elevator is required to be braced every 6 m of elevator height. This brace needs to keep the elevator from swaying, but also allow the outer casing to expand if necessary when under hot conditions. The bucket elevator is uninsulated during the operating modes for the SNL system. This allowed the team to build a surround brace around the elevator without having to account for constricting the growth of the elevator casing outward as the casing was cooling down to ambient temperatures during operation. Initially, room for thermal growth was accounted for in the brace design but resulted in swaying of the elevator that was deemed unfavorable by the vendor. The brace was shimmed against the elevator and resulted in a much more stable design. Future design concerns may include the need to insulate the full length of the elevator and adjusting the brace design to allow for thermal growth of the design.

2.3. Skip Hoist

A skip hoist elevator device is being considered for deployment in future particle system prototypes. This device acts like an elevator with a hopper that is filled from the top and also tilts to discharge the particles from the top (shown in Figure 7). This type of skip is called a Kimberly/overturning skip and is used commercially in mining applications. It has been shown that this type of elevating device allows for near zero particle leakage as the only inlet is at the top of the hopper. It can be used in high temperature operations by insulating the skip hopper. A disadvantage includes that the frame needs to be structurally sound and requires more material than other lift designs to account for high stresses during the over-turning movement of the hoist. This lifting device also seems to be more practical in a large system scenario for a 50-100 MW plant otherwise the small scale vs. cost scenario is not favorable.

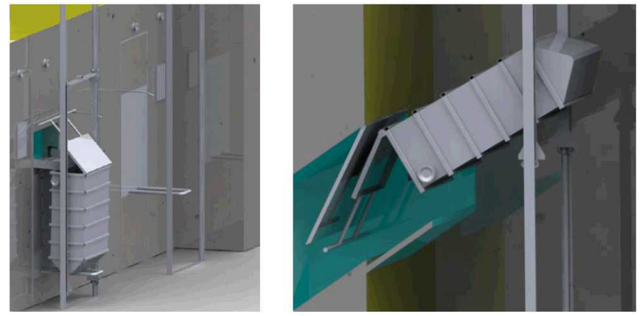

Figure 7. Skip hoist shown charging (left) and discharging (right)

2.3.1. Design Specifications

The elevator will have specific design specifications very similar to the other lifts discussed in this paper. The hoist must be able to lift particles at a rate sufficient to keep the feed hopper for the receiver filled. Utilizing this lift will require a larger feed hopper system as the hoist works in a batch operation mode. The hoist must be able to handle high temperature particles up to 750°C for operational conditions, but most likely a higher temperature will be required to account for thermal losses in the system.

The skip hoist has been evaluated through extensive literature and modelling and it was determined that efficiency could be as high at 80% [1]. Although not directly measured in this paper, this efficiency is the highest of the particle lifts evaluated by the team. When a design is finished, a high efficiency will be specified based on these values.

In addition to the other specifications, two other advantages are seen with the skip hoist. The hoist bucket has a low thermal mass compared to other lift designs. The hot particles are only in contact with the hoist bucket and not the support features of the lift as well. This results in a quick start up of the hoist in the event of an extended operational shutdown. The heat being localized to the hoist bucket is also advantageous as the moving parts are outside of the heated region. This results in less complex designs and more standard parts for the mechanisms driving the hoist.

3. DISCUSSION

Two of the lifts discussed in this paper have been used in the SNL particle receiver system. Both the screw-type and bucket elevator were exposed to high particle temperatures for extended operational times. The two lifts are compared with advantages being discussed.

3.1. Efficiency Comparison

Each elevator efficiency was measured under full load particle conditions. The screw-type elevator efficiency was measured to be 3% while the bucket elevator had an efficiency of 15.5%. A difference of 12.5% in component efficiency is significant during plant operation and needs to be considered when choosing equipment. The bucket elevator efficiency could theoretically be higher if the design of the inlet hopper were to be changed to aid in the scooping of particulate matter by the buckets reducing the frictional losses caused by the scooping action.

The skip hoist has a much greater efficiency, estimated to be 80%. This is advantageous to operations, but the lift is only really practical at the moment for large scale plant systems.

3.2. Operation Comparison

Installation/Setup: The screw-type elevator was installed simply by mounting the lift in place and connecting the required ductwork. The component does not require any adjustments by the operator except for hooking up the electrical power requirement. The bucket elevator requires manual adjustment to the take-up slide plates and tension spring that take some experience for tuning the system.

Inlet loading conditions: The screw-type elevator requires very specific inlet ducting configurations to avoid unbalanced loading and operation of the elevator. It is possible that operation modes may help to alleviate this issue but requires more complex operating procedures that can be unfavorable. The bucket elevator did not have issues in the inlet of the system. No issues were identified when the inlet was fully loaded with particles and the bucket elevator starting from this condition.

Mass flow rate regulation: The screw-type elevator has the ability to adjust the mass flow rate provided to components through a VFD. This range of flow rates is extremely useful during operation conditions. The bucket elevator was specified to have a mass flow rate of about 1 kg/s, but actually had a mass flow rate of 6 kg/s. Conversations with the vendor indicated that the higher mass flow rate could damage system components as the other component on the elevator (drive, motor) were specified for a lower flow rate. It was determined, to extend the life of other elevator components, the inlet of the elevator should ideally be regulated to the originally intended 1 kg/s. It should be noted that this design specification should be accurately identified when designing a bucket elevator for the required particle system.

External bracing: The screw-type elevator required bracing along the height of the elevator. However, due to the design of the equipment, the external casing of the elevator will always be at low temperature conditions because the rotating shaft is directly insulated. This simplifies the bracing of the elevator by not having to account for thermal expansion at this fixture points. The bucket elevator requires bracing along the height of the elevator, but the bucket elevator requires insulation on the outer casing of the lift. This creates a design requirement for the bracing to accommodate thermal expansion, but also remain snug against the elevator at low temperature conditions to prevent the equipment from swaying.

Design Limitations: Known design limitations for each lift are discussed here. The bucket elevator is limited to a certain height before additional lifts are required. The chain can only handle approximately 61 m of height before stresses cause failure. The screw-type elevator is also limited to a height before the motor/drive cannot provide enough power for the rotation of the shaft.

3.3. Heat Loss Comparison

An important consideration between the different lift types needs to be heat loss. The screw-type elevator and bucket elevator include insulation to prevent heat loss from the system, but the two designs differ significantly in total surface area for heat loss to occur from. The screw-type elevator only needs to insulate around the 0.254 m rotating lift tube casing resulting in surface area of 6.1 m^2. The bucket elevator requires external insulation around the entire elevator which is a surface area of 25.2 m^2. Thus, the bucket elevator has the potential for 4 times more heat loss than the screw-type elevator due to significantly more surface area.

4. CONTROL SYSTEM

An additional feature that is being established with the current screw-type elevator is control over the rotational speed through the VFD. This control will allow the operators of the test plant to maintain a consistent level of particles in the top hopper of the system. This will help to de-risk any faults that could cause receiver failure due to lack of flow through the receiver when particle inventory in the top hopper runs out.

4.1. Control Requirements

The objective of the control system is to maintain a constant particle level in the top hopper. Load cells are being added underneath the top hopper to have a constant measurement of weight (and mass flow rate) from the hopper. The control algorithm with need to regulate the particle level in the hopper based on the feedback from the load cells on hopper weight. If the level is low, the screw-type elevator will provide a higher mass flow rate to the system and vice-versa.

4.2. Control System Layout

The plan for the control system is shown the layout of Figure 8. The active feedback for the control hardware (PXI Chassis) will include the load cells from the top hopper (direct particle level quantity) and the slide gate for the top hopper (additional feedback for predictive changes). The top hopper load cells will be the primary control feedback in the PID loop used to control the 0-10V signal needed for the VFD control. The slide gate under the top hopper is responsible for releasing particles into the receiver to allow for heating and is actively changing to maintain the outlet particle temperatures from the receiver. This dynamic nature of the slide gate could be used in conjunction with the load cell measurements to make certain that particle levels won't drop below a certain requirement. The slide gate has the potential to open up to large depths allowing large mass flow rates in the receiver that could drop particle levels in the hopper quicker than the load cell feedback and VFD can respond.

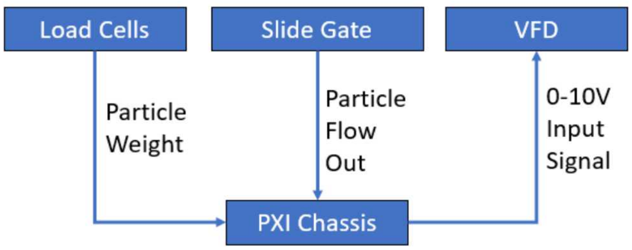

Figure 8. Initial control algorithm diagram

5. CONCLUSION

Detailed observations and analysis have been performed on different particle lift devices used for particle receiver systems. Each piece of equipment had a set of design specifications and it was determined that the screw-type and bucket elevators could meet the requirements with slightly specialized, but commercially available models. Requirements included high temperature, 600-815°C, and heights up to 7.62m. Experiments were performed at high temperature conditions and the operational characteristics were evaluated for each piece of equipment. K. In addition, a skip hoist elevator has been briefly evaluated and deemed most efficient and commercially available for large scale systems running >20kg/s of particulate material. Specialized control algorithms are being developed now to control the VFD of the screw-type elevator. Grouping of the load cells of the top hopper will result in a total pre-determined weight with a particular particle level that will be feedback for the control system. Also included in the control system will be a secondary check/PID integrated with the top hopper slide gate to try and account for any dramatic particle level changes that could impact the level in the top hopper. Yield of particles introduced into the top hopper will always be measured with the load cells.

6. AKNOWLEDGMENTS

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7. REFERENCES

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