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Designing and Testing of a High-Temperature Particle Lift for Concentrating Solar Power Applications

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Abstract. The use of solid particles in concentrated solar power (CSP) technologies enables operation at elevated temperatures (approximately 1000°C), resulting in improved thermal efficiencies and reduced costs for CSP applications. However, achieving high-temperature operation in particle-based systems presents significant challenges, as all key components must be rigorously evaluated under elevated temperature conditions. In a particle-based CSP system, a substantial amount of heat loss occurs during the handling of particles. Furthermore, as the system's capacity increases, the height of the tower also rises, leading to prolonged travel times for the particles and consequently greater heat loss. King Saud University and Sandia National Laboratories are collaborating on the design, testing, and risk mitigation of a cost-effective particle lift system (PLS) suitable for high-temperature applications. This paper outlines the design basis, sizing methodology, scaling considerations, and ground testing of two different PLS scales.

Keywords: Particle-Based Concentrated Solar Power, High Temperature Particle Handling, Particle Lift System

1. Introduction

Particle-based concentrating solar power (P-CSP) technology has emerged as a viable and energy-efficient solution, particularly in regions with abundant direct normal irradiance (DNI). A P-CSP system comprises several key components (shown in Figure 1), including a Particle Heating Receiver (PHR), where solar energy is captured to heat the particles; a High-Temperature Thermal Energy Storage (HT-TES) Bin, which stores excess thermal energy at elevated temperatures for later use; a Particle to Fluid Heat Exchanger (PFHX), where the captured solar energy is transferred from the heated particles to a working fluid; and a Particle Lift System (PLS), which facilitates the movement of particles between different components of the system.

However, achieving high-temperature operation in a P-CSP system poses significant challenges, as all critical components must undergo comprehensive research, design, and evaluation under elevated temperature conditions. This necessitates the development of materials and technologies capable of withstanding high thermal stresses to ensure reliable performance, complicating overall system integration and operation.

In a high-temperature P-CSP systems, a substantial portion of heat loss occurs during the charging and discharging processes, as particles are exposed to lower ambient temperatures [1, 2]. Furthermore, as the capacity of the P-CSP system increases, the height of the tower must also rise to accommodate larger thermal energy storage systems (TES), particle-to-fluid heat exchangers (PFHX), and particle heating receivers (PHR). This results in extended travel times for particles moving from the charging station to the top of the PHR, consequently increasing heat loss through the walls of the HT-PLS to the surrounding environment.

Therefore, it is essential for the HT-PLS to operate with high efficiency to minimize parasitic heat losses while remaining cost-effective. Extensive research has been conducted globally to identify and evaluate suitable particle lift systems for P-CSP plants. Various options have been explored, including bucket elevators, conveyor belts, screw elevators, and skip hoists, which are commonly utilized in the mining industry. Sandia National Laboratories (SNL) has evaluated several particle lift systems, with a particular emphasis on bucket elevators (BEs). BEs offer the advantage of operating at moderately high temperatures (greater than 200°C) and enabling continuous particle discharge. However, they are susceptible to significant heat losses due to the large surface area exposed to the heated particles, making it challenging to provide adequate insulation around the elevator housing. Research at the Georgia Institute of Technology (GIT) indicates that considerable heat loss is anticipated at 300°C, which is the minimum particle temperature in a baseline design.

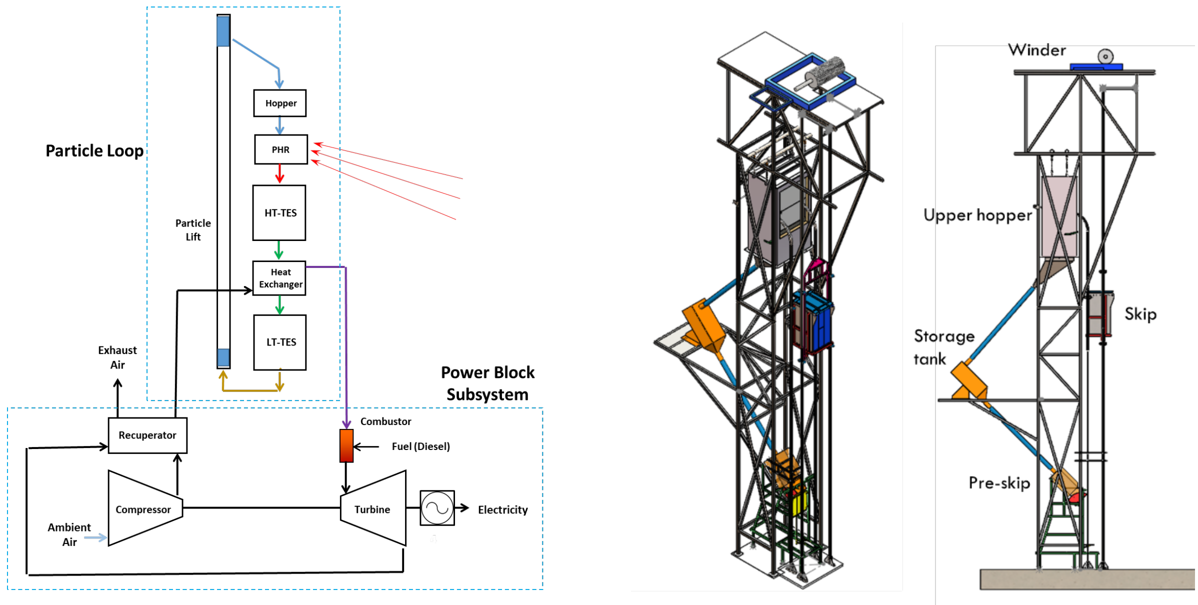

Figure 1. *(Left) Particle-based CSP plant layout, (Right) Skip-Hoist System*

Moreover, studies have highlighted that conventional bucket elevators often encounter operational issues such as backflow and excessive spillage, which can adversely affect the system's efficiency and reliability. Additionally, achieving the required high mass flow rates (approximately 1000 kg/s) and lift heights (around 250 m) for large-scale commercial concentrated solar power (CSP) plants (approximately 100 MWe) presents significant challenges for commercially available bucket elevator systems [3].

Screw-type particle lift systems utilize a rotating outer drum to transport particles up an internal helix through friction. While they can handle particles at elevated temperatures (up to 800°C) without interruption, the cost of screw elevators increases linearly with the height of the tower. Their lifting efficiency has been calculated at only 5%, and the excessive particle attrition and wear caused by friction result in significantly lower energy efficiency compared to bucket elevators or skip hoists.

Conveyor belts offer the advantage of minimal spillage; however, they are challenging to integrate into the power tower structure and cannot operate at the elevated temperatures required for P-CSP applications. These challenges underscore the need for innovative designs and modifications to existing PLS to meet the specific requirements and limitations of P-CSP applications.

Skip-Hoist system (shown in Figure 1) includes a pre-skip subsystem configured to store a given quantity of hot particles therein and to automatically discharge the particles into an empty skip placed in a loading area in front of the pre-skip subsystem. The loaded skip is then moved upwardly to dump the particles into an upper hopper which acts as a receiver feeding hopper. This system eliminates all issues pertaining to other particle lift systems, low parasitic load, reduced heat leak, and cost-effective. This paper outlines the design procedure and preliminary testing of a skip hoist system for a particle-based high-temperature power tower plant.

2. Sizing Methodology

Figure 1 illustrates the main components of a P-CSP plant. The thermal duty of the heat exchanger ($\dot{Q}_{thermal}$) is related to the plant net power output ($\dot{W}_{net}$), for a given conversion efficiency (η_{th})

$$\dot{Q}_{thermal} = \frac{\dot{W}_{net}}{\eta_{th}} \tag{1}$$

The required thermal power absorbed by PHR ($\dot{Q}_{PHR-abs}$) to achieve the design power output is calculated based on solar multiple as (MUX)

$$\dot{Q}_{PHR-abs} = \dot{Q}_{thermal}\, MUX = \frac{\dot{W}_{net}}{\eta_{th}} MUX \tag{2}$$

Therefore, the nominal thermal power incident on PHR aperture ($\dot{Q}_{PHR-inc}$) can be obtained based on receiver efficiency (η_{PHR}) as

$$\dot{Q}_{PHR-inc} = \frac{\dot{W}_{net}}{\eta_{th}} \frac{MUX}{\eta_{PHR}} = \eta_{Field}\,(DNI\, A_{Ref}) \tag{3}$$

The particle flow rate entering the PHR ($\dot{m}_{P_{PHR}}$) is obtained based on solar multiple (MUX), temperature rise across the PHR (ΔT_p), overall plant efficiency (η_{th}), and net electrical power of the turbine as

$$\dot{m}_{P_{PHR}} = \frac{\dot{W}_{net}}{\eta_{th}} \frac{MUX}{\int_{T_{PHRi}}^{T_{PHRo}} cp_p dT} \tag{4}$$

The particle flow rate through the heat exchanger ($\dot{m}_{P_{HX}}$) can be calculated as

$$\dot{m}_{P_{HX}} = \left(\frac{\dot{W}_{net}}{\eta_{th}} \frac{MUX}{\int_{T_{PHRi}}^{T_{PHRo}} cp_p dT}\right) \frac{t_{on-sun}}{t_{on-sun} + t_{storage}} \tag{5}$$

where t_{on-sun} is the nominal daytime operating hours and $t_{storage}$ indicates the storage hours. The difference between the mass flow rate of particles entering the high-temperature thermal energy storage HT-TES (denoted as $\dot{m}_{P_{PHR}}$) and the particles leaving HT-TES represents the particle accumulation in the HT-TES bin ($\dot{m}_{P_{Accu}}$), this can be expressed as

$$\dot{m}_{P_{Accu}} = \left(\frac{\dot{W}_{net}}{\eta_{th}} \frac{MUX}{\int_{T_{PHRi}}^{T_{PHRo}} cp_p dT}\right)\left(1 - \frac{t_{on-sun}}{t_{on-sun} + t_{storage}}\right) \tag{6}$$

Both TES tanks will have an inner volume adequate to accommodate the accumulated particles, flowing at a rate of $\dot{m}_{P_{Accu}}$ for during on-sun operation. Therefore, the inner volume of the TES ($\forall_{TES}$) is calculated as

$$\forall_{TES} = \left(\frac{\dot{W}_{net}}{\eta_{th}} \frac{MUX}{\int_{T_{PHRi}}^{T_{PHRo}} cp_p dT}\right)\left(1 - \frac{t_{on-sun}}{t_{on-sun} + t_{storage}}\right)\frac{t_{on-sun}}{\rho_P} \quad (7)$$

where ρ_P is the particle bed density (kg/m^3).

The volume of the skip ($\forall_{Skip}$) can be defined as the particle inventory to keep steady particle flow through the PHR.

$$\forall_{Skip} = \left(\frac{\dot{W}_{net}}{\eta_{th}} \frac{MUX}{\int_{T_{PHRi}}^{T_{PHRo}} cp_p dT}\right)\frac{t_{Skip_{Journey}}}{\rho_P\, N_{skip}} \quad (8)$$

where $t_{Skip_{Journey}}$ represents the time needed for the skip to complete a full journey, starting from filling at the bottom to tower, discharging to the upper hopper, and returning to the filling position, $t_{Skip_{Journey}}$ can be expressed as

$$t_{Skip_{Journey}} = t_{Skip_{loading}} + 2t_{travel} + t_{Skip_{discharging}} \quad (9)$$

The skip travel time is related to the skip speed and the elevation of the upper hopper. The skip speed is determined by the lifting mechanism; KSU employs a winder that can pull the skip at a nominal speed of 2 m/s, while SNL utilizes a rack-and-pinion system with a nominal speed of 0.5 m/s. The upper hopper is positioned slightly higher than the Particle Heating Receiver (PHR) to ensure adequate tilt, facilitating particle flow. The optical height of the tower (to the center of the PHR) can be obtained using SolarPilot at a specified plant capacity. To enable prompt skip loading, it is preferable to size the pre-skip equal to the skip, while the upper hopper should be 50% larger to provide a particle buffer and ensure steady particle flow through the PHR.

3. System components

The particle lift consists of four main subsystems: a pre-skip, a skip, an upper hopper, and a lift mechanism. The following section provides a detailed description of each subsystem and highlights the key similarities and differences between the KSU and SNL systems.

3.1 Pre-Skip

The pre-skip is the component that connects the skip to the thermal energy storage (TES) tank. It is regarded as the most challenging subsystem, as it must accumulate and provide an appropriate volume of particles to the skip during the relatively short charging process. Figure 2 presents a side-by-side comparison of the two pre-skip designs.

KSU's pre-skip features a pivoting chute that delivers particles to the skip. It is designed to retain as much heat as possible in the particles loaded into the skip. This is accomplished by equipping the pre-skip with an insulated particle storage chamber that features a chute at its downstream end. The chute is configured to open automatically when the skip arrives in the pre-skip area for loading. This opening allows the stored particles to be dumped into the skip. Additionally, as will be detailed later, the pre-skip includes a mechanism for automatically opening the lid of the skip when it is stationed for loading. This ensures that the correct quantity of particles (defined by the interior storage area of the pre-skip) can be quickly transferred into the skip, thereby reducing the time the particles are exposed to cooler ambient temperatures and minimizing heat loss.

SNL's pre-skip comprises two main components: a slide gate and a concentric tube feeder. This configuration is suitable for large-scale applications where an insulated chamber, as seen in KSU's design, is unnecessary. The operation of the slide gate is controlled by the arrival and departure of the skip, which minimizes the particle residence time outside the storage bin. The concentric tube feeder is responsible for delivering the high-temperature particles to the skip. The size of the charging duct must be adequate to achieve prompt charging process, ensuring minimal charging losses. Currently, both KSU and SNL systems are designed for a charging process of less than 5.0 seconds. Finally, the movement of the filling duct is precisely controlled by a pneumatic cylinder, whereas the movement of the pre-skip pivoting chute is fully automated.

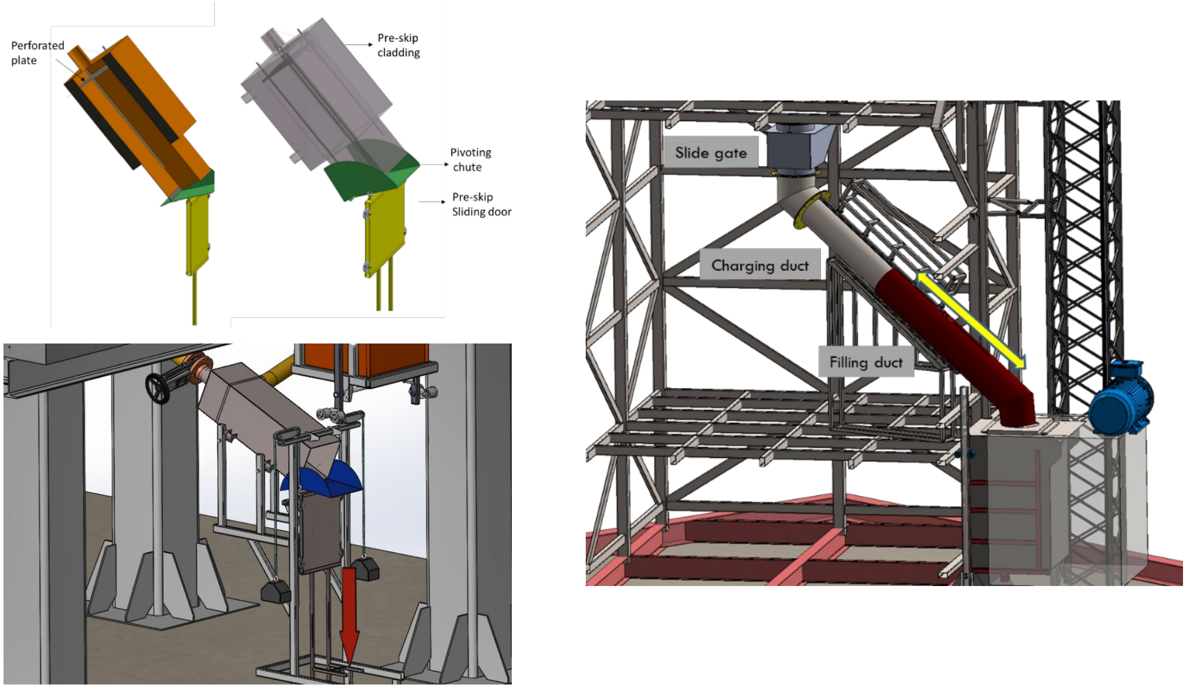

Figure 2. *Pre-skip final design, (left) KSU design, (right) SNL design*

3.2 Skip

The skip is an internally insulated chamber that is hoisted up and down a set of rails (traveling between the pre-skip station and the upper hopper) by a lifting system. It transports particles from the pre-skip to the upper hopper, where they are dumped inside. The skip design is similar for both systems, as shown in Figure 3, which illustrates the skip assembly consisting of two chambers.

The inner liner is designed to accommodate high-temperature particles, while the outer shell houses and protects the insulating material. The structural integrity of the skip is maintained by a support frame that acts as a fastener, holding the skip in place during thermal expansion and contraction that occurs during charging and discharging.

In KSU's design, the skip is configured so that its lid automatically closes by gravity (via its own weight) immediately upon leaving the pre-skip loading area while being hoisted upward toward the upper hopper. In contrast, SNL's design features a lid equipped with a filling port. Upon the arrival of the filling duct, the slide gates open, allowing the particle stream to open the filling port. This configuration is intended to minimize the amount of entrained air during the filling process. The filling port is equipped with a counterweight to ensure it closes immediately once the filling process concludes. Table 1 outlines the design parameters and operating conditions of both systems.

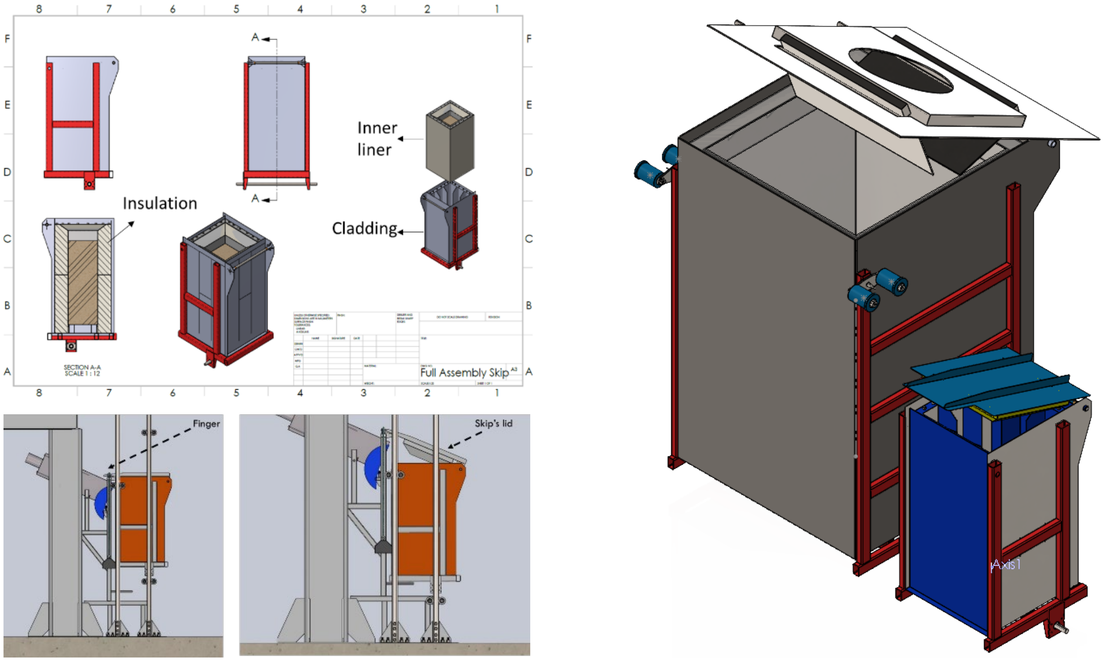

Figure 3. *Skips final design*

Table 1. *Main design parameters of both systems*

	KSU system	SNL system
Particle flow rate	1.0 [kg/s]	25.0 [kg/s]
Lifting speed	0.5-2.0 [m/s]	0.5 [m/s]
Lift mechanism	Drum hoist (Winder)	Man lifting system (Alimak rack)
Operating Temp.	400-600 [˚C]	400-800 [˚C]
Travel height	38 [m]	20 [m]
Inner volume	0.08[m3]	1.0 [m3]

3.3 Upper Hopper

In a PBCSP plant, the upper hopper serves as a buffer "tank" that receives the skip load and delivers it to the particle heating receiver (PHR) hopper. It is crucial to minimize heat loss during skip discharge to ensure the effective operation of the entire system. The design of the upper hopper incorporates several features aimed at this goal, including a double air-blocking system and a silicon carbide (SiC) foam filter, which prevents large particles or contaminants from entering the PHR.

The discharging mode, illustrated in Figure 4, shows the skip delivering particles to the upper hopper. The skip opens the vertical air-blocking door, allowing the flowing particles to activate the air-blocking trap door. This arrangement minimizes air entrainment and infiltration, thereby reducing advective heat loss. The SiC foam filter is employed to capture any large particles or contaminants.

Since the upper hopper receives particulates only intermittently, utilizing it as a mass flow measuring and monitoring bin presents a valuable solution to mitigate the challenges of measuring the mass flow of extremely hot particulates. This approach aids in data acquisition, performance monitoring, and control.

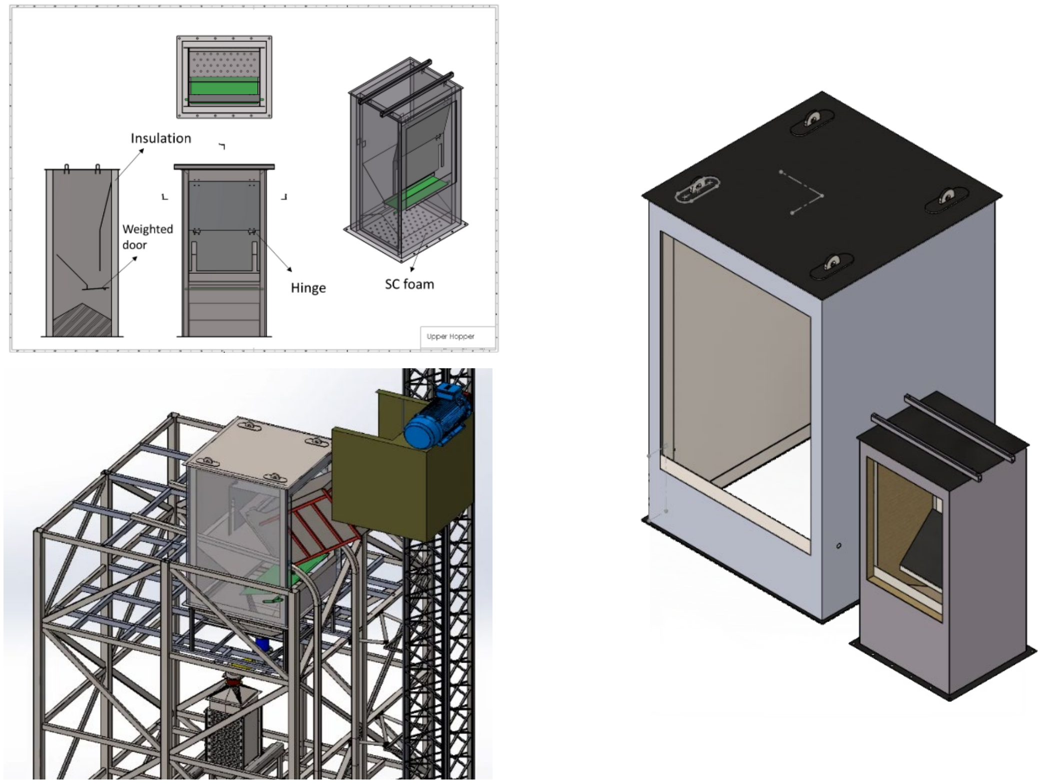

Figure 4. *Upper hopper final design*

4. Construction and Testing

The construction of the particle lift system has been successfully completed, as illustrated in Figure 5. The integration of all subsystems, including the upper hopper, skip, pre-skip, and winder, has been accomplished. Preliminary testing of particle handling has also been conducted, demonstrating smooth interaction among all subsystems.

Based on initial testing, the skip travel has been divided into three segments. To avoid any impacts, precise control of the skip's speed is necessary at the boundaries of each segment. As shown in Figure 5, the skip initiates its journey at Level 0, requiring a brief dwell time for skip charging (around 10 seconds). This charging period is kept minimal (around 5 seconds) to reduce exposure to ambient conditions. Once charging is complete, the skip is slowly pulled upward to facilitate the smooth closure of the pre-skip pivoting chute.

Upon reaching Level 1, the skip speed increases to its maximum. During this interval, the skip exerts minimal load on the guide rails, necessitating precautions to maintain its perpendicularity. As the skip approaches the upper hopper, it must gradually decelerate starting from Level 2 (around 5 seconds), with a recommended speed of less than 0.1 m/s. Upon reaching Level 3, a dwell time (around 5 seconds) is required to ensure the complete delivery of the skip's load. It is important to note that the return journey of the skip follows the same protocol as the departure.

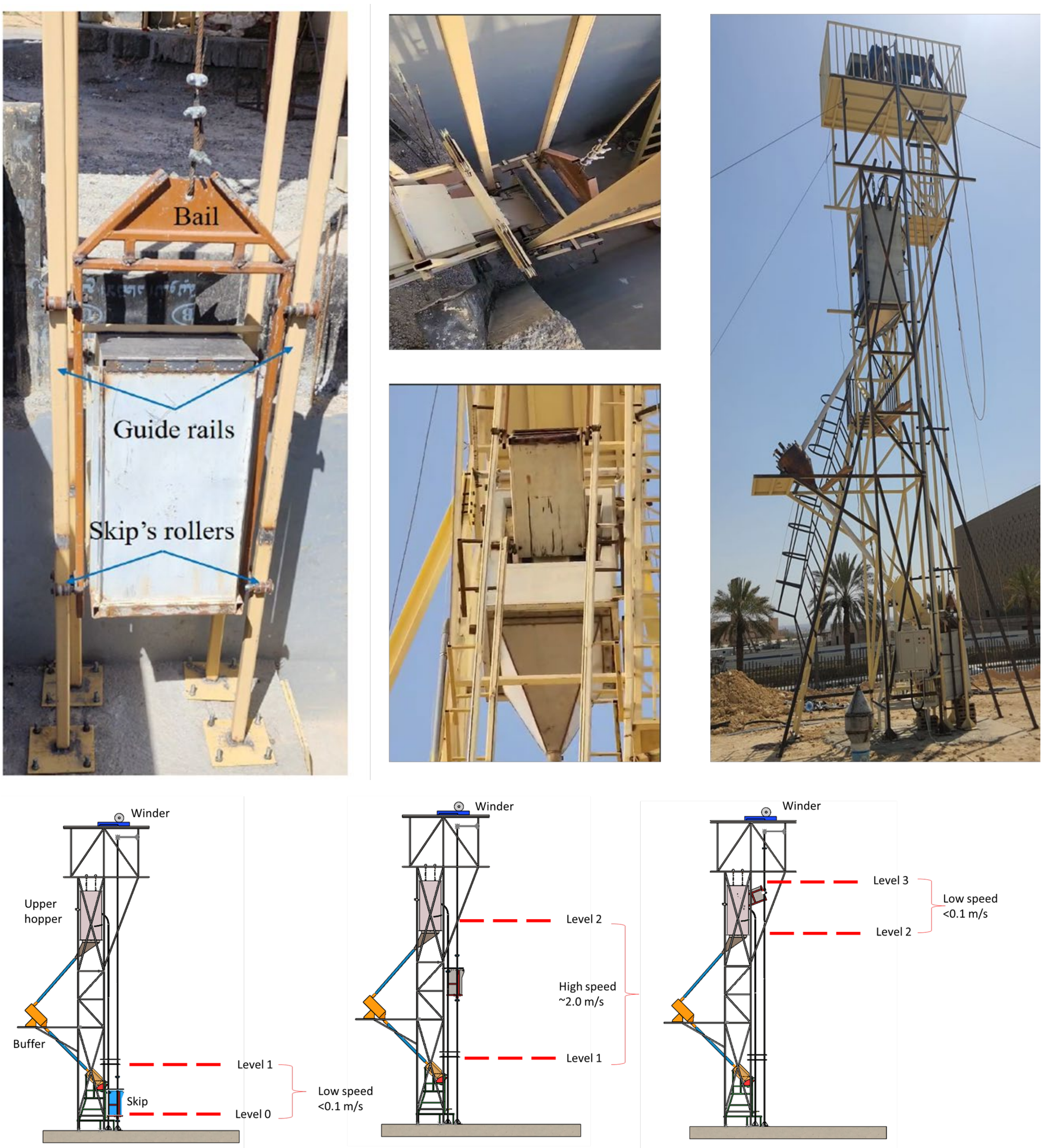

Figure 5. *Completion of the construction and pre-testing*

5. Conclusions

Two particle lift systems are set to be constructed at KSU and SNL at different scales to further investigate any scaling limitations and outline design requirements for implementing the current designs in high-temperature particle-based applications. A comprehensive design methodology that relates skip volume to the thermal duty of a particle-based plant is presented. The system merits address all risks associated with other lift mechanisms. The current design can effectively reduce heat loss by minimizing particle residence time within the particle lift system. Additionally, the use of a skip reduces the amount of particulate mass within the lift compared to screw and buck lifts. This approach is expected to significantly decrease parasitic loads, eliminate particle attrition, and substantially reduce dust generation. KSU's system has been successfully constructed and tested at ambient temperatures, demonstrating smooth skip traveling, loading, and discharging. The sizing, mechanical, and thermal analysis for the SNL system has been completed, with construction anticipated to commence by October 2024.

Data availability statement

The study is presented as-is, no additional underlying data is provided.

Author contributions

Shaker Alaqel: Conceptualization, Methodology, Investigation, Formal analysis, Visualization, Validation, Data Curation, Writing - Original Draft, Writing - Review & Editing, Supervision. **Nader S. Saleh**: Investigation, Validation, Data Curation, Writing - Original Draft, Writing - Review & Editing. **Nathan Schroeder**: Conceptualization, Methodology, Resources, Investigation, Formal analysis, Visualization, Validation, Data Curation, Supervision, Funding acquisition, Project administration. **Hany Al-Ansary**: Supervision, Funding acquisition, Project administration. **Jeremy Sment**: Supervision, Funding acquisition, Project administration. **Felicia Brimigion**: Investigation, Formal analysis, Visualization, Validation.

Competing interests

The authors declare that they have no competing interests.

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