SAND2020-10795C

Modeling thermal transients of bulk particle lifting systems with CFD simulations

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Abstract. Computational Fluid Dynamics modeling of two different high-temperature particle lifting systems was done in order to be able to capture the thermal behavior of these systems. The two lifting mechanism modeled were a closed bucket elevator that carries the particles up a shaft with a conveyor belt of buckets, and a skip hoist that goes through a cycle of loading, lifting, unloading, and lowering. Both of the modeled systems were subject to a validation process, where the bucket elevator was compared to IR images taken of a real bucket elevator in use under high temperature conditions, and the skip hoist was compared to a 1-D MATLAB model using the heat equation. Both models showed reasonable validation results, and therefore an insulation thickness study was done on both models in order to show the capability of using Computational Fluid Dynamics tools for analysis on these types of systems as a way to inform design decisions. The results were able to show the relationship between increased insulation and lower particle temperature loss of the systems and was able to do so for both steady state and transient results.

1. INTRODUCTION

As research into falling particle heating receivers (PHR) for concentrated solar power systems continues to move towards large scale applications, there is growing interest in finding ways to efficiently lift large amounts of bulk particles at high temperature. Several promising lift mechanisms have been proposed and tested including bucket elevators and skip hoists, both of which have been used in other industries for moving bulk material such as mining and agriculture [1]. However, previous applications of these mechanisms did not have the added level of complexity of dealing with a high temperature material. Previous analysis methods have not considered transient heat transfer in these dynamic systems, which is essential as we look to design larger scale lifting mechanisms for larger PHR systems.

One type of analysis tool that does possess the capability to perform thermal analysis of dynamic systems are computational fluid dynamics (CFD) simulations. These simulation tools can be used to characterize the heat transfer occurring with the particles as the lifting system operates. This allows for consideration of key design aspects such as heat loss of the system, change in particle temperature, and the time it takes for the system to reach a thermal steady state. It also provides insight into how the designs can be altered to improve efficiency, i.e. adding insulation to these lifting systems. All of the modeling and analysis in this paper was done using SOLIDWORKS and its built in CFD package SOLIDWORKS Flow Simulation.

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2. MODELING APPROACH

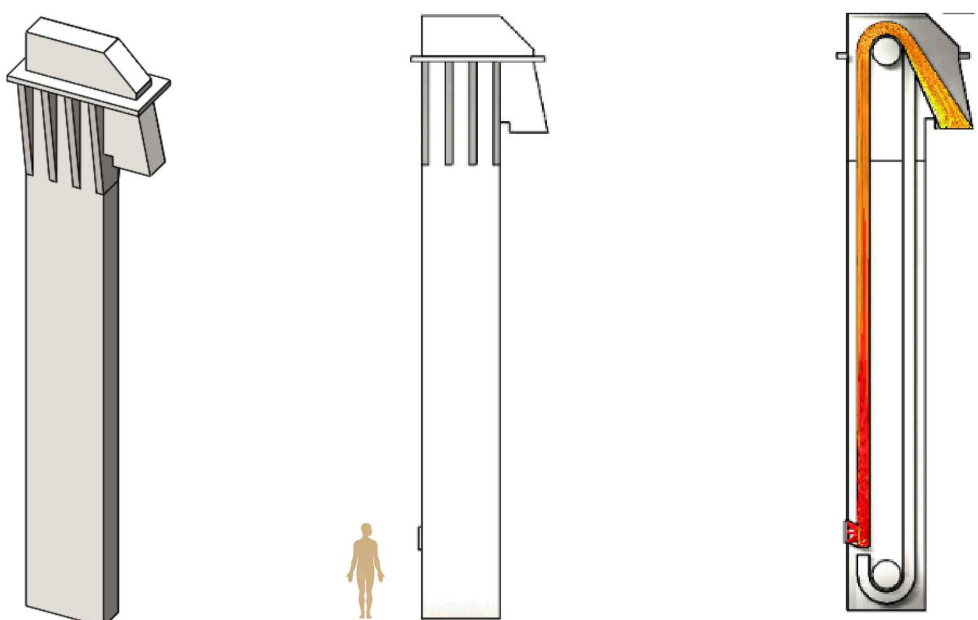
2.1 Bucket Elevator

The first lifting mechanism this paper will look at using computational fluid dynamics (CFD) modeling software is the bucket elevator. The bucket elevator consists of a closed vertical shaft where particles enter in a continuous flow through an opening at the bottom of the shaft. A conveyor belt/chain with attached buckets is driven by a motor to carry the particles to another opening at the top of the shaft.

Two different cases for the bucket elevator were used in this analysis. The first design that was used in the simulations was based on the system currently in use at the National Solar Thermal Test Facility (NSTTF), which was designed and manufactured by Materials Handling Equipment Company (MHE) and stands at a height of ~33ft tall from inlet to outlet. This will be referred to as the test-scale bucket elevator, and the model can be seen in Figure 1. The second bucket elevator that will be looked at is what has been proposed as the lifting mechanism for the Generation 3 Particle Pilot Plant (G3P3), which is ~150ft tall from inlet to outlet, and the designs of which were also done by MHE. This model will be referred to as the pilot-scale bucket elevator, and the model can be seen in Figure 2.
Besides their height, these two bucket elevators are very similar in many design aspects. Their footprints are similar, they use the same bucket design, and for both the casings and buckets are made from low carbon steel. Furthermore, both conveyor systems move at a speed of 100 ft/min or 0.508m/s, with the mass flow rate being determined by how full the buckets are.

In order to be able to model these bucket elevators with CFD tools one of the assumptions that had to be made was that it was reasonable to replace the individual buckets within the elevator with a continuous column of particles that flowed with the same speed and with the same mass flow rate as the real system. The column containing the particle flow path was also made of the same material as the buckets and had a thickness that was calculated to preserve the amount of mass of the buckets. This assumption had to be made because currently there is no software that can simultaneously handle moving parts like the buckets, particles studies, and thermal analysis. Therefore, to fit the capabilities of the CFD software, this approach was used.

2.1.1 Test Scale Bucket Elevator



(a) (b) (c)

FIGURE 1. CAD model for the Test Scale Bucket elevator that shows an isometric view of the model (a), the approximate size of the model relative to an average person (b), and a cut plane view that shows streamlines for the continuous path that the particles take through the bucket elevator (c).

The test scale bucket elevator model is useful for this problem because it can be compared against experimental results obtained from the operation of the bucket elevator that is in use at the NSTTF. IR images have been taken of the real bucket elevator while operating with high temperature particles and known mass flow and inlet temperature are chosen to be 0.1kg/s and 525°C respectively in order to match conditions that the real bucket elevator ran at, and that produced a set of IR images at steady state that the model can be compared to.

2.1.2 Pilot Scale Bucket Elevator

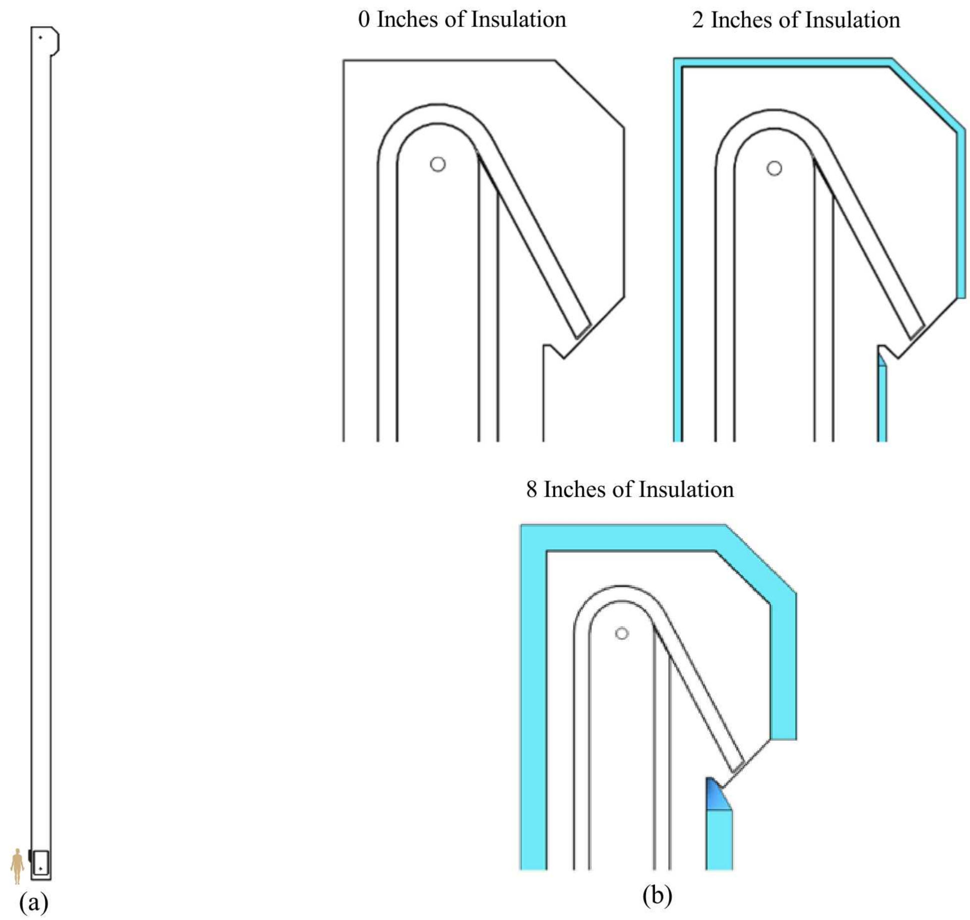


FIGURE 2. The Pilot Scale Bucket Elevator CAD model shown next to an averaged sized person for size comparison (a) and cut planes of the heads of the bucket elevator with a variety of insulation thicknesses shown in light blue (b).

The pilot-scale bucket elevator has been designed but not yet built for the prospective G3P3 project. One of the outstanding design questions for this bucket elevator is the amount of insulation that will be used. To model this, a layer of superwool insulation was applied to the entire outer casing of the elevator with different simulations being run for insulation thicknesses of 0, 1, 2, 4, and 8 inches. The insulation as it is applied to the upper portion of the bucket elevator can be seen for some of the thicknesses in Fig. 2b. The inlet temperature for this system was set to 10m/s and 600°C, which are rough estimate of what this elevator would operate at and were constant for all of insulation thicknesses.

2.2 Skip Hoist

The Skip Hoist model that will be looked at is more general than either of the bucket elevators, due to its applications likely being more practical for a commercial scale PHR rather than either the test or pilot scales. This is because a skip hoist will be best utilized when the mass flow of the particles can be non-continuous in a way that must be accounted for with long travel times of a large bulk of material. Since designs of this scale and their applications are still something to look forward to, the specifics of the model were simplified to show a proof of concept that CFD could also be a useful tool here. The scale of the skip hoist to be used was based off some of the preliminary estimates that the G3P3 team had derived for a commercial scale PHR concentrated solar plant [2]. These estimates include a particle bed density (ρ) of 2000kg/m^3, a tower height (h) of 250m, and a desired mass flow rate ($\dot{m}$) of 2000 kg/s. Furthermore, with a counterbalanced system that utilized two skip hoists, the mass flow rate of a single skip hoist ($\dot{m}_{single\ skip}$) would be 1000kg/s. Equation 1 was then derived from the definition of mass flow, while taking into account dwell time for the loading and unloading of the particles. The design parameters that must to be chosen here are the volume of particles the skip hoist can carry (V), the average speed at which the skip hoist travels when being lifted or lowered (u), and the averaged loading/unloading rate of the particles into and out of the skip hoist (q).

$$Vu\left(1-\frac{2\dot{m}_{single\ skip}}{q}\right)=\frac{2h\dot{m}_{single\ skip}}{\rho} \qquad (1)$$

$$Vu\left(1-\frac{2{,}000\frac{kg}{s}}{q}\right)=250\,\frac{m^4}{s}$$

The loading/unloading rate must also obey the Beverloo Law, shown as Eqn. 2 below, which is dependent on the density of the particles (ρ) which is once again 2000kg/m^3, the gravitational constant (g) which is 9.81m/s^2 the diameter of the particles (d) that is ~3*10^{-4}m, the diameter of the charge/discharge orifice (D) that has to be less than the edge length of the skip hoist, and empirical discharge coefficients (C) and shape coefficients (k) which for these particles are 0.13 and 1.5 respectively

$$q < C\,\rho\,\sqrt{g}\,(D-kd)^{5/2} \qquad (2)$$

Using these equations, a set of system parameters were chosen based on what seemed reasonable for the system. The Volume (V) was chosen to be 125m^3 which could be modeled as a cube with edges that are 5m in length. This also roughly corresponds to the size of the particle storage containers that are already used in handling large quantities of particles. The average travel speed (u) is set at 10m/s based upon the lower estimates of what mining skip hoists travel at. Finally, the charge/discharge rate (q) is set at 2500kg/s, which satisfies both Eqn. 1 and Eqn. 2.

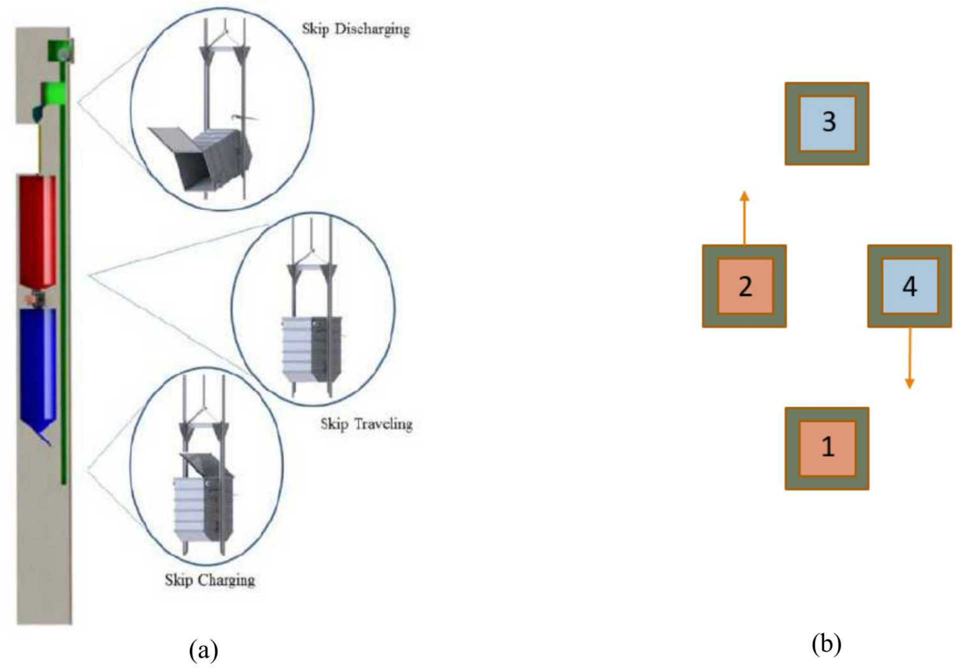


FIGURE 3. A depiction of a skip hoist as would be used on a PHR is shown [2] (a). Also shown are the four stages that the CFD model uses; (1) heated particles in the stationary skip hoist, (2) ambient air flows downward over the skip hoist with the particles inside to simulate it being lifted and the force convection that would occur, (3) the hot particles are replaced with ambient temperature air and the skip hoist sits stationary, (4) ambient air flows upward over the skip with the air inside to simulate it being lowered while empty.

The skip hoist can be thought of as going through four different stages to complete a single cycle. The first stage consists of the skip hoist sitting stationary at the bottom of the PHR tower while being loaded (or charged) with heated particles. When the charging is over, the skip hoist is raised up to the top of the PHR tower. The skip hoist then sits stationary at the top of the PHR tower while the heated particles are unloaded (or discharged), and ambient temperature air is allowed to fill the skip hoist. The final stage is when the skip hoist is being lowered while full of air that is heated by the walls of the skip hoist until it reaches the bottom of the PHR tower, and a new cycle begins. A representation of this process can be seen in Fig. 3a

For the sake of modeling this cycling process some assumptions were made. First, the design of the skip hoist was simplified to a hollow cube of thin stainless-steel inner and outer walls with a thickness of 0.00635m (0.25inches) each, and a layer of superwool insulation between them, as seen in Fig. 4b. The thermal and material properties for the stainless steel are those defined in the SOLIDWORKS database for Stainless Steel 321, and the properties for the superwool insulation are as defined by the manufacturer. The volume of the hollowed portion of the skip hoist is, as previously calculated, 125m^3 with edge lengths of 5m. Further simplifications were made in order to simulate the four stage cycling seen in Fig 3b, including treating the loading and unloading processes as instantaneous, where the particles do not fill or empty from the skip hoist as they would in reality, but instead the storage volume is instantly given the thermal and material properties of the particles with an initial temperature of 600°C at the beginning of every loading stage (stage (1) of Fig. 3b), and are given the properties of air with an initial temperature of 20°C at the beginning of every unloading stage (stage (3) of Fig. 3b). The stages where the skip hoist is moving are modeled by air being passed over the skip hoist using the CFD tools, as can be seen in Figure 4a. When the skip is in the stage where it is moving upward, air is forced downward at a constant velocity of 10m/s defined previously, and when the skip is in the stage where it is moving downward, air is forced upward at the constant velocity. Each of these cycles takes 250 seconds to complete. Also, much like the skip hoist, there is an interest in seeing the effects of different insulation thicknesses on this kind of system. Therefore, an insulation thickness study will also be performed here as well.

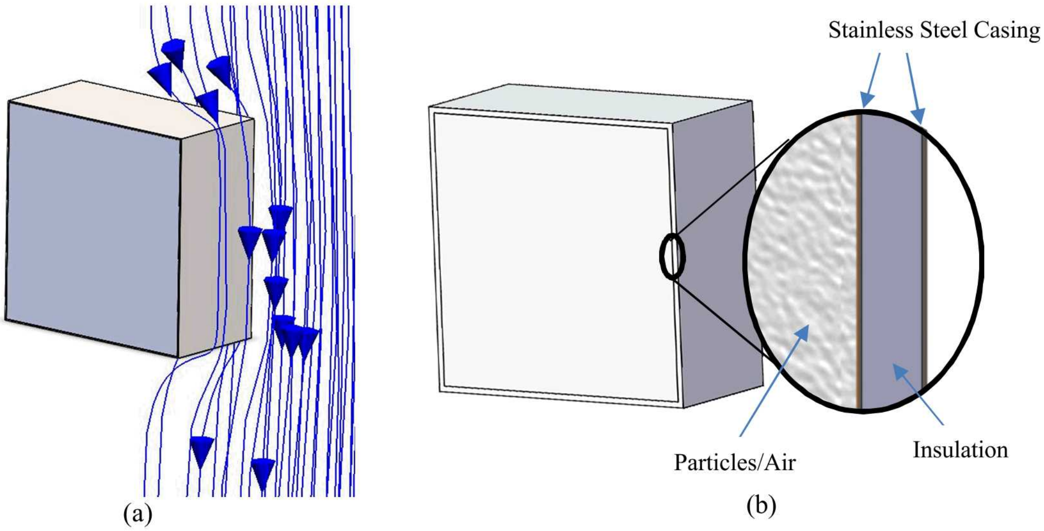


FIGURE 4. A midline cut of the skip hoist model where way the air flows over the model when it is in the "lifting stage" of the cycle is shown (a), as well as a close-up of the skip hoist box that shows the inner and outer stainless steel casing and the insulation.

Modeling this skip hoist with CFD in this was is meant to capture both the radiation and convection heat losses of the system in a way is not prescribed by defining an emissivity and convection heat transfer coefficient respectively. Although for this model these types of estimates might be accurate due to its simplicity, a more complex design would greatly benefit from the versatility that this kind of CFD model can offer.

3. RESULTS

3.1 Bucket Elevator

3.1.1 As Built Scale

The Test scale bucket elevator was used as a verification of the modeling technique, as it could be directly compared to IR images taken of the real elevator in the NSTTF facilities. The specifics of the test setup used include an input temperature of 525°C for the particles, and a mass flow rate of ~0.1kg/s. The comparisons between similar profiles at steady state are shown in Figure 5.

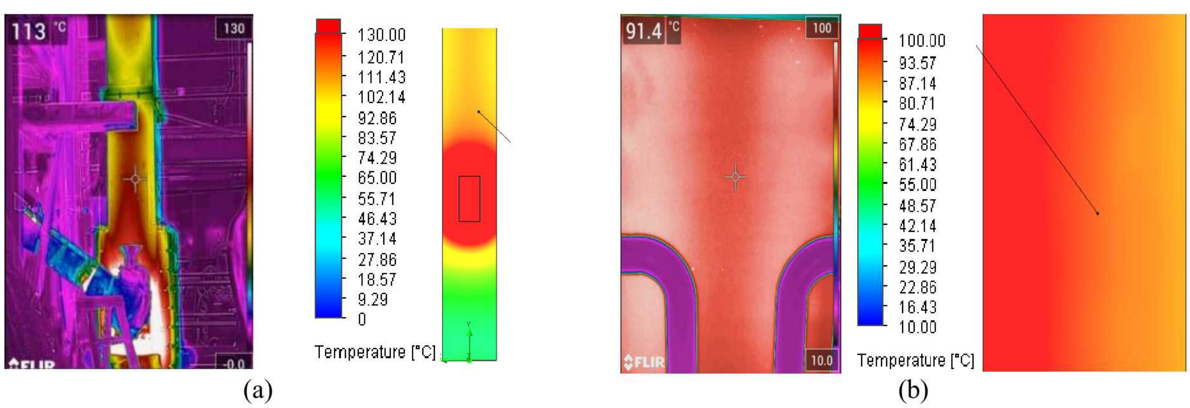


FIGURE 5. The IR images compared to the steady state CFD results for similar inlet conditions for the front profile of the bucket elevator (a), and a side profile of the bucket elevator (b). The Low temperature areas of the IR image of (b) are safety bars that were between the bucket elevator and IR camera.

The results show that the temperature profiles qualitatively and quantitatively do a very good job at matching the real system. One slight inconsistency that can be seen is the concentration of high temperatures at the base of the real system that can be seen in Fig. 5a, where the model has much lower temperature in that area. This can be attributed to the difference in how these two systems operate, with the real system storing a bulk of heated particles here that the buckets scoop from, where as the model does not account for this and instead has the particles running continuously from inlet to outlet. Another difference in the reality and model images is the left to right temperature gradient for the side view seen in Fig. 5b. This again has to do with the modeling process, where in the real system the buckets that were heated by the particles are coming up the left side and going down the right side. These buckets are still very hot after dumping the particles, and their radiation of that heat to the outer casing is what is seen. Because in the CFD model these moving parts are absent, the right side with the column of heated particles will be hotter than the left side without it.

It is also important to show that the CFD model is indeed performing as it is expected to. Figure 6 offers a series of cut planes that show profiles which are consistent with the intuitive results. It shows that we can observed the average temperature loss of the particles from inlet to outlet in Fig. 6b, which for this setup is 24.7°C. We can also see the effects of convection in Fig. 6a where air is heated by the surface of the bucket elevator casing, and that hot air then rises off the bucket elevator.

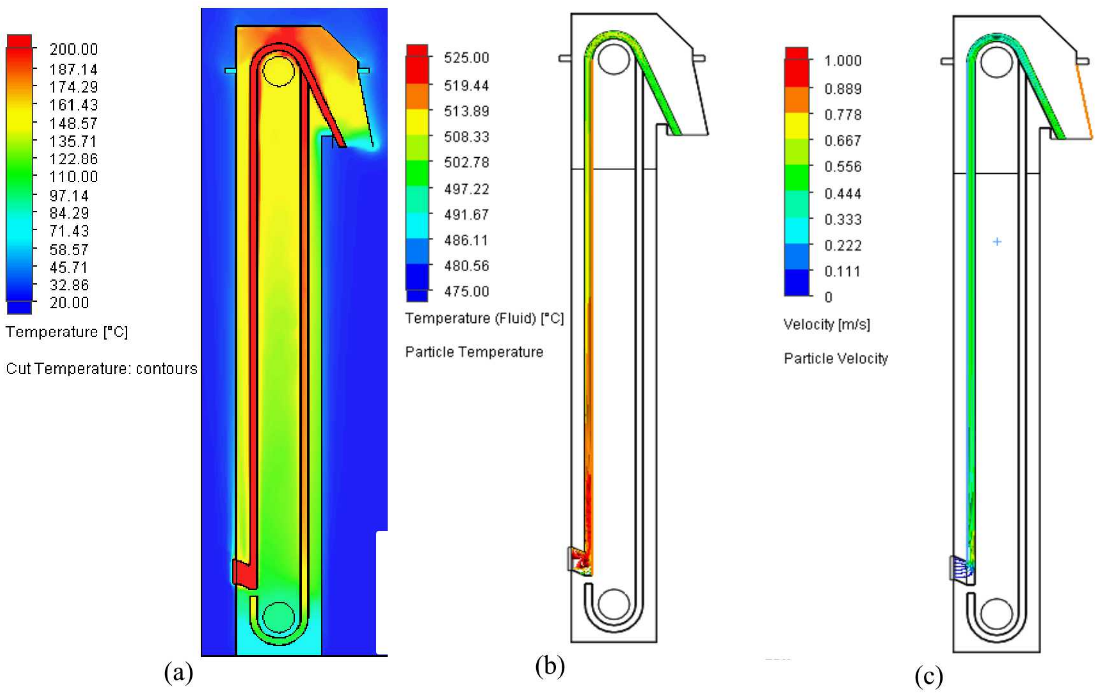


FIGURE 6. Cut profiles for the test-scale bucket elevator that show the temperature profile for the entire elevator and surrounding air (a), the flow lines that the particles follow and the temperature of the particles on the color contour (b), and the flow line that the particles follow with the velocity shown with the color contour.

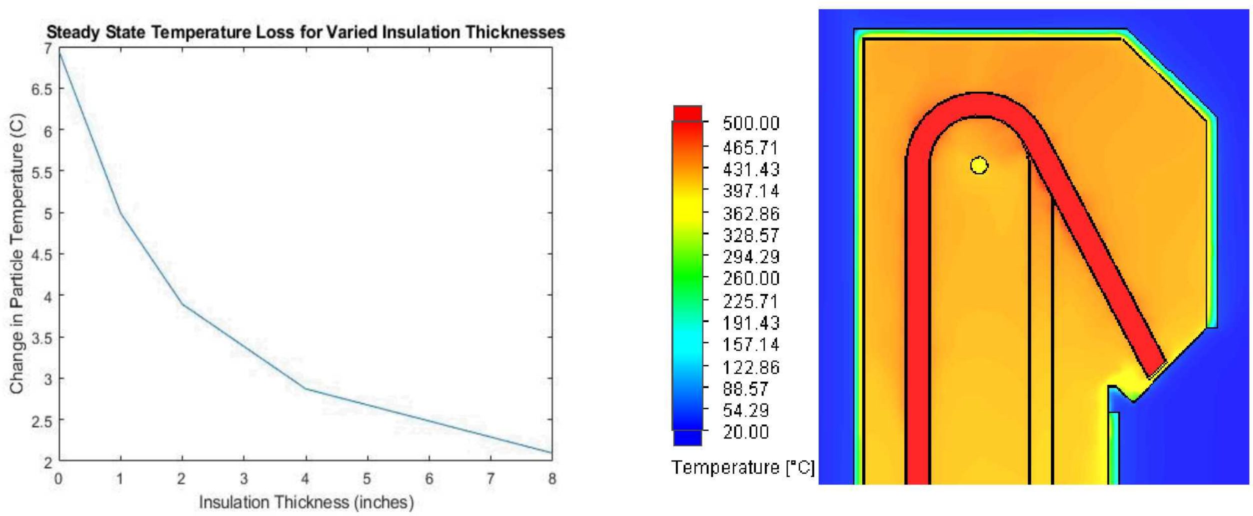
3.1.2 Pilot Scale

The results from the test-scale bucket elevator model seem to indicate some reasonable level of validity for this CFD based modeling method. This method was then applied to the pilot scale, with a specific interest in testing different insulation thicknesses as seen in Fig. 2. The goal of insulation here is mainly to reduce the heat loss of the particles from inlet to outlet, and thereby increasing the efficiency of the system. Table 1 displays the results for the pilot-scale bucket elevator as insulation thicknesses vary, with a 10kg/s mass flow rate, and an inlet particle temperature of 600°C.

TABLE 1. Results from the insulation thickness study performed on the pilot-scale bucket elevator

Insulation Thickness (in)	Average Particle Temp Loss at Steady State (C)	Heat Flux Through Surface of Insulation at Steady State (W/m^2)	Average Outer Surface Temp of Insulation at Steady State (C)	Time to Reach Steady State (min)
0	6.949	590.23	118*	257
1	4.991	305.55	78.63	334
2	3.893	253.56	71.49	561
4	2.87	170.57	58.19	721
8	2.095	93.1928	44.31	>1,000

Here we can see that these results do indicate that the model is capturing the effects of the insulation, and that it does make a moderate difference in particle temperature loss. Based on the desired efficiency for the system an insulation thickness can be chosen. It is also notable that, as can be seen in Fig. 7a, the effects of the insulation are not linear, and that it seems that even a small amount of this insulation can have a large effect on efficiency.



(a) (b)

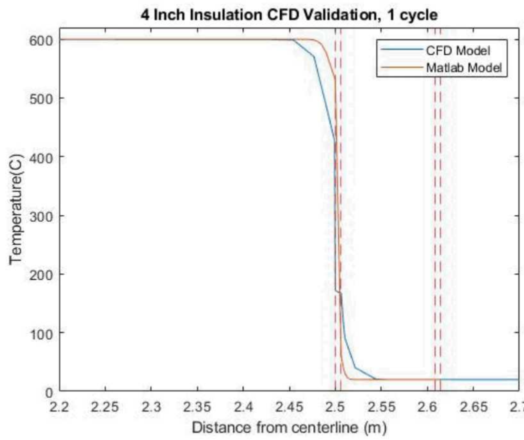
FIGURE 7. Steady state particle temperature loss from inlet to outlet for the pilot scale elevator with varying insulation thicknesses (a), and a temperature profile of the 2in insulation case of the pilot scale elevator (b)

3.2 Skip Hoist

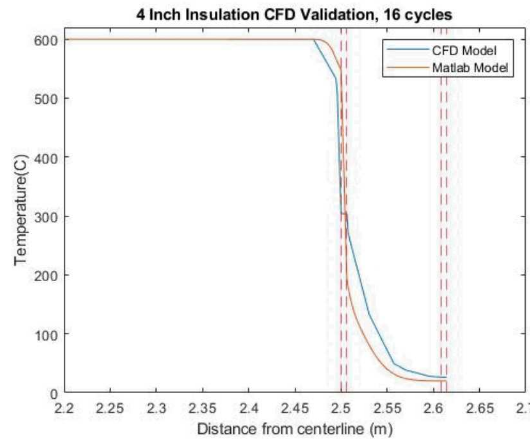
Much like the pilot-scale bucket elevator, the skip hoist needs to have some kind of model verification to ensure that any results produced are reliable, and to show that the CFD model is in fact a reasonable method to model the thermal effects of this type of system. To do this, a simple 1-D MATLAB model was created that utilized the heat equation shown as Eqn. 3 with thermal diffusivity (α), as well as the same thermal properties used in the CFD model. The convection heat transfer coefficient was derived using the Nusselt number separately for the stages where the skip hoist was moving and when it was stationary.

$$\frac{\partial T}{\partial t} = \alpha \, \frac{\partial^2 T}{\partial x^2} \tag{3}$$

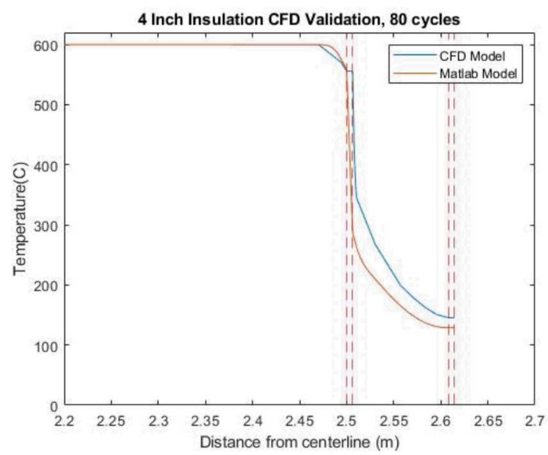
This 1-D MATLAB model was compared to the CFD simulation by plotting the temperature profile from the center of the cube to the center of one of the outer surfaces on the side of the skip. Figure 8 shows the caparisons between the CFD and MATLAB models for similar insulation thicknesses and initial conditions for after 1 cycle, after 16 cycles, and after 80 cycles.



(a)



(b)



(c)

FIGURE 8. Comparison of CFD model midline to a 1-D MATLAB after the lifting stage of cycle 1 (a), cycle 16 (b), and cycle 80 (c). The dotted vertical lines represent the boundaries between the particles, casing, and insulation, each with individual thermal properties. Importantly, this is also not the entire length of the skip hoist. There are 2.2 meters of heated particles from the left edge of the plots to the centerline that remains at a temperature of 600°C for all time that the particles are in the skip hoist.

The two models appear to correspond very well across these time spans with a growing, but still relatively small error between them. With slight adjustments to the convection heat transfer coefficient in the MATLAB model to better emulate the complexities of the CFD model, these results could easily be made to overlap. This gives confidence to the CFD model as a way to model this simplified skip hoist. With this validation, the insulation thickness study was performed, where insulation thicknesses of 0, 1, 2, 4, and 8 inches were tested. The cycling nature of the system means that the particles will not continue to lose heat, but instead the heat loss is measured at the end of the lifting stage of each cycle of 250 seconds

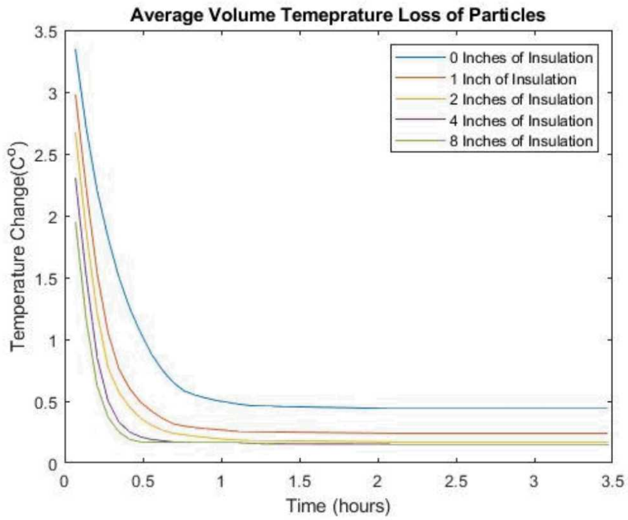


FIGURE 9. The average temperature losses of the particles with 0, 1, 2, 4, and 8 inches of insulation present a function of time.

Figure 9 shows that insulation does seem to make a difference in the efficiency of the system, but that the effects become less impactful as more is added. These results show universally low temperature losses, less than a 0.5°C temperature loss at steady state for all insulation thicknesses, largely because of the shear size of the skip hoist being modeled and the relatively short cycle time when the particles are losing heat. Even still, this method is able to show this difference, and the methods used should be just as applicable to smaller skip hoist type systems that have more detail as well.

4. CONCLUSION

CFD modeling has been done on two types of high temperature bulk particle lifting mechanisms in order to show the viability and usefulness of using CFD for thermal modeling of PHR systems. Simulations were run on the bucket elevator by treating the bulk particles as a fluid and describing the path they take up the elevator as a closed column. The results of the test-scale model showed method of modeling the particles to work well, as they were able to be matched with experimental results in the form of IR images of the physical bucket elevator in operation. A parameter study was then done on the pilot-scale bucket elevator for a variety of superwool insulation thicknesses. These results showed that only a few inches of insulation are needed to see a lessening of temperature loss in the particles.

The commercial sized simplified skip hoist was also modeled as a hollow cube with an inner and outer layer of stainless steel, with insulation between them. This model was able to use the tools of the CFD package to simulate the transient cycling process that such a system would experience in reality. The model was then compared to a 1-D MATLAB model of the same system and showed results that provided confidence that the model was behaving reasonably. Another parameter study was done for this model, again for insulation thickness. The model seemed able to simulate the particle heat loss though the transient cycling, although because of the small surface area relative to volume due to the size of the system the results were not drastically different. Still, this method could easily be transferred to smaller mechanisms with more complex and realistic designs.

5. ACKNOWLEDGMENTS

This work is funded in part or whole by the U.S. Department of Energy Solar Energy Technologies Office under Award Number 34211. This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

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