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EVALUATION OF AIR RECIRCULATION FOR FALLING PARTICLE RECEIVERS

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ABSTRACT

This paper presents simulations and designs of a prototype falling particle solar receiver with air recirculation as a means of mitigating heat loss and impacts of external wind on particle flow. The flow and dispersion of different sizes of ceramic proppant (CARBO HSP) particles (1 mm, 100 µm, and 10 µm) were simulated in recirculating air flows without heating effects. Particles on the order of 0.1 – 1 mm yielded desirable simulated flow patterns when falling through the cavity receiver with an air-injection velocity of 3 m/s. Simulations of smaller particles on the order of 10 microns yielded unstable flow patterns that may lead to large losses of particles through the aperture. A prototype cavity receiver with air recirculation was designed and fabricated to validate the unheated simulations. The blower nozzles and suction plenum were engineered to yield the most uniform flow pattern along the entire width of the aperture. Observed and simulated air velocity distributions around the aperture and particle flow patterns using CARBO HSP particles with an average diameter of ~0.7 mm were found to be qualitatively similar.

1. INTRODUCTION

The falling particle central receiver is an enabling technology that can increase the operating temperature of concentrating solar power (CSP) processes, improving efficiency and lowering the costs of energy storage. Conventional central receiver technologies are limited to temperatures of around 600 °C. At higher temperatures, nitrate salt fluids become chemically unstable. In contrast, direct absorption receivers using solid particles that fall through a beam of concentrated solar radiation for direct heat absorption and storage have the potential to increase the maximum temperature of the heat-transfer media to over 1,000°C. Once heated, the particles are stored in an insulated tank and used to heat a secondary working fluid (e.g., steam, CO_2, air) for the power cycle. The cooled particles are stored in another tank and then lifted to the top of the receiver using an elevator system (Figure 1).

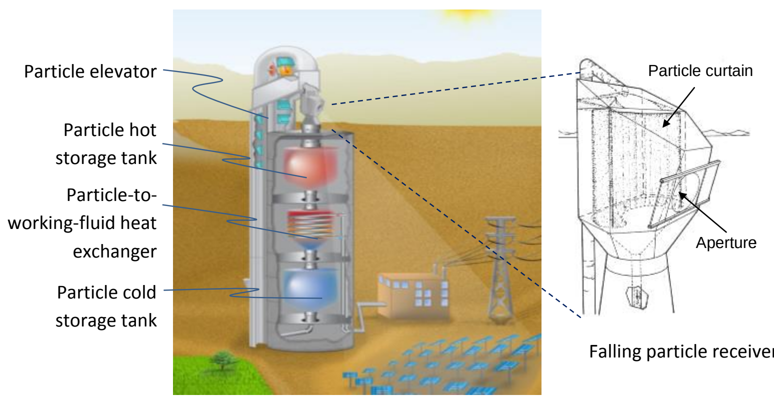


Figure 1. Sketch of conceptual falling particle receiver system.

A number of challenges exist with the falling particle receiver design and have been investigated in previous studies [1-8]; this paper focuses on the use of air recirculation within the receiver for mitigation of wind destabilization and convective heat loss. External winds at certain incidence angles can enter the cavity receiver and destabilize the falling particles, ejecting the particles from the receiver. In addition, as heated air within the cavity is exchanged with cooler ambient air, significant convective heat losses can occur, accounting for up to ~20% of the incident power on the receiver [9].

Sandia [10] received a patent on a suction/recirculation device to stabilize particle flows in falling particle receivers, and Tan et al. [8, 11-13] simulated the use of an aerowindow (transparent gas stream along the aperture) to mitigate heat loss and wind impacts in falling particle receivers. Tan et al.[13] found that aerowindows could reduce the heat loss by up to 10% depending on external wind direction and speed**.** However, no tests or validation studies were performed, and few parametric analyses have been conducted to evaluate important air-recirculation parameters.

In this paper, we describe models and experimental methods to investigate air recirculation within a falling particle receiver with the objective of mitigating convective heat loss and particle destabilization. Modeling is performed to evaluate the impact of air recirculation on particle flow with different particle sizes and air flow direction. The design and construction of a prototype falling particle receiver with air recirculation is also discussed.

2. MODELING

2.1 Evaluation of Particle Size and Flow Direction

A model of a prototype small-scale solid-particle receiver with air recirculation was developed in Solidworks (Figure 2). Air was injected along a vertical nozzle adjacent to the aperture, and air was withdrawn at the same rate from an opposing nozzle along the other side of the aperture. The direction of the flow (up vs. down) was varied in the simulations.

The flow and dispersion of different sizes of CARBO HSP particles (1 mm, 100 μm, and 10 μm) were simulated using Solidworks Flow Simulation, a computational fluid dynamics (CFD) code. The particle density was assumed to be 3.3 g/cm^3 based on a reported bulk density of 2.0 g/cm^3 [7] and an assumed porosity of 0.4. A grid independence study was performed to ensure that the flow patterns were independent of grid resolution. A total of 104,202 hexahedral elements were used in the model using a k-ε turbulence model with modified wall functions ($y^+ \sim 30$). Drag and gravitational forces on the particles were simulated assuming spherical particles [14]. All walls were assumed to be perfectly reflecting for the particles, except for the bottom, which was assumed to be perfectly absorbing. In these preliminary simulations, the particle impact on the forced air flow from the nozzles was neglected. In addition, heating effects (e.g., buoyancy) are not included. Future simulations will consider these impacts on particle movement and airflow.

Error! Reference source not found. shows the simulated airflow patterns (colored arrows) and the particle dispersion patterns (black lines) for a 1 kg/s particle release rate and an air injection velocity of 3 m/s. The aperture is on the left side of the images. Simulations were also performed with an air injection velocity of 8 m/s with similar results.

Particles with diameters of 1 mm and 0.1 mm exhibited a desirable curtain-like falling pattern, but the 0.01 mm particles were too light and followed the air flow patterns throughout the receiver, risking loss of particles through the aperture. The heavier 1 mm particles developed more momentum as they dropped and were pushed back toward the rear wall from the higher velocity air flow near the top of the cavity. The 0.1 mm particles were initially pushed back but then swept forward slightly as a result of the air recirculation near the bottom. The CFD simulations will be validated against experimental studies using similar model dimensions and operational parameters.

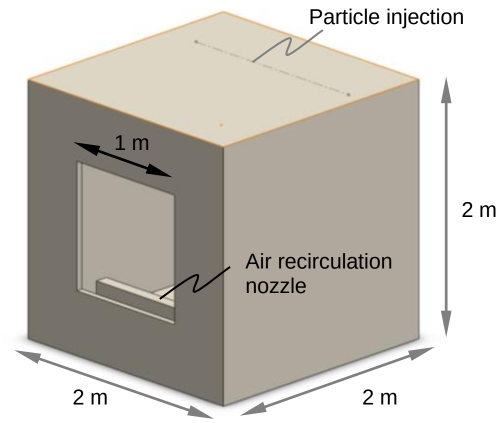


Figure 2. Initial model of prototype solid particle receiver with air recirculation and particle injection.

3. EXPERIMENTS AND TESTING

A small-scale prototype of a solid-particle receiver system was designed to validate the simulations and help understand the influence of various operating parameters on particle dispersion and heat loss. The prototype receiver system consists of (from top to bottom) a particle-release hopper, a cavity receiver with an air-recirculation system, a particle-collection hopper, and a bucket elevator to recirculate the particles back to the top of the release hopper. The following sections present the design, construction, and testing of the air-recirculation system in the cavity receiver.

3.1 Design of Air Recirculation System

The air recirculation system consists of an air blower and a suction plenum to create a recirculating air stream across the aperture (similar to air curtains found at the entrances of open-front stores). Figure 4 shows the drawing of the blower nozzles used to create a jet of air from the bottom of the aperture to the top. The initial air recirculation design is for a bottom-to-top air flow, but it could be reversed for top-to-bottom air-injection studies.

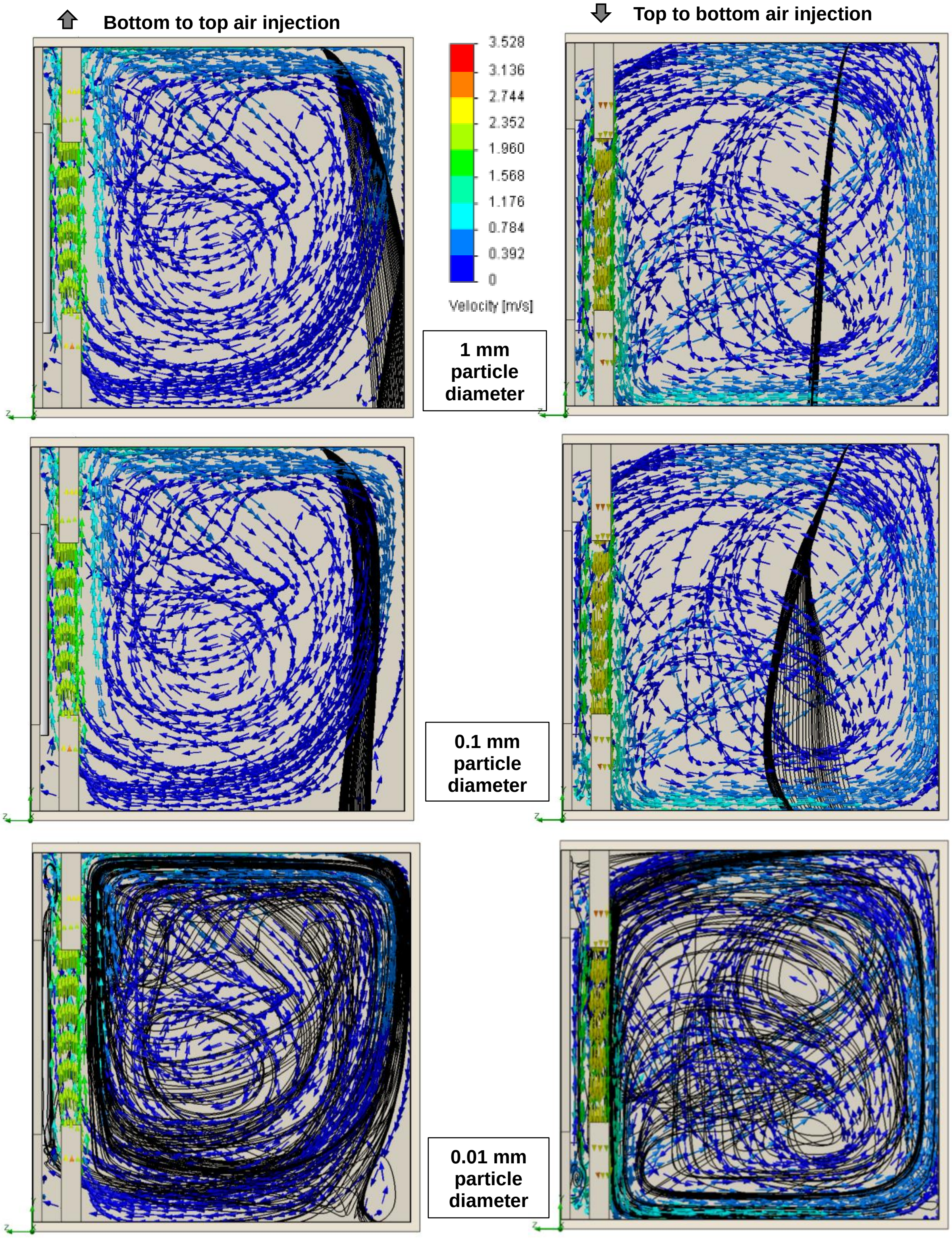


Figure 3. Simulated airflow (colored arrows) with 3 m/s air injection across the aperture (left: bottom-to-top, right: top-to-bottom) and different sized CARBO HSP particles (black lines) injected at 1 kg/s.

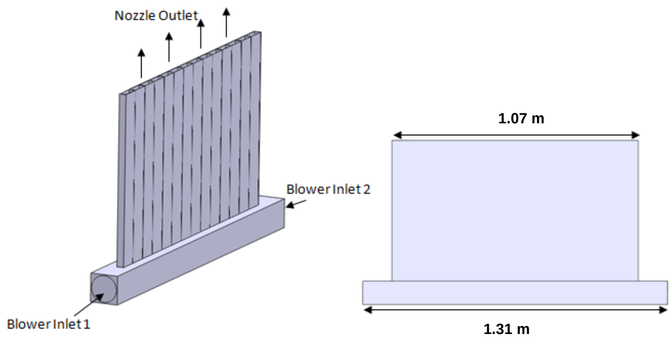


Figure 4. Drawing of blower nozzle for air injection.

One of the design considerations for the blower was to choose a length of the nozzle that would produce a uniform air flow across the length of the blower. Figure 5 shows the simulated velocity profiles for two different nozzle lengths. Results show that a longer nozzle length (61 cm vs. 6 cm) produced a more uniform flow.

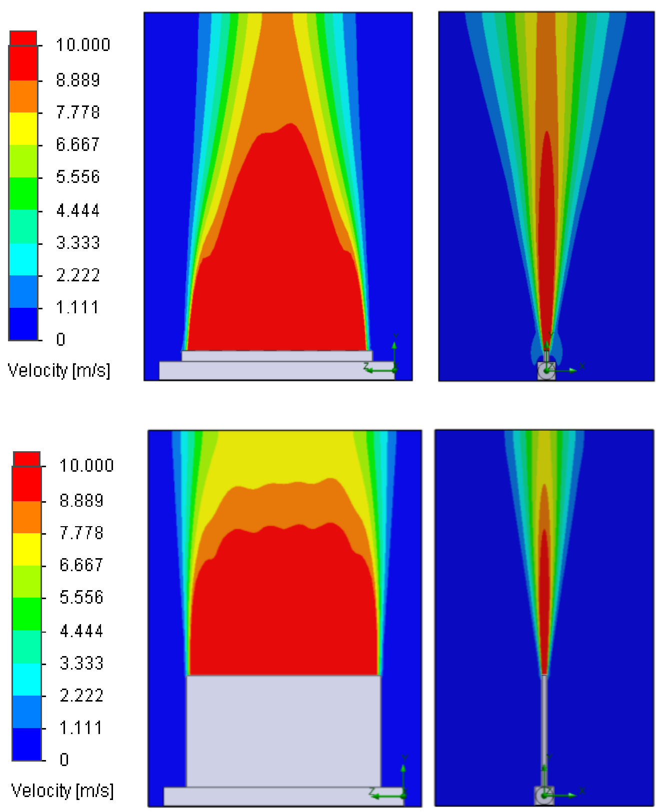


Figure 5. Cross sectional views of air velocity profiles using 6 cm (top) and 61 cm nozzle lengths.

Figure 6 shows the design of the suction/intake plenum that withdraws the air in the air-recirculation system. The top of the plenum is connected to a hose that pulls the air up via an in-line air blower, which then passes the air through the blower nozzles (Figure 4) back into the receiver. Figure 6 also shows the simulated velocity contours, which are non-uniform along the length of the plenum. As a result, a flow distributor consisting of a perforated interior channel was added to the plenum as shown in Figure 7. This yielded more uniform simulated velocity profiles along the entire length of the plenum.

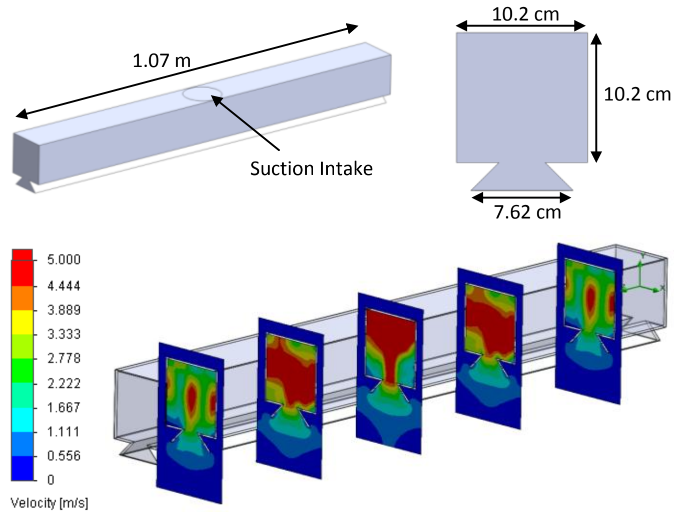


Figure 6. Original design of suction plenum and simulated velocity contours. Note the non-uniform velocity profiles along the length of the plenum.

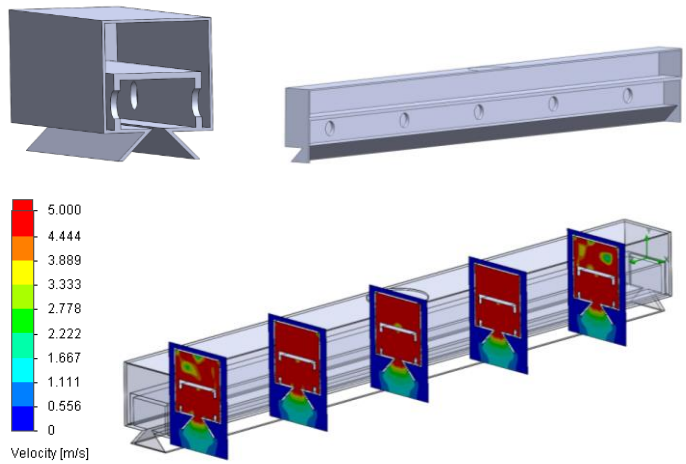


Figure 7. Revised design with additional flow distributor within plenum. Simulated velocity profiles are more uniform along the length of the plenum.

3.2 Fabrication and Testing of Air Recirculation System

Figure 8 shows the partially assembled receiver with the air-recirculation system. Not shown in the figure is the air blower that is connected in-line via hoses to the top of the suction plenum and the bottom of the blower nozzles. The sides of the receiver will be fabricated from Lexan so that particle flow paths can be observed. Eventually, this system will be tested on-sun using the 6 MW_{th} power tower and heliostat field at the National Solar Thermal Test Facility in Albuquerque, NM. In those tests, the walls will be replaced with refractory composite material (e.g., RSLE board) to withstand the high fluxes.

Twenty-five air-velocity measurements (5 x 5) were recorded within the air stream between the blower and suction plenum using a hot-wire anemometer probe. Figure 9 shows the measured air velocity distribution across the entire aperture at three different valve settings for the blower. Results are qualitatively similar to the simulated velocity distribution shown in Figure 5 for the 61 cm nozzles.

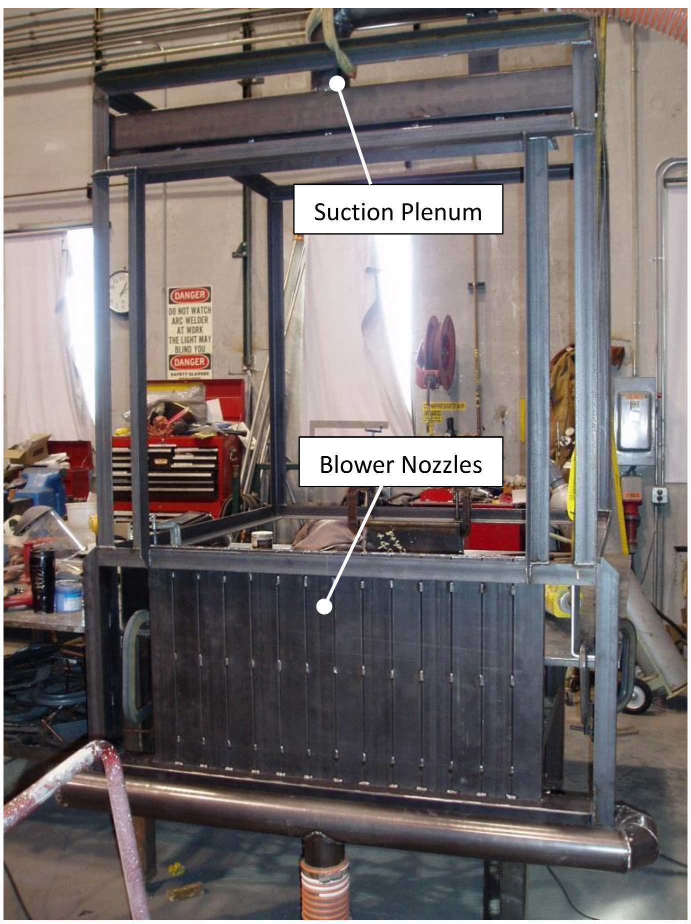


Figure 8. Construction of cavity receiver (~1m x 1m x 1m) with air recirculation.

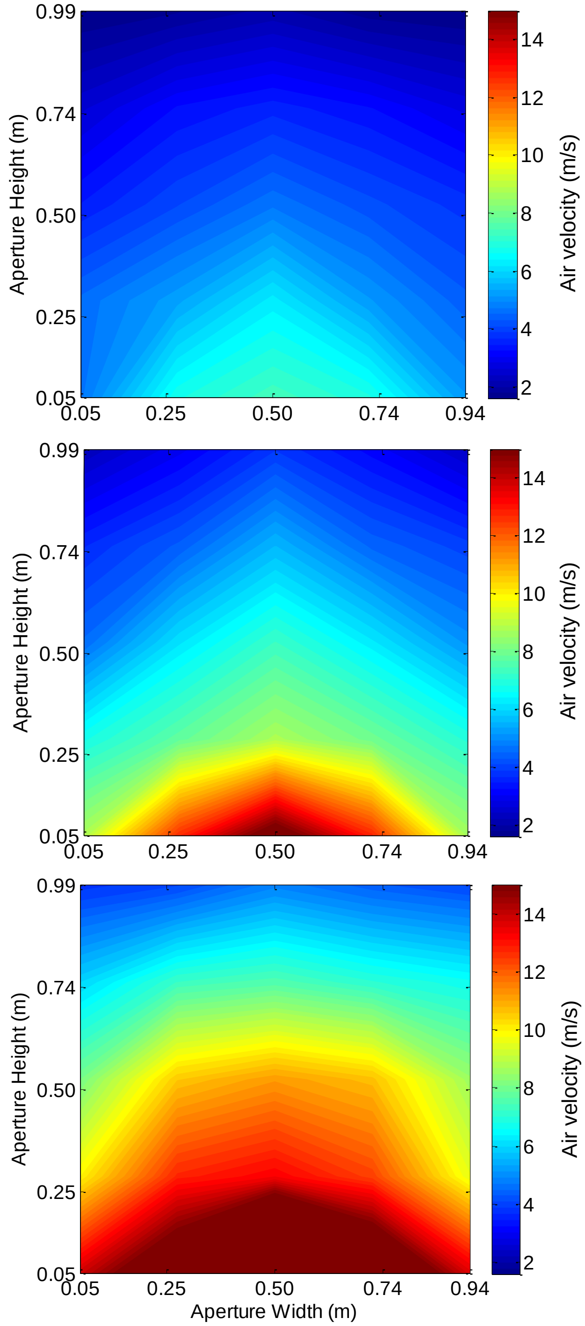


Figure 9. Measured air velocity distribution in the air stream across the receiver aperture at low (top), medium (middle) and high (bottom) blower settings. Air flow is from bottom to top.

3.3 Prototype Receiver System

Figure 10 shows the prototype receiver system being assembled. On top, a particle release bin holds the particles and releases them through a hydraulically actuated slot in the bottom. The receiver shown in Figure 8 slides into the section below the particle release bin. Another bin is located beneath the receiver to collect the particles and transfer them to the base of a bucket elevator, which lifts the particles back to the top of the particle release bin.

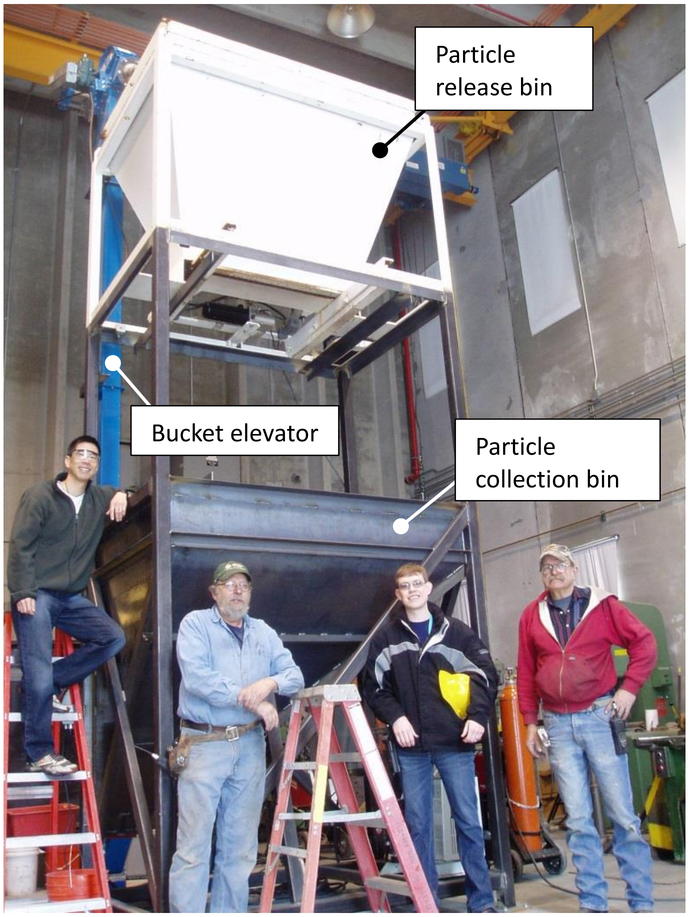
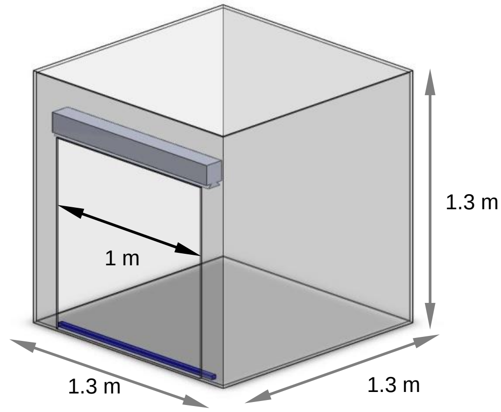


Figure 10. Construction of prototype particle-receiver system.

The as-built receiver dimensions differ from the initial simulations. The initial simulations assumed a receiver size of 2 m x 2 m x 2m with a 1 m x 1m aperture centered on the receiver. The actual receiver is 1.3 m x 1.3 m x 1.3 m with the aperture flush with the bottom. Figure 11 shows a drawing of the as-built receiver, along with a CFD simulation of particle and air flow. The adjustable release point of the particles was placed near the aperture and blower as a worst-case scenario. Results of the simulations (and preliminary testing) show that when 0.7 mm CARBO HSP particles are used, the particles spread due to the induced air flow from the blower nozzles, but the particle flow is stable.



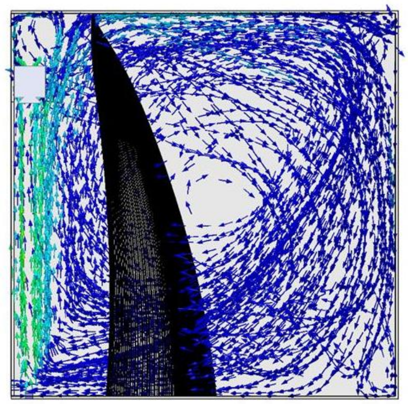


Figure 11. Drawing of the as-built receiver (top) and CFD simulation of 0.7 mm CARBO HSP particles (black lines) with mass flow rate of 5.1 kg/s and bottom-to-top air injection across aperture with blower at high setting.

Figure 12 shows the completed assembly of the prototype falling particle receiver system. Preliminary tests have shown that the particle release mechanism produces a uniform flow of particles. The particles (CARBO HSP, ~0.7 mm average particle diameter) exhibit a stable flow pattern, even with the air blower on the highest setting, which is consistent with the results of the CFD simulations using particle sizes between 0.1 and 1 mm.

Ongoing work is focused on simulating the impacts of various parameters and processes (e.g., particle size, particle mass flow rate, particle release location, air flow velocity, external wind) on the stability of the falling particles. Testing and validation of these simulations using the prototype falling particle receiver system are also underway.

Figure 12. Assembled particle-receiver system. Left: particles being released through receiver. Right: side-view showing Lexan panels for viewing particles falling through the receiver.

4. CONCLUSIONS

Air recirculation in a cavity receiver is being investigated for falling particle solar receiver systems as a means of reducing heat loss and mitigating the impacts of external winds on particle flow. This paper has presented simulations and designs of a prototype falling particle receiver with air recirculation. Findings include the following:

- Ceramic proppants (CARBO HSP) with sizes on the order of 0.1 – 1 mm yielded desirable simulated flow patterns when falling through the cavity receiver with an air-injection velocity of 3 m/s. A bottom-to-top air injection across the aperture yielded the most stable patterns. Simulations of smaller particles on the order of 10 microns yielded unstable flow patterns that will likely lead to large losses of particles through the aperture.
- A prototype cavity receiver with air recirculation was designed and fabricated. The blower nozzles and suction plenum were engineered to yield the most uniform flow pattern along the entire width of the aperture. Measured and simulated air velocity distributions around the aperture opening were qualitatively similar.
- Preliminary tests show that the prototype system yields a uniform flow of particles, and the particles (CARBO HSP, ~0.7 mm average particle diameter) exhibit a stable flow pattern, even with the air blower on the highest setting.

Future tests using the prototype receiver system will be performed to validate the simulations and to better understand the impact of operational parameters on particle flow and dispersion. Additional simulations will be performed to optimize the air-recirculation design to minimize both convective heat loss and particle destabilization.

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