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Particle Vertical Mixing and Horizontal Conveyance Within an Ambient Temperature Fluidized Bed

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Abstract. Previous studies have shown the advantages of particle-to-sCO2 fluidized bed (FB) heat exchangers, which include high heat transfer coefficients, low material cost, and the ability to horizontally convey solid particles. This paper outlines the design and testing of a compact cold flow FB test apparatus to characterize horizontal conveyance through convolutions within a 100 kW_{th} FB heat exchanger design. Horizontal conveyance is an advantage in FBs because it enables more compact designs for heat exchangers. Two mass flow rates, 0.5 & 1 kg/s, at the inlet & outlet of the FB. To determine consistency of the flow rates, Student's t-tests were used to assess whether the inlet & outlet values were statistically similar. The mass flow rate exiting the bed was statistically similar to the flow rate entering the bed for both cases, but each case featured a wider range and standard deviation. The range and standard deviation of the 1 kg/s flow rate was 0.69-1.23 kg/s and 0.12 kg/s respectively, and the 0.5 kg/s test featured a range and standard deviation of 0.37-0.73 kg/s and 0.09 kg/s, respectively. These measurements provide confidence that large-scale designs can successfully horizontally convey particles at ~1.5x minimum fluidization velocity (U_{mf}) without significant variation in flow rate. A method to characterize the degree of particle vertical mixing and bubble frequency within the FB is also introduced. By using a high-resolution camera together with particle velocimetry, particle motion in the X and Y directions can be estimated to assess bed mixing and bubble frequency.

Keywords: Fluidized bed, Horizontal Particle Conveyance, Particle to sCO_2 Heat Exchanger

1. Introduction

Solid particles are being considered as the heat transfer and storage medium for next generation high temperature concentrating solar power (CSP) due to their stability at temperatures greater than 1000°C, enabling high efficiency Brayton power cycles [1]. The solid particle medium used in these systems is directly heated by concentrated solar energy and stored in a high temperature silo before the thermal energy is transferred to a power cycle working fluid, such as supercritical CO_2, via a heat exchanger.

There are numerous types of heat exchangers being studied for use in particle-based CSP. Ho, et al. [2] compared three types of particle-to-sCO2 heat exchangers: 1) Fluidized-bed (FB), 2) shell-and-plate moving packed-bed, and 3) shell-and-tube moving packed-bed. A list of design requirements and particle properties were provided for the consideration of these three types of heat exchangers. For the evaluation of the three types, a list of 10 criteria was identified, weighed, and scored. Although the moving packed beds scored better in cost, manufacturability, parasitics & heat losses, compatibility, erosion & corrosion, and transient operation, the FB scored better in heat transfer coefficient (HTC), structural reliability, scalability, and ease of inspection.

FB heat exchangers are widely used in industry and feature high particle side heat transfer, low material & manufacturing cost, and compact design due to the horizontal particle conveyance enabled by the fluidization [3]. FB heat exchange technology has been commonly researched, with heat transfer and flow characteristics being a theme in many studies. Miller, et al. [4] demonstrated a particle receiver design that provided high wall-to-particle heat transfer rates. By injecting net-downward-flowing particles in a narrow vertical channel, irradiating an external wall with mid-IR quartz lamps, and providing upward-flowing gas to fluidize the particles, a HTC as high as 1000 W m^{-2} K^{-1} was achieved at between 2 and 4 times the minimum bed fluidization velocities.

Kim, et al. [5] studied the effect of gas velocity on average and local heat transfer coefficients between a submerged horizontal tube and a FB of silica sand particles. It was determined that an increase in fluidizing gas velocity led to an increase in bubbling frequency, a decrease in emulsion contacting time, and ultimately led to higher heat transfer coefficients. Molerus, et al. [6] also established a correlation between heat transfer coefficients, gas velocities, and particle size for glass beads in air at ambient conditions. It was observed that heat transfer coefficients typically increase as particle size decreases. A significant increase in heat transfer coefficient occurred at or greater than the minimum fluidization velocity (U_{mf}) for all particle sizes observed, with all particle size HTCs eventually leveling off at higher gas velocities. The smallest particle size studied had the lowest U_{mf} and achieved the highest HTC compared to the other, larger particle sizes.

A fluidized bed heat exchanger design is being explored for Gen 3 particle based CSP systems. This paper outlines the design and testing of a compact cold flow fluidized bed test apparatus to characterize particle horizontal conveyance through convolutions in a 100 kW FB heat exchanger plan area. Packed bed and fluidized bed height were measured to inform the void fraction of the bed. This paper describes a method to characterize the degree of particle vertical mixing and bubble frequency within the FB.

2. Approach

2.1 Horizontal conveyance

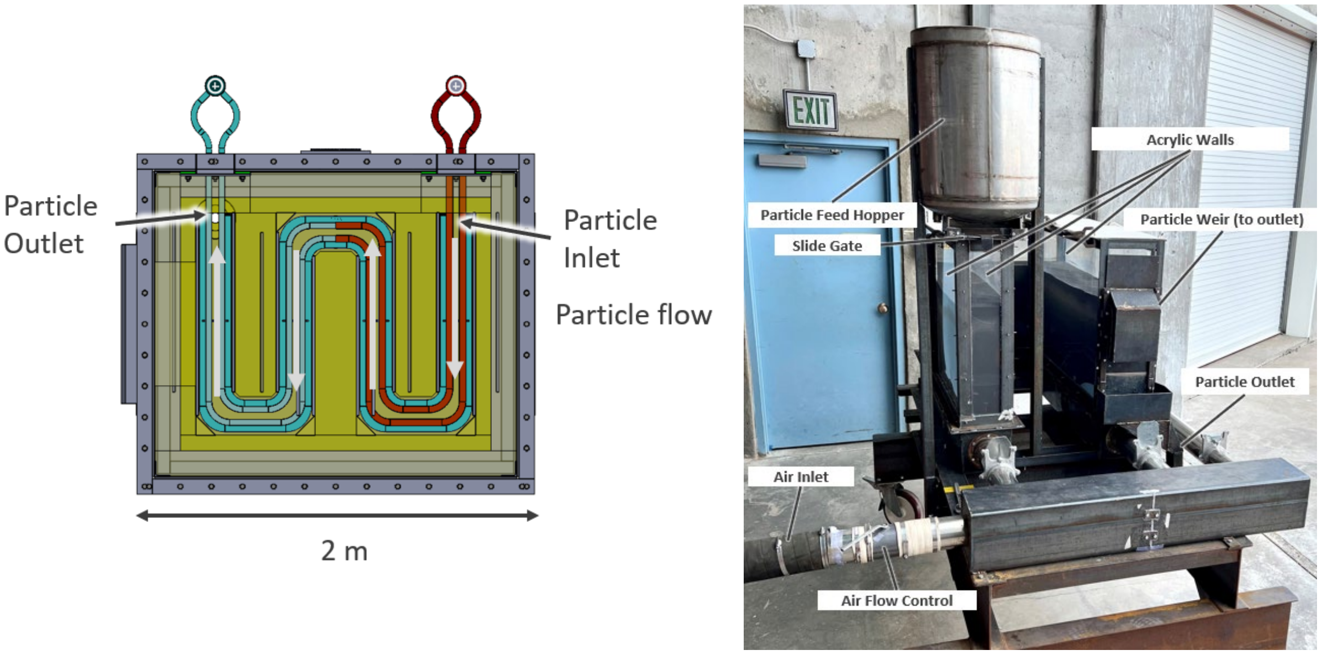

Figure 1. *(a) 100kW fluidized bed heat exchanger design cross section (b) cold flow test stand*

A 100kW particle-to-sCO2 fluidized bed heat exchanger design, shown in Figure 1a, created by Babcock and Wilcox, is being evaluated at Sandia National Laboratories and is scheduled for testing in 2024. The goal of this effort is to characterize the effectiveness of the heat exchanger to inform future large-scale deployment. The cold flow test stand apparatus shown in Figure 1b provides a method of examining the consistency of the particle horizontal conveyance.

The test stand is composed of an air blower, air distribution system, particle delivery system, and load cell measurement. A blower supplies the fluidizing air to the particle bed and is delivered through an air control valve, a header, and 3 plenums. Each plenum features a sintered bronze air distributor. A variable frequency drive is used to control the flow rate of air entering the bed while a control valve provides fine tune control. Blast gates located between the header and the plenums equalize the flow rate in each plenum.

The particle delivery system consists of a particle feed hopper located above one end of the fluidized bed. A manual slide gate is installed at the bottom of the feed hopper to control the particle flow into the bed. A weir at the opposite end of the bed allows particles to fill and overflow into a bucket. The bucket is weighed via a load cell to measure the mass flow rate of particles exiting the bed.

The width of the discharge slot below the top hopper is used to control the mass flow rate entering the bed. Two mass flow rates are considered, 0.5 and 1.0 kg/s. Two sets of spacers are used to set the slot width and thus flow rate following. A series of tests are conducted to characterize the slot width needed for a given flow rate.

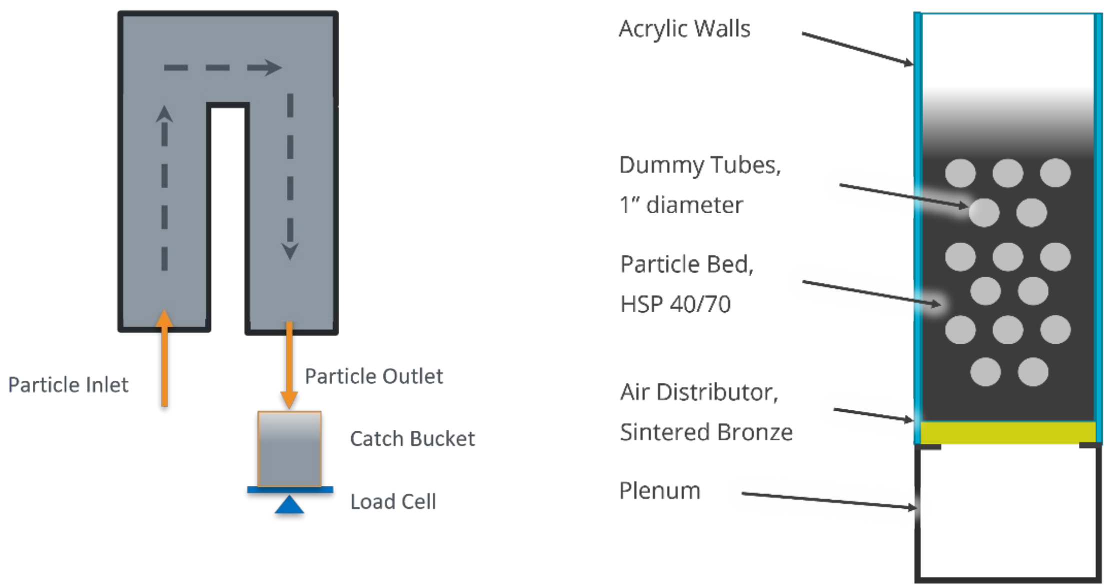

Figure 2. *(a) Particle horizontal conveyance test diagram (b) Fluidized bed cross section*

During operation, particles are deposited from a feed hopper to the surface of the fluidized bed at one end of the apparatus. The particles flow around two 90-degree bends before they drain from the outlet weir to the catch bucket, as shown in Figure 2a. Tests were conducted to determine the consistency of particle horizontal conveyance and particle vertical mixing within the bed. A staggered array of 1” solid dummy tubes, shown in Figure 2b, are added to simulate the particle flow within the 100 kW heat exchanger design. The horizontal particle conveyance rate is determined by measuring the difference between the mass flow rate entering and exiting the bed.

An important variable in fluidized beds is the minimum fluidization velocity (U_{mf}), which determines the point when particles begin to bubble within the bed. Cocco, et al. [7] describes how to determine U_{mf}, as it involves relating the Archimedes number, Ar, and Reynolds number at U_{mf}. First, Archimedes number is calculated with the following equation:

$$Ar = \frac{\rho_g d_p^3(\rho_p - \rho_g)g}{\mu^2} \tag{1}$$

where ρ_g is the gas density, d_p is the Sauter mean particle size, ρ_p is the particle density, g is the acceleration due to gravity, and μ is the fluid viscosity. The Wen and Yu equation is used to determine the Reynolds number, $Re_{p,mf}$, at U_{mf}:

$$Ar = 1650Re_{p,mf} + 24.5Re_{p,mf}^2 \tag{2}$$

Solving for $Re_{p,mf}$ ultimately leads to determining U_{mf}:

$$Re_{p,mf} = \frac{\rho_g U_{mf} d_p}{\mu} \tag{3}$$

The calculated U_{mf} will then be compared to the measured U_{mf} to determine if accuracy of flow rate can be achieved in the 100 kW test. By adjusting the fan speed of the air blower, the U_{mf} of the FB is determined by measuring the air flow rate entering the bed using an anemometer at the point when particle bubbling begins. The bed flow angle is measured through the estimation of bed height through the plexiglass walls, which is useful for informing pressure head supplied to the bed. This can especially be useful for the 100 kW test.

2.2 Particle vertical mixing

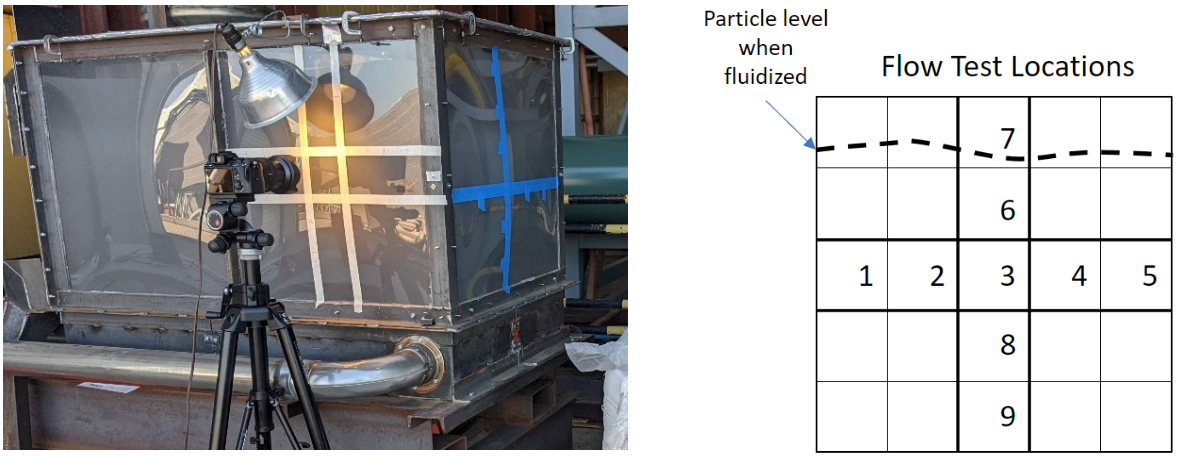

Figure 3. *(a) Particle image velocimetry (PIV) setup (b) Flow test locations*

Characterizing particle vertical mixing and bubble frequency will aid in determining the effectiveness of the notional 100 kW heat exchanger. Particle image velocimetry (PIV) is a method that will be used to determine these variables. The PIV setup, shown in Figure 3a, includes a light source, labeled locations along the exterior wall, and a high-resolution, fast frame rate camera to track particle motion. The various test locations are diagramed in Figure 3b. The videos of particle motion at each test location are collected by the camera, along with a fiducial, and are supplied to a MATLAB optical flow algorithm which outputs a particle velocity matrix. This matrix can be used to infer bubble frequency and mixing within the bed.

3. Results

3.1 Horizontal conveyance

A few metrics, including the minimum fluidization velocity and bed height difference during conveyance, were measured during the horizontal conveyance testing. The measured air flow rate entering the bed at the point at which it started to bubble was 310 SCFM, corresponding to an average air velocity within the bed of 0.27 m/s. The measurement was close to the calculated value (0.29 m/s) for the system providing confidence that the flow rate in the 100 kW test will likely be accurately estimated with the assumption made in the minimum fluidization velocity calculation. The bed height difference while conveying was 52 mm per horizontal meter of conveyance which is accounted for in the 100 kW heat exchanger design.

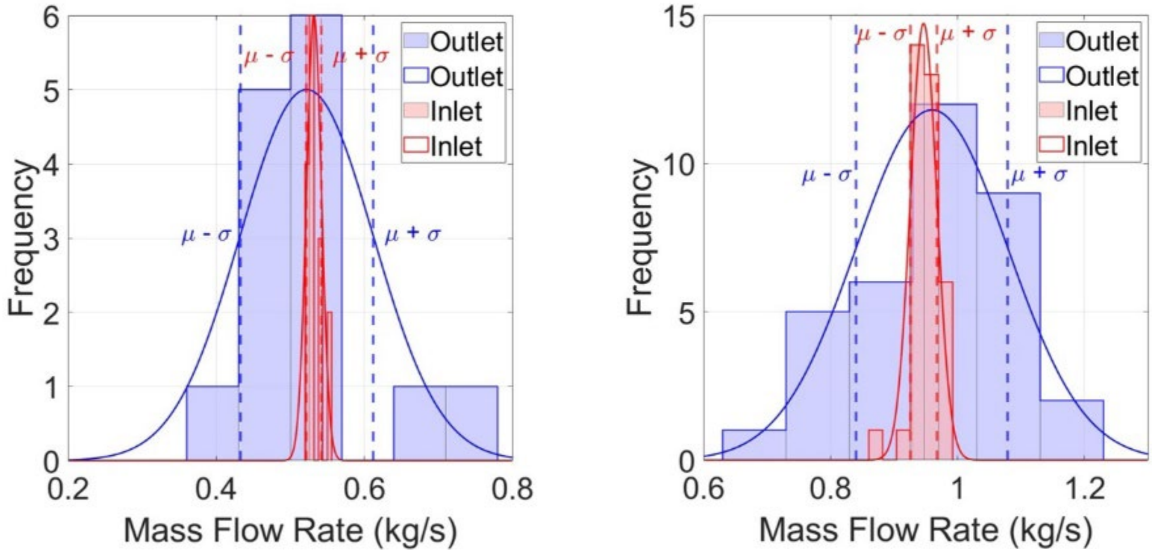

Figure 4. *Probability distribution of inlet vs. outlet mass flow rates (a) 0.5 kg/s (b) 1 kg/s*

A series of tests were conducted measuring two target particle mass flow rates, 0.5 & 1 kg/s, at the inlet & outlet of the fluidized bed to examine if the particles are horizontally conveyed. Figure 4 displays the distribution of particle mass flow rates measured at the inlet and outlet of the FB for the 0.5 and 1 kg/s flow rates, with a normal distribution line fitted to the data. The red curves refer to the inlet mass flow rates, and the blue curves refer to the outlet mass flow rates. The dashed vertical lines indicate the means and standard deviations. These graphs demonstrate that in the case of both desired mass flow rates, the inlet values have less of a standard deviation and are closer to the mean than the outlet values.

To ensure consistent data was gathered, each test was conducted for 15 seconds at ~1.5U_{mf} (0.39 m/s), and an equal number of tests was taken at each inlet & outlet. 14 tests were conducted on the inlet & outlet of the desired 0.5 kg/s mass flow rate. As shown in Figure 4a, this resulted in an inlet mean of 0.53 kg/s, standard deviation of 0.01, and range of 0.52-0.55 kg/s. The outlet of the desired 0.5 kg/s mass flow rate resulted in a mean of 0.52, standard deviation of 0.09, and range of 0.37-0.73 kg/s. 35 tests were conducted on the inlet & outlet of the desired 1 kg/s mass flow rate. As shown in Figure 4b, this resulted in an inlet mean of 0.95 kg/s, standard deviation of 0.02, and range of 0.87-0.99 kg/s. The outlet of the desired 1 kg/s resulted in a mean of 0.96 kg/s, standard deviation of 0.12, and range of 0.69-1.23 kg/s. Student's t-tests were then performed on the dataset at a 95% confidence interval and determined that the inlet and outlet data were statistically similar for both desired mass flow rates. This provides confidence that large scale designs can horizontally convey particles without significant variation in flow rate.

3.2 Particle vertical mixing

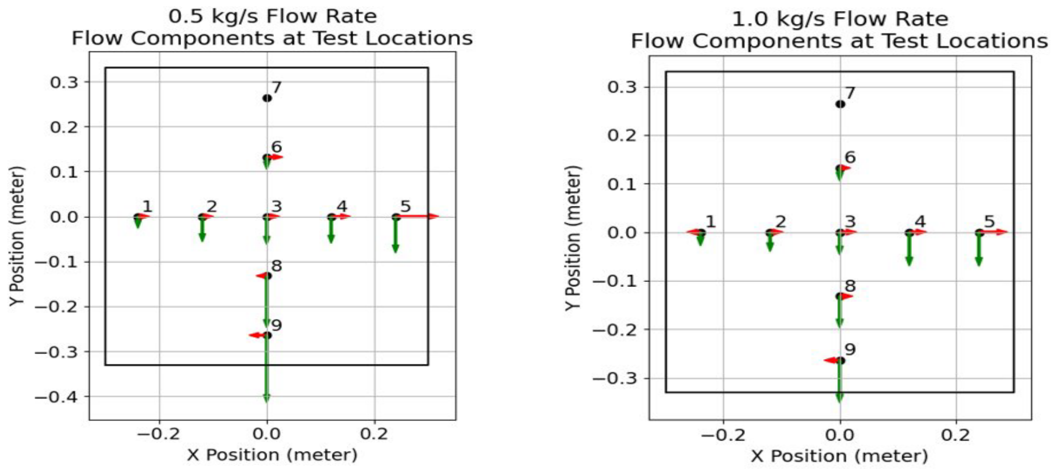

Figure 5. *Particle displacements (a) 0.5 kg/s (b) 1 kg/s*

Tracking particle motion aids in determining bubble frequency and particle mixing in the bed. In this study, particle motion was tracked using a PIV system, and a MATLAB PIV algorithm generated velocity plots to inform local motion. Particle velocity vectors were calculated at each test location for both desired mass flow rates, as shown in Figure 5. The particles' X and Y velocity heavily depend on the location within the bed.

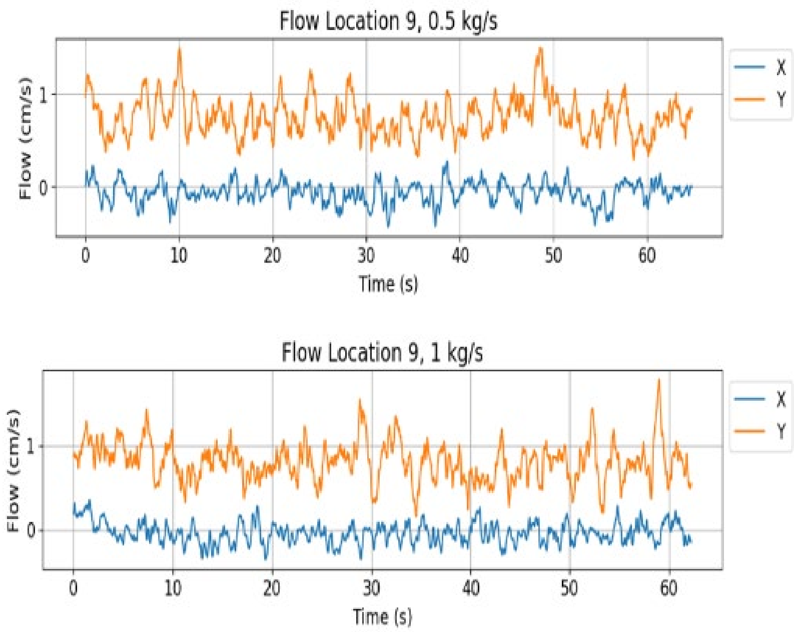

Figure 6. *Flow velocities at location 9 (a) 0.5 kg/s (b) 1 kg/s*

Figure 6 shows the flow velocities for both desired mass flow rates at location 9. The blue line represents the motion in the horizontal X-direction, and the orange line represents the motion in the vertical Y-direction. As the X line and Y line in both plots are closer to 0 and 1 cm/s, respectively, it can be inferred that there is more particle motion in the Y-direction than the X-direction. It can also be deduced that the oscillations and peaks within both plots are caused by particle bubbling within the bed. It is worth noting that since this method only examines particle motion on the exterior wall, there may be variations in behavior in the bulk of the bed. However, this method can inform local particle motion, as well as characterize particle motion in the large scale FB.

4. Conclusion

Various types of particle-based heat exchangers in the concentrating solar industry have demonstrated unique advantages. Some factors to evaluate effectiveness include cost, heat transfer coefficient, manufacturability, parasitics & heat losses, structural reliability, compatibility, erosion & corrosion, scalability, ease of inspection and transient operation. In fluidized beds, horizontal conveyance enables more compact designs for heat exchangers. The goal of this study was to outline the design and component sizing of a cold flow fluidized bed test apparatus, which will aid in developing compact, high efficiency particle-based heat exchangers by maximizing horizontal conveyance throughout the bed. Particles were successfully conveyed horizontally at ~$1.5U_{mf}$, and a PIV method used to track particle motion was established and could be used in further studies.

Author Contributions

JK contributed to the writing of the original draft, conceptualization, data curation, formal analysis, and methodology. BS contributed to the data curation, formal analysis, methodology, and validation. HH contributed to the methodology, conceptualization and data curation. NS contributed to the conceptualization, test rig design and troubleshooting, methodology, project administration, supervision, and review & editing of the writing.

Competing Interests

The authors declare that they have no competing interests.

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References

[1] C. K. Ho, "Advances in central receivers for concentrating solar applications," Solar Energy, vol. 152, pp. 38-56, 2017.

[2] C. K. Ho, M. D. Carlson, K. Albrecht, Z. Ma, S. Jeter, and C. Nguyen, "Evaluation of Alternative Designs for a High Temperature Particle-to-sCO2 Heat Exchanger," presented at the Conference: Proposed for presentation at the ASME 2018 Power and Energy Conference held June 24-28, 2018 in Lake Buena Vista, FL., United States, 2018. [Online]. Available: https://www.osti.gov/biblio/1515325
[3] C. Wu, H. Yang, X. He, C. Hu, L. Yang, and H. Li, "Principle, development, application design and prospect of fluidized bed heat exchange technology: Comprehensive review," Renewable and Sustainable Energy Reviews, vol. 157, p. 112023, 2022/04/01/ 2022, doi: https://doi.org/10.1016/j.rser.2021.112023.
[4] D. C. Miller, C. J. Pfutzner, and G. S. Jackson, "Heat transfer in counterflow fluidized bed of oxide particles for thermal energy storage," International Journal of Heat and Mass Transfer, vol. 126, pp. 730-745, 2018/11/01/ 2018, doi: https://doi.org/10.1016/j.ijheatmasstransfer.2018.05.165.
[5] S. W. Kim, J. Y. Ahn, S. D. Kim, and D. Hyun Lee, "Heat transfer and bubble characteristics in a fluidized bed with immersed horizontal tube bundle," International Journal of Heat and Mass Transfer, vol. 46, no. 3, pp. 399-409, 2003/01/01/ 2003, doi: https://doi.org/10.1016/S0017-9310(02)00296-X.
[6] O. Molerus, A. Burschka, and S. Dietz, "Particle migration at solid surfaces and heat transfer in bubbling fluidized beds—II. Prediction of heat transfer in bubbling fluidized beds," Chemical Engineering Science, vol. 50, no. 5, pp. 879-885, 1995/03/01/ 1995, doi: https://doi.org/10.1016/0009-2509(94)00446-X.
[7] R. Cocco, S. Karri, and T. Knowlton, "Introduction to Fluidization," Chemical Engineering Progress, vol. 110, pp. 21-29, 11/01 2014.