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Improved Particle Heat Transfer by way of Bimodal Particle Distributions for High Temperature Solar Thermal Energy

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Abstract. High temperature solar thermal facilities are looking to increase operating temperatures through novel heat transfer media, one such being solid particles. These particles operating at high temperatures will require transferring their thermal energy into another working fluid like supercritical carbon dioxide which can be used in advanced power cycles. Achieving high heat transfer between the particles and supercritical carbon dioxide is essential to high efficiency and low-cost operation. Therefore, optimizing the thermal conductivity of these particles is one potential way to ensure high performance. Traditionally, unimodal particle distributions have been employed in high temperature particle solar power plants. However, ambient temperature testing of bimodal particle distributions has revealed a superior thermal conductivity when compared to its unimodal counterpart at the same temperature. This data was obtained by certified, off-the-shelf instruments that can effectively simulate the conditions a particle would be exposed to in a high temperature solar thermal system. Data obtained in this way suggests that the increased thermal conductively imputed by a bimodal particle distribution is significant at working temperatures in solar facilities. Furthermore, the thermal conductivity of these bimodal particle distributions peaks when the best combination of large and small particles is applied. At high temperatures, binary particle distributions are compared to monodispersed distributions of larger particles where heat transfer is more prolific due to the increased surface radiation. Various thermal conductivity, porosity and heat exchanger models are explored in conjunction with data acquired up to 700 C.

Keywords: Heat Exchanger, High Temperature, Solar Thermal Facilities, Solid Particles

1. Introduction

High temperature solar thermal facilities are looking to increase operating temperatures through novel heat transfer media, one such being solid particles. These particles operating at high temperatures will require transferring their thermal energy into another working fluid like supercritical carbon dioxide which can be used in advanced power cycles. Achieving high heat transfer between the particles and supercritical carbon dioxide is essential to high efficiency and low-cost operation. Therefore, optimizing the thermal conductivity of these particles is one potential way to ensure high performance.

2. Experimental Method and Calibration

To make the necessary measurements, a TPS 2500 S, an off-the-shelf instrument from the company Hot Disk, will be utilized. Hot Disk employs a paper sensor that utilizes a transient plane source method to determine the thermal conductivity of the media it contacts (see fig. 1). The Hot Disk sensor is embedded within a media being tested which is set on an apparatus inside a Thermolyne FB1415M Compact Benchtop Muffle Furnace. In this way, environments of up to 800 C can be emulated. However, due to the nature of a non-inert, high temperature atmosphere within the muffle furnace and the durability of mica Hot Disk sensors, temperatures of up to only 700 C are exercised. To calibrate this setup, thermal conductivity measurements of CARBOBEAD HSP 40/70 were compared to other measurements where a tube furnace was employed [1].

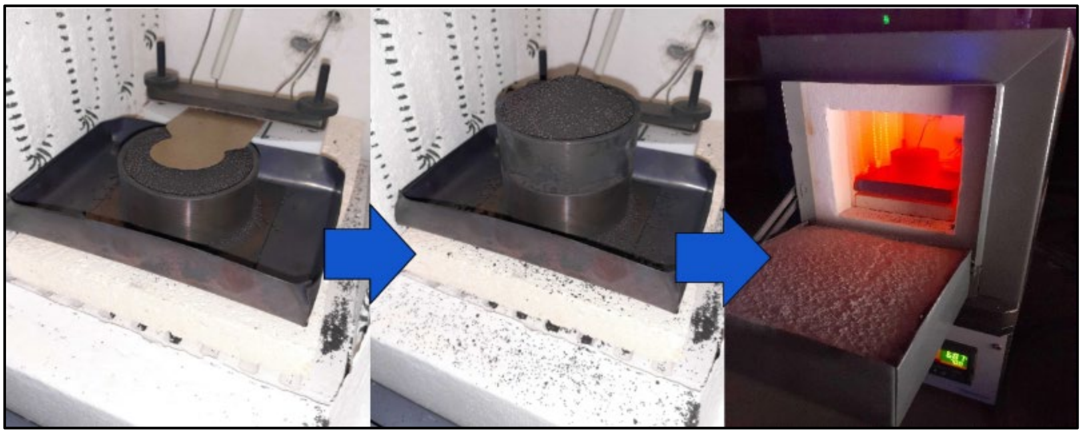

Figure 1. Experimental setup: Hot Disk mica sensor embedded within media cased in stainless steel chamber and placed inside muffle furnace for thermal conductivity analysis.

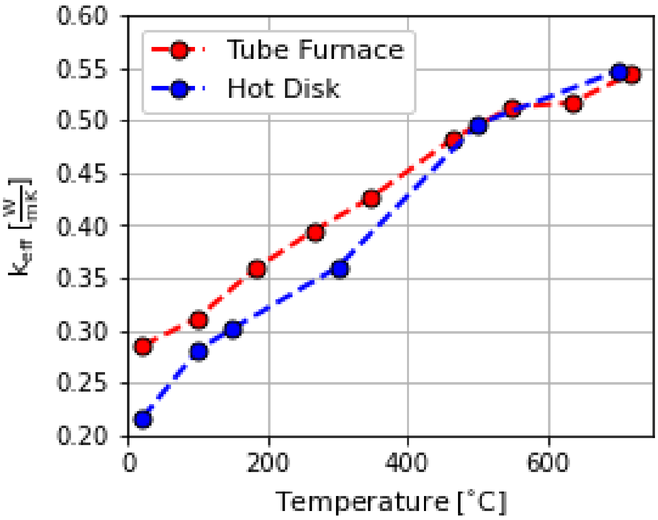

Figure 2. Instrument thermal conductivity comparison of CARBOBEAD HSP 40/70.

As can be seen in figure 2, the Hot Disk instrument very closely resembles measurements of the tube furnace, especially at temperatures above 300 C. Measurements of the Hot Disk and the tube furnace are nearly identical at temperatures exceeding 500 C.

3. Current Ambient Bimodal Particle Distribution Findings

Traditionally, unimodal particle distributions have been employed in high temperature particle solar power plants. However, ambient temperature testing of bimodal particle distributions has revealed a superior thermal conductivity when compared to its unimodal counterpart at the same temperature. Data observed in figure 3 suggests that the increased thermal conductively imputed by a bimodal particle distribution is significant at ambient temperatures.

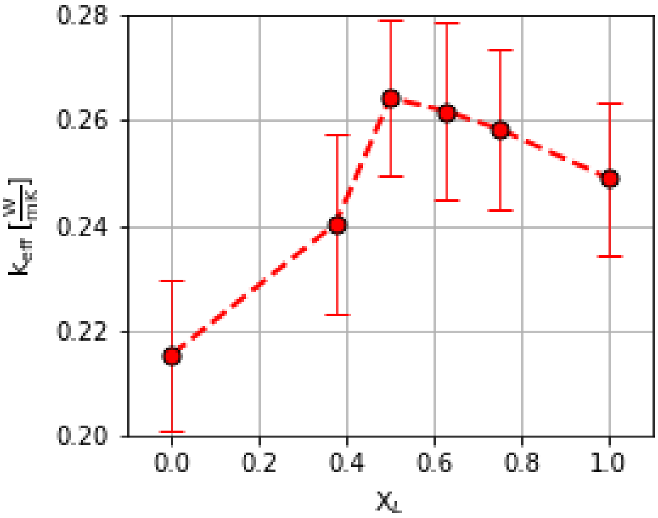

Figure 3. HSP 40/70 (smaller particle) and HSP 16/30 (larger particle) large particle volume fraction (X_L) thermal conductivity spectrum at ambient temperature. Error bars calculated with Uncertainty Analysis and Error Propagation Methodology from Georgia Tech [2].

4. Current High Temperature Bimodal Particle Distribution Findings

Data acquired for large particle volume fractions of HSP 16/30 and 40/70 up to 700 C illustrates the radiative properties associated with an increased particle diameter. This is due to the surface radiation which is significant at high temperatures and relatively small at ambient temperatures. This increase in surface radiation occurs in larger particles because the emission from one particle to an adjacent particle moves a larger distance and therefore acts as a radiative shield [3]. Using larger particle diameters will allow for fewer radiative shields and overall greater thermal conductivity at higher temperatures. This phenomenon is evident in figure 4 where a large particle volume fraction of 1 (or HSP 16/30, the larger particle of the mix) imputes the highest thermal conductivity and is significantly greater than all other volume fractions.

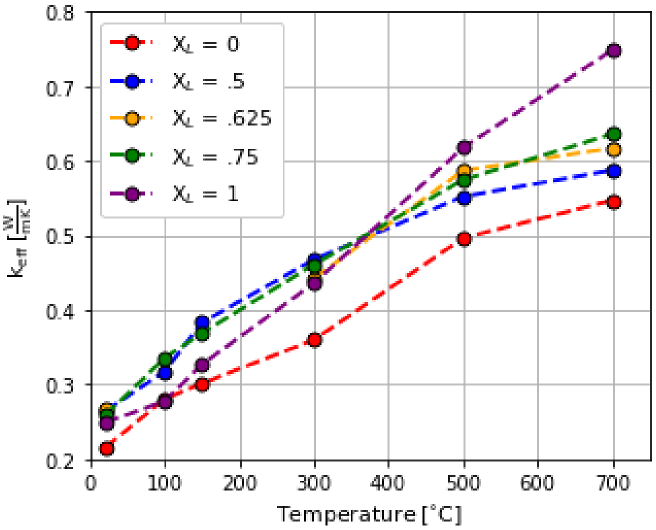

Figure 4. HSP 40/70 (smaller particle) and HSP 16/30 (larger particle) large particle volume fraction thermal conductivities at temperatures up to 700 C.

5. Thermal Conductivity Modeling with Bimodal Particle Distributions

Modeling mono-dispersed particle distributions provides difficulties. Understandably, modeling binary particle distributions is no easier feat. A critical component of modeling thermal conductivity of a packed bed is that of the bed's porosity. Two porosity models will be utilized here, that of Standish & Yu [4] and also of Chang & Deng [5]. Additionally, two promising candidates for modeling thermal conductivity at high temperatures for bimodal particle distributions are the ZBS [6] and Yagi & Kunii [7] models. Critical parameters utilized in both these models can be found in table 1. A distinct difference between the models is the empirical particle contact parameter (∏): .01 for the ZBS model [6] and for the Yagi & Kunii model, calculated according to that outlined in reference 7 [7].

Table 1. Critical parameters used in both ZBS and Yagi & Kunii thermal conductivity models.

Property	Symbol	Value	Units	Ref.
Particle Diameter	d_p	321 - 866	⌠m	[8]
Particle Emissivity	Σ_r	0.908	-	[1]
Particle Thermal Conductivity	k_s	2.0	W/m-K	[1]
Particle Density	$\rangle_s$	3,610	Kg/m^3	[8]
Particle Specific Heat	c_p	1,280	J/kg/K	[9]

The ZBS model projections for all size ratios and volume fractions between HSP 16/30 and 40/70 can be found in figure 5. The ZBS model is a conservative, popular approach that

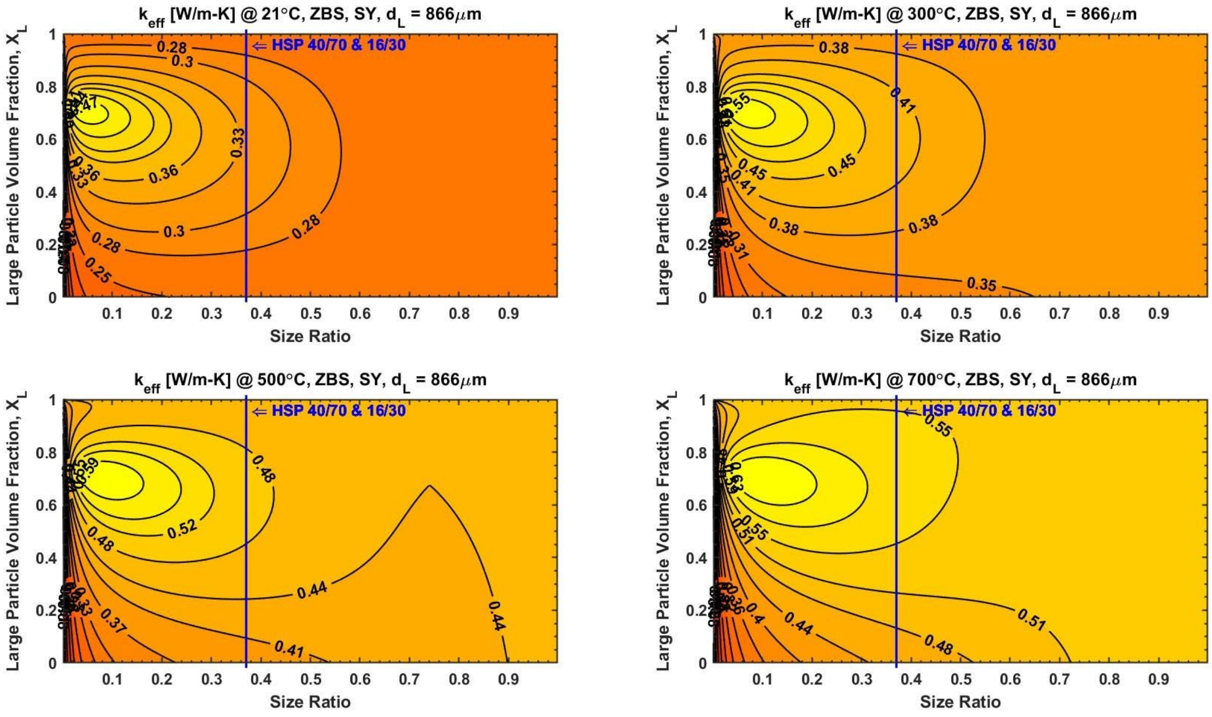

Figure 5. HSP thermal conductivity contour plots for various temperatures calculated with the ZBS and Standish & Yu models. The vertical blue lines on each plot represent the specific size ratio or "slice" of HSP 16/30 – 40/70 where data was collected.

compliments temperatures up to 300 C reasonably well, albeit slightly over and under projecting thermal conductivity lines. The ZBS model does not do well emulating high temperature data points as can be see in the HSP 16/30 – 40/70 “slice“ in figure 6. When comparing to experimental data, the model seems to undervalue the radiative benefits of high-volume fractions.

The Chang & Deng model also shows promise in use with higher temperature, particle thermal conductivity predictions. Not only does the Cheng & Deng model have closer predicted thermal conductivity values at ambient temperatures, but it also seems to adhere better to higher temperatures (namely 700 C) in that the concavity of its slope at volume fractions exceeding .5 is down while the Standish & Yu model line still is concave up in figure 6. The difficulty with the Chang & Deng is that predictions rely on a small amount of experimental data to base projections off of. For this reason, contour plots with the Chang & Deng porosity model are not utilized.

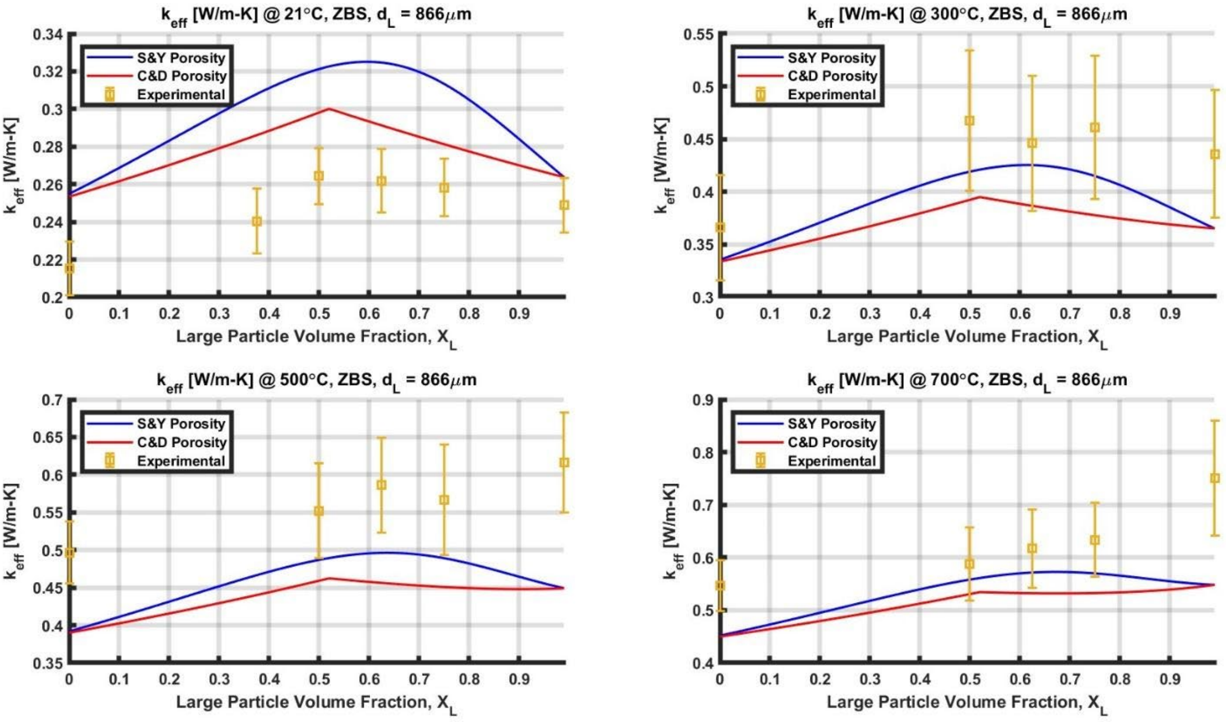

Figure 6. HSP thermal conductivity plots for various temperatures with experimental data calculated with the ZBS model. Porosity is modeled with both the Standish & Yu and Chang & Deng models. Error bars calculated with Uncertainty Analysis and Error Propagation Methodology from Georgia Tech [2].

The Yagi & Kunii model is a less popular thermal conductivity approach. However, while the model struggles where the ZBS model does relatively better (namely at 21 and 300 C), the Yagi model more closely resembles the experimental data acquired at temperatures of 500 and 700 C. In short, the Yagi model seems to do a better job accounting for the surface radiation of large particles at high temperatures (figures 6, 7). The Yagi & Kunii model suggests that starting at around 300 C, the surface radiation of the large particles begins to exceed the benefits of a binary particle mixture that has superior thermal conductivity at lower temperatures. At 500 C, figure 7 shows good agreement with experimental behavior. The Yagi & Kunii model projects that the surface radiation at 700 C is very significant and while the projection is above the experimental data, behavior is similar.

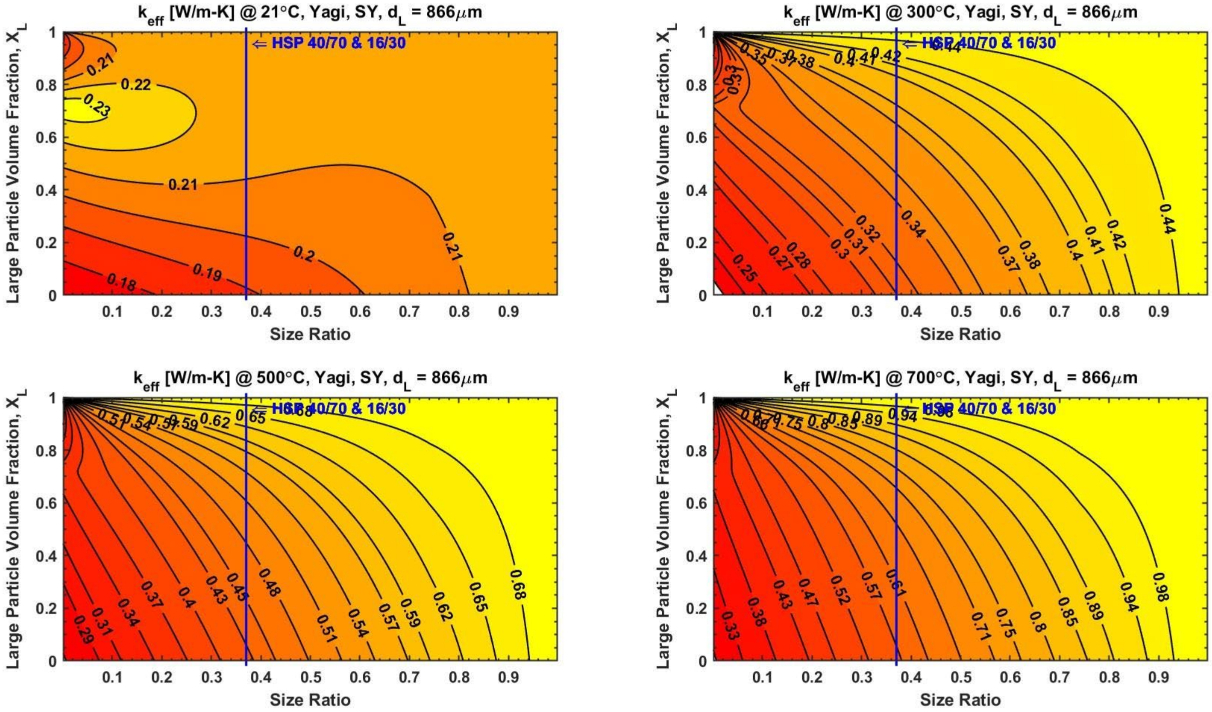

Figure 7. HSP thermal conductivity contour plots for various temperatures calculated with the Yagi & Kunii and Standish & Yu models. The vertical blue lines on each plot represent the specific size ratio of HSP 16/30 – 40/70 where data was collected.

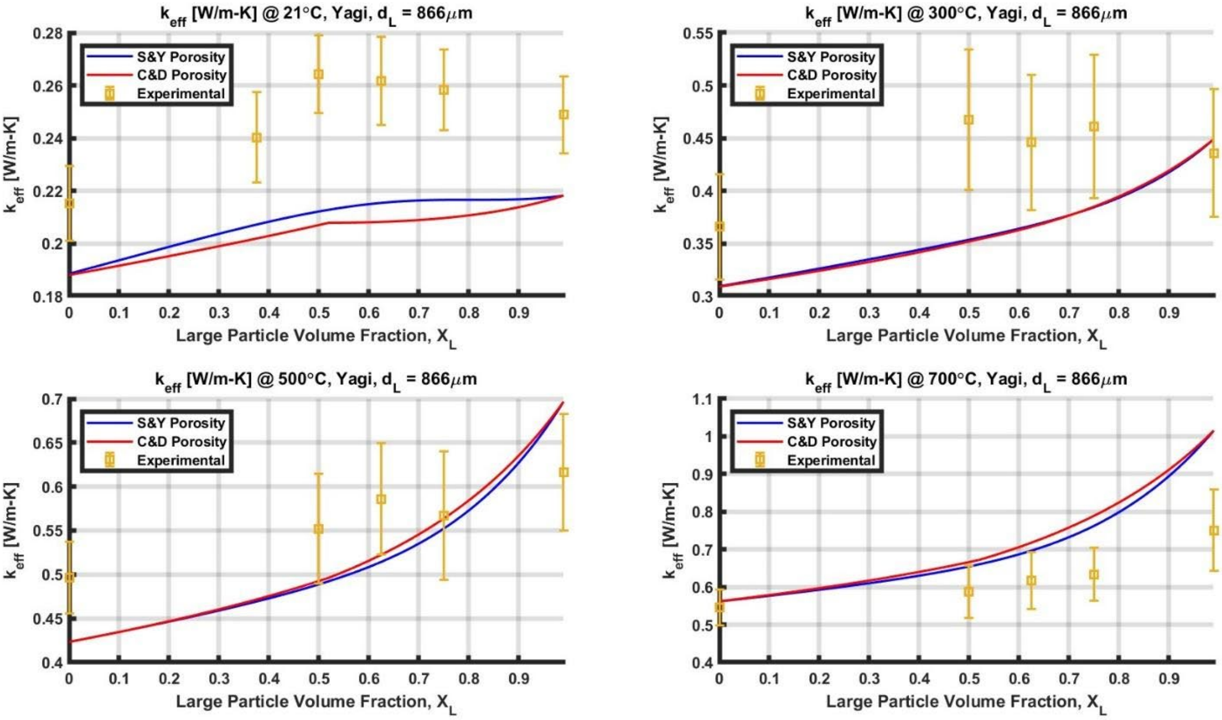

Figure 8. HSP thermal conductivity plots for various temperatures with experimental data and calculated with the Yagi & Kunii model. Porosity is modeled with both and Standish & Yu and Chang & Deng models. Error bars calculated with Uncertainty Analysis and Error Propagation Methodology from Georgia Tech [2].

6. Heat Exchanger Modeling with Bimodal Particle Distributions

Shell-and-plate moving packed bed heat exchangers using particles as a heat transfer media are a potential option for the particle-to-sCO2 heat exchangers in next-generation concentrating solar power (CSP) plants. Current modeling efforts have focused on the impact of monodisperse particle size and heat exchanger dimensions on performance. With either the ZBS or Yagi & Kunii thermal conductivity models it will be possible to model the bulk effective thermal conductivity and heat transfer for a bed of particles in a shell-and-plate moving packed-bed, particle-to-CO_2 heat exchanger [10]. The model follows that which is outlined by Alrecht and Ho [11] and can be seen in the diagram in figure 9.

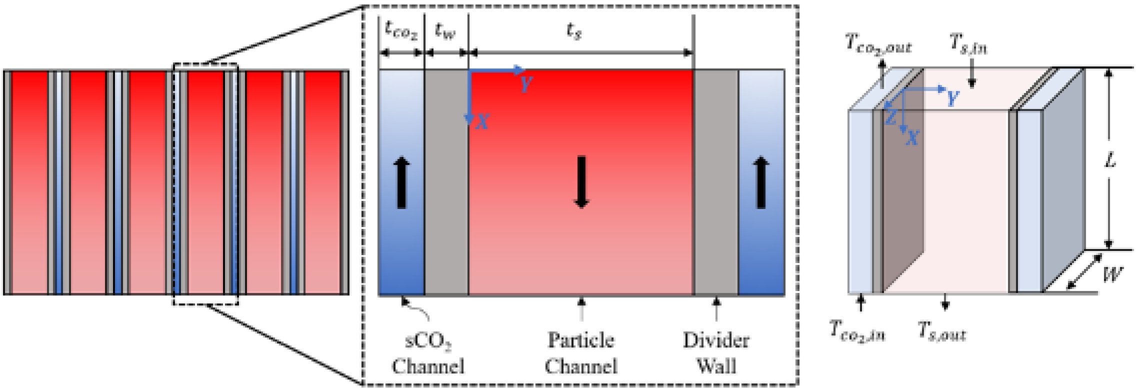

Figure 9. Moving packed bed heat exchanger [11].

With this moving packed-bed heat exchanger model, we can examine what the predicted thermal conductivity would look like for particle distributions calculated by either the ZBS or Yagi & Kunii models with the Standish & Yu porosity model (fig 10).

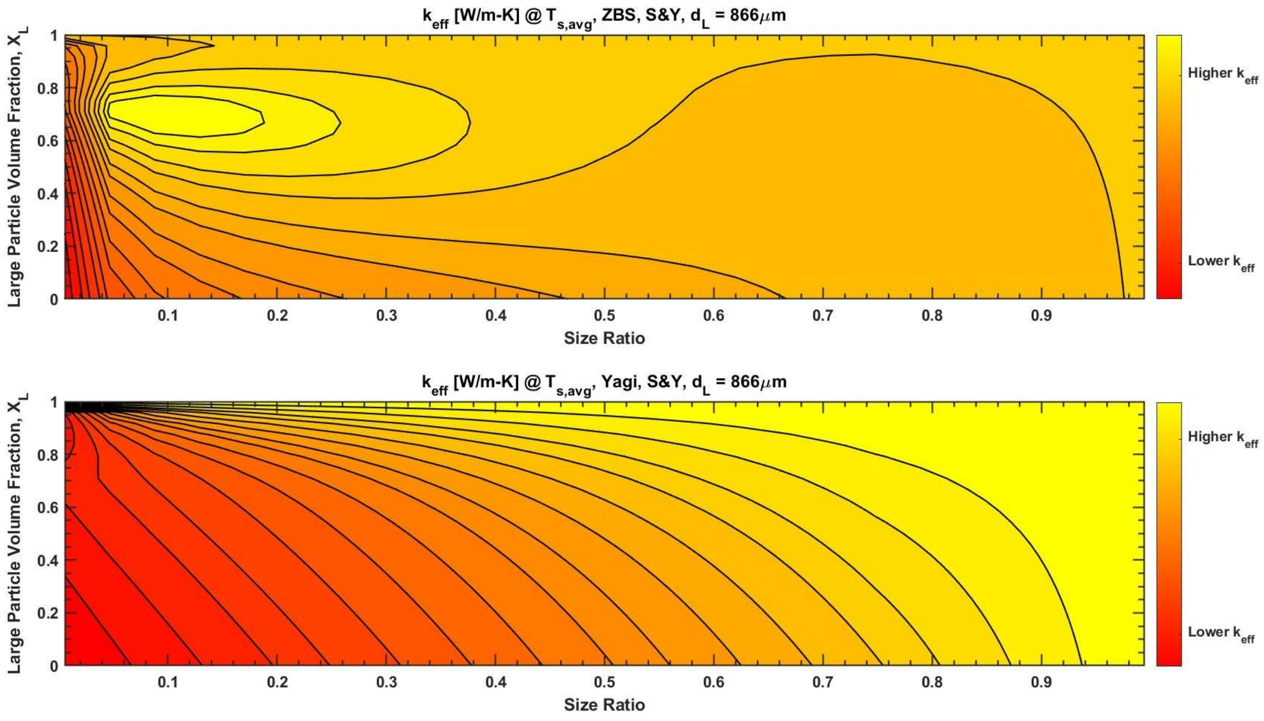

Figure 10. Heat exchanger model with ZBS and Yagi & Kunii thermal conductivity models and Standish & Yu porosity model. Contour levels not annotated as thermal conductivity models are still in refinement phase.

An inspection on figure 10 reveals that the Albrecht and Ho heat exchanger model with the ZBS thermal conductivity model produces the best thermally conductive particles when the size ratio is low, and the volume fraction is around .6-.8. From ambient temperature testing of binary particle mixtures, this is what we would expect. Adversely, the Yagi & Kunii model produces the most thermally conductive particles when the size ratio is 1, i.e., when only the large particle is utilized. This idea would agree with the data collected at 500 and 700 C for the large particle ($X_L = 1$) in figure 8 where it is apparent that the surface radiation effect from the large particle is significantly influencing the thermal conductivity of the mixture.

7. Conclusion

At this time, it is impossible to conclude which thermal conductivity model is more correct: the ZBS model better describes the behavior of particle mixtures from ambient temperature to around 300 C while the Yagi & Kunii model better describes the behavior at temperatures around 300 to 700 C. More research into the literature of these and other models will help dictate which of the two models is more reliable in the long run. Additionally, further particle characterization will need to take place as to verify the model behaviors of different particle size ratios at various temperatures.

8. Future Work

In order to validate whether either the ZBS or Yagi & Kunii thermal conductivity models more accurately describes the behavior of binary particle mixtures at high temperature, further particle characterization will need to take place. Currently, we are in the process of acquiring CP 12/18, a CARBOBEAD product similar to that of HSP. CP 12/18 has a diameter of ~1100 μm. With this particle, we will be able to see if the thermal conductivity exceeds that of pure HSP 16/30. If this is the case, this would most likely be due to the fact that CP 12/18 has a greater diameter and therefore greater surface radiation. Furthermore, a binary mixture of HSP 16/30 – CP 12/18 would be able to be characterized which would allow more insight into the validity of the ZBS model as the size ratio of this particular mixture would be around .25. This size ratio would put the experimental “slice” of data more towards the optimal thermal conductivity portion of the ZBS contour maps found in figures 5 and 10. Ultimately, the CP 12/18 will help determine which model is more reliable at high temperatures and if binary mixtures are more or less efficient than large particle, mono-dispersed distributions.

Data Availability Statement

Data is unavailable for public consumption at this time.

Author Contributions

Dallin Stout: Methodology, Investigation, Writing – original draft. Todd P. Otanicar: Conceptualization, Writing – original draft, Supervision. Nirmala Kandadai: Conceptualization, Writing – original draft, Supervision.

Competing Interests

The authors declare no conflicts of interest. The authors would like to acknowledge partial support of this work from the U.S. Department of Energy Solar Energy Technologies Office under award number DE-EE0009375.

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