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Design & Optimization of Solar Receiver Geometries

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Abstract

Concentrating solar power (CSP) applications use large arrays of mirrors to reflect solar radiation onto a receiver, generating high temperature heat-transfer fluid that is used in a heat engine to generate electricity. Currently, the geometry of the heat exchanger at the focal point of the CSP system is typically a bank of tubes. This geometry yields high convective losses as well as radiation losses due to reflection.

The objective of this work was to design and optimize solar radiation receiver geometries, minimizing heat losses and maximizing radiation capture. Parametric analyses were performed to simulate the thermal behavior of different receiver geometries. After identifying high efficiency receivers, stress analysis were performed to determine the feasibility of proposed geometries.

Introduction

Concentrating solar applications utilize mirrors and other reflective materials to redirect incident solar radiation onto a receiver. There are several configurations of CSP systems, such as parabolic trough, linear Fresnel lenses, and solar power towers (Figures 1a, 1b, and 1c respectively).[1]

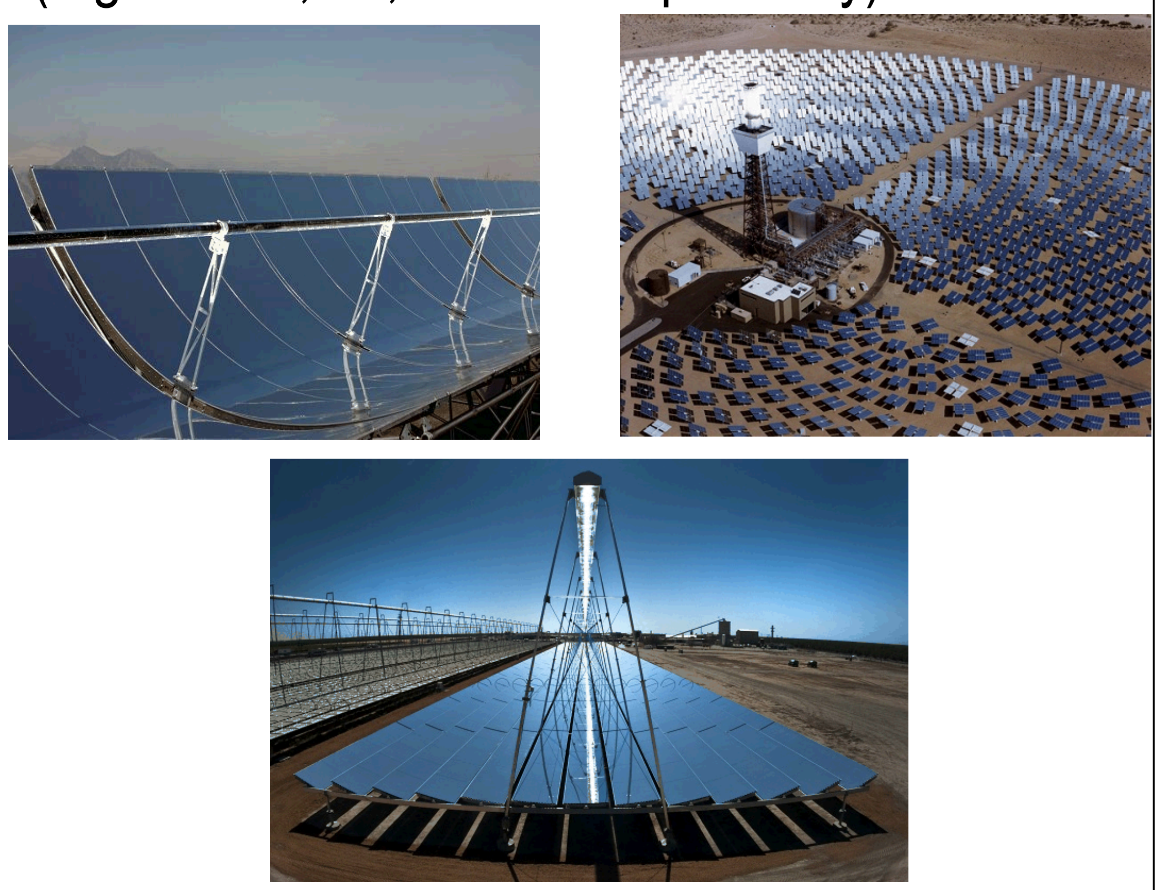

Figure 1. Configurations for Concentrated Solar Power applications.[1] From top left clockwise, a) parabolic trough, b) solar power tower, and c) linear Fresnel lens system.

One important aspect of all solar power configurations is the receiver, which rests at the center of the concentrated solar energy. This receiver is the mechanism by which the solar radiation is transmitted to the working fluid. In the past, receiver geometries have typically been banks of tubes for solar power tower applications.

The purpose of this work was to propose and simulate novel receiver geometries, which utilized reflection as well as geometry to maximize radiation capture while minimizing heat transfer losses.

Methods

Geometries were developed from qualitative considerations of radiation trapping, radiation losses, and convective losses. Radiation trapping is a phenomena in which the reflective properties of a material allow it to capture thermal radiation in certain geometries. A well studied case of radiation capture is a cavity, in which an enclosed volume captures radiation more effectively as a black body.

Several geometries were developed, and considered in a thermal analysis of concentrated solar radiation.

The efficiency of the fractal receiver was designed by considering control volume and evaluating net energy input. The efficiency of the receiver is given by

$$\eta_{Receiver} = \frac{\dot{Q}_{Solar} - \dot{Q}_{Emitted} - \dot{Q}_{Convection}}{\dot{Q}_{Solar}} \qquad (1)$$

Geometries were varied parametrically for optimization. Key parameters, such as material thickness and absorptivity, were used to develop a design map of potential receiver geometries.

Results

Several receiver geometries were generated to evaluate their thermal behavior. Sample geometries can be seen in Figure 2, though more sophisticated geometries were also simulated.

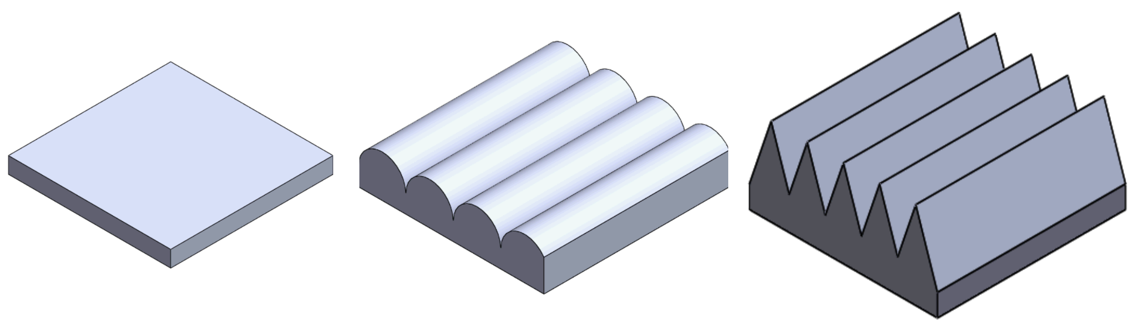

Figure 2. Sample geometries for simulation and testing.

A sample temperature profile can be seen in Figure 3. The temperature distribution and maximum were significant for the later evaluation of thermal and mechanical stresses throughout the system.

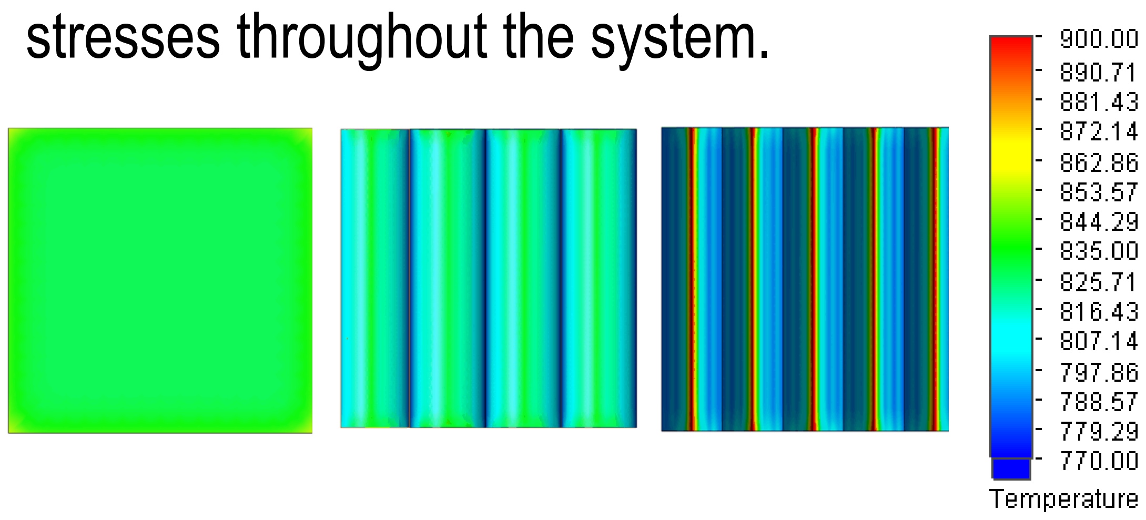

Figure 3. Temperature (K) profiles on top face of sample geometries.

The flow characteristics for promising geometries have also been simulated to determine if they can successfully achieve the required heat transfer.

Convergence studies were performed to determine that the results were independent of mesh size.

Discussion

Typically, thinner geometries were able to conduct heat more effectively. The thinner material presents less of a thermal resistance between the isothermal fluid and the outside radiation. This reduces the outer wall temperature, thereby reducing losses from the surface. Secondly, the lower temperature also reduces convective losses to the air. Therefore, an important design characteristic is to develop geometries with thin walls while simultaneously maintaining structural strength.

Geometries which posses greater surface area both allow for greater solar absorption as well as more contact area for convective losses. Therefore, the design optimization is a combination between these two factors. There are certain geometries wherein a factor, such as a length or angle, was varied parametrically and it was determined there was a maximum point for balancing radiation absorption and convective losses.

Finally, it was determined that simulating the flow behavior through the receiver geometry was essential to validate the assumption of isothermal internal temperature. If the flow is not able to move through the receiver geometry, the receiver will have higher surface temperatures and consequently lower efficiencies.

Conclusion

Several geometries have been developed and simulated for the purposes of evaluating thermal behavior. Key aspects of the thermal behavior, such as device thickness and the relatively of importance of convective losses, have been identified.

Future Work

Next steps are to proceed with more advanced simulations of optimized devices, accounting for fluid flow behavior on the internal device boundary as well as stresses within receiver geometries. Parametric studies will be performed, considering the wall thickness of the receiver and absorptivity.

Once several optimal geometries have been identified, Proposed geometries will be fabricated using additive manufacturing methods to validate thermal simulations.

References

1. SEIA, “Concentrating Solar Power”, www.seia.org

Numerical & Analytical Simulation of a Falling Particle Receiver

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Abstract

Concentrating solar power applications entail focusing solar radiation, generating high temperatures. Currently molten salts are used in concentrated solar power systems, which are limited in temperature to approximately 500 – 600°C. One possible replacement to molten salt as a heat transfer fluid is solid particles.

The objective of this work has been to develop simulations, both numerical and analytical, of a falling particle curtain. From first principles, heat transfer and flow characteristics of a falling particle curtain have been developed. Numerical simulations have also been performed and compared to analytical models. Simulations will be validated by experiment. An understanding of the particle cloud will allow for better design of solar power towers.

Introduction

Ceramic particles have potential to outperform molten salts in CSP systems, both through their optical as well as heat transfer properties. Particles have several beneficial advantages for use in CSP applications. They can achieve temperatures exceeding 1000°C, while molten salts are limited to ~600°C. Particles have tunable optical properties, and therefore their thermal efficiency can be maximized by high absorptivity in the visible spectrum and low emissivity in their emitting spectrum. Finally, particles can be used as a direct heat transfer storage mechanism.

The purpose of this work was to develop an understanding of particle behavior within a receiver. This was performed through analytical heat transfer analysis as well as computational simulation, considering complex particle flow physics and heat transfer properties.

Methods (1/2)

Analytical considerations were performed to predict the behavior of the particle cloud, using previous work at Sandia as a basis[1].

First, an effective absorptivity of a particle cloud was defined. This absorptivity was developed by considering the probability a beam of solar radiation would be able to pass through a particle cloud [2]. The total radiation absorbed by the particle cloud could be considered by defining an effective absorptivity, given by

$$\epsilon_{Curtain} = \frac{1}{an} e^{-anl} \qquad (1)$$

Where *n* is the concentration of particles, *a* their area, and *l* the width of the particle cloud.

Methods (2/2)

The cloud absorptivity could be used in subsequent calculations, considering the particle cloud as a fluid. A transient 1D formulation could be used to evaluate particle temperature as a function of residence time and be compared to previous Fluent models.

Simulations in ANSYS Fluent that could be tested experimentally were generated. Idealized cases of the particle cloud behavior have previously been considered at Sandia, but there is currently a design of a of an on-sun test to take place later this year. The experimental geometry was used and will be compared to analytical and numerical simulations.

Results

The temperature of a representative particle as a function of its time in the particle receiver is presented in Figure 1. The Fluent simulation, an analytical model, and another analytical model are presented.

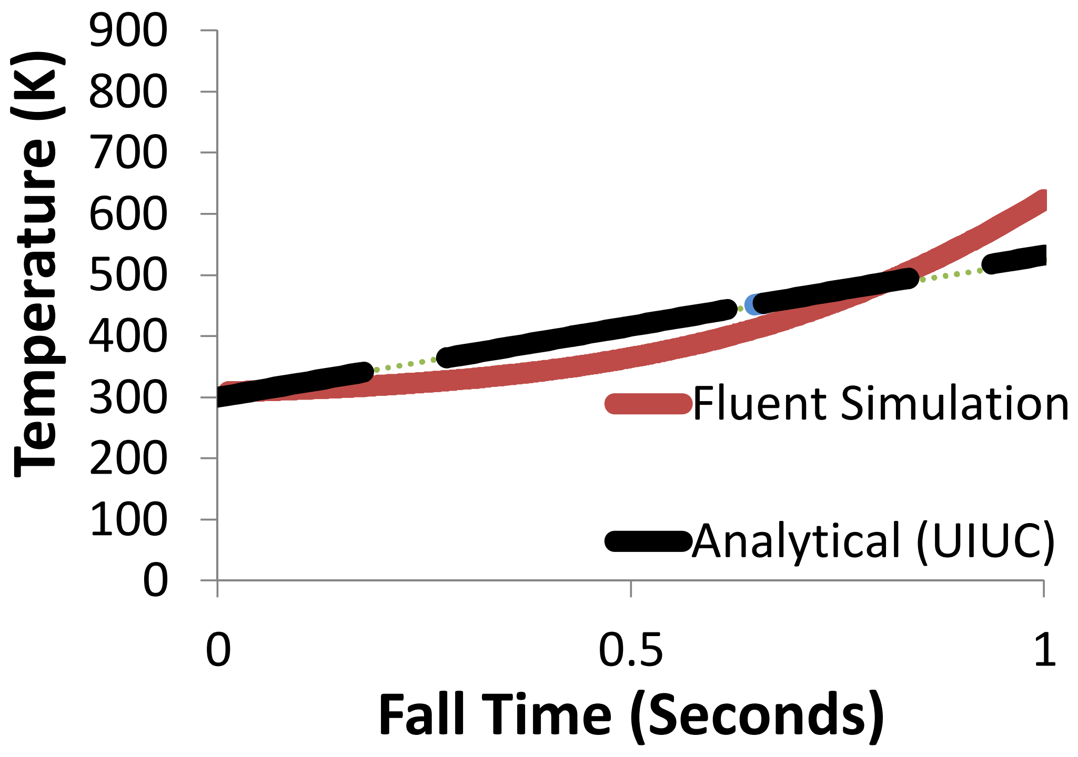

Figure 1. Fluent and analytical temperature profile for falling particle.

The effect of particle distance on re-radiation is presented in Figure 2.

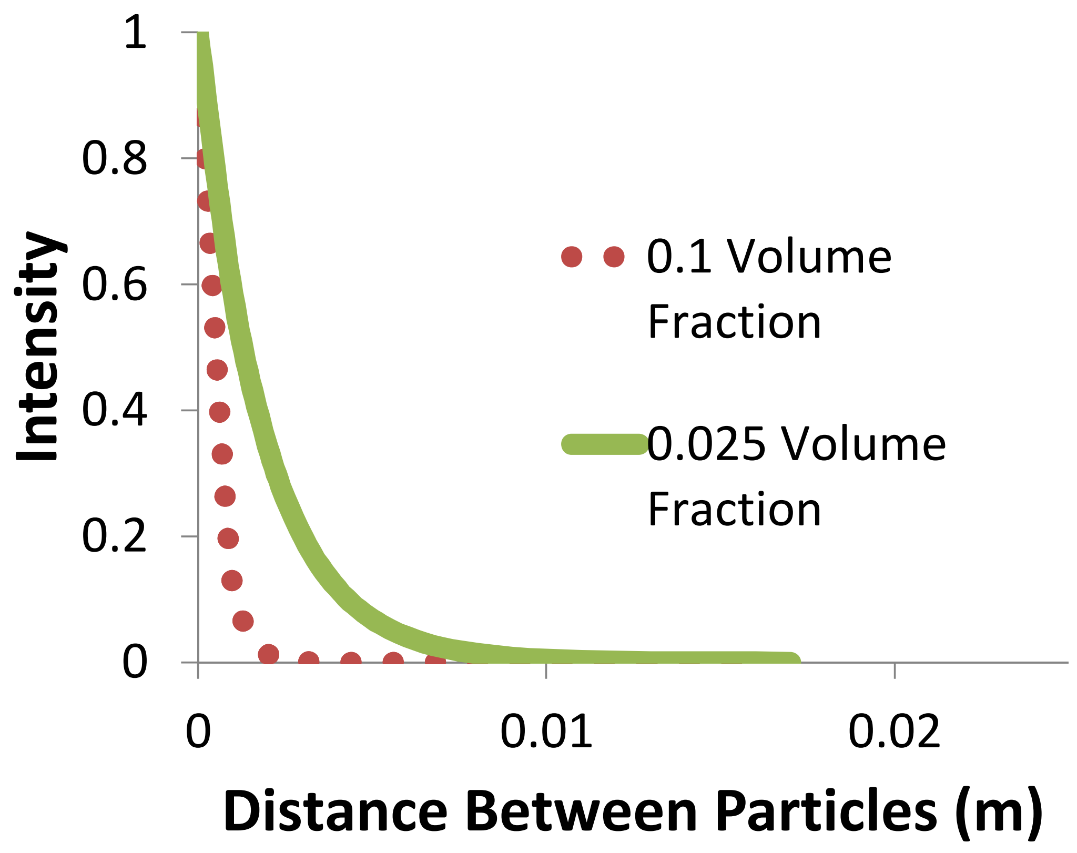

Figure 2. Blocking factor or re-radiation between particles.

The revised geometry and mesh for the simulation of the on-sun test is presented in Figure 3.

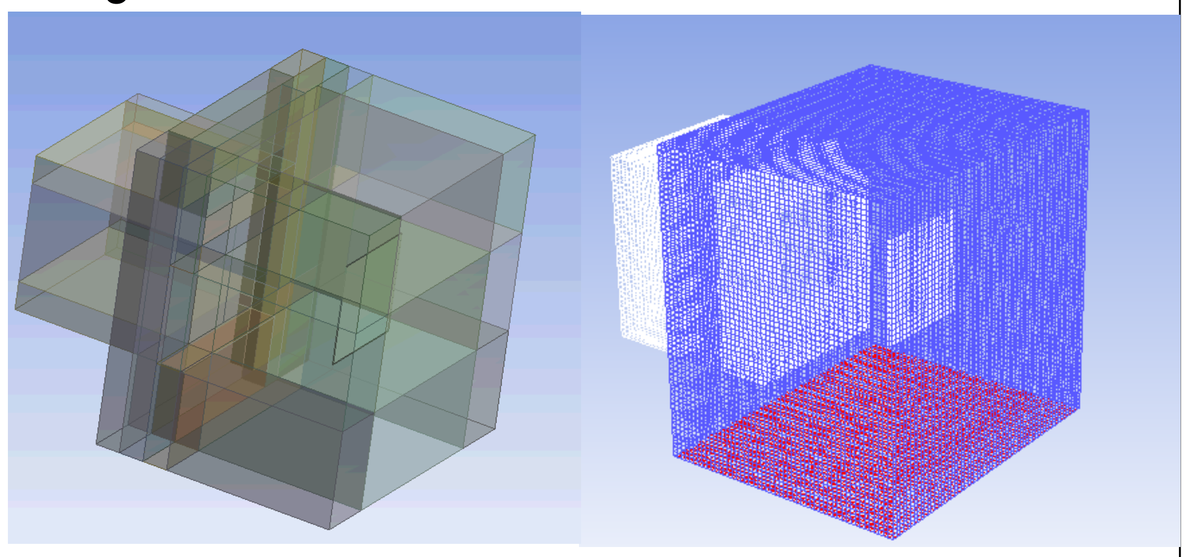

Figure 3. Geometry (left) and mesh (right).

Discussion

The two simulations for the analytical particle flow show similar trends, but it was determined that this is because of the high heat flux relative to convective losses. The properties of the air around the particles was only estimated, and this may constitute a much more significant portion of the heat transfer characteristics for the system. Therefore, these air properties should be more effectively resolved analytically before drawing conclusions regarding the system.

The effect of thermal re-radiation on particles has been demonstrated to be minimal, and therefore does not need to be considered in analytical models of the particle cloud.

The geometry for the experimental setup has been set up and meshed within Fluent. Boundary conditions have been applied and the simulation is currently running. The results from this simulation will be compared to both analytical results as well as previous simulations for validation.

Conclusion

A methodology has been developed to analytically evaluate the thermal behavior of a falling particle cloud. Particle heating time has been evaluated and compared to computational methods. Several important characteristics, such as cloud emissivity and particle re-radiation effects, have been defined and quantified for particle clouds of varying geometry.

Future Work

Future work is to finish the simulation of the particle cloud in Fluent and compare it to both the previous Fluent simulations as well as the analytical results.

The analytical results should be investigated. The Fluent simulation shows a parabolic profile to particle heating, while the analytical simulations are linear. The linearity of the analytical simulations are explained by the huge component of the flux to the particle heat transfer equation relative to the other factors. Therefore, the other effects present in the Fluent simulation should be evaluated and either accounted for in the analytical model or be justified in being neglected.

References

1. Falcone, Noring, Hruby, “Assessment of a Solid Particle Receiver for a high Temperature Solar Central Receiver System”, Sandia Report, 1985.
2. Johnstone, Chapin, “Heat Transfer to Clouds of Falling Particles”, University of Illinois Buletin, 1941