SAND2014-4578C
Proceedings of ASME 2014 8th International Conference on Energy Sustainability & 12th Fuel Cell Science, Engineering and Technology Conference
ESFuelCell2014
June 30-July 2, 2014, Boston, MA, USA

ESFuelCell2014-6446

DESIGN AND EVALUATION OF AN ON-SUN PROTOTYPE FALLING-PARTICLE CAVITY RECEIVER

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ABSTRACT

Cavity receivers have been an integral part of Concentrated Solar Power (CSP) plants for many years. However, falling solid particle receivers (SPR) which employ a cavity design are only in the beginning stages of on-sun testing and evaluation. A prototype SPR has been developed which will be fully integrated into a complete system to demonstrate the effectiveness of this technology in the CSP sector. The receiver is a rectangular cavity with an aperture on the north side, open bottom (for particle collection), and a slot in the top (particle curtain injection). The solid particles fall from the top of the cavity through the solar flux and are collected after leaving the receiver. There are inherent design challenges with this type of receiver including particle curtain opacity, high wall fluxes, high wall temperatures, and high heat losses. CFD calculations using ANSYS FLUENT were performed to evaluate the effectiveness of the current receiver design. The particle curtain mass flow rate needed to be carefully regulated such that the curtain opacity is high (to intercept as much solar radiation as possible), but also low enough to increase the average particle temperature by 200°C. Wall temperatures were shown to be less than 1200°C when the particle curtain mass flow rate is 2.7 kg/s/m which is critical for the receiver insulation. The size of the cavity was shown to decrease the incident flux on the cavity walls and also reduced the wall temperatures. A thermal efficiency of 92% was achieved, but was obtained with a higher particle mass flow rate resulting in a lower average particle temperature rise. A final prototype receiver design has been completed utilizing the computational evaluation and past CSP project experiences.

1. INTRODUCTION

Solid Particle Receivers (SPR) have the ability to become a viable receiver design for current concentrated solar power (CSP) plants. An SPR utilizes small solid particles to collect thermal energy and then transfer that energy to a working fluid for the power cycle. The particles are released at the top of a cavity receiver, fall through the cavity and collect thermal energy, then are collected at the bottom of the cavity. The particles are then stored in a hot collection bin for use in the power cycle. The advantage of using particles as the main heat transfer fluid is their ability to reach temperatures of greater than 600°C and up to 1000°C without significant material degradation. Currently there are design challenges with this type of receiver. The particle curtain opacity needs to be balanced such that the particle curtain is opaque enough to absorb a large amount of the incoming thermal energy, but has to be low enough to allow the particles to achieve their required temperatures. There are possibilities for high fluxes incident on the walls of the cavity causing high wall temperatures. Finally, heat losses also need to be evaluated to verify that a high thermal efficiency can be achieved. This research effort was focused on the design of a small-scale (1MWt) prototype receiver utilizing computational fluid dynamics (CFD).

2. PREVIOUS WORK

There have been several studies focused in the area of the SPR concept. These studies have spanned across analytical solutions, numerical solutions, and experimental results.

2.1 Analytical/Numerical Results

One of the first SPR evaluations were performed by Hruby et al. [1] in the mid-80's at Sandia National Laboratories using two-dimensional particle cloud modeling with a radiative model to determine the important design factors for this type of receiver. Hruby determined particle residence time is critical, thermal cycling of the particles, and high flux levels are needed for high efficiency. Experimental studies were also performed verifying the modeling efforts. The SPR idea seemed to have been abandoned for a long period of time before it was evaluated again. Chen et. al [2] developed a CFD model of gas-particle flow in an SPR based on the experimental models created by Sandia National Labs. Chen's modeling effort showed that the particle mass flow rate is critical to achieve high particle temperatures, but also is very important for efficiency. Kim et al. [3] performed very small scale experiments and then verified that CFD models could accurately predict the particle curtain behavior. Kim's work also evaluated how wind affects the particle curtain. It was determined that an oblique angle of attack can have significant effects on particle curtain stability. These previous studies all focused on small scale receivers with some experimental validation. Lessons learned from this compilation of numerical and analytical results revolved around particle curtain stability and heat transfer effects of the particles. Particle mass flow rate is a critical feature in an SPR as well the particle material properties.

Khalsa et al. [4] evaluated commercially sized SPR receivers to see the effects on thermal efficiency on such a large scale. Two receivers were evaluated here: a north facing and a surround-field face down receiver. The north facing receiver was predicted to have a thermal efficiency of 72% while the face down receiver had an efficiency of 79%. Further efforts have been conducted to show computationally how these receivers could be improved. Gobereit et al. [5] describes in detail the face down receiver designs. These results show that this receiver type can achieve over 90% efficiency. Christian et al. [6] evaluated further designs for a north facing receiver including modifying the geometry and nod angle of the receiver to boost thermal efficiency. This receiver analysis also showed over 90% thermal efficiency is possible on this large scale receiver. Commercial scale receiver designs have not been experimentally validated, but the previous studies have shown that CFD particle analysis and experimental comparisons have matched closely.

2.2 Experimental Results

Kim et al. [3] performed small scale experiments to evaluate wind effects on particle curtain stability. However, only one "large" SPR experiment has been performed on sun. Siegel et al. [7] performed an experimental analysis with CFD model validation on a fairly large receiver with up to 5 MWt incident radiation. The aperture was 1.5 m wide by 3 m high and the receiver had a total height of 6.3 m. This cavity receiver was modeled in FLUENT to predict particle outlet temperatures as a function of incident radiation into the receiver. Experimental results matched well with the predicted computational results indicating that CFD models can also accurately predict the effects of an SPR. This test evaluated the receiver only and not the rest of the components needed for a full SPR system including the particle bins and required particle lifting mechanisms if required. The receiver designed in this work will be part of the entire system required for an SPR to work properly.

3. PROTOTYPE DESIGN

The prototype receiver described in this paper will be part of a larger system. The entire process needed for an SPR to work continuously will be the ultimate outcome, but the receiver needed to be carefully evaluated and designed as it is a critical component in the system. The receiver design includes the cavity, aperture, and particle curtain. The particle injection and collection methods are not described in this work.

3.1 CFD Modeling

CFD modeling was used to inform design decisions for this prototype receiver. Two main analyses were performed: nod angle analysis and cavity dimension study with a particle drop location analysis included as well. Important metrics recorded during each study included radiation heat loss, convective heat loss, thermal efficiency, peak and average wall temperatures, peak and average wall incident fluxes, and particle outlet temperatures. Each analysis only had a single particle drop with the particles initially at a temperature of 300°C. There was 1 MWt incident radiation on the aperture with a uniform distribution (achievable at the National Solar Thermal Test Facility (NSTTF)). A block of heliostats based on the NSTTF heliostat field was chosen which would provide 1 MWt power on our receiver, but this also provided a beam direction and beam spread to evaluate in the CFD models. The beam width was 38° and the beam height was 9° with the beam direction considered to be the vector from the center of the receiver to the power-weighted centroid of the heliostats.

In all cases the Discrete Ordinates radiation model was used with an 8x8 division and 3x3 pixelation. It was a two band model with the solar band ranging from 0-4.5 µm and a thermal band ranging from 4.5-100 µm. These ranges were based on the emissivity of the insulation board which covers the walls of the receiver. The insulation had an emissivity of 0.2 and 0.8 for the respective wavelength ranges. The particles had an emissivity value of 0.93 (single band emissivity) and a scattering factor of 0.3. The particle density was 3550 kg/m^3 and they had a temperature dependent specific heat with an average value of ~1122 J/kg-K.

The k-omega SST was employed as the turbulence model for all studies. This model provides good solutions all the way to the viscous sub-layer while also providing good approximations for free-stream turbulence flow. The mesh was refined around the particle drop locations to help capture air effects around the particles. The particles are interacting with the air phase causing unique air flow patterns along the particle curtain drop. The air had temperature dependent properties, but was assumed to have an absorption coefficient of zero. The Discrete Phase Model (DPM) was utilized to simulate the particle curtain as it drops through the receiver. The particles interacted with the radiation and were coupled with the turbulence model. The solids fraction of the particle curtains in all simulations were below 10% which is suitable for the FLUENT DPM models.

Each study had over 600,000 elements which were shown to provide a good mesh-independent solution. An external domain was added to the front of the receiver to simulate the ambient air conditions surrounding this component. It has been shown through past simulations that the external domain was necessary in order to predict convective losses from similar receivers. Any air within the receiver is able to leave to the external domain through the aperture.

3.1.1 Nod Angle Analysis

One way to reduce convective losses from a cavity receiver is to include a nod angle to the aperture. This causes the cavity to "look" towards the heliostat field at a more direct angle. This keeps rising hot air within the receiver. However, the addition of a nod angle on this small scale prototype had to be evaluated to see if it was a valuable enough component since it does add to the complexity of the structure. Three nod angles were evaluated: 0° (no nod angle), 38° (power centroid direction of field), and 50°. The beam direction was held constant throughout the three studies. This study evaluated a receiver size of 1.3 m x 1.3 m x 1.3 m and had an aperture of 1 m x 1 m. Table 1 displays the results from this analysis.

Table 1. Nod angle analysis results

Study	Thermal Efficiency	Radiative heat loss as percentage of total incident power	Convective heat loss as percentage of total incident power	Particle Outlet temperature (°C)	Peak Wall Temperature (°C)
0°	80.2%	12.1%	7.7%	624	1396
38°	76.6%	16.9%	6.5%	612	1376
50°	79.2%	17.0%	3.7%	621	1369

The nod angle performed as expected and reduced the convective loss from the aperture by up to 4% from the 0° nod to extreme 50° nod. However, the efficiency of the 0° nod case is higher due to an increase in radiative loss from the cavity. As the cavity nod angle increased, this also increased the surface area of the side walls of the cavity. This increase in surface area caused the radiation losses to increase therefore canceling out the effects of the convective heat transfer loss. Figure 1 shows the change in geometry after the nod angle is added to the model.

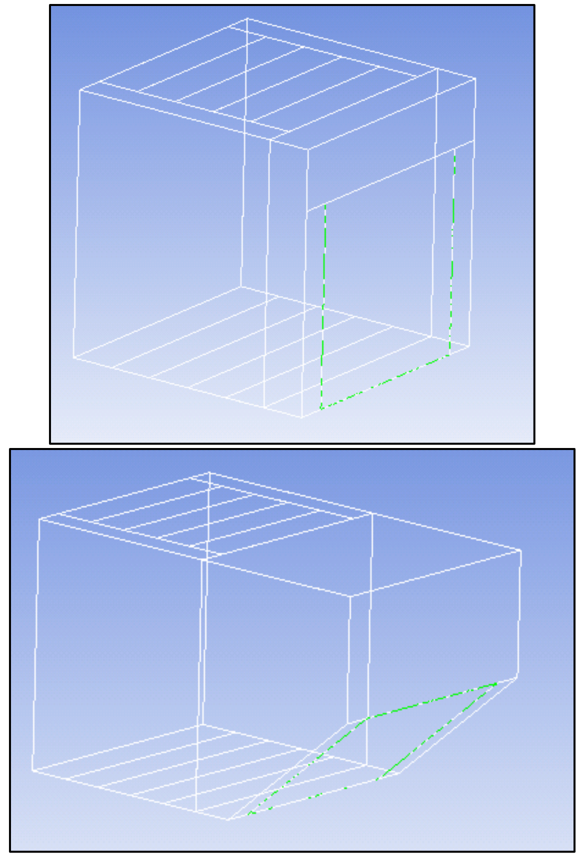

Figure 1. Nod angle on receiver showing change in geometry, (Top) 0° nod angle, (Bottom) 50° nod angle

From this analysis it was concluded that a nod angle would be excluded from the receiver. One important metric that needs to be addressed is the peak wall temperature within the cavity. RSLE board (the chosen insulation for the cavity walls) is rated for up to 1200°C of continuous service. At ~1370°C for each of the nod angle analysis studies the receiver walls would be failing in the high temperature regions. Figure 2 shows the regions of high flux/temperature in the receiver without a nod angle (the other nod angle temperature and flux profiles were similar).

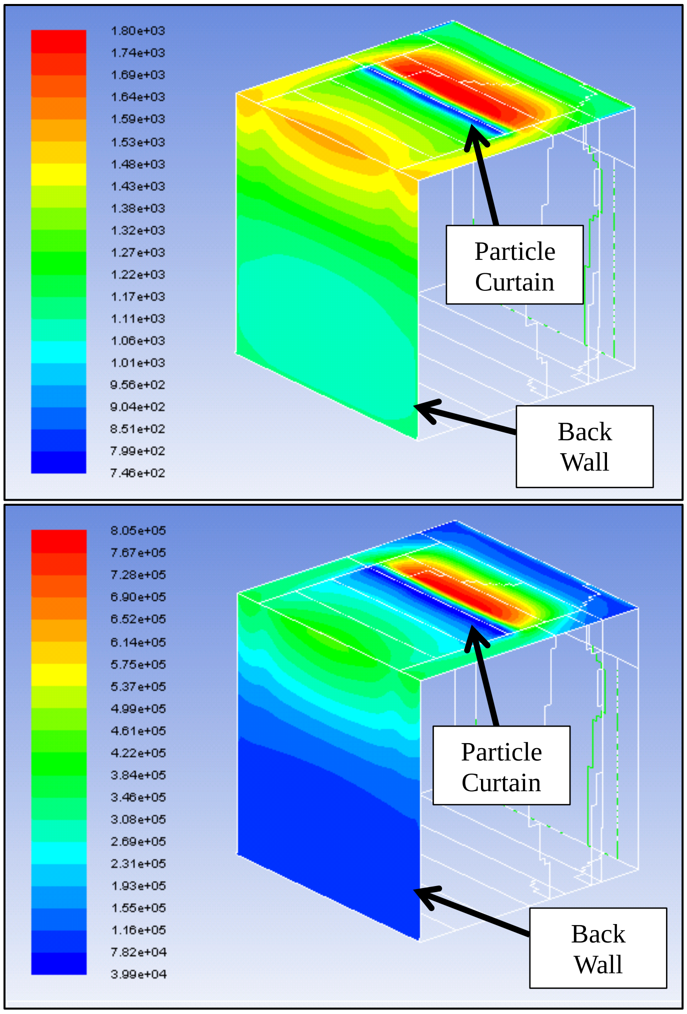

Figure 2. 1.3 m cube receiver with 0° nod angle contour plots, (Top) Wall temperatures (K) of top and back wall showing high temperature before the particle curtain, (Bottom) Surface incident radiation (W/m^2) of the receiver (corresponds to high temperature zones)

The wall temperatures are hottest right before the particle curtain on the top wall because of the incoming angle of the radiation. To reduce this high temperature zone, the height of the cavity needs to be increased to accommodate the incoming irradiation beam angle. This would then shift the "hot" spot to the back of the receiver so it was hypothesized that the peak wall temperatures could be reduced everywhere by increasing the cavity size of the receiver. This led to the next phase of modeling where different cavity sizes were compared in order to try and reduce wall temperatures and high flux concentrations on the walls.

3.1.2 Geometry Dimension Study

The size of the cavity is an important consideration in designing the receiver for both feasibility of construction and thermal performance. This receiver has to be constructed at the NSTTF so it could not be larger than a 2 m cube, but still had to be large enough to provide valuable experimental results. Two receiver sizes were considered: a 1.3 m cube and a 2 m cube. Each receiver had a one square meter aperture and had a particle mass flow rate of 2.5 kg/s/m. The other difference between the receivers was that the particle curtain width changed from 1 m in the 1.3 m cavity to 1.5 m in the 2 m cavity. Increasing the cavity size allowed an increase in the particle curtain width. The smaller cavity size was not large enough to prevent direct irradiation from the heliostat field from being incident on the side walls adjacent to the particle curtain. The larger cavity size width was able to accommodate the heliostat field beam spread thus more incident radiation was on the particle curtain rather than the side walls. Another effect of increasing the receiver size is that the irradiation within the receiver spreads more before hitting the wall. As the flux spreads, the wall temperatures should be decreased due to the lower flux concentrations. A larger cavity height will prevent the issue of high flux concentrations on the top wall before the particle curtain due to the incoming radiation angle. Table 2 shows the changes as a result of varying the cavity size, along with variation is mass flow rate, and particle curtain drop location.

Table 2. Geometry dimension study

Study	Thermal Efficiency	Radiative heat loss as percentage of total incident power	Convective heat loss as percentage of total incident power	Particle temperature rise (°C)	Peak Wall Temperature (°C)
1.3 m cavity, 2.5 kg/s/m, front drop	80.2%	12.1%	7.7%	324	1396
2 m cavity, 1.7 kg/s/m, front drop	87.2%	9.67%	3.11%	250	1433
2 m cavity, 2.7 kg/s/m. front drop	93.6%	4.75%	1.69%	161	1185
2 m cavity, 1.7 kg/s/m, back drop	88.3%	4.84%	6.85%	252	1340
2 m cavity, 2.7 kg/s/m, back drop	93.3%	3.26%	3.45%	158	1197

The 2 m cavity with a 2.7 kg/s/m flow rate decreased the peak wall temperatures within the receiver. This flow rate is the upper value for a possible flow rate for the experiment and produces a curtain with ~15% opacity (taken at a center plane location along the height of the particle curtain). The 1.7 kg/s/m flow rate for this receiver size produces a curtain with ~10% opacity (taken at a center plane location along the height of the particle curtain). The particle curtain opacities were taken at a center plane along the height of the particle curtain. Due to the complex nature of the particle curtain (interaction with air phase) the opacity of the particle curtain may vary along the height of the particle curtain drop. It was observed in particle cold flow simulations and experimental work at Sandia that the particle curtain spreads as it falls along the length of the receiver impacting the opacity of the curtain along its drop height. These experimental results showed that the particle curtain spread can be captured fairly accurately with the current CFD particle models. Another effect on the particle curtain is a "wave" prevalent in the curtain along the height of the drop. This "wave" effect reduces or increases the particle curtain thickness across the width of the curtain and is more prevalent in lower mass flow rates. These effects are not taken into account in the opacity values here, but are captured during the simulations.

Varying mass flow rates changes the opacity of the particle curtain which has an impact on temperatures within the receiver. Varying the particle curtain drop location can also impact wall temperatures, but has less of an impact with larger mass flow rates. Table 2 displays the differences in wall temperatures, drop locations, and mass flow rates. While comparing the 1.7 kg/s/m cases (front and back drop locations), wall temperatures decrease by 93° from changing the particle drop location. Radiative losses are reduced by having a "back drop" location, but convective losses are increased. The increase in convective loss seems to be the reason for the decreased wall temperatures as they are being more effectively cooled by convection. However, if you look at the 2.7 kg/s/m cases, wall temperatures increase by 12° with the change in drop location. The small differences in temperature can be attributed to the increase in flow rate and thus increase in the particle curtain opacity. The thermal efficiencies for the 2.7 kg/s/m case are nearly identical and at ~93% very effective at absorbing the incoming radiation preventing the wall temperatures from being too high. Radiative losses are only slightly decreased in this drop location case (1.5%) compared to the 1.7 kg/s/m cases (4.8%). Convective losses for the 2.7 kg/s/m cases are increased by 1.7% between the front and back drop locations compared to 3.7% increase for the 1.7 kg/s/m cases. Two main results can be inferred from the Table 2 results. The first is that increasing particle mass flow rate reduces peak wall temperatures of the receiver with little difference in where the particle drop location is. The second is that particle drop location can become critical for wall temperatures if particle flow rate low.

Figure 3 shows the wall temperatures and associated flux concentrations on the back and top wall for the 2 m cavity with a flow rate of 2.7 kg/s/m. These will be the critical "hot spots" within the receiver cavity and will be well instrumented during experimental testing.

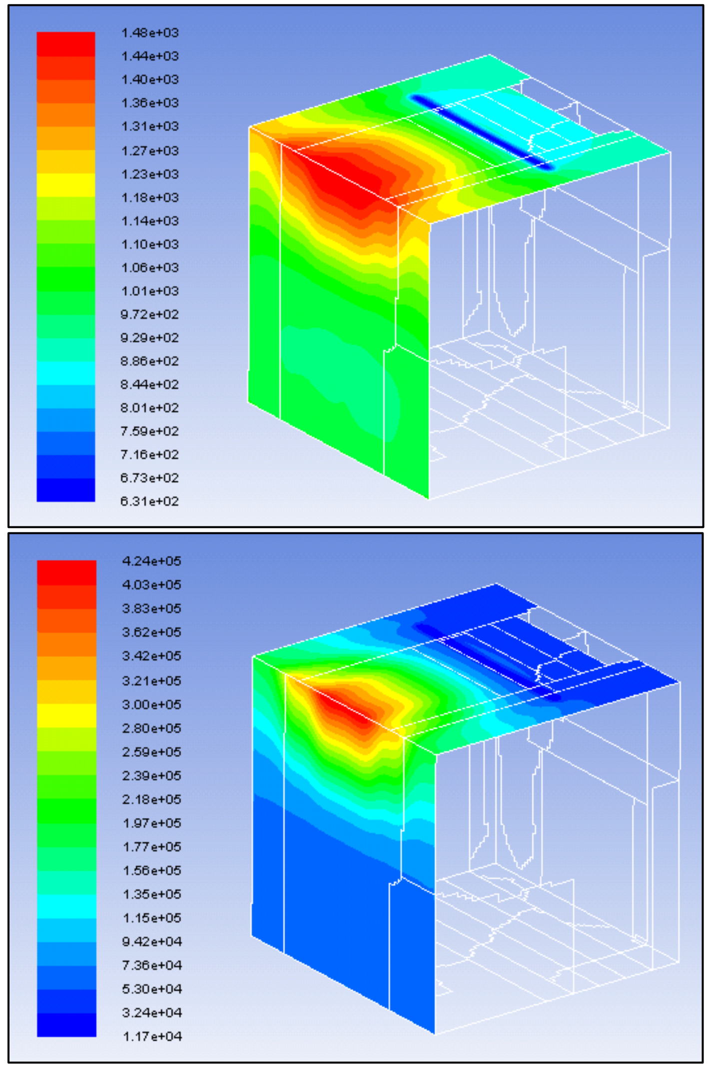

Figure 3. 2 m x 2 m x 2 m, 4 kg/s total particle mass flow rate, (Top) Cavity wall temperatures (K) of top and back wall showing high temperature at the joint of the back and top walls, (Bottom) Surface incident radiation (W/m^2) on top and back wall showing the high flux concentration on the same joint with high temperatures

The particle outlet temperature rise needs to be ~200° in order to get the wanted final outlet temperature of 500° for these cases. The 2.7 kg/s/m flow rate in the 2 m receiver had an outlet temperature increase of 160° which is close to the required temperatures. Decreasing the mass flow rate would increase the particle outlet temperatures, but the wall temperatures would also increase causing structural integrity problems. There is a delicate balance between particle mass flow rate and receiver wall temperatures. Figure 4 displays particle curtain temperatures for the 2.7 kg/s/m, front drop location simulation.

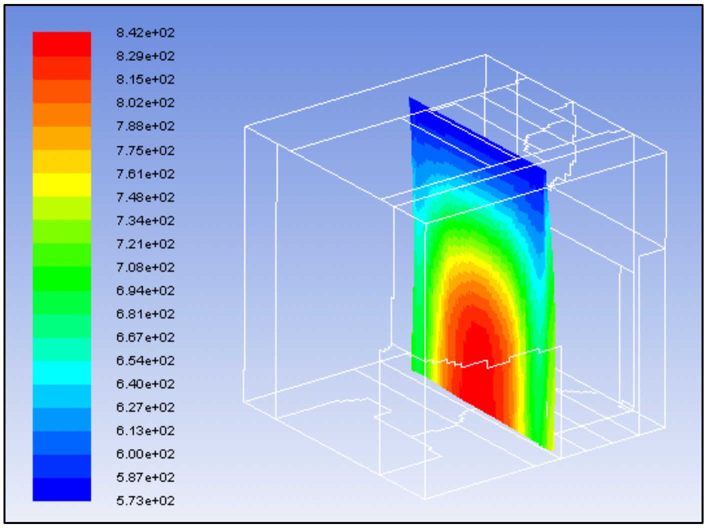

Figure 4. Particle curtain temperatures (K) for a 2 m x 2 m x 2 m cavity, 4 kg/s total particle mass flow rate, and 1.5 m particle curtain width

As the aperture size remains constant, but receiver size grows, the radiative losses go down due to the cavity effect. The lower wall temperatures and lower radiative losses are reasons for choosing a 2 m cavity size. The prototype receiver will be a 2 m cube. Mass flow rates around 2.7 kg/s/m should be used to avoid excessively high wall temperatures in the cavity with a decent particle temperature rise (although not the 200°C temperature rise goal).

3.2 Experimental Design

The experimental design of the receiver was informed from the CFD simulations. A prototype receiver with 0° nod angle, 2 m x 2 m x 2 m overall size, and 1 m x 1 m aperture was chosen. This size produced acceptable wall temperatures and a size which we can construct and modify at the NSTTF if required. The specific structure of the receiver walls though is more complex than the CFD simulations show. There can be very little heat transferred between the inside of the receiver and the support structure for the receiver. The support structure will be constructed of standard mild steel which decreases in strength with increases in temperature. To avoid any temperature rise of the structure, the receiver walls are to be built as a "sandwich" structure. Each wall is composed of stainless steel all thread bolts, a layer of Duraboard HD board, a layer of Zircar RSLE board, and air gaps between layers. The HD board and RSLE board come in panels so the joints will be overlapping in the final design to prevent any flux spillage onto the structure. Figure 5 shows a diagram of a piece of the receiver wall.

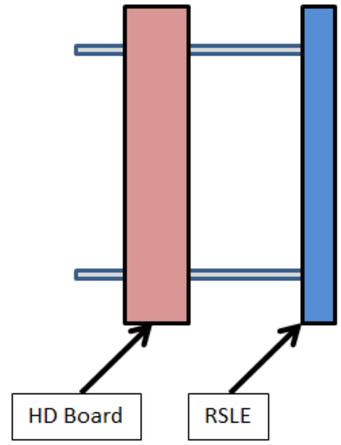

Figure 5. Cross-sectional view of a piece of the prototype receiver walls

The RSLE board is a refractory sheet silica matrix composite with a low coefficient of expansion (0.3 x 10^{-6} °C) and resistance to thermal shock up to 1200°C. If the temperature is high, but localized, it still retains its high temperature strength and durability. The 0-4.5 μm wavelength band emissivity is estimated at 0.2 while the higher bands emissivities are 0.8. Past experiments at the NSTTF have taken the RSLE board up to 3000 suns for short durations without any material degradation which make it a suitable material for the cavity walls. The RSLE board is 1.27 cm thick and will be cut to size from initial 91.4 cm x 121.9 cm panels. The RSLE board takes the brunt of the solar flux, but an air gap and then an HD board layer in the wall will prevent any heat/flux that passes through the first layer due to gaps or thermal conductivity from heating the structure.

The HD board is a "backup" layer for the receiver walls to prevent any unforeseen flux spillage and thermal conductance/radiation from heating the supporting structure. HD board is composed of alumina-silica fibers and binders with a low thermal conductivity (unspecified in tech sheet) and rated for 1260°C. HD board can only withstand 1000 suns of incident flux before material degradation. The main difference between HD board and RSLE are the flux limitations due to the density of the material. HD board has a density of 419 kg/m^3 while RSLE board 2,100 kg/m^3 which allows for exposure to higher flux levels. The HD board and RSLE board combination, plus air gaps will prevent any heat from being transmitted to the support structure.

The receiver walls will be held together by stainless steel all thread bolts and will see extreme temperatures at the tip of the bolt where it attaches to the RSLE board. There are two methods to protect the bolt from these high temperatures. The first method has been examined and used in previous studies at the NSTTF and uses an RSLE "plug" over the bolt.

The bolt hole and bolt is covered with a custom fit covering or "plug" made of RSLE that will protect the bolt from high temperatures. The second method of protection was suggested by Zircar and is a silica adhesive (Silbond LE) provided by Zircar. This type of protection would just use a layer of this adhesive over the bolt and this should protect it from the high temperatures. This protective option is easier to apply and thus would be a better fit for the experimental work; however it will first be tested under high flux conditions to verify that it will protect the bolts.

The experimental conditions include a mass flow rate of ~2.7 kg/s/m in order to maintain acceptable wall temperatures. The front and back particle drop locations will be tested. Finally, the CFD models will be validated against the experimental results.

4. CONCLUSIONS

A prototype solid particle receiver has been designed, modeled, and is currently being fabricated for on-sun testing at the NSTTF. CFD models were used to compare important metrics such as thermal efficiency, wall temperatures, and particle temperatures in possible cavity designs for this prototype. The prototype will not have a nod angle as this contributes to a higher radiative loss from the cavity resulting in slightly lower efficiencies. The nod angle did reduce convective losses, but not significantly enough compared to the increase in radiative loss. The prototype receiver size was increased from a 1.3 m cube to a 2 m cube after evaluating peak wall temperatures in the cavity. The incoming beam angle from the heliostat field was causing the irradiation to strike the top of the receiver before being absorbed by the particles. This effect is avoided with the larger cavity size. The larger cavity size also reduced flux concentrations on the walls resulting in lower wall temperatures. These temperatures are within the rated temperature range for RSLE board making it a suitable material for the walls of the receiver. The receiver prototype will be a 2 m cube with different particle drop locations and mass flow rates.

ACKNOWLEDGMENTS

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. The United States Government retains and the publisher, by accepting the article for publication, acknowledges that the United States Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce the published form of this manuscript, or allow others to do so, for United States Government purposes.

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