On-Sun Experiments on a Particle Heating Receiver with Red Sand as the Working Medium

Hany Al-Ansary[1,a)], Abdelrahman El-Leathy[1], Sheldon Jeter[2], Eldwin Djajadiwinata[1], Shaker Alaqel[1], Matthew Golob[2], Clayton Nguyen[2], Rajed Saad[1], Talha Shafiq[3], Syed Danish[3], Said Abdel-Khalik[2], Zeyad Al-Suhaibani[1], Nazih Abu-Shikhah[4], Mohammad I. Haq[4], Ahmed Al-Balawi[4], Fahad Al-Harthi[4]

[1] *Mechanical Engineering Department, King Saud University, P.O.Box 800, Riyadh 11421, Saudi Arabia*
[2] *Georgia Institute of Technology, School of Mechanical Engineering, 771 Ferst Drive, Atlanta, GA 30332, USA*
[3] *Sustainable Energy Technologies Center, King Saud University, P.O.Box 800, Riyadh 11421, Saudi Arabia*
[4] *R&D Department, Saudi Electricity Company, P.O.Box 22955, Riyadh 11416, Saudi Arabia*

[a)]Corresponding author: hansary@ksu.edu.sa

Abstract. Particle heating receivers are a promising technology that can allow operation of CSP systems at temperatures higher than what today's commercial molten salt systems can achieve, making them suitable for use in a variety of applications, including supercritical CO_2 cycles, air Brayton cycles, and high-temperature process heat. One of the ways to improve cost-competitiveness of particle heating receivers is to use low-cost particulate materials, such as sand, as the working medium. Red sand is particularly attractive due to its abundance and acceptable absorptance. This paper presents the results of on-sun testing of a particle heating receiver that uses red sand as the working medium. Tests were conducted at the experimental central receiver facility at King Saud University in Riyadh, Saudi Arabia. Performance of the receiver was assessed in two ways. First, the rate of thermal energy absorption was calculated using the measured temperature rise across the receiver, particle flow rate, and red sand's specific heat. Second, receiver efficiency was calculated using the rate of thermal energy absorption and the thermal power incident on the receiver, which was estimated using a raytracing software. Results show that a temperature rise of 130°C was achieved with an incident heat flux of 230-280 kW/m^2. Receiver efficiency was found to range from 60% to 70%. These results are encouraging and show that red sand is a promising particulate material, especially when it is used with a proper cavity receiver design where the effect of absorptance of the particulate material becomes less significant.

1. INTRODUCTION

Particle heating receivers (PHR) are a relatively new type of receivers that are used in conjunction with central receiver systems, where solid particles are heated directly or indirectly by incoming concentrated sunlight. PHRs aim to overcome the current limitations of steam receivers and molten salt receivers where temperatures cannot generally exceed 600°C. With the higher temperatures that can be achieved by PHRs, a variety of applications become feasible, such as supercritical CO_2 power cycles, air Brayton power cycles, and high-temperature process heat applications.

A number of PHR concepts have been studied, including centrifugal receivers [1], fluidized bed concepts [2,3], beam-down receivers [4], and face-down receivers [5]. The falling particle receiver is another alternative that is characterized by simplicity and low cost. The idea is to release solid particles into a cavity. As the concentrated sunlight enters the cavity, it strikes the particles and heats them directly. Two types of the falling particle receiver have been considered. The first type allows the particles to fall freely, while the other type introduces obstructions in the path of falling particles to allow more residence time. Both types have been successfully tested [6], with temperature rises of as much as 350°C observed over a 1-m drop, and with a receiver efficiency approaching 90%. These tests were conducted using engineered particles that are characterized by their black color which is highly absorptive. However, given the relatively high cost of these particles, it is desirable to find natural, less expensive alternatives. One of the attractive alternatives is red sand which is abundant in many countries where CSP systems are viable. Previous studies have shown that red sand can withstand cycling without sintering or attrition. One disadvantage of red sand is that its absorptance is relatively lower than dark engineered particles; however, this disadvantage is mitigated when the PHR is placed well within a cavity. In this case, the actual absorptance of the particles becomes less important, since the cavity approaches what is called a “blackbody cavity”.

The main objective of this study is to estimate the temperature rise and receiver efficiency achieved during a test campaign on a falling particle receiver (with obstructed flow) that uses red sand. The tests are conducted at a test facility in King Saud University (KSU) in Riyadh, Saudi Arabia, which provides up to 300 kW of thermal power. Section 2 describes the KSU facility. The next section provides details about the PHR experimental apparatus. Section 4 presents the results of experiments, followed by some concluding remarks.

2. DESCRIPTION OF THE KSU FACILITY

The facility at which tests were conducted is located on the campus of King Saud University in Riyadh, Saudi Arabia (shown in Fig. 1). Just like a typical CSP system, the facility consists of a heliostat field, a receiver on top of a tower, thermal energy storage, a power block, and balance of plant.

FIGURE 1. Photograph of the particle heating receiver test facility at King Saud University during an on-sun test

The heliostat field consists of 66 single-sheet heliostats, each of which has an area of 8 m^2, a reflectivity of 94%, and a focal length of 40 m. All heliostats are programmed to reflect sunlight on the PHR receiver located on the tower 22.5 meters above the ground. The receiver uses a patented design in which particles are released through a perforated plate at the top of the receiver and passes through and around chevron-shaped meshes to increase the particles’ residence time. These chevrons are currently made of stainless steel SS316, but plans are underway to build a new receiver with a higher temperature alloy; namely Inconel 601, to ensure the durability of the receiver. Figure 2 shows the flow through the chevron PHR.

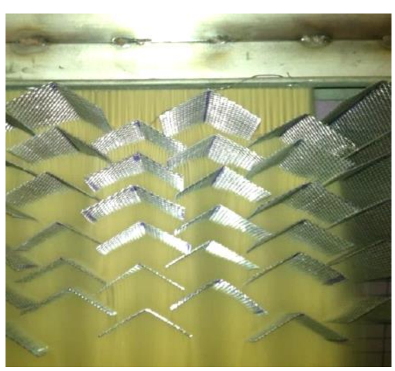

FIGURE 2. Flow of sand through a chevron particle heating receiver

Just beneath the receiver, a small thermal energy storage (TES) tank is located that has a capacity of 1 m^3. It is intended to demonstrate the technical feasibility of running the power block from storage, albeit for a short period of time. The TES tank feeds a tubular heat exchanger where particles flow on the shell side in bulk mode, whereas compressed air flows inside the tubes. The heat exchanger has 6 passes and operates in counter flow to minimize the temperature difference between the particles and air. The overall surface area is approximately 90 m^2. The estimated capacity of the heat exchanger is between 100 and 150 kW(thermal). The heat exchanger is connected to a recuperated turbine, such that compressed air leaving the recuperator is fed to the heat exchanger to be heated by the incoming hot particles. The hot compressed air leaving the heat exchanger then returns to the turbine. Depending on the temperature of that air, a certain amount of fuel will be added to the combustion chamber to reach the firing temperature of the turbine, which is nominally at 950°C. This way, the turbine will always be able to produce power at its nominal capacity of 100 kWe, with the contribution from the solar field depending on the particle temperature leaving the PHR, i.e. the higher the particle temperature, the higher the solar contribution, and the less fuel needed. This scheme is called a hybrid system, and it is illustrated in Fig. 3.

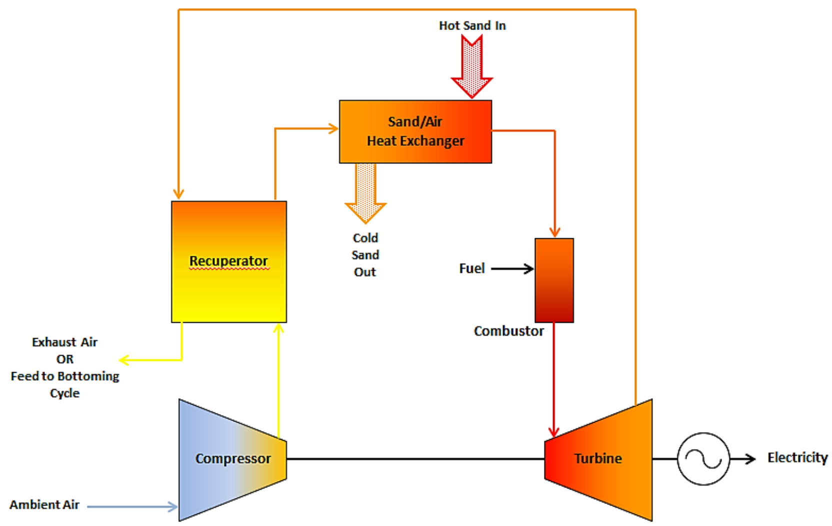

FIGURE 3. The hybrid solar-fossil fuel power system

Finally, once heat is extracted from the particles in the heat exchanger, the particles are then lifted back to the PHR level to be heated again by the heliostat field. The particles are lifted using a type of screw conveyor called Olds Elevator. It uses a proprietary technology in which the shell of the conveyor rotates while the screw is stationary. The rotational speed is strongly correlated with the particle throughput. For this reason, the Olds Elevator is equipped with a variable frequency drive to provide flexibility of operation at a desired particle flow rate.

3. THE PHR EXPERIMENTAL APPARATUS

To estimate the thermal energy collected by the PHR, three important pieces of information are needed: (a) temperature difference across the receiver, (b) particle mass flow rate, and (c) the specific heat of red sand. Once this information is available, the following well known form of the energy equation can be used to estimate the energy collected:

$$\dot{Q} = \dot{m} \times C_p \times (T_{\text{out}} - T_{\text{in}}) \tag{1}$$

where, $\dot{Q}$: the rate of thermal energy collection by the red sand (in kW)
$\dot{m}$: particle mass flow rate (in kg/s)
C_p: specific heat of red sand (in kJ/kg. °C)
T_{out} : particle exit temperature from the receiver (in °C)
T_{in} : particle inlet temperature into the receiver (in °C)

To obtain accurate temperature measurements, three thermocouples are inserted upstream of the receiver, at the exit of the particle conveyor. The particles leaving the receiver are collected in a funnel, the exit of which is instrumented with three other thermocouples whose locations are shown in Fig. 4.

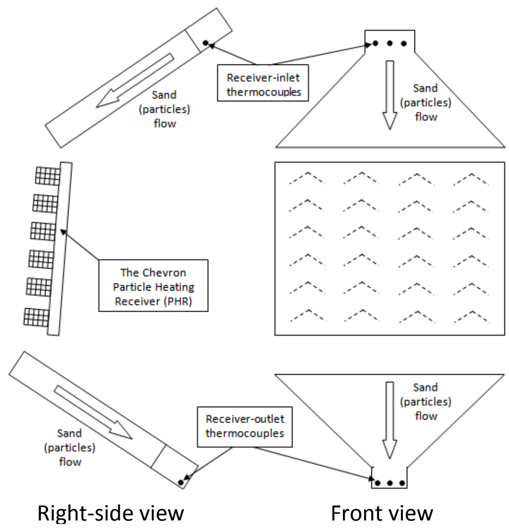

FIGURE 4. Locations of thermocouples in the PHR

The flow rate is controlled by varying the speed of the particle conveyor motor as explained earlier. At each motor speed, the mass flow rate of red sand is measured repeatedly using a simple weight and time measurements, such that a clear relationship between the particle flow rate and motor speed is established.

Finally, there was no instrumentation available to measure the specific heat of red sand, especially at high temperatures. As an alternative, published data on the specific heat of silica [7] was used. The composition of silica is quite similar to red sand except for the lack of traces of hematite that are found in red sand. Based on this published data, the temperature-dependent behavior of silica follows the following correlation:

$$C_p = A + B\,t + C\,t^2 + D\,t^3 + E/\,t^2 \tag{2}$$

where, C_p = specific heat in J/kg.°C
A = -101.134
B = 4,188.707
C = -5,405.677
D = 2,805.398
E = 0.042407
t: temperature in kelvin / 1000

4. EXPERIMENTAL RESULTS

A series of experiments were conducted over the course of a few months. For the sake of brevity, and since the patterns in all experiments are similar, only a sample of the results is presented here; namely, results from an on-sun test conducted on August 2nd, 2017. Figure 5 shows the direct normal irradiance (DNI) during the test.

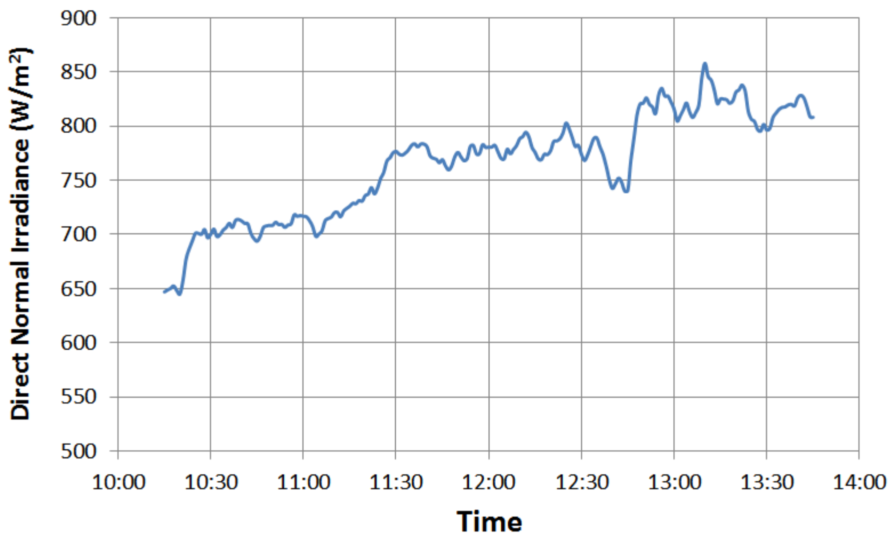

FIGURE 5. Direct normal irradiance during the testing period on August 2nd, 2017

Figure 6 shows the inlet PHR temperature, and exit PHR temperature. For convenience, the figure also shows the temperature rise across the PHR.

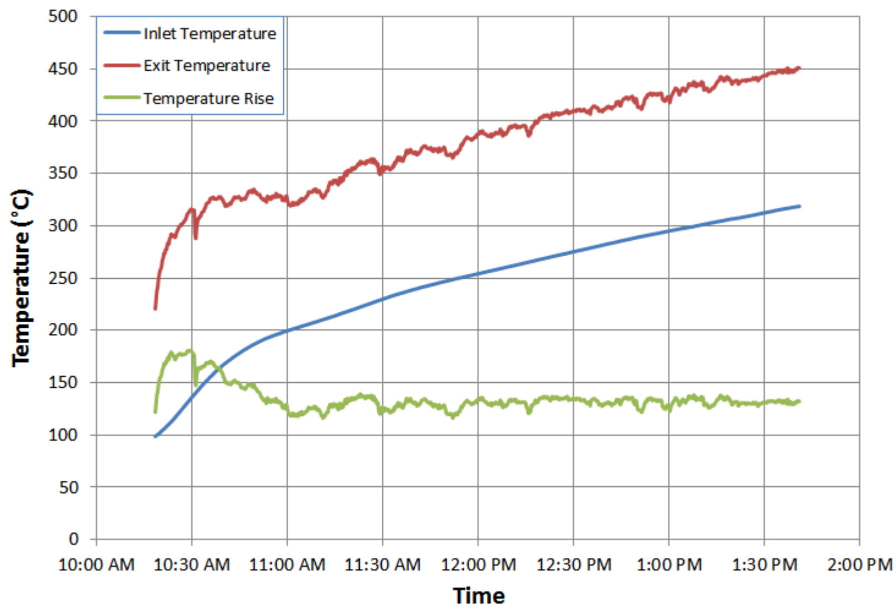

FIGURE 6. Inlet temperature, exit temperature and temperature rise across the PHR during the test

Results show that the temperature rise across the receiver was significant, averaging about 130°C for most of the testing period, even though DNI values were significantly lower than what would be expected in locations where CSP systems are usually deployed (due to the typical high dust loading during the summer in Riyadh, Saudi Arabia).

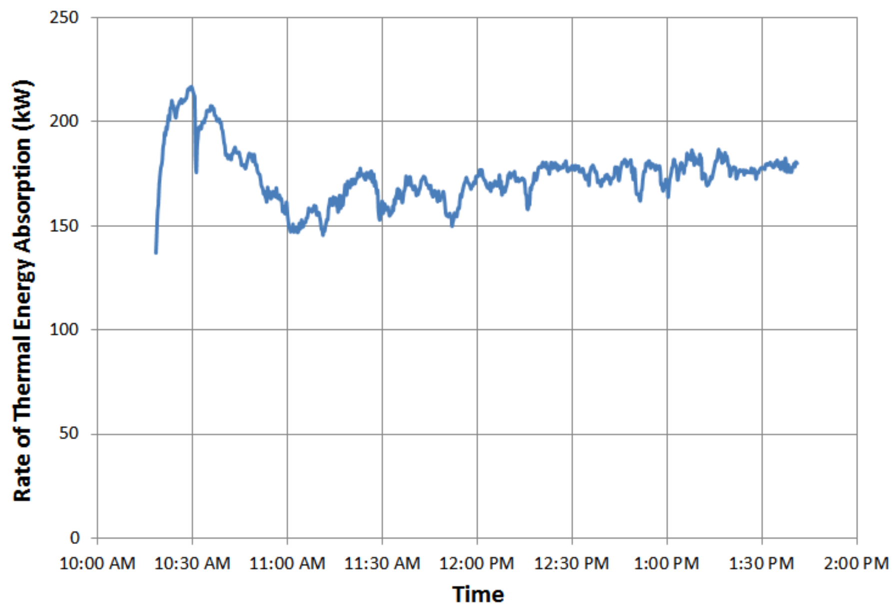

FIGURE 7. Rate of thermal energy absorption at the PHR during the test

Figure 7 shows the rate of thermal energy absorption by the PHR during the testing period. This rate is calculated using Equations 1 and 2. The mass flow rate during this test was 1.223 ± 0.09 kg/s. It can be seen that that the rate of thermal energy absorption increased slightly during the test, due to the slight increase in DNI over the testing period. It is interesting to mention that the thermal energy absorbed increased even though the temperature rise remained nearly constant. The reason is that the specific heat of sand increases with temperatures as Equation 1 shows.

To estimate the receiver efficiency, an accurate measurement of the flux incident on the receiver is necessary. Since there were no flux measurement tools available, an alternative approach was adopted, which is to rely on the flux map generated by a raytracing software using input parameters that closely match the actual parameters in the field. Figure 8 shows the thermal power incident on the receiver as estimated by SolTRACE program for selected times.

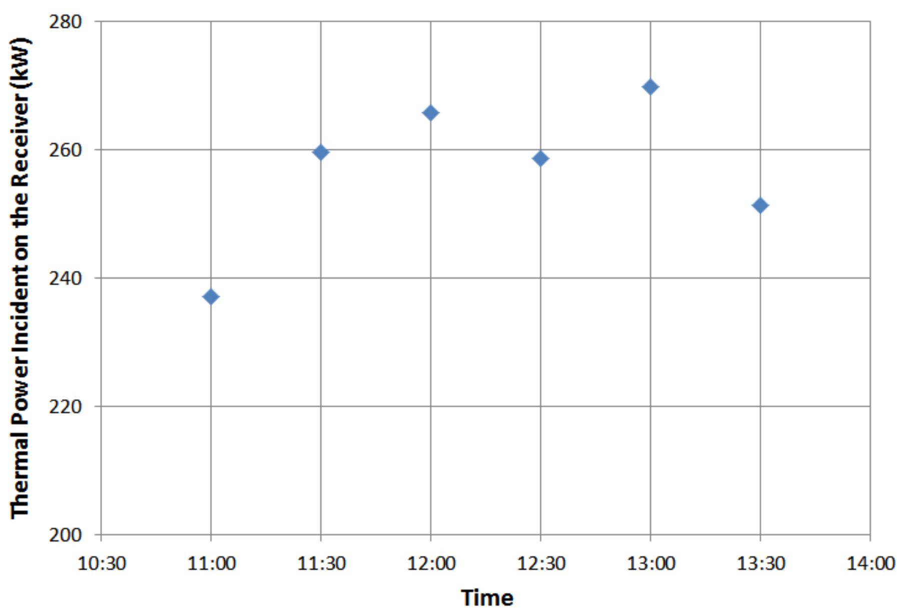

FIGURE 8. Thermal power incident on the receiver during the test as estimated by SolTRACE

Using this data, an estimate of the receiver efficiency can be made, which is the ratio of the rate of the thermal energy absorption to the thermal power incident on the receiver. Figure 9 shows the estimated receiver efficiency for the same selected times during the test. The efficiency is generally between 60% and 70%, which is expected given the relatively low absorptance of red sand. However, in a large-scale system where a true receiver cavity is built, the effect of the low absorptance of red sand will become less significant due to the blackbody cavity effect.

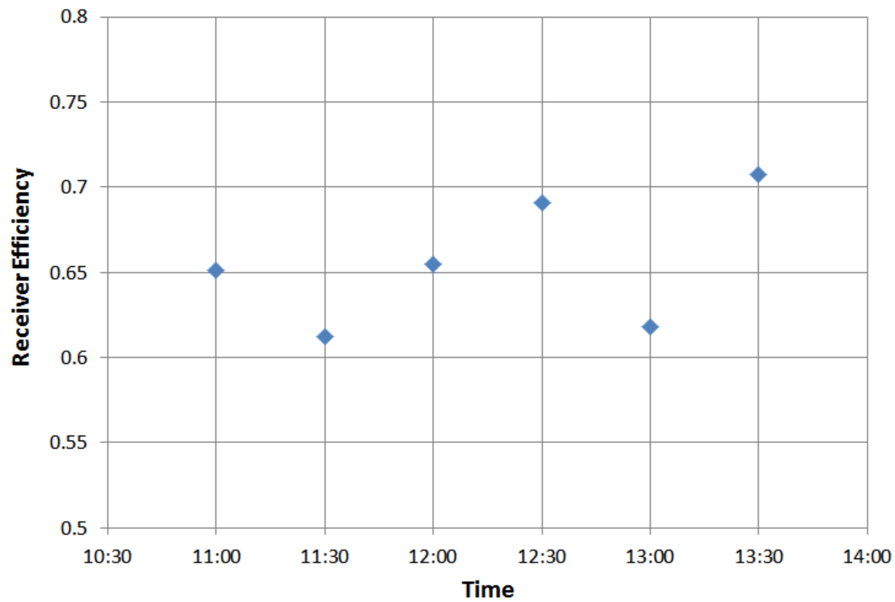

FIGURE 9. Receiver efficiency during the test

CONCLUSION AND RECOMMENDATIONS

This study focused on the thermal performance of a particle heating receiver (PHR) using red sand particles. Performance was assessed based on the results of on-sun tests that took place at the experimental 300-kW(thermal) central receiver facility at King Saud University in Riyadh, Saudi Arabia. The rate of thermal energy absorption by the PHR was calculated by performing an energy balance on the receiver. It was found that the temperature rise was significant (around 130°C) despite the particle drop height being limited to just 1.2 m and at an estimated heat flux between 230 kW/m^2 and 280 kW/m^2. Receiver efficiency was found to be generally between 60% and 70%, which, although apparently low, is surprisingly high given that red sand (with its relatively low absorptance) is the working medium. This study shows that red sand has great promise as a working medium, especially when it is used in conjunction with a true cavity, such that the effective receiver efficiency becomes much higher than the efficiency observed in the current study. Further refinement of the study is needed, especially the parameters used in raytracing. This can be done when a flux measurement tool is employed in the field at King Saud University such that the SolTRACE model can be "calibrated" based on actual operating parameters.

ACKNOWLEDGMENT

This work is generously funded by the Saudi Electricity Company. Their support is greatly appreciated.

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