Steady-Flow-Type Particle Receiver for High-Temperature Solar Thermal Storage

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Abstract. The concentrated solar power is utilized for industrial thermal usage, electricity generation and fuel production. To increase the solar thermal temperature is essential for enhancing the thermal efficiency of the energy conversion and for widening application. The synthetic oil, widely used for solar thermal storage, pyrolizes at 400 °C, and this cannot be used for very high temperatures. The authors used quartz sand as thermal storage medium in the fluidized bed receiver, and achieved the thermal receiver temperatures beyond 1000 °C in the previous report. The research work was further made on using the particle steady flow for high-temperature solar thermal storage. The steady-flow-type particle receiver was designed through visualization of cold model and numerical simulation. The experimental apparatus was fabricated and tested using beam-down sun simulator of 1.0 kWth. The apparatus comprises of the internal-circulating fluidized bed receiver placed between a loop seal with an inlet port and another loop seal with a weir and an exit port of the particles. The tested particles are quartz sand of 0.1 – 0.2 mm and fused brown alumina of 0.09 – 0.1 mm. The experimental set up produces hot particles of quartz sand at 428 °C and those of fused brown alumina at 491 °C. The highly efficient steady-flow-type particle receiver created steady particle flow smoothly. This apparatus takes in the concentrated light through the quartz window to continuously discharge the particles at high temperatures beyond the criterion in synthesis oil (400 °C) for solar thermal storage.

Keywords: high-temperature solar thermal storage; sun simulator; experiment; visualization; simulation

1. Introduction
The concentrated solar power (CSP) is commercialized in the sunbelt of Europe, United States and Asia. The condensed light collected from the solar field using the heliostats is used for heat source of desalinization, power generation and fuel production [1-3]. The solar thermal is advantageous against other renewable energy in capability of the massive storage at low cost. The solar thermal storage enabled 24 hour power generation in Europe and United States. Recent progress on solar fuel production is opening the way to recover carbon dioxide into synthetic gas. The newest CPS plants use the molten nitrate as heat transfer and storage medium. The solar receiver receives the concentrated irradiation to create the sensible enthalpy at as high temperatures as 560 °C [4]. To increase the solar thermal temperatures is very important for enhancing the thermal efficiency of energy conversion and for widening the industrial application. However, the nitrate salt cannot be used for high temperatures beyond 600 °C since the thermal medium is thermally broken up at such high temperatures. New
technologies of heat transfer media are studied by national institutes and universities for high-temperature solar absorption and thermal storage. This study aims to create new solar particle receiver which utilizes the steady stream of the particles for solar thermal acquisition. The present authors develop the fluidized bed solar receiver for high temperature solar absorption, and achieved very high temperatures above 1000 °C [5]. The previous apparatus applied the cylindrical fluidized bed with quartz window to take in the concentrated light which directly irradiated onto the bed surface. The present study describes the newer apparatus extended to utilize the steady stream in the fluidized bed configuration. Visualization was made for cold model of the apparatus to investigate the smoothness of the polystyrene particle flow. Numerical simulation was then conducted for analyse the flow field of the ceramic particles. The experimental model was designed based on these analysis, and this was fabricated and tested using sun simulator of 1.0 kWth.

2. Visualization of cold model
Prior to the design of the hot model of steady-flow-type particle receiver, visualization was conducted for cold model of it to confirm the validity of the configuration.

2.1. Experimental method
Figure 1 shows experimental apparatus for visualization of the cold model of steady-flow-type particle receiver. The transparent channel comprises of the inner-circulating fluidized bed placed between two loop seals. One seal on the left is equipped with inlet port for particle feeding and the other seal on the right has the weir and the outlet port for particle discharging. The feeder feeds the polystyrene particles with 0.7 - 1.4 mm diameter into the transparent channel for visualization. The air was provided by the compressor into the channel through the bottom distributor plate. Four lines of air stream fluidized the particles and exit from outlet port on the top.

![Figure 1. Experimental apparatus for visualization of cold model of steady-flow-type particle receiver](image)

2.2. Experimental results
The experimental visualization was conducted changing the flow rate of air and particles. Figure 2 exemplifies the photograph of particles, where particle flow rate was 52.7 g/min and air flow rate was 40 NL/min, 60 NL/min, 20 L/min and 20 NL/min for each part of the air distributors. The superficial velocities are the same at the inlet side and outlet side of loop seals. However, this velocities differ between two towers, which creates the internal circulation of particles. At the initial state, blue and white particles fill separately each sub-channels as shown in figure 1 (a). These two colour particles enabled to observe the stream of the particles. As presented in figure 2 (b), the particles drop from the feeder onto the inlet side of the loop seal, stream inside the channel and internally circulates in the central two-tower channel and reaches the exit side of the loop seal and overflows from the weir. The
experimental visualization was made for systematically changing the condition and the flow pattern was summarized by the flow map which separates the no-stream and stream area.

(a) Initial state  
(b) $t = 3$ s

**Figure 2.** Photograph of particle stream

3. **Numerical simulation of cold model**
Two-dimensional numerical simulation was made for design of the irradiation-experiment model. The particle considered in the simulation was quartz sand for high-temperature experiment.

3.1. **Numerical method**
The simulation was performed using ANSYS Fluent Ver. 16.0. Eulerian-Eulerian approach based on granular method was applied for two-dimensional model of steady-flow-type receiver. The particles simulated are quartz sand with 0.1 mm diameter. This particle was selected since they are used for irradiation experiment. The computational domain resembles the cold model for visualization. Some minor changes were made in preparation for irradiation experiment; inlet port was shaped in triangle and the whole height and width were shrunken to half of the visualization apparatus. The down-sizing was performed considering capacity of the sun simulator and easy handling. Numerical conditions are air flow rate = 52.7 g/s, particle flow rate = 29.3 g/s assuming 30mm receiver depth.

(a) $t = 0.1$ s  
(b) $t = 5.0$ s

**Figure 3.** Volume fraction of particles in cold model

3.2. **Numerical results**
The volume fraction of particles is indicated in figure 3. The particles are continuously fed from the inlet port. These particles are observed to stream inside and exit from the channel. The particle stream was smooth in this down-sized model. The volume fraction is large at 0.1 second from the start of the providing air and this quantity decreases when time proceeds 5.0 second. The experimental set up was designed extending the two-dimensional model of the simulation into three-dimensional configuration.

4. Experiment of irradiating receiver

Experiment is made for steady-flow-type particle receiver using sun simulator. Experimental conditions are scrutinized by preliminary experiment with electrical heating wire before the irradiation experiment. Two kinds of particles are used for the experiment with condensed light irradiation.

4.1. Experimental method

The sun simulator for irradiation experiment is shown in figure 4. This apparatus is equipped with a xenon lump and an elliptic reflector. The light source of the lump is placed on the first focal of the reflector, and the reflector collects light onto the second focal point. The figure includes the distribution of heat flux at the focal point. The Gorden gouge was traversed at 5.0 mm interval to measure the heat flux distribution point-by-point. The heat flux distribution was peaky as shown in figure 4. The peak value is almost 500 kWth/m². Thermal power enclosed by 50 mm x 50 mm square is 0.75 kWth.

![Figure 4. Sun simulator](image_url)

The experimental model of steady-flow-type receiver has a frustum-shape head with a quartz window (120 mm x 120mm) on the top to take in the concentrated light as shown in figure 5. The main parts of the receiver are made of stainless steel, SUS304. The apparatus is equipped with a stainless steel distributor with mesh size 40μm. The visualized and simulated model separated the air room below the distributor in order to differentiate the superficial velocity to each channel of the receiver. However, the experimental model was simplified so that the room is not separated and the same superficial velocity is provided to each channel. The apparatus is set inside the cabin of sun simulator. The top surface of the particle bed is placed on the second focal point of the elliptic reflector for efficiently absorbing the concentrated light. The receiver is surrounded by the adiabatic sheet for insulation. Temperatures are measured at several positions of the apparatus using thermocouples. Air installation and irradiation started at the same time, and they continue during 90 minutes. Experiments are made changing the particle supply rate at different levels of flow rate of air. Two kinds of the particles are used as heat transfer medium; quartz sand with 0.1 - 0.2 mm diameter and brown fused alumina with 0.09 - 0.1 mm diameter.
4.2. Experimental result

Figure 6 shows the experimental result of temperature measurement for the case of quartz sand particles. The location of the temperature measurement is in the light tower of two-tower area at middle height of the particle bed. In the figure, the temperature becomes highest at the particle supply rate of 20 g/min and air mass flow rate of 110 L/min. However, the temperature becomes lowest at the same particle supply rate at air mass flow rate of 120 L/min. The temperature measurement was also made in the loop seal with exit port. The temperature was found lower by about 20 - 40°C in the loop seal than in the two tower. It is suggested that the thermal insulation is not enough for attenuating the heat losses. In the figure, the maximum temperature which occurs at the former condition is nearly 430 °C. Therefore, the newly designed apparatus can absorb the concentrated light at the higher temperatures than criterion of the synthetic oil.

![Figure 5 Experimental set up for irradiation experiment.](image)

![Figure 6 Temperature in two tower of steady-flow-type receiver using quartz sand.](image)

The temperature measurement at the same position using brown fused alumina is shown in figure 7. This type of particle was used because it has preferable absorption characteristics. Quartz sand is white and its absorption coefficient is low. Brown fused alumina is abrasives produced from melting calcined bauxite. Its particles are dark colored and absorption coefficient is high. The experimental data are limited to only five cases. The temperatures tend to decrease at two level of air mass flow rate. The maximum temperature is achieved at particle supply rate of 10 g/min at air mass flow rate of 120 L/min. This maximum value is 490 °C, and this is quite higher than the limitation of synthetic oil usage. In this condition, The thermal power of heated particles is 62 W, and that of air exit port is 192 W.
The efficiency is thus calculated as 33.9%. It is suggested that heat losses occur due to the air flow exiting from the particle outlet and inlet ports. This heat leakage can be fixed by the improvement of the design of receiver.

![Figure 7 Temperature in two tower of steady-flow-type receiver using brown fused alumina.](image)

**Figure 7 Temperature in two tower of steady-flow-type receiver using brown fused alumina.**

5. Conclusions
This paper describes visualization, simulation and irradiation experiment of the steady-flow-type solar receiver. Conclusions can be summarized as follow:

(1) The newly designed steady-flow-type receiver comprises of a two-tower-type inner-circulating fluidized bed placed between two loop seals with inlet and exit ports. Visualization of cold model demonstrated that this apparatus could maintain steady flow of the particle and the inner-circulating of the particle at the same time. Two-dimensional simulation evidenced that the particle of quartz sand can stream in the down-sized model of the receiver.

(2) The receiver for irradiation experiment was designed based on the visualization and numerical results. This was tested using the sun simulator with 0.75 kWth. The experiment using quartz sand achieved 430 °C at maximum at the two-tower area.

(3) The receiver was tested using sun simulator with the brown fused alumina with higher radiation absorption coefficient. This experiment showed the highest temperature at 490 °C at the two-tower area. This highest temperature is quite higher than the limitation of synthesis oil usage (400 °C).

6. References
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