Numerical modeling of a two-tower type fluidized receiver for high temperature solar concentration by a beam-down reflector system

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Abstract

This study describes the flow and thermal field of a two-tower fluidized receiver, aimed to be incorporated into a beam-down reflector system. An experimental visualization and numerical simulation were made to accumulate phenomenological knowledge, in order to complete the design of a demonstration model. Visualization of the cold particle bed with no irradiation revealed that global circulation occurs between the two towers by the aeration with different line velocities. The numerical simulation revealed that this global circulation enhances the transport of sensible heat from the irradiated layer in the high pressure tower to the low pressure tower. The global circulation in the two-tower fluidized receiver has the potential to be extended for use in a thermal receiver and direct storage system. Unexpectedly, local circulations occur on the high and low pressure sides, and are stronger than the global circulation. These local circulations contribute to the thermal mixing in each tower. The bottom distributor on the low pressure side can cause an uprising flow which leads to the local circulation. The design of the distributor is suggested to be elaborated based on these findings.

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1. Introduction

Concentrated solar power (CSP) has been introduced in Southern Europe and the United States. It is expected to prevail in the sun belt of Middle East and North Africa and in Asian countries, including China and India. Commercial CSP plants use synthetic oil or molten salt as heat transfer fluid (HTF) [1]. Some plants employ heat storage systems for buffering cloud cover and improving dispatchability [2]. Newer point concentration power plants receive solar heat at temperatures around 560°C. This limitation results from thermal cracking of molten nitrate. High temperature receivers are being developed to have a higher energy retention rate. The Deutsches Zentrum für Luft- und Raumfahrt (DLR; German Aerospace Center) tested an open-type volumetric receiver at the Jülich tower plant to produce hot air exceeding 700°C. Sandia National Laboratory developed a falling-sand receiver for high temperature absorption and storage [3]. The DLR also experimented with an air–particle heat exchanger for high temperature CSP [4].

The authors of the present study proposed the fluidized receiver—a windowed fluidized bed directly irradiated by concentrated light [5]. This was meant to be incorporated into a beam-down reflector system. Previously, numerical simulation and experiments were conducted on a cylindrical type fluidized receiver to show the flow and thermal field of particles. Air streams with varying velocities were shown to cause circulation of particles within the cylindrical receiver. This inner circulation enhanced the thermal mixing of particles, which can contribute to attenuation of the re-radiation loss. The concept of a fluidized receiver originates from the fluidized bed reactor for thermo-chemical water splitting [6, 7]. The previous paper revealed the potential of a fluidized system to be extended to high-temperature thermal concentration [5].

This study describes the visualization and numerical simulation of a two-tower type fluidized receiver. This receiver can transport irradiated particles from a high pressure tower to a low pressure one, which is intended to act as a thermal storage system. This fluidized receiver is meant to be installed in a 100 kWth Miyazaki beam-down reflector system. In preparation for a demonstration of this system, the visualization and numerical simulation were conducted in order to gain insight into the thermal and fluidal characteristics of the receiver. A flow visualization was made of the cold particles in the transparent channel. The numerical model of the two-tower type receiver was developed for designing the demonstration solar system. The input data for the concentrated light was taken from flux measurements of the Miyazaki beam-down system. Two-dimensional contours of temperature and vector diagrams were examined to reveal the physics of solar light absorption into the solid particles and air.

2. Experimental visualization of cold bed

The authors propose to utilize a fluidized bed as a high temperature receiver for a beam-down reflector system.
The high temperature receiver is suitable as a heat source for an external fired (EF) gas turbine. Hot air of temperature as high as 900°C is required for this purpose. The solar gas turbine system fueled by solar light is conceptualized in Fig. 1. A fluidized bed is suitable for use as the thermal receiver because it can allow the heated particles to flow for thermal storage through an external loop.

Figure 2 shows the transparent channel for cold bed visualization. This is comprised of a rectangular box 105 mm wide, 140 mm long, and 60 mm deep. The high pressure tower (left) and low pressure tower (right) can interact with each other through gaps in the center plate. Distributers made of porous stainless steel plates separate the particle bed from the pure air pressurized by the compressor. The high pressure side is equipped with a cone, through which concentrated light is absorbed. Normally, the high pressure side is provided with high velocity air from the bottom distributor, whereas the low pressure side with low velocity from that. The velocity difference leads to induce internal circulation of particles between two towers.

Fig. 2. Transparent channel for visualization of a two-tower fluidized bed.
The experiments were conducted using polystyrene beads of diameter 0.7–1.4 mm. The density of the material was 1.04 g/cm³. The beads, weighing a total of 291 g, filled a total volume of 475 cm³. The apparent density was 0.613 g/cm³. The air flow rate was evaluated by the linear velocities.

\[
U_{wi} = \frac{G_H}{A_H} \quad (1)
\]

and

\[
U_{w2} = \frac{G_L}{A_L} \quad (2)
\]

where \(G_H\) and \(G_L\) are volume flow rates at the high and low pressure sides, respectively, and \(A_H\) and \(A_L\) are the cross sections of each side. The experiment was conducted by changing each linear velocity from 0.1 m/s to 1.0 m/s. Initially, white particles filled the high pressure side and blue particles filled the low pressure side. Figure 3 shows the time evolution of the system for linear velocities of \(V_H = 0.32\) m/s and \(V_L = 0.31\) m/s. White particles were observed to move into the region of high blue-particle concentration by passing through the upper slit. Blue particles were seen to move into the region of white particles through the lower slit. The clockwise inner circulation of the particles is thus suggested to occur by aeration due to the linear velocity difference.

Figure 4 summarizes the flow pattern in the particle bed. When the linear velocities were as low as 0.3 m/s, no fluidization occurred throughout the channel. Increasing the linear velocities to over 0.4 m/s lead to particle fluidization. Clockwise inner circulation or fluidization of only the high pressure side occurred when the linear velocity of the high pressure side was higher than that of the low pressure side, \(U_{m1} > U_{m2}\). Anti-clockwise inner circulation or fluidization of only the low pressure side occurred when \(U_{m1} < U_{m2}\).
3. Numerical computation of fluidized receiver

The two-tower type fluidized receiver is intended to be incorporated into a beam-down reflector system. A solar demonstration is planned to be made using the Miyazaki beam-down system shown in Fig. 5. This system has a central tower 16 m high, with an elliptical reflector and 88 heliostats. The total mirror area of the heliostats is 176 m². Figure 6 shows the distribution of heat flux at the second focal point of the elliptical mirror [8]. The peak of the flux was as high as 500 kW/m². The total heat in a square of 130 cm at the second focal point of an elliptical mirror was 113.2 kW. A complex parabolic concentrator is planned to be installed to further condense the light in the solar demonstration of the fluidized bed. The heat flux input for the numerical simulation will be decided from the measurement of heat flux.
Figure 7 shows the computational model of two-tower type fluidized bed. The two-dimensional model was designed in such a way as to keep the computational time reasonably small. The widths of the high and low pressure towers were 200 mm and 133 mm, respectively, and the height of both towers was 400 mm. The thermal input was assumed to be 100 kWth and applied to a 200 mm diameter aperture at the top of the high pressure tower. The linear velocities of air were 0.06 m/s and 0.033 m/s at the high and low pressure sides, respectively.

The granular approach introduced by Sakurai et al. was extended to simulate the two-tower type fluidized bed via a structured grid mesh. The structured grid was generated by ICEM module of FLUENT. FLUENT ver. 13 was used as the computational software for solving the fluid dynamics. The governing equations of the granular approach are as follows.

\[
\frac{\partial}{\partial t} \left( \alpha_s \rho_s \right) + \nabla \cdot \left( \alpha_s \rho_s \vec{u}_s \right) = \dot{m}_{fs}
\]

\[
\frac{\partial}{\partial t} \left( \alpha_s \rho_s \vec{u}_s \right) + \nabla \cdot \left( \alpha_s \rho_s \vec{u}_s \vec{u}_s \right) = -\alpha_s \nabla \rho_f + \nabla \cdot \vec{\tau}_s + \sum_{i=1}^{n} \left( R_{fs} + \dot{m}_{fs} \vec{u}_s \right) + \vec{F}_s
\]

The second term on the right-hand side of equation (4) is the solid stress tensor. The third term in parenthesis on the right-hand side of equation (4) is the phase interaction term. The basic equation for the granular-phase temperature is as follows.

\[
\frac{3}{2} \left[ \frac{\partial}{\partial t} \left( \alpha_s \rho_s \theta_s \right) + \nabla \cdot \left( \alpha_s \rho_s \vec{u}_s \vec{\theta}_s \right) \right] = \vec{\tau}_s \cdot \nabla \vec{u}_s + \nabla \cdot \left( \kappa \theta_s \nabla \vec{\theta}_s \right) - \gamma_s + \phi_{lm} + \phi_{fs}
\]

The first term on the right-hand side is the production term, the second term is the diffusion term, the third is the dissipation term due to inelastic collisions, and the fourth and fifth terms are the exchange terms. The input properties of the particles were a density of 6.87 g/cm³, a specific heat of 456 J/kg·K, and a thermal conductivity of 0.76 W/m·K. The particle diameter was assumed to be uniform at 450 μm. The apparent density of particles was 2.92 g/cm³. The particles filled a volume of 21,400 cm³. The mass of the particles was 62.5 kg.

Figure 8 shows the volume fraction of the fluidized particles 3.0 s after the start of aeration. There were low volume fraction blobs in the upper half of the channel, and air bubbles were starting to form in the particle bed. The particle bed surface of the high pressure side was elevated above that of the low pressure side, which is believed to have caused the inner circulation observed in the experiment. The distributor on the low pressure side had a slope to
assist the inner circulation, but unexpectedly, its upper corner caused the formation of a slender bubble along the vertical wall. This unexpected bubbling induced a fast upward flow of gas and solid matter, which will be discussed later. The design of the distributor needs to be elaborated, since the fast upward flow from the corner can deteriorate the inner circulation of particles; this will be discussed later.

![Image](image1.png)

**Fig. 8.** Volume fraction of the solid part after 3 s.

The particle velocity vectors are displayed in Fig. 9. An upward flow occurred along the vertical wall of the low pressure side. This upward flow caused anticlockwise local circulation within the low pressure side. The global circulation between the two towers was not as strong as the local circulation on the low pressure side, but it can be observed in the diagram. There was particle transport from the high pressure side to the low pressure side through the upper slit, and the opposite transport through the lower slit. This global circulation was consistent with the experimental visualization. The global circulation can be utilized for particle transport in a heat storage system. The design of the distributor needs to be refined to stabilize the global circulation by preventing disturbance caused by the local circulation.

![Image](image2.png)

**Fig. 9.** Particle mean velocity during 3 s.
Figure 10 shows the contours of the particle temperature from 10 s to 3.0 min following the start of aeration. The particle bed surface at the high pressure side was irradiated by concentrated light, so that its temperature exceeded 1400°C after 10 s of aeration. The particle temperature increased with time. Note that the temperature rise in the low pressure side proceeded before that in the high pressure side. This is consistent with the global circulation between the two towers observed in the experiment and the vector diagram. The local circulation on the low pressure side was not intended during the design of the channel. However, this local circulation is thought to have enhanced the thermal mixing within the low pressure side. There was also local circulation on the high pressure side, as suggested in Fig. 9. This enhanced the local mixing of heated particles on the high pressure side.

Flow simulations were conducted for three computational models with bed heights of 120 mm, 230 mm, and 400 mm. The pressure at the bottom of the particle bed is presented in Fig. 11. The pressure was almost proportional to the particle bed height. The pressure loss was estimated to be 12 kPa for a 100 kWth receiver with a bed height of 120 mm. The fluidized receiver was considered as a heat source for the external gas turbine system. The pressure
ratio of the gas turbine is as high as 3.0 to 8.0 depending on the system configuration. The pressure loss of the fluidized receiver is confirmed to be much smaller than the pressure rise because of the compressor of the gas turbine system.

![Graph showing the relationship between pressure and height of particle bed](image)

Fig. 11. Relationship between the height of the particle bed and the pressure on the center of the bottom.

Currently, the obtained experimental data are only for cases without thermal irradiation. Whereas, the simulation was made only for irradiated cases. There is quantitative discrepancy between experimental visualization and simulation, which comes from the temperature dependence of solid / air two phase flow. However, qualitative consistency was confirmed between experiment and simulation. There is observed global circulation between two towers both in the experiment and simulation.

4. Conclusions

This study uses experimental visualization of a cold model and numerical simulation of an irradiated model to consider a two-tower type fluidized receiver for use in a beam-down system. The flow and thermal fields were discussed to elaborate the design of a demonstration model of the Miyazaki beam-down system. The conclusions can be summarized as follows:

1. An experimental visualization was made for a transparent cold model 140 mm high without thermal radiation. This revealed that the particles were globally circulated between two towers when the line velocities at the high and low pressure towers were set at 0.32 m/s and 0.31 m/s, respectively. There was particle transport from the high pressure side (solar intake tower) to the low pressure side (thermal storage tower) through the upper slit of the separation wall, and the opposite transport through the lower slit. A flow map was made experimentally and suggested that global circulation occurred for line velocities of 0.3 m/s or over, and that the circulation could be reversed by reversing the line velocity.

2. A flux measurement in the Miyazaki beam-down system was referenced the thermal input for the numerical simulation. Summing up, the local fluxes suggested that 113.2 kWth heat was concentrated on a square of 130 cm at the second focal point of an elliptical mirror. The 100 kWth heat was used as input for the numerical model.

3. A numerical simulation for the two-tower fluidized receiver with a height of 400 mm showed that bubbles were formed and grew in the particle bed. The sloped distributor of the low pressure side induced a narrow uprising bubble over the side wall. This uprising caused local circulation on the low pressure side.
(4) In the vector diagram of the particle velocity, the global circulation between two towers could be seen to transport the particles from the high to low pressure sides and then retract them. Such global circulation was weak compared with the local circulation due to the intensified uprising flow in the low pressure side; this also occurred in the high pressure side. The inclined distributor needs to be elaborated to keep the local circulation consistent with the global circulation.

(5) The temperature of the particles was visualized by the numerical simulation. The surface of the particle bed on the high pressure side was irradiated by the concentrated radiation to a temperature of 1400°C after 10 s of aeration. The temperature rise occurred on the low pressure side faster than that on the high pressure side. The global circulation was thus suggested to have the potential to convey heated particles for the thermal storage system.

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