Direct Simulation of Volumetric Solar Receiver with Highly Concentrated Radiation

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Abstract. The volumetric solar receiver is a promised technology for high-temperature solar absorption in the concentrated solar power, industrial solar thermal usage and solar fuel production. Existing numerical simulation separated computations of light and convective flow and two-way coupling was not perfectly integrated between radiation and convective transport. This paper describes conjugate analysis of radiation, convection and conduction heat transfer in the volumetric receiver for perfect three-way coupling between three mechanisms of heat transfer. The numerical scheme was used for the volumetric receiver with plane surface and that with cut-back inlets for optimization of the geometry. The simulation was made for single cell of honeycomb with 2.4 mm pitch and 0.5 mm wall thickness. Two cases of surface geometry was computed: plane surface; cut-back inlet with 10 mm depth. Basic equations are momentum and energy equations with radiation transport equation. The discrete ordinates method was applied for solving the radiation intensity to consider perfect interaction between radiation, convection and conduction. The material of the receivers are assumed as stainless steel. The numerical simulation demonstrated the superiority of the cut-back receiver which increased the exit temperature by 30 K and decreased 2 Pa for the smallest beam angle of 10°. The contour plot of total heat flux on the wall revealed that the shadow effect was attenuated by the cut-back inlet leading to heat transfer enhancement. The novelties of this work are to treat perfect interaction between radiation and convection in volumetric receiver and to demonstrate the excellence of cut-back inlet receivers.

Keywords: conjugate radiation and convection analysis; volumetric solar receiver with cut-back inlets; total heat flux including radiation and convection

1. Introduction

The volumetric air receiver is utilized for concentrated solar power generation, solar fuel production and returning carbon dioxide into fuel [1-3]. Conventional receiver adopting molten nitrate salt collect thermal energy at 560 ºC in the newest solar power plant. However, this thermal medium cannot be used at the higher temperatures than 600 ºC since this is thermally broken up beyond this criterion. To increase the heat source temperatures is essential for enhancing the thermal efficiency of energy conversion and for broadening the applicability of solar heat. Therefore, there are research works on air receivers for high-temperature solar acquisition. Numerical simulation is powerful tool for designing and optimizing solar receivers. Most of the simulations made for volumetric solar receivers utilize the volume-averaged equations for solving flow and temperature fields. Recently, porous structures are considered by using the Monte Carlo approach for ray tracing and the conventional Eulerian method for flow and heat transfer. Most of these simulations lack the consideration on full interaction between condensed light and convective transport.
The present paper describes the simulation for single cell of honeycomb receiver with highly concentrated light irradiation [4, 5]. The simulation employs the discrete ordinates (DO) approach for considering three-way coupling between radiation, convection and conduction. Simulation was made for stainless steel honeycomb with plane surface and with cut-back inlets for optimizing the surface geometry.

2. Numerical method

2.1. Numerical model

Figure 1 shows the numerically treated situation, honeycomb irradiated by concentrated light. The air streams inside the honeycomb cells and absorbs sensible enthalpy created on the honeycomb wall. Simulation was made for a single cell of honeycomb as shown in figure 2. Across the top boundary, irradiation and air stream enters the computational domain. The radiation is absorbed and reflected by diffuse reflection on the honeycomb wall. Re-radiation occurs from the honeycomb wall according to the Stefan-Boltzmann law. The net radiation on the wall is balanced with the convective transport in the fluid side and the conduction in the solid side. All the three mechanisms of heat transport are considered in the simulation.

2.2. Cell geometry

Two kinds of receivers shown in figure 3 are treated in the simulation. One is a simple cell with plane surface. The cell pitch is 2.9 mm, and the cell wall is 0.5 mm. The other is a cut-back inlet cell with 2.4 mm × 2.4 mm cut with 10.0 mm depth. These cell have 50 mm length. The previous study experimentally tested the honeycomb block of ceramics with the same geometry as the simple cell [4]. The experimental data was used for validation of the numerical simulation [5]. This paper simulates the honeycomb cell made of stainless steel. The complex geometry of ceramics requires high level of manufacturing technology. Whereas recently emerging three-dimensional metal printer enabled complex geometry of metal at low level of fabrication skills.

2.3. Computational conditions

Table 1 summarizes computational conditions. In this paper, the heat flux of incidence is fixed at 500 kW/m² and air mass flow rate at 6.17 × 10⁻³ g/s. The maximum incidence angle is changed from 10 to 90° in nine steps for each of two kinds of cells. Grid convergence test was made between two kinds of grid resolution with number of grid cells of 34,560 and 276,480. The discrete ordinates number was...
changed in the range of $3 \times 3 \times 8$ to $18 \times 18 \times 8$. There are almost no effects from the grid resolution and discrete ordinates in these conditions. The simulations listed in table 1 was made using the grid number of 34,560 and discrete ordinates of $18 \times 18 \times 8$.

3. Numerical result

The distribution of solid and fluid mean temperatures along with vertical position are presented in figure 4. The mean temperature of solid is the temperatures averaged across the cross-section. The mean temperature of fluid is bulk mean temperature. In figure 4 (a), the solid temperature increases from the simple cell to cut-back cell by 70 K at the inlet. Two cells are made of the same material with the same absorption coefficient; however the solid temperature differs a lot between two cases. It is thus suggested that the effective absorptivity is changed by the cut-back inlets. The temperature difference between two cases remain in the deep area of each cell. In figure 4 (b), the temperature of cut-back inlet is clearly higher than the simple cell at the cell exit. This demonstrates that the thermal performance is improved by the cut-back inlet and modification of the effective absorptivity thus resulted. Regarding the effects from the maximum incident angle on the cut-back cell, the smaller angle of incident resulted in the lower solid temperatures at the inlet area but increases the solid temperatures at the deep area of cell. This tendency is similarly observed on the fluid temperatures. The fluid temperature of cut-back for the case of lower incident angle becomes higher than that for higher incident angle. These trends are consistent
with the fact that the irradiation can intrude more deeply when the incident angle becomes smaller. Therefore, low angle of incident radiation increases the thermal performance of the receiver to achieve the higher heat acquisition by the air flow.

Figure 4. Mean temperature distribution along with vertical position.

Figure 5 shows the thermal power transported to air flow at the receiver exit and the pressure drop at the same position. In the figure, the quantities are presented against the maximum incidence angle. In figure 5, clear advantage of the cut-back receiver can be observed in the thermal power and pressure drop. Namely, the thermal power increases and the pressure drop decreases by changing the simple cell to cut-back cell. There are relatively high dependency of thermal power on the maximum incidence angle. The thermal power increases as the incidence angle decreases as implied from the temperature distribution earlier discussed.

In figure 5 (a), the difference between simple and cut-back cell becomes larger as the maximum incidence angle decreases. In figure 5 (b), pressure drop increases as the maximum incidence angle decreases to 30° or 20° and this decreases for smaller angles. This dissimilarity of thermal and flow performance may come from the change of the temperature distribution. When the incidence angle reduces, the temperature decreases around the inlet area to reduce the pressure loss but increases in the deep area to increase it. The pressure drop characteristics are resultant of the two opposite effects to decrease and increase it. The decrease of the pressure loss by the decreasing the maximum incident angle from 20 - 30° means that decreasing temperature near the receiver inlet and resulted reducing pressure loss effects excels increasing temperature in deep area and resulted increasing pressure loss.

Figure 5. (a) Thermal power air and (b) pressure drop at the receiver exit.

Wall variables are visualized using contour map for discussion of the heat transfer mechanisms. Cell walls A, B, C, D are defined as shown in figure 6. The temperature distribution on each walls of two types of cells are presented in figure 7.
In figure 7 (a), temperature on simple cell inner walls increases across the whole area as the maximum incidence angle decreases. In figure 7 (b), temperature on cut-back cell decreases around the leading edge and increases in the deep area. Therefore, incidence angle effects to the temperature differ between two cases regarding trends near the inlet area. There are conspicuous temperature decrease on the cut-back cell near the leading edge compared with other area. When $\alpha = 90^\circ$, a lot of light beam reaches inner walls near the leading edge due to low shadow effect. When $\alpha = 30^\circ$, light beam tends to come to deep inside the cell and temperature decreases near the leading edge. The cut-back receiver thus is affected by the incidence angle more greatly than the simple receiver.

Figure 6. Definition of inner walls: (a) simple cell; (b) cut-back inlet cell.

Figure 7. Temperature distribution on inner walls: (a) simple cell; (b) cut-back inlet cell.

Total heat flux is presented in figure 8 by the same manner. In this figure, positive heat flux aims from the wall to fluid side and negative heat flux from the wall to solid side. In the case of simple cell, there are negative values of heat flux in a short distance from the leading edge, which correspond to the direct irradiation for the maximum incidence angle $\alpha = 90^\circ$. This negative value decreases with decrease of the incidence angle. In the case of cut-back cell, negative value little apart from the leading edge is conspicuous, which corresponds to very large direct irradiation. This negative value decreases with decrease of the incidence angle similarly to the case of simple cell. There are remarkable difference between two types of receiver in the negative values corresponding to the direct irradiation. The improved efficiency of the cut-back cell is attributed to the attenuation of shadow effect which take in the light more efficiently on the inner walls.
4. Conclusions
This paper describes direct numerical simulation of honeycomb receiver with plane surface and cut-back inlets. The simulation considered full interaction between three mechanisms of heat transfer using the discrete ordinates (DO) model for radiation computation. The conclusions can be summarized as follow:

(1) The honeycomb receiver with cut-back inlet cell is superior to the receiver with plane surface cell in heat transfer and pressure loss characteristics. Numerical simulation demonstrated that thermal power (receiver efficiency) increases and pressure loss decreases due to cut-back inlet cell.

(2) The thermal power increases with decrease of the maximum incidence angle since the radiation intrudes more deeply. However, pressure loss increases with decrease of incidence angle up to a certain criterion and decreases at very small incidence angle. This is because temperature decrease near the inlet area contributed for the decrease of pressure loss in the case of very small incidence angle.

(3) On the inner walls, the negative heat flux corresponding to irradiation is larger in the case of cut-back cell than in the case of simple cell. Attenuation of the shadow effect is thus suggested in the case of cut-back cell. The attenuated shadow effect comes to enhancement of the receiver efficiency.

5. References
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Figure 8. Total heat flux on inner walls: (a) simple cell; (b) cut-back inlet cell.