Central Receivers Design in Concentrated Solar Thermal Power Plants: A review

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Abstract. Fossil fuel has been used for electric power generation for many decades, due to CO₂ emission and its effect on climatic change, besides its massive effect on human health caused by environmental pollution and the high operation cost. As a result, researches and development studies rose to change this type of energy source to another clean source; a solar thermal power plant is one of the promises options. This paper focused on the significant component studies during the past ten years of central receiver tower (CRT) design in concentrating solar power (CSP) technology to enhance the amount of absorbed heat from the sun. After an introduction to solar thermal power plants concepts, a detailed survey of developing technologies that been done on external central receivers design, the last section contains the novelty of our upcoming study, by designing an external receiver with a variable inclination angles configuration system used in CRT technology and investigate the inclination effect numerically and experimentally on the solar receiver efficiency.

Keywords. Central receiver system, External receiver efficiency, Concentrating solar power, Receiver inclination.

1. Introduction
Oil, coal, and natural gas are non-renewable energy resources that produce environmental problems[1]. Due to the above major reason, renewable energy resources have been attracted by science attention, especially solar energy utilization technology [2]. For the power generation purpose, concentrating solar power (CSP) is considered as one of the most useful technology when a thermal energy storage system combined with it [3]. So far, four basic concepts of concentrating solar power technologies have been used, which are central receiver tower or solar power tower (SPT), parabolic trough collected system, parabolic dish collector system, and linear Fresnel reflector system [4], as shown in Figure 1. For a large-scale energy utilization bases, the central receiver tower system (CRT) is considered promising technology due to the system’s satisfactory performance with a very high solar concentration ratio [5], as shown in Figure 2, besides the energy cost reduction. CRT plant with a solar receiver fixed above the tower and with hundreds or more of the heliostat field surrounded the tower to reflect the solar radiation and heats the receiver heat transfer fluid. This system, with a high concentrated solar field and updated solar receiver design, can produce higher temperatures than the other systems, which are used in a different thermodynamic cycle as a power conversion system [6]. The most crucial component of the solar power tower is the solar receiver. So far, four types of receivers have been investigated, including tubular external receiver [7], tubular cavity receiver [8], the volumetric receiver [9], and particle-based receiver [10]. By comparing the above typical
receivers, the promising choice is the external receiver due to large scale solar energy utilization provided by the surrounding heliostat field [6].

**Figure 1.** CSP concepts: (a) Central receiver tower[11], (b) Parabolic dish collector[12], (c) Parabolic trough collector[13] and (d) Linear Fresnel reflector [14].

**Figure 2.** Gema solar power plant, heliostat field, spain[12].

2. **Operation mechanism of solar central receiver tower plant**
   Central receiver tower systems consist of three major components: the solar field, the solar receiver, and the power conversion system, as shown in Figure 3. Numerous sun-tracking mirrors are called the
heliostat (represent the solar field), which reflects the incident sun ray to the surface of the solar receiver placed above the centenal tower. The absorbed solar irradiation raises the heat transfer fluid inside the receiver, as the solar receiver works as a heat exchanger. The receiver hot fluid product with a very high temperature reaches above 500 °C, using a molten salt heat transfer fluid or any other sufficient fluids[15] is enough to generate a superheated steam used to generate electrical power by traditional steam power cycle plants, or any other power conversion cycles.

Figure 3. Major components of the solar central receiver tower plant [6].

3. Recent developments technology of external central receivers design

Wang et al. [16] evaluated numerically and experimentally a new receiver design to increase both the thermal and the optical efficiency of CRT to compensate for the efficiency drop of the traditional old cylindrical central receiver design, which has been accrued by increasing the design temperature from 560 °C to more than 700 °C. As this change increases the heat losses with the surrounding, leading to a drop in the receiver efficiency, they used a fin-like shape receiver to decrease the losses of the reflected solar energy from the receiver body to the environment by reabsorption method, as shown in Figure 4. Their results have shown that with the same receiver tube diameter, the optimal fin-like receiver efficiency of 12 fins number and 1.0m inner diameter has been improved by 3.8% compared with the traditional cylindrical receiver, at the same location and environment condition. Moreover, the fin-like receivers achieved higher efficiencies for a different condition. On the other hand, a 38.6% reduction in peak solar flux for the fin-like receiver than the amount of the traditional cylindrical receiver.

Figure 4. Schematic diagram :(a) Three-dimensional structure and top view of the cylindrical receiver, (b) Three-dimensional structure and top view of the cylindrical receiver of the fin-like receiver [16].
Wang et al. [17] studied the effect of varying the receiver output temperature of CRT on the central receiver efficiency; they used a molten salt binary nitrate as a heat transfer fluid. Their results show that when the produced receiver temperature is optimized from 550°C to 700°C, the central receiver’s efficiency will decrease by about 6.4%. Garbrecht et al. [18] investigated the thermal efficiency numerically for a newly designed pyramidal structures external receiver with a molten salt heat transfer fluid. Many hexagonal pyramid configuration elements with the alveolar arrangement and their apexes pointing toward the heliostats, as shown in Figure 5. Their results show that the obtained thermal efficiency was 91.2%, and a 1.3% reduction in energy losses has been obtained by reabsorbing methods related to the reflected radiation energy. In comparison, 2.8% appeared losses by emission.

Figure 5. Outside geometry of some pyramids receiver arrangement and its inner geometry.

Christian et al. [19] studied four simple models as an external receiver configuration with the same exposed surface area (4 m²). They selected an external receiver with a flat model, an external receiver with a vertical finned structure model, an external receiver with a louvered finned structure model, and an external receiver with radial finned structures model configurations, as shown in Figure 6. Their study has been concentrating on how to reduce the lost heat to the environment through the investigation of different receiver configurations. The model thermal efficiency, the heat loss by convection, and the characteristics of airflow around each receiver design had been found using “the computational fluid dynamics (CFD) code ANSYS FLUENT.” Their results show that the horizontal slate fin receiver had 95.5% thermal efficiency with 4.5% over the flat plate configuration.

Figure 6. Receivers configuration (a), Base case study-flat plate, (b) Radial finned receiver,(c) Linear vertical fin receiver, (d) Horizontal slate fin receiver[19].
Wang et al. [20] have proposed five novel designs with a tubular fin-like receivers configuration aiming to improve the optical efficiency of SPT plant, including a vertical fin with flat base receiver structures, a vertical fin with concave base receiver structure, a vertical fin with convex base receiver structures, horizontal angled fins receiver and traditional cylindrical receiver, as shown in Figure 7. They investigated numerically and validated experimentally in a plant-scale size the optical efficiencies of the novel receivers and compared with traditional cylindrical receiver for the same tube number. By parametric optimization, they found that the optimal novel receiver is the vertical fin with flat base receiver structures configuration has the best optical efficiency with 3.2% higher than the cylindrical receiver configuration. In contrast, the peak solar flux increased and nearly double than the cylindrical receiver. High peak solar flux causes severe thermal stress failure in the receiver due to high local temperature [21].

![Figure 7. Receiver schematic diagram: (a), Cylindrical receiver, (b) Vertical fin with flat base receiver structures, (c) Vertical fin with concave base receiver structure, (d) Vertical fin with convex base receiver structures, (f) Horisontal angled fins receiver [20].](image-url)

Ya Ling He et al. [22] introduced and reviewed features to solve the problems of non-uniform flux distribution in all CSP technologies, including the solar power tower, the parabolic-trough collector, the linear Fresnel collector system, and the parabolic-dish collector system. High local temperature produces a steep temperature gradient in CSP receivers, which leads to a massive decrease in the receiver thermal efficiency and could cause receiver thermal deformation or burn out the receiver absorbing coating, then receiver failure. They show a solution summary based on two approaches to
reduce the above-mentioned effect. The first is the passive approach by optimizing and enhancing the ability of heat transfer in the receiver to reduce the non-uniform flux distribution, and the second is an active approach by improving the flux distribution uniformity in the receiver. Luo et al.[23] proposed a novel dual-receiver design with solar field surrounding to improve the efficiency of SPT, by using a combined external receiver for boiling and cavity receiver for superheating on the same tower as shown in Figure 8. They conducted 11 MW solar power plant as a case study, and controllable heat flux distribution has been used; their results show that the present novel dual design has an improvement in the global thermal efficiency of 3.2% when compared with the two-external cylindrical receiver.

![Figure 8. Schematic diagram of the novel dual-receiver design[23].](image)

Kim et al.[24] studied numerically and validated the radiation and convection losses experimentally from different receiver types, including four-receiver models with external and cavity configuration by changing the opening ratios (cavity aperture to receiver area), as shown in Figure 9. The simulation has been carried out using “Fluent computational fluid dynamics software (CFD)” for different temperatures range, wind velocities range, and direction. They found a fraction with a simple proposed correlation to calculate the receiver heat losses and efficiency. Their results show an agreement with a 5.9% average absolute deviation for total heat losses and 11.4% for convection heat losses.

![Figure 9. Two different cavity receiver models](image)
Cantone et al. [25] investigated numerically and experimentally the thermal behaviors of three different tubes to solve the thermal fatigue due to high stress caused by the temperature gradient in tubular receivers of CSP and increase the component lifetime. They studied the smooth tube, repeated helical ribs tube, and repeated annular ribs tube, as shown in Figure 10, and they have been tested on a solar furnace. The aim of their tests was the reduction of the peak one side wall temperature during solar. By comparing the performance of these three different types on one side heating and in the same condition, their results show that the best performance was in the helical rib tube.

Boerema et al. [26] investigated the resultant receiver surface temperature in SPT for four different tubular flat receiver’s design, they studied a constant diameter tubes receiver with an ideal flow receiver, a variable diameter tubes receiver, and series multi-pass panels receiver, at the same operation condition by changing the aim point of heliostat array, as shown in Figure 11. Their results show that high temperatures and sensitivity occurred in single tube diameter and variable tubes diameter receivers. While the receiver with multi-pass tubes had the minimum surface, they illustrated their results in a table to provide insights on flat receivers design, SPT life extension, and tube’s material selection.
Liao and Faghri [27] proposed a novel concept for heating the pipes of the molten salt solar central receiver. The receiver element consists of a secondary reflector, wick heat pipe, and receiver tube, as shown in Figure 12. The secondary reflector redirects the concentrated sun ray received from the heliostats to the wick heat pipe. This will heat the heat transfer fluid inside the wick and transport heat to the molten salt in the receiver tubes by crossflow. They considered this concept no irradiation occurs directly between the receiver and the sunlight; this will maximize the daily operating time and the delay freezing time of molten salt. In this study, their study validated by numerical solution and obtained receiver efficiency of 88.5%.

Figure 11. (a) A tubular, flat receiver with a single pass, (b) Receiver with variable tubes diameter and (c) Multi-pass receiver [26].

Figure 12. Receiver schematic diagram: (a) Complete receiver panel, (b) Receiver flow bath, (c) Novel element and (d) Receiver enclosure structure [27].
Hazmoune et al. [28] presented an external serial flow receiver model for SPT numerically, as shown in Figure 13. They studied the influence of multivariable factors, including inlet flow velocity, incident solar flux to the receiver wall, and the heat transfer fluid type on the efficiency of the serial receiver. Their results showed that this model would help in choosing the best value for different conditions.

Piña-Ortiz et al. [29] investigated numerically and experimentally the thermal behavior of a finned receiver model, as shown in Figure 14. They used a 1232 extended fins type cylinder for a receiver flat surface area of 1.47 m². The incident solar radiation reflected from the heliostat heats the flat surface of the receiver, and by conduction, the temperature of the finned side will rise to cause increasing the water temperature, which was used as a heat transfer fluid. Their results show that the receiver thermal efficiency was 94.4%; they noticed that this efficiency dropped by increasing the incident solar flux and rose with increasing the heat transfer fluid flow. Das et al. [30] discussed the advanced design concepts of Alstom commercial receiver, Alstom design features aimed to maximize the solar heat received from the sun and the produced energy of working fluid (hot salt production) by optimizing the receiver design with minimum pressure losses, using a multi passes flow configuration design, and by maximizing the solar field utility. Figure 15 shows the flow process of the Alstom molten salt receiver design.

Figure 13. Receiver geometry [28].

Figure 14. Finned receiver view.

Figure 15. Flow process of alstom advanced design [30].
Rodríguez-Sánchez and Santana [31] proposed a novel design concept for the solar receiver by allowing a variable flow velocity for the used heat transfer fluid to maximize the receiver optical efficiency, minimize the required solar field (number of heliostats), reduce the effect of peak heat flux and increase the operating time heat gain. They modified the traditional design of the tubular external receiver with valves to divide the receiver into a multi passes serial flow panels, aiming to increase the flow velocity in specific parts on the receiver panels, as shown in Figure 16. Numerically their results show that the number of heliostats had been reduced by 12.5% compared with traditional tubular receiver for the same capacity and reduce the total plant cost by 5%.

![Figure 16. Flow configuration: (a) Traditional tubular receiver, (b) Alstom receiver [30], (c) Variable velocity receiver working as alstom receiver and (d) Receiver with variable velocity [31].](image)

Mahmoud et al. [32] investigated numerically and experimentally a novel receiver design with a serial flow and staggered configuration system. For experimental validation purposes, they designed and built a small-scale model with 0.25 m² external receiver surface area located in Baghdad, Al-Nahrain University, with a heliostat tracking system to minimize the cosine losses of the incident irradiation and to get the optimum heliostat position during the system operation [33], as shown in Figure 17. Their results show that the receiver thermal efficiency had been enhanced by 6.17% than the model of one row serial flow design configuration for the same tube length as the receiver configuration presented in Figure 13, which has been reviewed previously.
Figure 17. (a) Solar power tower system small-scale model, (b) Staggered tube configuration [32].

Table 1 shows an overview of the above-mentioned recent ten years of development review. Most studies focus on improving the efficiency of external receivers. However, 40% of SPT investment cost is in the solar field components, so to reduce this cost, it is mandatory to continuously develop and update the design of the traditional receiver’s configuration, at least to obtain the same receiver efficiency or even more with a minimum number of the heliostat, so to minimize the Levelized cost of energy (LCOE) of SPT, all components efficiencies have to be improved. One of the crucial factors in enhancing the receiver absorptivity depends on incidence irradiation to remove the spillage and cosine losses by making the incident irradiation perpendicular to the receiver surface. To do so, a proposed novel external receiver design with variable inclination angles will be study, the proposed design will be investigated experimentally and numerically by considering the inclination effect on the serial flow and staggered external solar receiver configuration, aiming to get the optimum inclined position for maximum efficiency. This will be done at the same condition on the designed novel system by Mahmoud et al. [32], then comparing the thermal behavior with the results obtained from the vertical receiver position, as shown in Figure 18.
Figure 18. The novel design of external receiver with variable inclination angles configuration.

4. Conclusion
From the above-presented reviews, which were specialized in external solar receiver’s configuration design used in SPT systems, it can be concluded that the most reviewed published papers and studies focused on the high capacity of hot heat transfer fluid (HTF) production by the system to be sufficient for power conversion cycles. Commercially to attract the attention worldwide about this renewable source technology, even in low solar irradiance regions or in the winter season, all reviewed studies aimed to achieve that by maximizing both the optical and thermal efficiencies of the external solar receivers, besides solving the problem of peak heat flux, solving the non-uniform heat flux distribution on the surface of receiver tubes and its effect on the system life components, in addition to minimizing the pressure losses of the heat transfer fluid flow inside the receiver, which will minimize the parasitic consumption.
| Year | Authors | Analysis | Research Purpose | Enhancement method | Proposed receiver design | Receptors efficiencies and findings |
|------|---------|----------|------------------|-------------------|--------------------------|--------------------------------------|
| 2013 | Boerema et al.[26] | Numerical | Provide insights into flat receivers design, SPT life extension, and tube’s material selection. | Comparing different receivers configurations | Constant diameter tubes, variable diameter tubes, and series multi-pass panels receivers | High surface receiver temperature occurred in a single tube and variable tubes diameter model. The receiver with multi-pass tubes had the minimum surface temperature. |
| 2015 | Luo et al.[23] | Numerical & experimental | Improve the global thermal efficiency of CRT systems. | Novel design with Dual receivers | External receiver for boiling and cavity receiver for superheating on the same tower. | 3.2% improvement in the global thermal efficiency when compared with a two-external cylindrical receiver. Correlation results show an agreement with 5.9% average absolute deviation for total heat losses and 11.4% for convection heat losses. |
| 2015 | Kim et al.[24] | Numerical & experimental | Obtain a Correlation to calculate the heat losses by radiation and convection from a receiver. | changing the opening ratios | Four receiver models with external and cavity configuration. | Optimized the receiver design, with maximized heat absorption and minimum pressure losses. |
| 2015 | Das et al.[30] | Analytical | Increase the hot salt production from the receiver. | Comparing various design feature | Advanced commercial ALSTOM receiver with multi-flow passes design | |
| 2016 | Liao and Faghri [27] | Numerical | Avoid non-uniform heat flux to increase the receiver’s life. | Indirect receiver heating method | A novel receiver design with a secondary reflector and wick heat pipe | 88.5 % receiver efficiency. |
| 2016 | Hazmoune et al.[28] | Numerical | Effect of different variables on the receiver efficiency. | Comparing method | One row serial flow flat receiver | Reached results help to choose the best value for different conditions. |
| 2017 | Wang et al.[17] | Analytical | Effect of varying the receiver output temperature of the CRT system on the efficiency | - | - | 6.4% drop when the output receiver temperature increased from 550°C to 700°C. |
| 2017 | Garbrecht et al.[18] | Numerical | Increase the thermal efficiency of the solar receiver | Reabsorption method | pyramidal structures external receiver | 91.2% receiver thermal efficiency with 1.3% losses, while 2.8% appeared losses by emission. |
| 2017 | Rodríguez-Sánchez and Santana[31] | Numerical | Maximize the optical receiver efficiency, minimize the number of the heliostat, reduce the effect of peak heat flux, and increase the operating time heat gain. | Modify receiver flow configuration | Modified ALSTOM receiver with variable flow velocity design | The number of heliostats has been reduced by 12.5% compared with the traditional tubular receiver for the same capacity and reduce the total plant cost by 5%. |
| Year | Authors             | Methodology                      | Task                                                                 | Receiver Configurations                                                                                       | Notes                                                                 |
|------|---------------------|----------------------------------|----------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------|
| 2018 | Christian et al. [19] | Numerical                        | Reduce the lost heat from the surface of the solar receiver to the environment | Flat model. Vertical fin different receiver configurations Horizontal finned Radial finned Vertical fin with a flat base. Vertical fin - concave base. Vertical fin- convex base. Horizontal angled fins. Traditional cylindrical. | Horizontal slate fin receiver had 95.5% thermal efficiency with 4.5% over the flat plate configuration. The vertical fin - flat base receiver design has the best optical efficiency with 3.2% higher than the cylindrical receiver. While the peak solar flux had been doubled. |
| 2018 | Wang et al. [20]     | Numerical & experimental          | Improve the optical solar receiver efficiency                        | Different receiver configurations Flat surface receiver with inner finned surface Vertical fin with a flat base. Vertical fin - concave base. Vertical fin- convex base. Horizontal angled fins. Traditional cylindrical. | The vertical fin - flat base receiver design has the best optical efficiency with 3.2% higher than the cylindrical receiver. While the peak solar flux had been doubled. |
| 2018 | Piña-Ortiz et al. [29] | Numerical & experimental          | Steady the behavior of a new receiver design                           | Flat surface receiver with inner finned surface Flat surface receiver with inner finned surface | The receiver thermal efficiency was 94.4%, dropped by increasing the incident solar flux, and rose with increasing the heat transfer fluid flow. A passive approach by optimizing and enhancing the ability of heat transfer in the receiver and the active approach by improving the flux distribution in the receiver. |
| 2019 | Ya Ling He et al. [22] | Analytical                        | Non-uniform flux distribution in all CSP technologies.                 | Passive and active methods - Passive and active methods - | 3.8% improvement, compared with the cylindrical receiver. |
| 2020 | Wang et al. [16]     | Numerical & experimental          | Maximize the thermal and the optical solar receiver efficiency of the Central receiver tower system and minimize the peak heat flux solve the thermal fatigue due to high stress caused by the temperature gradient in Tubular receivers of CSP | Reabsorption method fin-like shape receiver Smooth tube, repeated helical ribs tube and repeated annular ribs tube | The best performance was in the helical rib tube. |
| 2020 | Cantone et al. [25]  | Numerical & experimental          | Solve the thermal fatigue due to high stress caused by the temperature gradient in Tubular receivers of CSP | Turbulence flow promoters role | The receiver thermal efficiency has been enhanced with 6.17% than the model of one-row serial flow design. |
| 2020 | Mahmoud et al. [32]  | Numerical & experimental          | Enhance SPT system efficiency                                         | Modify receiver flow configuration with a solar tracking system Novel external receiver design with Serial flow staggered configuration | The receiver thermal efficiency has been enhanced with 6.17% than the model of one-row serial flow design. |
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