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A Review of Concentrated Solar Power Technologies: Design, Performance, and Environmental Sustainability

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Abstract
The global dependence on fossil fuels has resulted in severe environmental challenges, including climate change, air pollution, and ecosystem degradation, which have negatively impacted both society and economic development. As a sustainable alternative, solar energy—particularly Concentrated Solar Power (CSP)—is gaining increasing attention for its ability to provide large-scale, dispatchable, and low-emission electricity. CSP systems utilize solar concentrators, receivers, thermal energy storage units, and power blocks to transform solar radiation into usable energy, offering advantages such as thermal storage capability, hybridization with conventional fuels, and reliable grid integration. This study provides an in-depth analysis of the thermo-hydraulic performance of solar tower receiver configurations, with a focus on staggered and series pipe arrangements. Key performance indicators, including Reynolds number, Nusselt number, friction factor, convective heat transfer coefficient, and thermal-hydraulic performance parameter, were evaluated using experimental and numerical methods. Additionally, a novel dual-axis tracking system and staggered receiver configuration were investigated to enhance thermal efficiency and overall system effectiveness. The findings demonstrate that optimized heliostat field design and receiver configuration significantly improve energy capture, heat transfer efficiency, and cost-effectiveness, making CSP a competitive and environmentally sustainable alternative to fossil fuels in regions with high solar irradiance potential.
Keywords: *Concentrated Solar Power (CSP), Renewable Energy, Heliostat Field Design, Thermal Energy Storage, Solar Power Tower*

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I. Introduction

The environmental challenges associated with fossil fuel utilization have adversely affected society and economic progress. The utilization of solar energy is a very competitive solution to the issues at hand [9]. Among the diverse solar energy methods, concentrated solar power (CSP) represents a viable alternative. In recent years, promoting this technology for low-cost and large-scale application has emerged as a developmental trend [1]. Elucidate Yan et al. (2021) [2] A conventional CSP facility primarily comprises a solar concentrator, a receiver, a thermal storage system, a heat exchange network, and a power block. In the facility, solar radiation is initially focused and subsequently transformed into thermal energy, which is then extracted by a heat transfer fluid (HTF) in the receiver. Subsequently, the thermal energy may be retained in a thermal storage unit or utilized to generate high-temperature steam or gas in heat exchangers. Ultimately, the steam or gas will propel an engine. Solar energy is a primary source of renewable energy that may be harnessed using solar panels. Iraq possesses several renewable energy sources, including solar energy and hydropower. Regrettably, these energy sources, particularly solar energy, are not comprehensively harnessed. The efficiency of solar cells is directly contingent upon the variable nature of sunlight. Consequently, the output of a stationary solar panel fluctuates considerably based on the sun's position [3]. Solar energy, characterized by its abundance, non-polluting nature, environmental sustainability, and widespread availability, significantly contributes to fulfilling the increasing global energy demands. A substantial quantity of solar energy is accessible across the whole surface of the Earth and can be transformed into electricity. The annual total solar radiation incident on the Earth's surface is 3,400,000 Exa joules, significantly exceeding world annual energy consumption. Among all renewable energy sources, such as wind, geothermal, solar, biomass, and tidal energy, solar energy is the most extensively utilized and possesses the highest energy potential. Concentrating solar power (CSP) is an emerging power production technology that is approaching the growth phase of its technology life cycle [4]. The value of Concentrated Solar Power (CSP) is comprehensively known from a contemporary perspective; nonetheless, its significance and potential within a power generation network remain ambiguous. The complexity stemming from a swift shift in electrical networks to intermittent energy resources and energy storage exacerbate the necessity for systems-based forecasting and expertise. Modern Concentrated Solar Power (CSP) with thermal storage does not conform to the established classifications of conventional or renewable energy sources, particularly as energy systems planning begins to address substantial proportions of intermittent renewables. Concentrated Solar Power (CSP) may represent the most valuable power generating technology of our day; nevertheless, thermo-economic scales and the associated capacity for technological advancement could substantially hinder its potential [5].

CSP is a class of power generation technology with several sub-types or variants that are distinctly different, but all share key attributes that label them as CSP technologies. CSP plants are characterized by the concentration of sunlight that is converted to high temperature thermal energy for direct or indirect operation of a heat engine and electricity generator. The initial conversion to thermal energy arguably enables the sensible and intrinsic [6].

CSP in comparison to alternative renewable or conventional technologies

The primary advantage of Concentrated Solar Power (CSP) over other renewable energy sources, such as photovoltaic (PV) energy and wind power, is its capacity to store thermal energy for electricity generation as needed. Consequently, Concentrated Solar Power (CSP) can be integrated with Thermal Energy Storage (TES) as well as with a combustion chamber utilizing conventional fuels or biogas, resulting in hybrid plants. Currently, alternative hybridization strategies are under investigation, including connection with photovoltaic, wind, biogas, or geothermal systems, [7]. Both hybrid and TES systems facilitate high dispatchability and stabilize power production. Consequently, the generation can be transitioned to periods devoid of sunlight, such as overcast intervals or even nocturnal irradiance. The ability of CSP to integrate with thermal storage and co-firing to satisfy demand requirements is regarded as a significant advantage. It is anticipated that photovoltaic (PV) or wind technologies would supplement concentrated solar power (CSP) in the future [8]. CSP can fulfill production requirements during periods when PV is less effective. Consequently, the augmentation of electricity generation through photovoltaic systems can enhance the deployment of concentrated solar power. Pietzcker et al. conducted a comprehensive examination of the prospective interrelationships between photovoltaic (PV) and concentrated solar power (CSP), examining the future evolution of their production costs in a review [9]. CSP demonstrates favorable outcomes in three primary local environmental aspects associated with both renewable and conventional technologies: land utilization, water accessibility, and landscape alteration. One square kilometer of parched terrain can provide electricity equivalent to a conventional 50 MW plant operating on coal or gas. The area needed by CSP to produce 1 MWh is comparable to that of wind or biomass. The water requirements of Concentrated Solar Power (CSP) systems are minimal, even lower than those of gas turbine cycles, where the working fluid is not water vapor and water is only necessary for specific refrigeration processes. [10]

Principles of CSP Operation and Geometric Configurations

The solar radiation that reaches the Earth is referred to as global radiation. It comprises two components: direct and diffuse solar radiation. Direct Normal Irradiance (DNI) is the paramount factor in solar concentrating energy generation, representing the quantity of solar irradiance that strikes a surface oriented perpendicularly. Consequently, the optimal locations on Earth for Concentrated Solar Power (CSP) generation are those exhibiting elevated Direct Normal Irradiance (DNI) values, specifically those situated between 15° and 40° latitude, both north and south, as well as areas at higher elevations. Consequently, places like as Chile, Peru, northern Mexico, and the southwestern United States; territories in western Australia; southern and northern Africa; certain Mediterranean locales; the Middle East; as well as northwestern India and western China in Asia possess significant potential for Concentrated Solar Power (CSP). [11], Elucidate Kabir et al. (2018) presented a comprehensive overview of solar energy technologies, including their potential, prospects, constraints, and associated regulations on a worldwide scale. Dowling et al. have specifically examined the economic evaluation of concentrated solar power technologies as of 2017, analyzing CSP markets and needs concerning technological status in a report for the National Renewable Energy Laboratory (NREL), USA [12].

The operational principle of concentrated solar power (CSP) is straightforward: direct solar radiation is concentrated to achieve high temperatures (approximately 500 to 1000 °C) of thermal energy, which is subsequently converted into electrical energy. Despite variations in configurations, CSP systems fundamentally consist of the same components.

A solar reflector, or a system of reflectors, that collects and concentrates solar radiation. A solar receiver, in which solar energy is concentrated and absorbed A power conversion system that transforms focused solar heat into mechanical energy. An electric generator converts mechanical energy into electricity.

Heliostat

It is a planar reflective surface, such as mirrors or panels, utilized to direct solar radiation towards a central tower (receiver) that is fitted with a solar tracking mechanism. This investigation utilized two heliostats. The reflective surface employed is a mirror with a reflectivity of 0.88 and a projection area of 0.8 m^2, set on a pole with a height of 1.2 m above the ground. The (1680) kWh/m2 [13] facilitates the utilization of a reduced quantity (n) of heliostats, while also regulating the temperature differential for the receiver. The useful energy absorbed by the working fluid could be enhanced by optimizing the primary factors. A genetic algorithm was employed to determine the optimal coordinates for each component, considering the heliostat position, offset, and tower height of 4.5 m 49. The heliostat field constitutes roughly 50% of the capital expenditure for Concentrated Solar Power (CSP) systems (Kolb et al., 2007) and is accountable for 40% of overall energy losses (Behar et al., 2013; Deng et al., 2020; Romero et al., 2002). The substantial expense related to the heliostat field can be further dissected into its constituent components. [14] An extensive analysis of the expenses related to a standard hybrid CRS and the PS-10 CRS in Spain is provided in (Romero et al., 2002). Romero states that the total expenditure for the PS-10 project is 27.9 million USD, with the heliostat field accounting for 11.7 million USD, without including land costs. [15] In this instance, the expense of heliostats constitutes 41% of the whole cost. Given the substantial expenses associated with heliostats, it is imperative to optimize the design of the heliostat field to maximize power output. The addition of each supplementary heliostat in the field increases the system's cost, which can be mitigated by optimizing various design parameters. (Bhargav et al., 2014) examined the optimization of heliostat lifecycle costs. Various designs of STS have been created and evaluated historically, establishing it as one of the most advanced technologies for solar energy harvesting. The generation of electricity by CRS closely aligns with traditional energy production methods in thermal power plants, facilitating seamless integration into existing energy networks, as demonstrated in various evaluated research studies [16].

Heliostat Field Design

A heliostat is an essential element of a solar tower system. It comprises a high-reflectivity mirror that follows the sun, directing the reflected light onto the receiver positioned at the apex of the tower. The heliostat maintains an angle such that the normal to the mirror's surface consistently bisects the angle formed by the sun and receiver vectors. In the optimization problem, the mirror is defined as a rectangle with specified length (l) and width (w), oriented at a tilt angle (θi) measured from the horizontal and an azimuthal angle (γ) measured from a predetermined geodetic direction. These factors are utilized to compute the mirror area and, subsequently, parameters such as cosine efficiency and land coverage. The heliostat's height from the ground, denoted as (h), is regarded as constant in an optimization issue. Certain research studies have examined various heliostat heights and the impact of inclined and uneven terrains. This section provides a comprehensive assessment of the current advancements in heliostat design and will outline some prevalent heliostat fields [17].
Designs delineated in the literature. The designs can be categorized into patterned and non-patterned fields (Deng et al., 2020). This section will further examine several patterned and non-patterned heliostat designs. [18]

Structured Arrangements

Pattern field layouts adhere to a predetermined geometric configuration and are traditionally employed in commercial heliostat fields. The positioning of heliostats in a geometric configuration is determined by specific deterministic principles. The primary benefit of patterned layouts is their simplicity in design and optimization. Several defining variables can regulate the layout, as will be elaborated upon in the subsequent sections. A drawback of patterned design is that fixed configurations create prohibited areas where a heliostat cannot be positioned, even with sufficient space, due to constraints imposed by geometric principles [19].

a) Rectangular Agricultural Field Configuration

A rectangular cornfield configuration, or the North-South Cornfield plan, depicted in Fig. 2.1, features heliostats arranged in linear rows and columns within a rectangular grid. This layout is regarded as the most straightforward and economical for small heliostat fields, owing to the minimal expenses related to civil works and the simplicity of determining heliostat positions for foundation construction. [20]

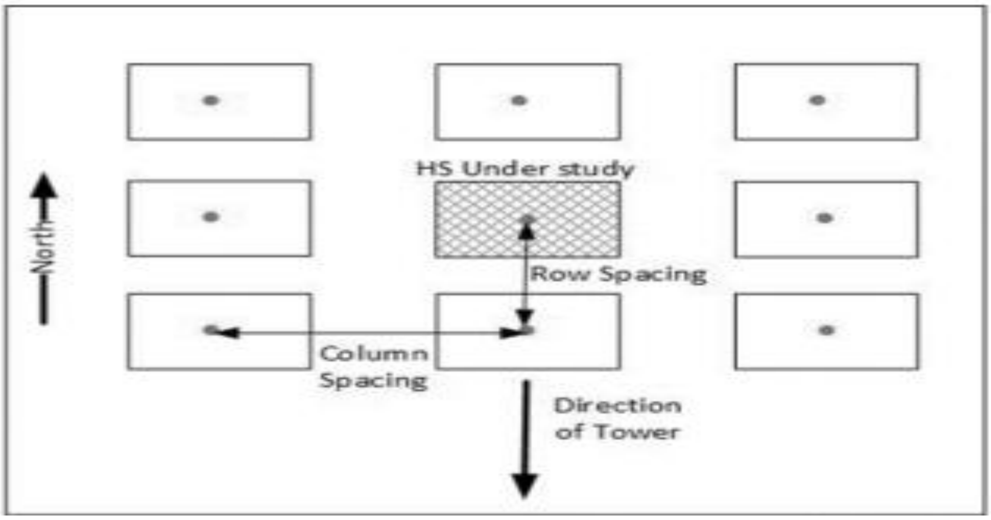

Figure Error! No text of specified style in document.**-1 Construction of a north-south rectangle cornfield plan.**

A model of rectangular cornfield configuration was examined in (Lipps and Vant-Hull, 1978) and compared with different configurations, including staggered cornfield, radial staggered, and radial cornfield designs [21]. The rectangular cornfield configuration is determined to be the least efficient type of heliostat fields in terms of blocking efficiency. This is due to the direct obstruction caused by a blocking heliostat positioned in front of any heliostat in the second row and subsequent rows. Blocking can be circumvented by properly positioning the heliostat in relation to the tower. By detecting the obstructing heliostats and utilizing the tower's height and the distance from the receiver, the minimum placement distance may be determined to ensure that a heliostat remains unblocked by neighboring units. This approach is employed to design radial staggered fields without obstruction [22]. An illustrative instance of a rectangular cornfield configuration is the King Saud University (KSU) prototype CRS project located in Riyadh, Saudi Arabia, as depicted in Fig. 2.2.

Figure Error! No text of specified style in document.**-2 King Saud University, pilot CRS project using a rectangular cornfield configuration (Sustainable Energy Technologies Centre).**

The pilot project is founded on the innovative concept of particle heating receivers [23]. To prevent obstruction in the field, the row spacing expands with the distance from the tower. The heliostats are maintained at an optimal distance to reduce shadowing from adjacent units. The KSU heliostat field is oriented northward, resulting in minimal yearly cosine loss.

b) Rectangular Staggered Cornfield Configuration
A rectangular staggered layout, or North-South Staggered cornfield layout, resembles the rectangular cornfield layout, with the distinction that alternating rows are staggered. Instead of positioning heliostats directly behind one another, the heliostats are shifted to the midpoint between the front two heliostats, thereby preventing direct obstruction. Figure 2.3 illustrates the building of a rectangular staggered cornfield plan.

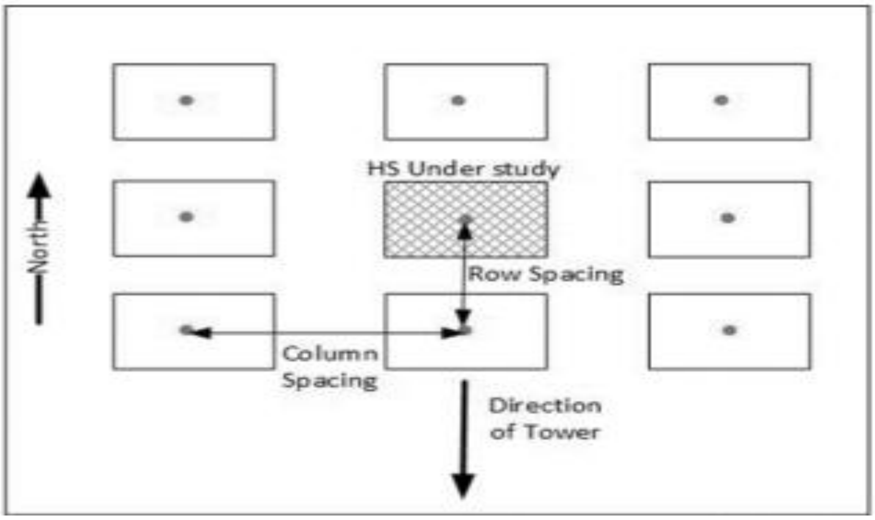

Figure Error! No text of specified style in document.**-3 Design of staggered rectangular cornfield arrangement.**

b) Radial Cornfield Configuration

The rectangular cornfield configuration can be transformed into a radial cornfield by arranging the heliostat at uniform intervals in concentric circles surrounding the tower. The azimuthal spacing between the mirrors, defined as the angle between the two lines linking the centers of the heliostats to the tower, remains constant across the field. The mirrors in two successive rows are consistently positioned opposite one another, with a separation referred to as row-spacing. Figure 2.4 illustrates the radial cornfield configuration. The layout was initially examined in Lipps and Vant-Hull (1978). The separation between two rows remains constant across the field, whereas the distance between nearby heliostats rises with the addition of each row. This results in inadequate ground coverage and an elevated blocking factor, similar to the rectangular cornfield (seen in Fig. 2.5).

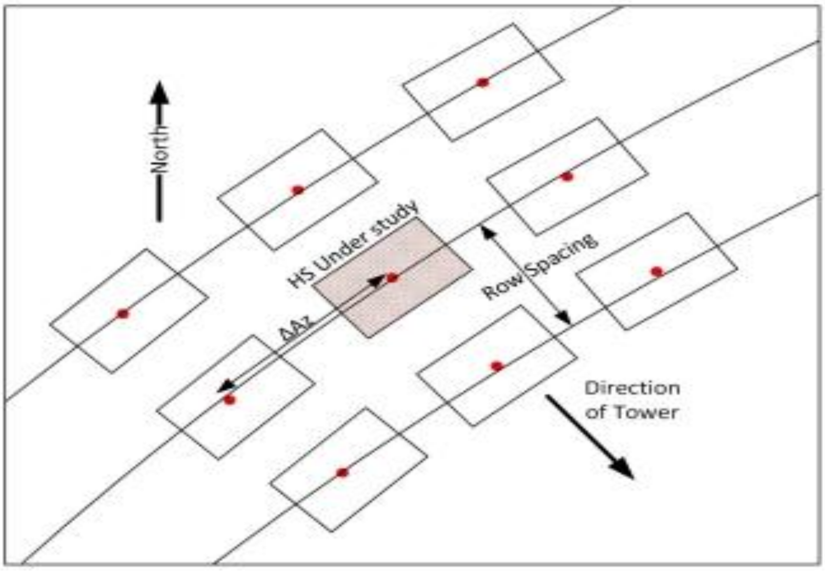

Figure Error! No text of specified style in document.**-4 Development of a radial cornfield configuration.**

d) Radial Staggered Configuration

A radial staggered configuration resembles a radial cornfield arrangement, with the distinction that the rows are staggered, meaning the heliostats are not aligned directly in front of one another in consecutive rows. The azimuthal spacing remains uniform across the field. The cornfield and radial staggered configurations were initially examined by [24]. A comparison was conducted about the optical effectiveness of various layout variants. Radial staggered fields demonstrated superior blocking efficiency relative to cornfields for the aforementioned reasons. Figure 2.6 illustrates the design of a radial staggered arrangement.

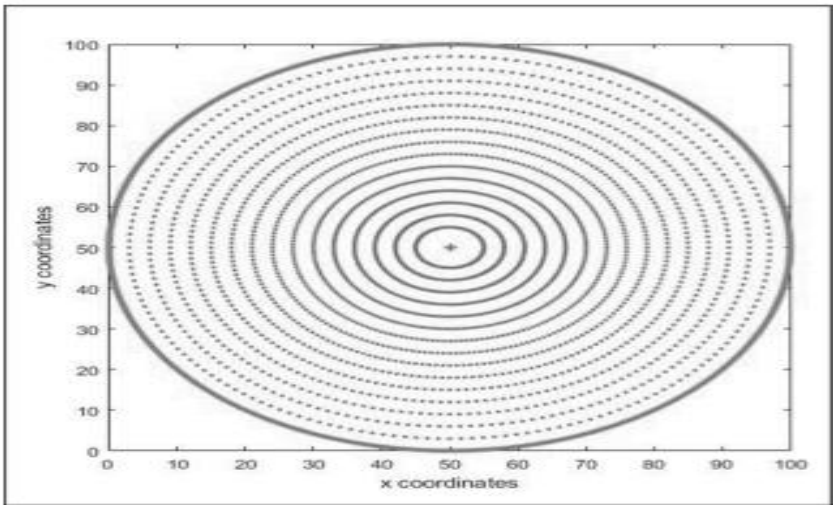

Figure Error! No text of specified style in document.**-5 Aerial perspective of a heliostat arrangement in a cornfield, illustrating the greater distance between outer heliostats relative to those situated within.**

The dense radial staggered architecture is the predominant foundational design employed in several research studies. The construction technique of a densest radial staggered arrangement is detailed [25].

Figure 2.7 illustrates a compact radial staggered configuration with three zones.

Figure 2.8 illustrates the step-by-step construction technique for the dense radial staggered arrangement. The azimuthal distance between the heliostats remains uniform throughout.

Objective functions Optimizing all parameters of CRS is a computationally intensive endeavor; thus, identifying a specific objective function is crucial.

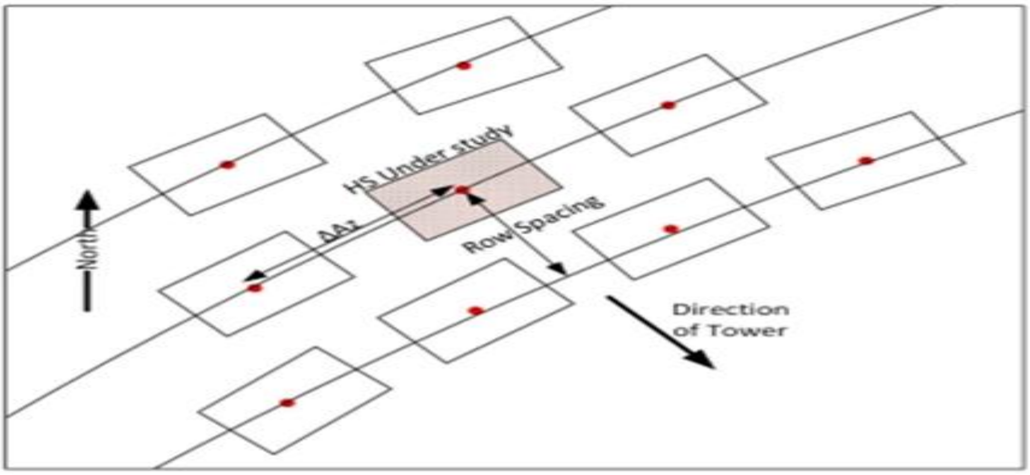

Figure Error! No text of specified style in document.**-6 Construction of a radial staggered arrangement**

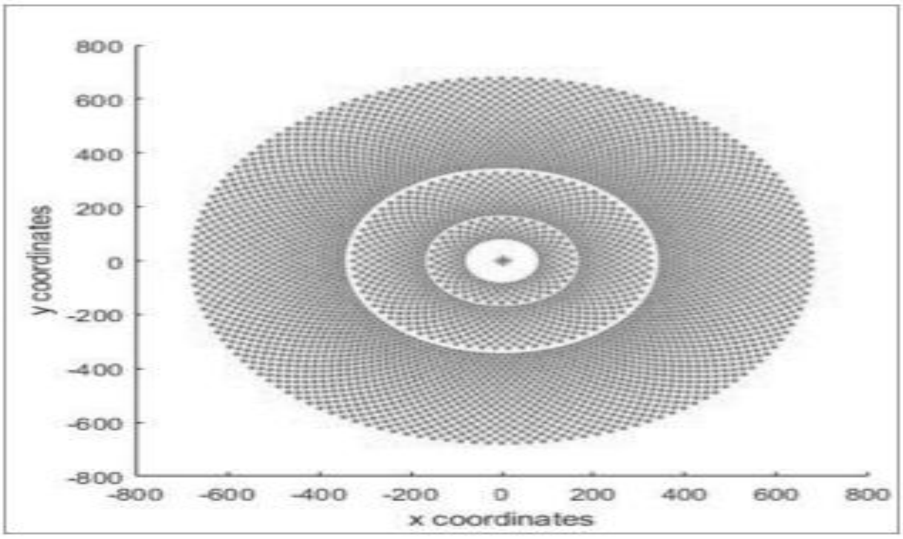

Figure Error! No text of specified style in document.**-7 Dense-radial staggered configuration – reconstructed using the guidelines provided in (Collado and Guallar, 2012).**

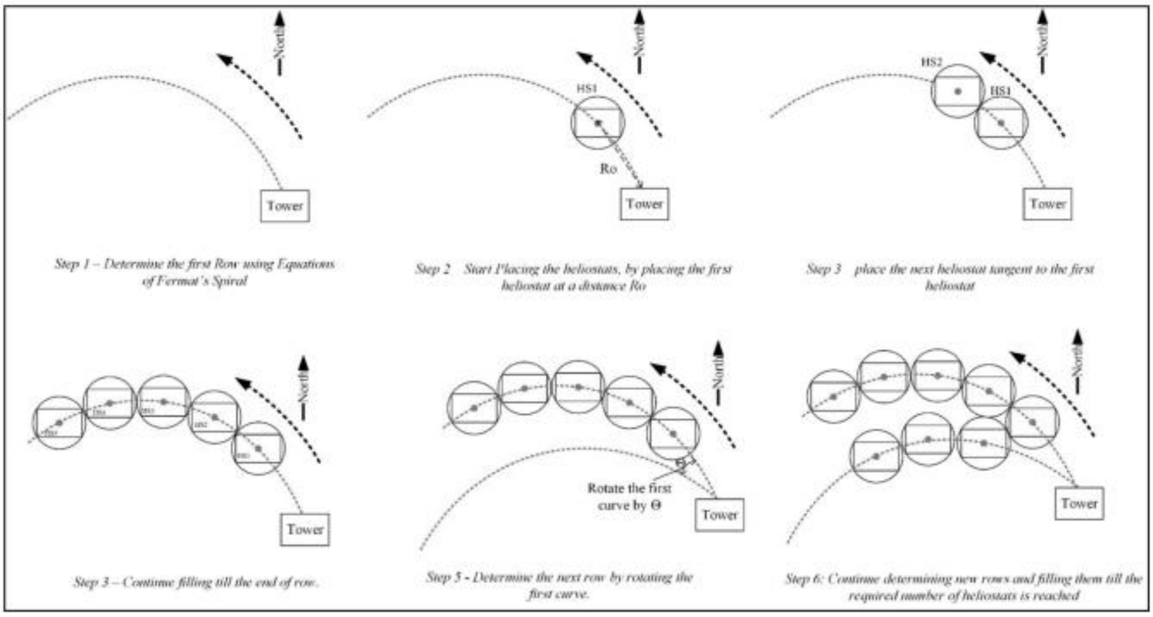

Figure Error! No text of specified style in document.**-8 Construction of a radial staggered arrangement as detailed in Collado and Uallar (2012).**

Numerous objective functions have been delineated in the literature. Several of these will be addressed here. Table 3 enumerates many objective functions employed in research studies along with the methodologies for their optimization [26].

Strategy models.

The design concepts for SPTP depends on the application used by the plant and it was investigated by several researchers; in this section a brief description is shown.

Ramos and F. Ramos (2012), [27] defined a method for estimating the impact of design variance on plant performance to decide which variables are essential to optimum plant design and which ones are less critical by using different local and global algorithms and differences between them also established an exciting technique to obtain information about different variables that affect the performance and to speed up the optimization process reaching an optimal plant design for that eleven design variables was specified and founded that Nevada Solar Power Optimization Code (NSPOC) local algorithm give the same results as other more complex optimizers with significantly less computing effort. The research helped develop the design of the plant and enhanced the regular optimization cycle.

Xiaoping Yang and colleagues (2012) [28] Utilize computational fluid dynamics to simulate molten salt tube receivers in order to analyze a complex heat transfer scenario, focusing on temperature and heat flux distributions, with varying heat flux applied to one half of the tube's circumference while the other half remains insulated. The results indicated that the temperature distribution of the molten salt on the tube wall varies in both radial and axial directions; the temperature of the inner tube wall is a critical factor in preventing the decomposition of the molten salt. The local Nusselt number remains relatively constant with variations in the cosine angle around the tube circumference, whereas the heat flux density fluctuates with the velocity of the working fluid, resulting in a significant temperature gradient of 34 K across the heating surface.

Ramadan Abdiwe and Markus Haider (2015) [29] utilized ANSYS FLUENT for modeling and calculating convective heat losses at wind speeds between 2 and 10 m/sec in both the cavity and exterior solar tower receiver (STR). A fixed tilt angle of 90° is employed for the cavity receiver. The results indicate that convective heat loss from the cavity receiver is marginally lower, around half of that associated with exterior receivers.
G. Colomer et al. (2015) [30] introduced a novel method for the thorough simulation of fluid dynamics and thermal transfer in the solar tower receiver. Four secondary models were evaluated: heat conduction, solar and thermal radiation, two-phase flow, and free convection. A comprehensive dataset obtained from computational fluid dynamics simulations of free convection around the tubes, where the two-phase fluid simulation within the tubes employs the measured convective heat transfer coefficient, the convective heat transfer equation, and the quantification of losses attributed to radiation using the average temperature within the tubes. Contemporary technology was employed to model the intricate and unstable phenomena of heat transport and fluid dynamics.
Nidal H. Abu-Hamdeh and Khaled A. Alnefaie (2016) [31]; a prototype for the solar power tower system (SPTS) was developed and constructed.

Ten heliostats were installed to direct sun energy to the central receiver situated atop a 7-meter high tower. The heliostat's rotating and elevation movements were controlled by two motors. In the heat exchanger, 11.26 kW of thermal energy is transmitted to the water as it is heated by the molten salt. The thermal power supplied by the molten salt in the heat exchanger was calculated to be 12.31 kW. The system's thermal power was 13 kW. The percentage inaccuracy in the measured thermal power is around 5.3%.
M. Hazmoune et al. (2016) [32]; A comprehensive model for the three-dimensional (3D) numerical simulation of solar serial receivers for power towers is introduced. The suggested model seeks to account for all significant variables affecting the performance of a serial receiver, including the transfer medium, the heat flux applied to the wall, and the velocity of the heat transfer fluid. This study use ANSYS CFX software and utilizes an unstructured grid comprising 825,300 cells. It assists in selecting the optimal fluid, the inlet fluid velocity corresponding to the turbine employed for the solar tower, and the heat flow imposed on the receiver, necessitating the selection of the most suitable site.

Saad S. Alrwashdeh (2018) [33] conducted an analysis of the energy output from a solar tower in the Ma'an region of southern Jordan utilizing 3D energy modeling software. The dependence of power output on tower height is examined, demonstrating that adjusting tower height can enhance power production. The correlation between the height of the solar tower and its energy generation capacity has been examined. Two solar towers, measuring 16 and 32 meters in height, were utilized. The premise was that the energy output is directly proportionate to the tower's height. The closest mirrors to the tower are the most efficient at generating power, as they effectively concentrate solar radiation compared to the more distant reflectors. The maximum yearly power output from the initial solar tower field, which has a height of 16 meters, is 1.3 MWh, whilst the total annual power production from the second field, featuring a tower height of 32 meters, is 2 MWh.

Heat Transfer Enhancement.
Peipei Xu et al. (2014) [34]; Employed numerical and experimental methodologies to examine diverse entrance velocities and their impact on flow output and thermal efficiency of the tube receiver. A five kW Xe-arc lamp was utilized to replicate sun radiation. The results indicate that the temperature distribution of the water and tube wall is highly uneven in both axial and radial directions. The alteration in entrance velocity results in a marginal enhancement of the thermal capacity of the tube receiver. The thermal efficiency of the tube receiver diminishes as the volume flow rate drops. Convection losses are almost double the radiation losses. The temperature of the central working fluid is lower than that of the tube walls.
Daniel Potter (2015) [35] evaluated the heat transfer and optical performance of a central tower plant, improving the heliostat field arrangement and receiver geometry for a 1MW cavity receiver. A polar heliostat array consisting of 413 heliostats, paired with an aperture positioned 60 degrees below the horizon and having a radius of 55 cm, demonstrated an average annual thermal efficiency of 50.35 percent for the facility. The thermal efficiency at the design point of the improved receiver configuration was determined to be 91.6%, with a maximum cavity radius of 82.5 cm.

Mathieu Lemyre Garneau (2015) [36]; The integral approach is employed to quantify the optical output of the heliostat field throughout the day, disregarding the shadowing effects among heliostats. The acquired results provide the necessary data to compute the temperatures and thermal storage capacities. Complications arise about the types of variables (integer, real, categorical) and the quantity of variables utilized (5 - 29), the number of constraints (5 - 17), and their configurations (continuous or binary). An integral Monte Carlo approach has been employed to ascertain the optical efficiency of the heliostat field throughout the day; the outcomes of these calculations provide data to estimate thermal storage rates and temperatures.

Present Study scope

From above mentioned studies it is obvious that there are many studies that deals with solar central tower across the global. In our study there are some parts that will be covered that are not mentioned previously like the new staggered configuration for the solar receiver heat exchanger and the new designed dual axes tracking system all mentioned points were conducted in experimental and numerical methods. Also, the primary objective of this study is to conduct a detailed thermal-hydraulic performance analysis for two specific solar receiver configurations: a two-raw staggered pipe arrangement and a one-raw series pipe arrangement. This analysis aims to systematically calculate critical dimensionless parameters, including the Reynolds number (Re), Nusselt number (Nu), and friction factor (f). Furthermore, derived engineering properties such as the convective heat transfer coefficient (h) and the Thermal Hydraulic Performance Parameter (THPP) will be determined. All calculations are predicated on experimental data provided and specific design parameters unique to each receiver configuration.

II. Conclusions

This study highlights the critical role of Concentrated Solar Power (CSP) in addressing the environmental and economic challenges associated with fossil fuel dependency. The experimental and numerical investigations conducted on solar tower receivers demonstrate that system configuration, heliostat field design, and tracking mechanisms are decisive factors in determining thermal-hydraulic performance. The staggered pipe receiver arrangement and dual-axis solar tracking system yielded superior results in terms of heat transfer enhancement, reduced energy losses, and improved thermal-hydraulic performance compared to conventional configurations. Moreover, CSP's inherent capacity for thermal energy storage and hybrid operation positions it as a highly dispatchable renewable technology capable of complementing intermittent resources such as photovoltaics and wind power.

Overall, the outcomes confirm that CSP technologies can be effectively adapted to regions with high Direct Normal Irradiance (DNI), including Iraq and other Middle Eastern countries, where solar energy remains underutilized. By optimizing receiver design, field layout, and system integration strategies, CSP can significantly contribute to achieving energy security, environmental protection, and sustainable economic growth. Future research should focus on cost reduction strategies, advanced materials for receivers, and hybrid renewable integration to maximize CSP deployment at a global scale.

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