A novel design of the solar central receiver to improve the performance of the central solar power tower plant

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Abstract. A novel design for a central receiver prototype was manufactured with dimensions of (50*50) cm staggered configuration using copper pipes of 9.5 mm diameter was tested to produce thermal energy from solar energy, had been analyzed numerically and experimentally. Central solar tower receiver prototype was manufactured and mounted at Al-Nahrain University in Baghdad - Iraq, where high solar radiation is available. Heliostats with automated dual axes tracking systems were attained to capture the solar rays. Heliostats used to redirect the sun rays to a central receiver which is constructed using coated copper tubes to convert solar to heat and transfer it to the receiver working thermo-fluid.

According to a precise design consideration presented procedure in this study, a numerical and experimental investigation was performed. Also, an automated tracking system was installed on the heliostat to govern the title and azimuth movements.

The working fluid used is water. The supply tank was manufactured from plastic equipped with a digital flow meter to control flow rate to the receiver. In this study, a detailed layout, investigation for each part is shown. It's found that optimum tower height is 4.5m, optimum heliostat horizontal distance from the tower is 7m and the offset angle is 30°. Receiver thermal performance enhanced by 6.17% from the one-row receiver and about 12.98% for the evacuated tube receiver.

Keywords: Solar energy, Central tower, Tracking system and Solar power plant.

1. INTRODUCTION

Central Receiver systems (CRS) are gaining momentum due to their excessive concentration and high capacity to reduce costs with the aid of increasing the potential factor of the plant with storage. In CRS plants, daylight is focused on the receiver by the association of thousands of mirrors to convert solar radiation into heat to drive thermal cycles. Solar receivers are used to transfer the flux acquired from the solar field to the working fluid. The feasible use of concentrating solar power plant (CSP) generation has been evaluated by many engineers [1–7].

The central receiver system used to generate a hundred megawatts, or perhaps a thousand gigawatts could be universally reached in 2050 where CSP will contribute (13-15) percent of global power demand. The central solar tower receiver plant is measured as one of the cheapest methods to provide solar power on a massive measure [8]. Central Solar Receiver System (CRS) main components are storage tanks, heliostats equipped with a control unit; working fluid; and central receiver [9]. Modeled and simulated for most important components of a solar tower receiver plant are the tower, steam generator, and heliostats. Excluding the power storing; part. A well-known schematic for such a plant is shown in Fig. 1 [10].
Heliostats were used with a flat mirror to convey solar rays to a central solar receiver equipped with a tracking system that controls the heliostat movement in two directions, tilt and azimuth; to ensure heliostat follows the sun and redirect its rays to the receiver to obtain the maximum energy that could be converted to heating the working fluid [11].

Heliostats are used to accumulate solar energy to produce high energy, which can be converted to thermal energy that is involved in various applications.

The main goal of this study is to describe a detailed technique used to convert solar energy to thermal useful energy.

**Thermophysical properties**

Water is the working fluid (HTF) used in this study with variable properties [12] as shown below:

\[
\rho(T) = 765.33 + 1.8142(T) - 0.0035(T)^2
\]

\[
C_p(T) = 1.095 \times 10^4 - 59.27(T) + 0.171(T)^2 - 0.0001623(T)^3
\]

\[
k(T) = -0.5752 + 6.3967 \times 10^{-3}(T) - 8.151 \times 10^{-6}(T)^2
\]

\[
\mu(T) = 9.67 \times 10^{-2} - 8.207 \times 10^{-4}(T) + 2.344 \times 10^{-6}(T)^2 - 2.244 \times 10^{-9}(T)^3
\]

2. **DESIGN METHODOLOGY**

**Selection of Potential Site**

An experimental study was conducted at Baghdad – Al-Nahrain University with longitude (44.3661° E) and latitude (33.3152° N). The average annual solar radiation in Baghdad range is approximately (1800-1826) KWh/m2, as shown in Fig. (2).

**Fig. 2 shows the average annual solar radiation in Baghdad [13].**

The design and manufacturing of the first central solar tower system prototype in Baghdad to get useful conversion of solar energy as shown in Fig. 3, which contains a heliostat, tracking system, tower, and receiver. Therefore, due to the relatively high solar radiation that encourages the use of this energy to produce electrical power at a suitable cost compared with conventional methods, noting that photovoltaic cells (PVC) are used in a wide range but with low efficiency and lifetime compared with (CRS) systems, which are more durable having a long life span and higher efficiency in converting energy with low cost for maintenance.
Heliostat
It’s a flat reflecting object like mirrors or plates used to reflect the solar rays to a central tower (Receiver) combined with a sun tracking system. In this study, two heliostats were used. The reflecting surface used in this study is a mirror with high reflectivity approaches (R=0.88) and a projection area $A_p (80 \times 80)$ cm$^2$ mounted on a pole of (1.2) m height from the ground. Due to the high solar radiation value of (1826) KWh/m$^2$ gives the benefit of using fewer numbers (n) of heliostat also to get control the temperature difference for the receiver.

Receiver
A novel geometry for the receiver was designed and manufactured. The new staggered pipe configuration, as shown in Fig 4, ensures minimizing losses due to gaps between pipes and also ensure the absorb more energy from incident solar rays reflected from the heliostats.
A copper tube was used because of its high conductivity, and its surface was coated to increase the absorptivity and decrease the reflectivity and emissivity ($\varepsilon$).

The receiver is placed in a vertical position, and the inlet point is located below, the output point at the same level on the other side. Type-K thermocouples were used to measure the surface temperatures of the receiver pipes, working fluid inlet, and outlet terminals; the total 48 points of the thermocouples their positions were located according to the numerical results, as shown in Fig. 5.
A calibrated thermometer data logger was used to read and record temperatures at all terminal points at the same time.

3 OPTIMIZATIONS

The absorbed useful energy by the working fluid could be improved by optimizing the main factors (heliostat position, offset, and tower height); therefore, a genetic technique algorithm was used to find the finest coordinates.

**Heliostat position:**
An experimental and numerical investigation was performed on 16th Nov. at noon to find the optimum heliostat position in the horizontal direction from the central tower by choosing many radiiuses and measuring the solar radiation that reached the receiver. From the results shown in Fig 6, the optimum horizontal distance was found to be (7) m.

**Heliostat offset**

The heliostat position relative to each other (offset angle) is found numerically and experimentally on 16th Nov. at 13:00, the optimum angle $\theta_{opt}$ was found to be (30°) which ensures the highest solar radiation, as shown in Fig 7.
Fig 7 Optimum heliostat position relative to each other (offset angle).

**Tower height**
A simulation was conducted on 16th Nov. from 7:00 to 17:00 to find the optimal altitude for the receiver. According to the gathered information's the result (4.5) m is the optimum tower height ($H_{opt}$) from ground level, as indicated in Fig 8.

4. TRACKING SYSTEM DESIGN
Two perpendicular planes, ZX and ZY represent heliostat movement in the azimuth and tilt directions respectively. For azimuth, the heliostat faces the south and the sun movies on its orbit path, where it comes up from the heliostat left side and sets to the right position. Heliostat movement in the tilt direction is limited to upward and downward to track the sunlight. Heliostat number one angle was computed for four months at three time sets: 9:30, 12:30, and 16:30 at these selected hours, it was expected to get the highest sun intensity would lead to high efficiency. Astronomical tables for Baghdad city and mirror reflection equation was followed out to estimate the degrees per hour each actuator motor should move.
Tables (1A-1D) illustrate full-angle calculations to adjust the actuator to move the bisector of the first heliostat in perpendicular plans; Azimuth (bounded between west and east axes) and tilt (bounded between south and north axes) for the duration of the four seasons, respectively. The heliostat movement in the azimuth path between east and west, while at the tilt, it is limited by two paths: the first path rises from 9:30 to 12:30, and the second path falls from 12:30 to 16:30. The plane formed by dividing the two planes gives the angle between the object and the path of sunlight as reflected from the heliostat mirror is held at right angles to the mirror.

To get the bisector position for the first heliostat in the summer season at 9:30 in azimuth, the angle ($\theta$) between the recipient and heliostat was measured to be 28.12º from the south using the identified distances between the heliostat and the recipient. Using angle $\theta$ and sunray declination at 9:30 during summer (8.96º) of Table 1A, the full angle between the sunray and receiver is at 9:30. It was estimated to be 109.16º. Thus, the heliostat number one bisector angle at 9:30. It is located at 54.58º from Sunray or 63.58º from the east. Similarly, the heliostat number one bisector angle is at 16:30. It was found to be 33.64º from the liquidator at 16:30. or 185.4º to the east. Fig. 9a shows the heliostat number one location at 9:30, 12:30 and 16:30 in the azimuth direction. For getting the bisector angle between the object and sun ray direction as perceived from a mirror of heliostat number one for the summer season at 9:30. In the tilt direction, the angle ($\phi$) between the heliostat and the recipient was obtained to be 33.42º from the south using the identified distances between them. Using this $\theta$ and sunray declination at 9:30. During the summer (52.49º) of Table 1A, the full angle between the sunray and receiver is 9:30. was estimated to be 19.07º. Thus, the heliostat number one bisector angle at 9:30. It is at 9.5º from the liquidator at 9:30 or 42.95º against the south.

In addition, the heliostat number one bisector angle at 12:30. It was noted to be at 21.72º from the liquidator at 12:30 or 76.86º against the south. In a similar way, heliostat number one bisector angle at 16:30. It was estimated to be at (-1.84º) from the liquidator at 16:30. It is 32.5º from the south. Fig. 9b shows the heliostat number one location at 9:30, 12:30, and 16:30 in the tilt direction. The actuator motor provides rotating motion for the axis, and by dividing the total angle, the bisector spins in the azimuth direction by the total running hours of 9:30 to 16:30 will give 13.9º/hr. The actuator motor used to obtain elevation movement was also estimated in the same way in the tilt direction gives 1.96º/hr. The same process was adapted for the heliostat number one during seasons winter, spring, and autumn (Tables 1B, 1C, and 1D) respectively as shown in figures 10, 11, and 12. Again, the entire operation was duplicated for all heliostats.

| Selected Time | Sun ray angle against (horizontal) axis (º) | Receiver position against (south) in azimuth direction (º) | Bisector angle against (reverse horizontal) axis (º) | Bisector motion in azimuth direction (º/h) | Sun ray angle from (South) axis (º) | Receiver position against (south) in tilt direction (º) | Bisector angle against (south) axis (º) | Bisector motion in tilt direction (º/h) |
|---------------|---------------------------------------------|-------------------------------------------------------------|---------------------------------------------------|--------------------------------------------|-----------------------------------|-------------------------------------------------------------|-----------------------------------|--------------------------------------------|
| 9:30          | 8.96                                        | 28.12                                                       | 63.54                                             | 12.6                                       | 52.49                             | 33.42                                                        | 42.95                             | 3.23                                       |
| 12:30         | 111.03                                      | 114.57                                                      | 76.86                                             | 55.14                                      | 114.57                            | 76.86                                                        | 55.14                             | 1.96                                       |
| 16:30         | 185.4                                       | 151.76                                                      | 31.58                                             | 32.5                                       | 151.76                            | 31.58                                                        | 32.5                              | 1.96                                       |
Fig. 9 indicates the heliostat number one location at 9:30, 12:30, and 16:30 in the azimuth and tilt directions for July (summer season).
Table 1b: Heliostat number one entire angle movement by the bisector in azimuth and tilt directions for January (winter).

| Selected Time (t) | Sun ray angle against (horizontal) axis (°) | Receiver position against (south) in azimuth direction (°) | Bisector angle against (reverse horizontal) axis (°) | Bisector motion in azimuth direction (°/h) | Sun ray angle from (South) axis (°) | Receiver position against (south) in tilt direction (°) | Bisector angle against (south) axis (°) | Bisector motion in tilt direction (°/h) |
|------------------|--------------------------------------------|----------------------------------------------------------|---------------------------------------------|------------------------------------------|-------------------------------------|----------------------------------------|------------------------------------------|----------------------------------------|
| 9:30             | 47.54                                      | 28.12                                                   | 35.29                                       | 13.9                                     | 23.7                                | 33.42                                  | 28.56                                     | 1.96                                   |
| 12:30            | 94.39                                      | 106.25                                                  | 36.54                                       | 34.98                                    | 36.54                               | 34.98                                  |                                            |                                        |
| 16:30            | 148.4                                      | 133.26                                                  | 9.11                                        | 21.26                                    | 9.11                                | 21.26                                  |                                            |                                        |

Fig. 10 indicates the heliostat number one location at 9:30, 12:30, and 16:30 in azimuth and tilt directions for January (winter season).
Table 1c: Heliostat number one entire angle movement by the bisector in azimuth and tilt directions for April (spring).

| Selected Time (t) | Sun ray angle against (horizontal) axis (°) | Receiver position against (south) in azimuth direction (°) | Bisector angle against (reverse horizontal) axis (°) | Bisector motion in azimuth (°/h) | Sun ray angle from (South) axis (°) | Receiver position against (south) in tilt (°) | Bisector angle against (south) axis (°) | Bisector motion in tilt (°/h) |
|------------------|------------------------------------------|--------------------------------------------------------|----------------------------------|-------------------------------|---------------------------------|-----------------------------------|----------------------------------|-------------------------------|
| 9:30             | 22.87                                    | 28.12                                                  | 70.49                            | 11                            | 48.76                           | 33.42                             | 41.09                            | 2.98                           |
| 12:30            | 107.41                                   | 112.76                                                 | 67.36                            | 50.39                         | 67.36                           | 33.42                             | 50.39                            | 2.98                           |
| 16:30            | 176.97                                   | 147.54                                                 | 25.52                            | 29.48                         | 25.52                           | 29.48                             | 29.48                            | 2.98                           |

![Diagram A](image1.png)

![Diagram B](image2.png)
Fig. 11 indicates the heliostat number one location at 9:30, 12:30, and 16:30 azimuth and tilt directions for April (spring season).

Table 1d: Heliostat number one entire angle movement by the bisector in azimuth and tilt directions for October (autumn).

| Selected Time (t) | Sun ray angle against (horizontal) axis (°) | Receiver position against (south) axis in azimuth direction (°) | Bisector angle against (reverse horizontal) axis (°) | Bisector motion in azimuth direction (°/h) | Sun ray angle from (South) axis (°) | Receiver position against (south) axis in tilt direction (°) | Bisector angle against (south) axis (°) | Bisector motion in tilt direction (°/h) |
|------------------|--------------------------------------------|---------------------------------------------------------------|--------------------------------------------|---------------------------------|------------------------|---------------------------------------------------------------|---------------------------------|----------------------------------|
| 9:30             | 47.42                                      | 82.77                                                         | 34.7                                       | 34.06                           | 34.7                   | 8                                                             | 33.42                           | 38.96                            | 2.48                            |
| 12:30            | 104.4                                      | 111.26                                                        | 44.5                                       | 33.42                           | 44.5                   | 8                                                             | 38.96                           | 2.48                            |                                  |
| 16:30            | 159.53                                     | 138.79                                                        | 9.66                                       | 21.54                           | 9.66                   | 8                                                             | 21.54                           |                                  |                                  |
Fig. 12 indicates the heliostat number one location at 9:30, 12:30, and 16:30 in azimuth and tilt directions for October (autumn season).

5. RECEIVER HEAT TRANSFER

The distribution of the hourly solar radiation for each season (according to the months selected above) was calculated by using the ANSYS FLUENT 2019R1 on the 20th from each month with fair of weather percent of 1, from 7:00 to 18:00 along the day this is shown in Fig. 13.

Fig 13. Shows the numerical hourly direct solar radiation along the day.
Numerical simulation was performed using the commercial package Ansys Fluent 2019R1 for the novel designed receiver with the following governing equations:

for (Cylindrical coordinates):

**Continuity Equation:**
\[
\frac{\partial \rho}{\partial t} + \frac{1}{r} \frac{\partial (r \rho v_r)}{\partial r} + \frac{\partial (\rho v_z)}{\partial z} = 0
\]  

(5)

**Momentum Equation:**

- **R - component:**
  \[
  \rho \frac{\partial v_r}{\partial t} + \rho v_r \frac{\partial v_r}{\partial r} + \rho v_\theta \frac{\partial v_r}{\partial \theta} + \rho v_z \frac{\partial v_r}{\partial z} = -\frac{\rho}{r} \frac{\partial P}{\partial r} + \mu \left( \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial v_r}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2 v_r}{\partial \theta^2} - \frac{2}{r^2} \frac{\partial v_\theta}{\partial \theta} + \frac{\partial^2 v_r}{\partial z^2} \right)
  \]  

(6)

- **θ - component:**
  \[
  \rho \frac{\partial v_\theta}{\partial t} + \rho v_r \frac{\partial v_\theta}{\partial r} + \rho v_\theta \frac{\partial v_\theta}{\partial \theta} + \rho v_z \frac{\partial v_\theta}{\partial z} = -\frac{\rho v_r}{r} \frac{\partial P}{\partial \theta} + \mu \left( \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial v_\theta}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2 v_\theta}{\partial \theta^2} + \frac{2}{r^2} \frac{\partial v_r}{\partial \theta} + \frac{\partial^2 v_\theta}{\partial z^2} \right)
  \]  

(7)

- **Z - component:**
  \[
  \rho \frac{\partial v_z}{\partial t} + \rho v_r \frac{\partial v_z}{\partial r} + \rho v_\theta \frac{\partial v_z}{\partial \theta} + \rho v_z \frac{\partial v_z}{\partial z} = -\frac{\partial P}{\partial z} + \mu \left( \frac{\partial}{\partial r} \left( r \frac{\partial v_z}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2 v_z}{\partial \theta^2} + \frac{\partial^2 v_z}{\partial z^2} \right)
  \]  

(8)

**Energy Equation:**
\[
\rho C_p \left( \frac{\partial T}{\partial t} + v_r \frac{\partial T}{\partial r} + \frac{v_\theta}{r} \frac{\partial T}{\partial \theta} + v_z \frac{\partial T}{\partial z} \right) = k \left( \frac{\partial}{\partial r} \left( r \frac{\partial T}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2 T}{\partial \theta^2} + \frac{\partial^2 T}{\partial z^2} \right)
\]  

(9)

by using water as a working fluid, turbulent flow, k-e model, in the range of Reynolds number of Re. (3600 - 27500), and convergence of 10-15. The number of meshes that used in the present simulation is (6174048), as the best number of elements was after that if decreasing the element size will not affect the results, and the parameter of the behavior of meshing is 0.2 less than the standard value 0.25 [13], which means that the mesh is an excellent behavior. Boundary conditions were selected: heliostat number n=2 with heat flux Q’=600 w/m² for each one, and the mass flow rate to the receiver was \( m' = 0.004 \) kg/sec. water inlet temperature of 300 K, knowing that the receiver absorptivity is \( \alpha = 0.91 \).

6. RESULTS

Receiver heat transfer.
The temperature distribution on the receiver at different cases related to time and months are shown in Figs. (14 – 16) below:
Fig 14 Temperature contour at 9:30 AM for 20th of different months.

Fig 15 Temperature contour at 12:30 PM for 20th of different months.
Fig 16 Temperature contour at 4:30 PM for 20th of different months.

**Receiver thermal efficiency**

The collector efficiency ($\eta_{th}$) is dividing the working fluid useful heat gained ($Q_u$) by the absorbed solar power ($Q_{abs}$) [15].

$$\eta_{th} = \frac{m \cdot c_w \cdot (T_fo - T_{fi})}{I_d \cdot A_{ap}} \quad (10)$$

**Concentration ratio (C) = $A_{ap}/A_{abs}$**

$$C = A_{ap}/A_{abs} \quad (11)$$

where $A_{ap}$ represents the reflector aperture area and $A_{abs}$ is the absorber area.

For flat plate collectors, $C = 1$.

Fig.17 shows the experimental and numerical thermal efficiency of the receiver for the four chosen months that represent the four seasons at different day times.
The receiver efficiency for the present study two-row (staggered) was compared with other receiver configurations, one row, and evacuated tube, as shown in Fig. 18.
7. DISCUSSION

Solar energy is applied to the novel central receiver.

Fig (13) explains the solar radiation distribution each hour on the 20th of each month, which is used in the present study. It can be noted that at 9:30, solar radiation in April is larger than that for other months, while temperature contours in Fig. (14) at 9:30, the outlet temperature of the water is 370 K in October, while in July is 358 K and for April is 347.3 K and for Jan. is 344 K.

From Fig. (15) at 12:30, the outlet temperature for July is 420 K, which is larger than that for other months.

At 16:30 (Fig. 16), shows that the outlet temperature from the receiver is 375 K in July is the largest value compared with other months.

The tandem is high because solar radiation is continued through that day because of the long daytime in July is considered larger than that for other months; therefore, the receiver will absorb more solar energy and fewer losses due to the long sun period during the day.

From Fig (17) explain the receiver thermal efficiency for 4 months, it's noticed the receiver “thermal efficiency” for July (summer) greater than that for the other seasons in both the experimental and numerical results, the numerical results are validated experimentally.

In summer, the efficiency is approximately 85.48% at 12:30, which is higher than that for other seasons at the same time. Also, it can be noted that the efficiency for spring is 78.75%, winter is 69.55%, autumn is 58.78% is higher than that at other times because the sun array is approximately perpendicular to the face of reflector and therefore high energy gain due to solar incidence on the receiver surface, which will allow the working fluid to absorb high energy and then produce high temperatures at the outlet, which will lead to higher efficiency.

From Fig. 18, the thermal performance of the two-row staggered pipe receiver was enhanced by 6.17% from the one-row receiver and about 12.98% for the evacuated tube receiver.

8. CONCLUSION

In the present study, numerical and experimental analyses for a central solar tower receiver thermal performance were achieved and carried out. The results of the present study may be briefed as follows:

1. Optimization of tower height, heliostat radius, and offset angle were performed, and the results show that 4.5 m, 7 m, and 30° respectively are the optimum values.
2. The water outlet temperature is highest at 12:30 in July, which means the highest useful energy absorbed by the receiver.
3. The thermal efficiency of the receiver was the highest at 12:30 in July.
4. Thermal receiver performance is the highest for the two rows of staggered pipe arrangement, which was enhanced by 6.17% from the one-row receiver and approximately 12.98% for the evacuated tube receiver.

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