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Performance Investigation of a Concentrated Solar Dish for Heating Applications

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Abstract

Concentrated collectors offer a broad variety of solar energy uses, including heating, cooling, power production, and water desalination. This study was conducted to construct and test a concentrated parabolic solar dish water heater. The aperture size of the dish is 4.556m^2, and a copper absorber has a surface area of 0.2278m^2, a volume of 0.015m^3, and a concentrating ratio of 20. The water is heated up to 120°C at a solar radiation intensity of 700W/m^2 and a 20°C ambient temperature. The absorber's stagnation temperature reached 246°C in roughly 1500 seconds. The thermal efficiency of the system was found to be 46%.

Paper type: Research paper

Keywords: dish solar collector, water heating, solar heater, stagnation temperature, concentration.

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Introduction

Jordan has a severe water shortage and ranks among the world's countries. As Jordan's population rises, so too will the country's water shortage. According to projections, Jordan's yearly renewable water resources will fall below 100 m^3 per person by 2025, well below the 500 m^3 per person criterion for extreme water shortage (Hadadin, *et al*., 2010). Solar water heating captures the sun's energy to raise the water's temperature from its low initial temperature to the required hot temperature. (Esdras, *et al*., 2019) discuss various perspectives about solar thermal water heaters, including their thermal efficiency and cost, especially among users who desire to retrofit from conventional water heating systems to solar ones. The collector was emphasized in the manufacture of solar water heaters. Using slotted, black-painted aluminium as an absorber plate instead of galvanized iron increased the system's efficiency.

In the coming decades, desalination will become an important way to get water to meet the needs of a world population that is growing quickly. Desalination uses a lot of energy and fossil fuels, both of which contribute to climate change and water scarcity problems. The use of solar power to power desalination facilities helps to lessen the process's environmental impact. Several practical concerns must be addressed in solar-powered desalination facilities (William, *et al*., 2020).

Atul, *et al*., (2017) examined the thermal performance of concentrated solar dish-type collectors employing various cavity receiver designs for various applications, including water heating, industrial process heat, thermal power production, and more. The thermal efficiency of a concentrated solar dish water heater for a small industrial heat process is evaluated in the current work employing a helical-coiled truncated cone receiver that has a black chrome selective coating. With a 0.0056kg/s water flow rate, the proposed system produces an average instantaneous efficiency of 63%.

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Rahul and Adroja (2018) used different receiving tubes to test a solar parabolic trough collector. In the first case, the spherical ball was filled into the receiving tube without any attachment. The receiver in the second case was filled with uniform aluminium chips. The iron 2mm roll of netting was filled in the receiver in the third case. At low fluid velocity, the 2 mm iron mesh had the highest performance evaluation criteria value.

Experimental research on water heating technology using parabolic trough solar collectors was conducted by Tabassum *et al*., (2019). The performance of the concentrating collector was investigated by altering the reflector materials (aluminium foil, aluminium sheet, and mirror film). In comparison to other reflectors, it was discovered that the mirror film had maximum durability and could provide a greater outlet water temperature.

Majeed, *et al*., (2021) created a novel parabolic trough solar heater with a dual-axis sun-tracking system based on the algorithm's time-based tracking mechanism. An Arduino Uno R3 microcontroller was used in the solar tracking system microcontroller. When compared to PV panel tracking technology, the proposed tracking design increased energy efficiency by 3.43%.

According to the available literature, parabolic trough solar collectors have received the lion's share of attention for heating purposes, whereas parabolic dishes have been used mostly for direct electricity production. Studying how well a solar dish can perform in heating applications is the primary goal of this study. To put it simply, a concentrated dish was utilized to passively heat water with the help of solar energy. This design is best used with a dual-axis solar tracking system. This article presents a thermal simulation study of a concentrated solar dish for heating purposes, conducted with the help of the Engineering Equation Solver (EES). Stagnation temperature and duration to reach stagnation are calculated for the absorber. With different absorber temperatures, thermal efficiency was also determined.

1 Materials and Methods

1.1 System Modeling

Utilizing meteorological data from Aqaba, Jordan, the study is carried out. **Table 1** provides specifics about Aqaba's weather and solar radiation. The parabolic dish and its main characteristics are shown in **Figure 1** with a concentration ratio is given by equation (1).

$$C = \frac{A_a}{A_{abs}} \quad (1)$$

Where the area that faces the sun's radiation is the absorber A_{abs} and the area that captures the solar radiation is the dish aperture area A_a. The highest angle at which an incoming ray may deviate from the aperture plane and still enter the absorber is known as the acceptance incidence angle θ and the angle between the edge and the centre of curvature away from the focal point is known as the rim angle φ.

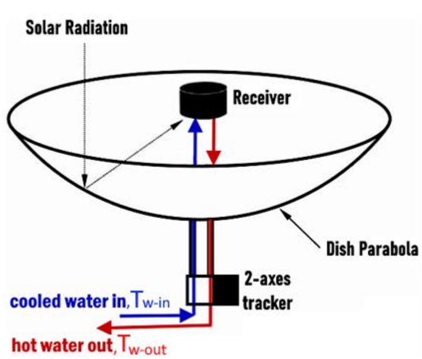

Fig. 1 Solar dish heating system.

Table 1 Aqaba average ambient temperature and local sun radiation intensity.

Month	Outside Temperature,(ºC)	Solar Intensity (W/m^2)
January	18	510.04
February	18	568.95
March	20	699.30
April	22	773.75
May	22	734.90
June	28	685.92
July	30	646.67
August	30	629.38
September	29	607.04
October	29	539.92
November	23	498.68
December	18	528.73

The dish's optical efficiency η_o is a function of the material's optical characteristics, the collector's geometry (geometric factor A_f), and the different flaws in the collector's design. One may express the optical efficiency as follows (Prado, *et al.*, 2016):

$$\eta_o = \rho_m \tau_m \alpha_m \gamma \left[1 - A_f \tan\theta \cos\theta\right] \quad (2)$$

Since the implemented system has solar tracking, it is assumed that the angle of incidence θ is equal to 0, which reduces equation (2) to equation (3) as follows:

$$\eta_o = \rho_m \tau_m \alpha_m \gamma \quad (3)$$

Where α_m is the absorber's absorptivity, τ_m is the cover glass's transmissivity, ρ_m is the reflectivity of the reflector material, and γ is the intercept factor. The majority of solar concentrators have optical efficiencies between 0.6 and 0.7 (Ahmet, *et al.*, 2021). The energy balance distribution through the absorber exposed to solar convection and radiation may be used to determine the thermal efficiency η_{th} of a solar concentrator and forecast the steady temperature and the duration needed to attain it, as shown in **Figure 2**.

$$\rho_s V_s C_{Ps} \frac{dT}{dt} = q_{in} - q_r - q_{conv.} \quad (4)$$

Where ρ_s is the absorber's density, V_s is its volume, and C_{ps} is its heat capacity, q_{in}, q_r, and q_{conv} refer to the reflected radiation, radiation loss from the absorber to the surrounding environment, and loss due to convection, respectively.

When the actual numbers are substituted into equation (4), the resulting balancing equation will be:

$$\rho_s V_s C_{Ps} \frac{dT}{dt} = \eta_o A_a I_d - A_{abs}\left[\sigma(T^4 - T_a^4) + h(T - T_a)\right] \quad (5)$$

With $T=T_a$ as the starting point, equation (5) may be numerically solved.

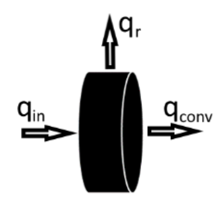

Fig. 2 Distributing energy through the cylindrical dish absorber.

The case of crossflow over a cylinder is the closest to calculating the average heat transfer coefficient in terms of thermal conductivity K and Nusselt number Nu, the correlation presented by Churchill and Bernstein can be used (Evangelos, *et al.*, 2019):

$$h = \frac{\mathrm{NuK}}{\mathrm{D}} \quad (6)$$

The Nusselt number, Nu may be calculated based on cylindrical receiver diameter (D) in terms of the Reynolds number Re and Prandtl number Pr as follows:

$$Nu = 0.3 + \frac{0.26\, Re^{1/2} Pr^{1/3}}{(1+(0.4\mathrm{Pr})^{\frac{2}{3}})^{1/4}} \left(1 + \left(\frac{Re}{282000}\right)^{5/8}\right)^{4/5} \quad (7)$$

$$Re = \frac{\rho \mathrm{V a D}}{\mu} \quad (8)$$

The wind speed was set to be constant in this investigation (V=3m/s) and the lost heat by conduction was neglected as recommended by the literature (Hafez, *et al.*, 2017).

1.2 Design Computations

The specified absorber capacity (volume) is set to $0.01\mathrm{m}^3$ with a thickness (t_{abs}) of 2mm. The following equation is used to calculate the cylinder's internal volume $V_{c\text{-}in}$:

$$V_{c\text{-}in} = \frac{\pi d_{abs}^2}{4} L \quad (9)$$

Where L is taken as $d_{abs}/2$.

The absorber's effective surface area is given as:

$$A_{abs}=\frac{\pi D_{abs}^2}{4}+\pi D_{abs}L \quad (10)$$

The half-acceptance angle *ϴ/2* is a crucial metric for determining the solar dish's concentration ratio. It is recommended that the value be more than 10 (Hafez, *et al.*, 2017).

$$C=\frac{1}{\sin(\Theta/2)} \quad (11)$$

The dish's focal length, *f*, can be calculated as follows:

$$\frac{f}{Da}=\frac{1+\cos(\phi)}{4\sin(\phi)} \quad (12)$$

The useful heat gained is calculated by taking the average optical efficiency $\eta_o = 0.65$) using the following balance formula (Duffie, *et al.*, 2013):

$$q_u = \eta_o A_a I_b - A_{abs}[\sigma(T^4 - T_a^4) + h(T - T_a)] \quad (13)$$

This useful energy could also be calculated in terms of the water temperatures in T_{win} and out T_{wout} of the absorber multiplied, the water mass flow rate m_w, and the heat capacity of water C_{pw}, as:

$$Q_u = m_w C_{Pw}(T_{w\,in} - T_{w\,out}) \quad (14)$$

The ratio of the useful energy gain that hits the concentrator aperture is the thermal efficiency η_{th} and can be found by using the following formula:

$$\eta_{th} = \frac{q_u}{A_a I_b} \quad (15)$$

2 Results and Discussion

Using engineering equation solver (EES) software, the solar water heater is designed with an absorber volume of 0.015m^3 and a concentration ratio of 20. An EES code was used to determine how the absorber's temperature varies with time and to calculate the steady stagnant temperature, which is the temperature at which the absorber is at rest when no water is moving through it. Copper is the substance of the absorber.

Figure 3 depicts the time variation of the absorber temperature. According to the results, for a solar intensity of 700W/m^2, the temperature of the heated absorber rose from 20^{o}C outside to a steady temperature of 246^{o}C in 1500 seconds. Also, the figure shows how the steady stagnant temperature varies with solar radiation intensity I_d. For the same surrounding temperature of 20^{o}C, it is observed that the absorber temperatures increased as the intensity of solar radiation I_d increased.

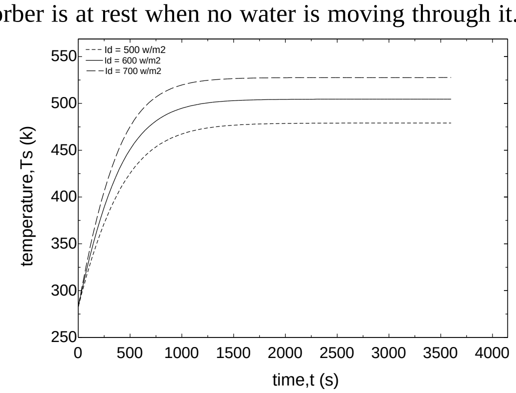

Fig. 3 Variation in the temperature of the dish absorber under various solar radiation intensities.

Figure 4 depicts the variation of stagnation temperature as a function of solar radiation intensity. The absorber stagnation temperatures rise as the value of solar intensity I_d rises. This is due to the accumulation of energy in the absorber that is not removed or used as useful energy. For calculating the parabolic dish size and analyzing the dish performance, an EES code is built. **Table 2** provides a summary of the analysis's findings. The output temperature was discovered to be 110°C when the surface and ambient temperatures were set to be 20°C and 135°C, respectively.

The temperature of the absorber is one of the key factors affecting its thermal efficiency. **Figure 5** shows that the thermal efficiency decreases as the solar absorber temperature rises.

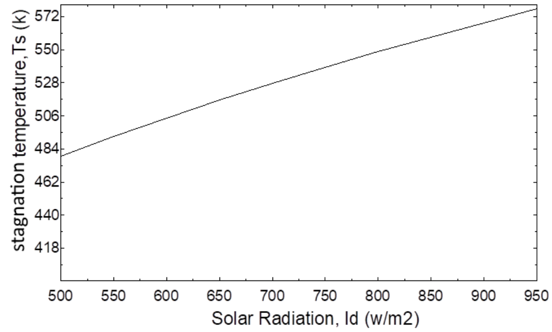

Fig. 4 Variation of the dish stagnation steady temperature with solar intensity.

Table 2 EES solar heater modelling results.

Outside Temperature (°C)	20
Water Output Temperature (°C)	120
Solar Intensity (W/m²)	700
Concentration Ration	20
Dish Optical Efficiency	0.62
Dish Thermal Efficiency	0.46
Absorber Volume (m³)	0.015
Absorber Area (m²)	0.2278
Aperture Area (m²)	4.556
Half-Acceptance Angle	13.62
Rim Angle	80°
Dish Focal Length (m)	0.81
Water Flow Rate (Kg/s)	0.005

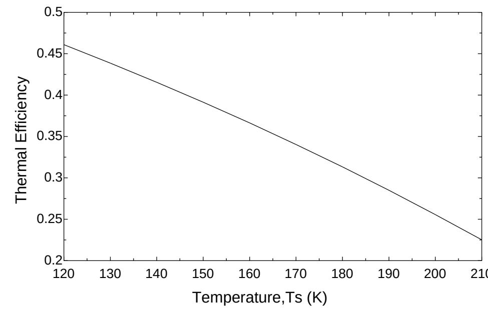

Fig. 5 Variation of dish thermal efficiency with the absorber temperature.

Conclusions

A solar water heater with a parabolic dish was modelled and designed to produce steam for use in various heat processing applications. To predict the equilibrium stagnant temperature of the absorber, a dynamic temperature analysis was done on a solar dish design with an aperture and absorber areas of 4.556m² and 0.2278m², respectively. As a result, a thermal efficiency of 0.46 is attained at 700w/m² of solar radiation intensity. The equilibrium temperature obtained was 246°C, and it took 1500 seconds to reach this steady temperature. As the absorber temperature rises, the system's efficiency decreases, and this is primarily due to an increase in radiation heat losses, which have the greatest impact on decreasing the dish's thermal efficiency.

Nomenclature

A_a	=aperture area	[m²]
A_{abs}	=absorber area	[m²]
C	=concentration ratio	[-]
C_{pw}	=water heat capacity	[kJ/kg.°C]
C_{ps}	=heat capacity of the absorber	[kJ/kg.°C]
D	=absorber diameter	[m]
D_a	=aperture diameter	[m]
D_{abs}	=internal diameter of absorber	[m]
f	=focal length	[m]
h	=heat transfer coefficient	[W/m².K]
I_d	=solar radiation	[W/m²]
K	=thermal conductivity	[W/m.K]
L	=height of absorber	[m]
m_w	=water mass flow rate	[kg/s]
N_u	=Nusselt number	[-]
Pr	=Prandtl number	[-]
q_{in}	=radiation received the absorber	[W/m²]
q_r	=energy radiated from the absorber to the ambient	[W/m²]
q_{conv}	=convected radiant loss	[W/m²]
q_u	=useful thermal energy delivered	[W]
Re	=Reynold number	[-]

t_{abs}	=thickness of the absorber	[m]
T	=temperature	[ºC]
T_a	=ambient temperature	[ºC]
T_{win}	=absorber inlet water temperature	[ºC]
T_{wout}	=absorber outlet water temperature	[ºC]
V_s	=volume of the absorber	[m^3]
V_a	=air velocity	[m/s]
θ	=acceptance angle	[degree]
φ	=rim angle	[degree]
μ	=dynamic viscosity	[kg/m.s]
ρ	=air density	[kg/m^3]
ρ_m	=surface material reflectivity	[-]
ρ_s	=density of the absorber	[kg/m^3]
τ_m	=glass cover transmissivity	[-]
α_m	=absorptivity of the absorber	[-]
Υ	=intercept factor	[-]
σ	=Stefan Boltzmann constant	[W/m^2.K^4]
η_{th}	=thermal efficiency	[%]
η_o	=optical efficiency	[%]

References

Ahmet, A., and K., Yağmur, Solar System Characteristics Advantages, and Disadvantages. In: Ahmet A., and Yağmur K., editors, Academic Press. Solar Hybrid Systems Design and Application, editors. 2021, 1-24.

Hafez, A., Z., A., Soliman, K., A., El-Metwally, and I., M. Ismail, "Design analysis factors and specifications of solar dish technologies for different systems and applications," *Ren. and Sust. Energy Reviews*, **67**, 1019-1036, (2017).

Atul, A. S., Satish A., and S., Narayani. Thermal performance of parabolic dish water heater with helical coiled receiver. In: Techno-Societal, International Conference on Advanced Technologies for Societal Applications, Prashant M. Pawar, Babruvahan P. Ronge, R. Balasubramaniam, Sridevi Seshabhatta editors. Springer International Publishing, June, 833-844, 2017.

Esdras, N., and J., Wang 'Thermal efficiency and cost analysis of solar water heater made in Rwanda', *Energy Explor. and Explo.*, **37**, 3, 1147-1161, (2019).

Evangelos, B., Erion, B., Christos, T., snf P., Sasa 'Optical and thermal analysis of different cavity receiver designs for solar dish concentrators', *Energy Conv. and Manag.*, **2**, 100013, (2019).

Duffie, J. A., and W., A., Beckman, 'Solar Engineering of Thermal Processes', 4th Edn., John Wiley and Sons, Inc. (2013).

Hadadin, N., M. Qaqish, E. Akawwi, and A. Bdour, "Water shortage in Jordan-Sustainable solutions", *Desalination*, **250**, 197-202, (2010).

Majeed, M., Alwan, N., Shcheklein, S., and A., Matveev "Electromechanical solar tracker system for a parabolic dish with CPU water heater.", Materials Today: Proceedings, 42, 2446-2352, (2021).

Prado, G., L., Vieira, and J., Damasceno, "Solar dish concentrator for desalting water," *Solar Energy*, 136, 659-667, (2016).

Rahul, V., and F., Adroja, "Improvements of Water Temperature in Solar Parabolic Water Heater", *Int. J. for Sci. Res. and Dev.*, **6**, 388-391, (2018).

Tabassum, S., L., Sharmin, M., Bashar, M., Rahaman, S., Debnath, and M., Khanam "Design and Analysis of Parabolic Trough Solar Water Heating System*", J. of Archit. Env. And Struc. Eng. Res*., **2**, 1-6, (2019).

William, R., D., Timothy B., and S., Luzzadder-Beach "Solar desalination: Cases synthesis and challenges", *Wires Water*, **7**, 1-12, (2020).