JJMIE

Volume 17, Number 3, September. 2023
ISSN 1995-6665
Pages 413– 419
https://doi.org/10.59038/jjmie/170310
Editor-in-Chief: Prof. Ali M. Jawarneh

Jordan Journal of Mechanical and Industrial Engineering

Simulation-Design and Performance Analysis of a Small-Scale Concentrating Solar Parabolic Dish System for Hot Water Generation

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Received 3 Apr 2023 Accepted 16 May 2023

Abstract

Classic solar collectors were used in most heating applications. Concentrated solar collectors heat water inconceivably. A comprehensive analysis of a small-scale designed solar parabolic dish for domestic-hot water application at the northern part of Jordan (32.49º N, 35.9º E) has been conducted using the Engineering Equation Solver Software. The water tank provides96 liters per day of hot water with sun tracking system for best performance. The investigation examines the effect of different operating parameters on the output temperature. The simulation results revealed that the optimum operating thickness, reflectivity, and wind speed were found to be 0.004 m, 0.92, and 4.6 m/s respectively. The maximum output temperature achieved was 289 ºC and occurs at 75.5 concentration ratio.

Keywords: parabolic dish, concentration ratio, performance, solar radiation, thermal efficiency.

Nomenclature

A_{abs}	absorber area of the receiver
A_{con}	aperture area of the concentrator
AST	apparent solar time
C	concentration ratio
C_p	water specific heat
D_{abs}	absorber outside diameter.
d_{abs}	absorber inside diameter.
D_{con}	aperture diameter of the concentrator
EES	Engineering Equation Solver Software
f	focal length
G_{on}	normal plane solar radiation
G_{oH}	solar radiation on a horizontal surface
G_t	global irradiance
G_{Bt}	beam radiation on inclinedsurface
G_{Dt}	diffuse radiation on inclined surface
G_{Gt}	ground-reflected radiation on a tilted surface
h	hour angle
h_{air}	convective heat transfer coefficient
$\dot{m}$	mass flow rate.
P_{abs}	energy absorbed by the absorber.
q_{useful}	useful thermal energy.
t	time (sec.).
Ta	ambient temperature.
T_{rec}	output temperature
T_{sky}	sky temperature
T_w	water temperature
t_{wall}	thickness of absorber wall
U_L	overall heat loss coefficient
V	volume of fluid

Greek Symbols

δ	declination angle
η_{inst}	instantaneous thermal efficiency
η_{opt}	optical efficiency
ρ	mirror reflectivity
Φ	acceptance angle
ψ	rim angle

1. Introduction

The usage of sustainable energy sources is thought to be the best option for tackling the serious environmental issues brought on by the use of global fossil fuels [1]. In spite of the fact that there are many various sustainable energy resources (like geothermal, wind, and solar etc.), solar energy is a distinct option because it is abundantly available [2]. Global energy consumption has risen as a result of lifestyle shifts. Due to climate change and increasing energy prices, renewable energy is becoming more common. Solar collectors transform inbound sun rays into usable heat, making solar energy the most prevalent and potential energy resources. This heat is transferred to the cargo or storing device by an operating fluid. Applications involving high temperatures rely on fluid exergy movement, which is influenced by temperature. In many uses, concentrating collectors are used to increase the working fluid temperature and exergy rate. Solar thermal collectors focus sunlight on heat that can be used for various thermal processes.

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Concentrated solar thermal collectors are extensively used in industry, domestic water heating, and steam generation [3, 4, 5].

Sunlight energy is concentrated onto a sensor by solar focusing collectors. Concentrating collectors are available in a range of temperatures and ratios. The most popular focused collectors are linear, compound, Fresnel, and solar dish. There are solar heating devices with low, middle, and high temperatures. The Concentrated Solar Power (CSP) system may be implemented to heat water rather than fossil fuel combustion and to preheat feed-water rather than live-steam extraction from the steam turbine [6, 7].

Due to their high-temperature heat output, concentrated solar power (CSP) methods are gaining popularity. Dish solar collectors turn solar energy into heat energy efficiently due to their high concentration ratio [8]. It works by concentrating solar energy onto a tiny receiver, which transfers heat along with the working fluid. As solar radiation is correctly focused on parabolic solar dishes, the implementation of the cavity receiver has been discovered to be a very helpful method [9].

Solar dish collectors' usable heat gain can be used in many industrial applications such as products-drying, hydrogen generation devices, and different power cycles [10, 11]. The effectiveness of a 20 m^2 solar parabolic dish collection with the modified cavity receiver was empirically assessed by Reddy et al. [12]. A number of approximately 356 W/m^2 was found to be the norm for the total rate of heat loss.

In order to examine the different elements that can be successfully combined in zero or positive energy districts, both in built and rural environments, a polygeneration parabolic trough concentrated solar plant is designed on the roof of a building in Irbid city and is then analyzed. The design was based on the findings of an on-site energy audit, which revealed the high frequency of summer cooling demand. The investigation's findings support the promising use of small-scale solar plants for heating [13].Pavlovi et al. [14] presented a study on the optical design and ray tracing of a concentrating solar dish that utilizes twelve curved trapezoidal mirrored surfaces. The objective was to present optical configuration of a cost-effective solar concentrator that can serve as an affordable tool for conducting laboratory-based investigations on thermal processes of moderate temperatures, refrigeration, industrial operations, and polygeneration systems. A six-meter parabolic trough collector was developed, built, and tested theoretically and experimentally for water heating and steam generation. At 2 bars pressure, the steam peak temperature obtained was 123 °C withhighest efficiency of 22.4%[15].

A parabolic dish solar water heater was thermally simulated to generate steam for heat processing using meteorological data from Aqaba, Jordan. A solar dish design with aperture and absorber areas of 4.556 and 0.2278 m^2 was studied for dynamic temperature. For 1500 seconds, equilibrium temperature reached 246°C [16].

The purpose of this research study is to develop and construct a compact small-scale solar parabolic dish system to be used in heating process applications in the northern region of Jordan. Through the utilization of Engineering Equation Solver software (EES), the research presents an in-depth simulation to examine the performance of the solar dish heating system.

2. Method and System Description

The solar parabolic dish system is depicted in Figure 1 and consists of a dish-shaped parabolic reflector with a supporting structure, a heat exchanger mounted on the focus of the parabolic solar dish to receive direct beam radiation, and a generator to produce electrical energy or heat.

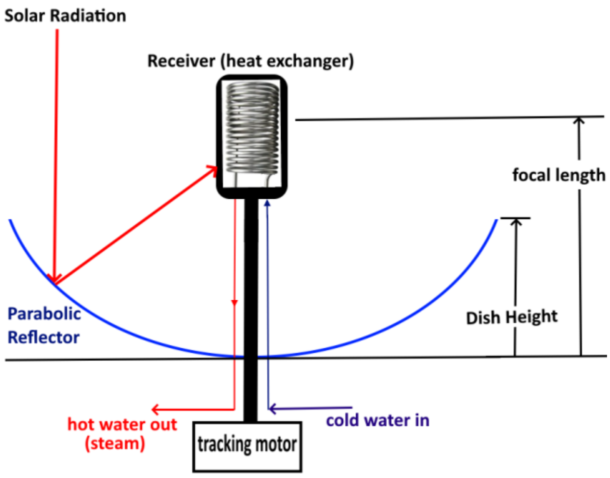

Figure 1. Schematic diagram of parabolic solar dish system.

The overall system design of parabolic solar dish system is divided into three main stages: design of solar parabolic dish system, solar radiation calculations and thermal-opticalanalysis of the receiver. The selection of the solar reflector material and shape is a major step in designing the solar dish since the material reflectivity of the concentrator affect the amount of the direct solar radiation being absorbed by the receiver. Table 1 presents some of the solar reflector material that can be used in designing the solar dish, the reflector of the dish was chosen to be constructed from aluminum with 0.98 reflectivity. The working fluid which has been used is water and the amount of the water in the tank is around 96 liters with an ambient temperature of 25℃. The parabolic reflector is made of stainless steel sheets and the receiver is made by galvanized steel pipe. The solar dish system is to be installed and tested outdoor at32.49° N latitude, 35.9° E longitude (northern region of Jordan). In addition, it will be oriented in the direction of East-West to reduce tracking process requirement[1].

Table 1.Characteristic of selected materials used to form solar reflector [16]

Construction Material	Reflectivity	Emissivty
Non-metal, Polymeric film	0.98	0.2
Acrylic, Aluminum	0.98	0.2
Aluminum acrylic, Silver	0.97	0.3
Acrylic, Silver	0.95	0.5
Aluminum	0.86	0.14
Polyethylene, Aluminum	0.97	0.3
Acrylic Plexiglass Mirror Sheet	0.90	0.9-1.0
Polished stainless	0.50	0.5
Glass/Silver 4mm	0.938	0.62
Glass/Silver 2mm	0.94	0.6
Glass/Silver 4mm	0.946	0.6

3. Parabolic Dish Design

After deciding on the substance and form of the solar dish concentrator, the next stage is to calculate the parabolic dish diameter($D_{con.}$). The heater's absorber tank will be a cylindrical with an outside diameter of D_{abs}, an interior diameter of d_{abs}, a height of L, and a thickness of t_{wall}. The cylinder's interior volume (V) is determined using equations 1, 2, and 3 [17].

$$V_{water} = V_{cylinder} = \frac{\pi d_{abs}^2 L}{4} \tag{1}$$

$$D_{abs} = d_{abs} + 2t_{wall} \tag{2}$$

$$A_{abs} = \frac{\pi D_{abs}^2}{4} + \pi D_{abs} L \tag{3}$$

The concentration ratio (C) is defined as apeture area of the concentrator area ($A_{con.}$) to the receiver area of the absorber$(A_{abs}) = (A_{rec})$. It can be calculated from equation 4[17]:

$$C = \frac{A_{con.}}{A_{rec.}} = \frac{A_{con.}}{A_{abs}} \quad (4)$$

The total concentrator aperture area $(A_{con.})$ is the area that receives the direct (beam)solar radiations and its influence on the amount of direct solar radiation delivered to the absorber[17]:

$$A_{con.} = \frac{\pi}{4} D_{con.}^{2} [m^2] \quad (5)$$

The acceptance angle (Φ) is the worst-case angle at which the concentrator collects all reflected solar energy in a short amount of tracking time [17].

$$C = \frac{1}{\sin^2 \Phi} \quad (6)$$

The angle between line of the rim of the mirror to the focus and optical axis is known as rim angle (ψ) andis given in terms of acceptance angle (Φ)in equation 7 below[17].

$$\psi = 90^o - \Phi \quad (7)$$

The solar parabolic concentrator uses mirrors to reflect and focus the direct solar radiation into the recevier at a focal point (*f*). The focal point iwhich defined as the vertex of the parabolic axis - focus distance and it can be written as [17]:

$$\frac{f}{D_{con.}} = \frac{1+\cos(\psi)}{4\sin(\psi)} \quad (8)$$

The distance from the vertex to the focus is the detention of the focal length (y). The height of the dish is the distance from the vertex to a line across the aperture of the parabolic reflector and can be calculated as[17]:

$$y = \frac{D_{con.}^2}{16f} \quad (9)$$

Through an entire year, the N[th] daynormal-plane radiation (G_{on})in $(\frac{W}{m^2})$and solar constant (G_{sc}) is 1366.1$(\frac{W}{m^2})$ is given as [18]:

$$G_{on} = G_{sc}\left[1 + 0.003\cos\left(\frac{360N}{365}\right)\right] \quad (10)$$

Fortilted-surface, thebeam solar radiation(G_{Bt}), diffuse solar radiation (G_{Dt}), and ground-reflected solar radiation make up the total global radiation (G_t)[18].

$$G_t = G_{Bt} + G_{Dt} + G_{Gt} \quad (11)$$

The tilted-surface beam radiation can be calculated in terms of incident angle(θ) as[18]:

$$G_{Bt} = G_{Bn}\cos(\theta) = G_{Bn}\left[\sin(L-\beta)\sin(\delta) + \cos(L-\beta)\cos(\delta)\cos(h)\right] \quad (12)$$

Where the angles (L, β, h, δ) are the latitude, tilt, hour, and declination angle respectively. The declination angle could be estimated in terms of N[th] day of the year starting from 1 January as[18]:

$$\delta = 23.45\sin\left(\frac{360}{365}(284 + N)\right) \quad (13)$$

In concentrating solar thermal power technologies, only the direct beam radiation is taken into consideration.

4. Concentrated Solar Dish Receiver-Thermal Analysis

The useful energy estimated for one cycle of the concentrator at a given mass flow rate is given in terms of concentrator area (A_{con}), tilted surface-beam radiation (G_{Bt}) and concentrator efficiency (η_{con}) by[18]:

$$q_{useful} = \eta_{con} G_{Bt} A_{con.} = \dot{m}_w C_p (T_{out} - T_{int}) \quad (14)$$

Where $\dot{m}_w$ is the water mass flow rate(kg/sec), $C_p(KJ/kg°C)$is the specific heat of the fluid,T_{out} *and* T_{in} is the water outlet and inlet temperature. The time rate of mass flow could be estimated in as $\dot{m}_w = \rho V/t$ where ρ *is the* density of the fluid, V is the volume of water and t is the time taken to heat the fluid.

The amount of energy received$(q_{in})$was estimatedin terms of the concentration ratio (C), mirror reflectivity (ρ) and tilted surface total beam radiation (G_{Bt})as[16]:

$$q_{in} = C\rho G_{Bt} \quad (15)$$

The total energy loss is the sum of both radiative and convective heat lost $(q_{rad} + q_{conv} = \sigma\epsilon\left(T_{rec}^4 - T_{sky}^4\right) + h_{air}(T_{rec} - T_a))$[19].

Where σ *is the stefan* − *Boltzmann constant* $= 5.67x10^{-8}$, ϵ is the emissivity between the receiver and the sky with sky temperature approximated to ambient temperature as$(T_{sky} = T_a - 6)$,T_{rec} is the receiver output temperature and h_{air} is the convective heat transfer coefficient approximated as a function of air speed $(h_{air} = 2.8 + 3V)$.

The ratio of the useful energy production of the supplied solar energy to the incoming energy on the concentrator is known as the thermal efficiency of the concentrator[18].

$$\eta_{th} = \frac{Usefulenergy}{EnergyReceived} = \frac{q_{useful}}{q_{in}} \quad (16)$$

The collector optical efficiency can be estimated in terms of the receptor absorptance (α_c), the transmittance of the glass coating (τ) and the shape factor (S) as[20]:

$$\eta_{opt} = \alpha_c \tau p S \quad (17)$$

The parabolic solar dish system illustrated in figure 2 has been simulated based on the flow chart shown in figure 3 and using Engineering Equation Solver (ESS) to examine its performance. The relationship between different performance parameters were found and discussed as follows.

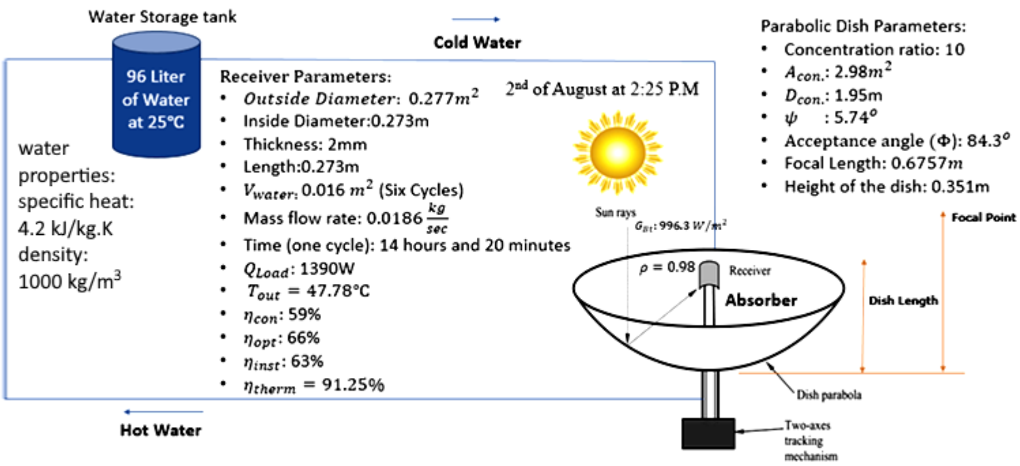

Figure 2. Schematic diagram of solar dish parameters.

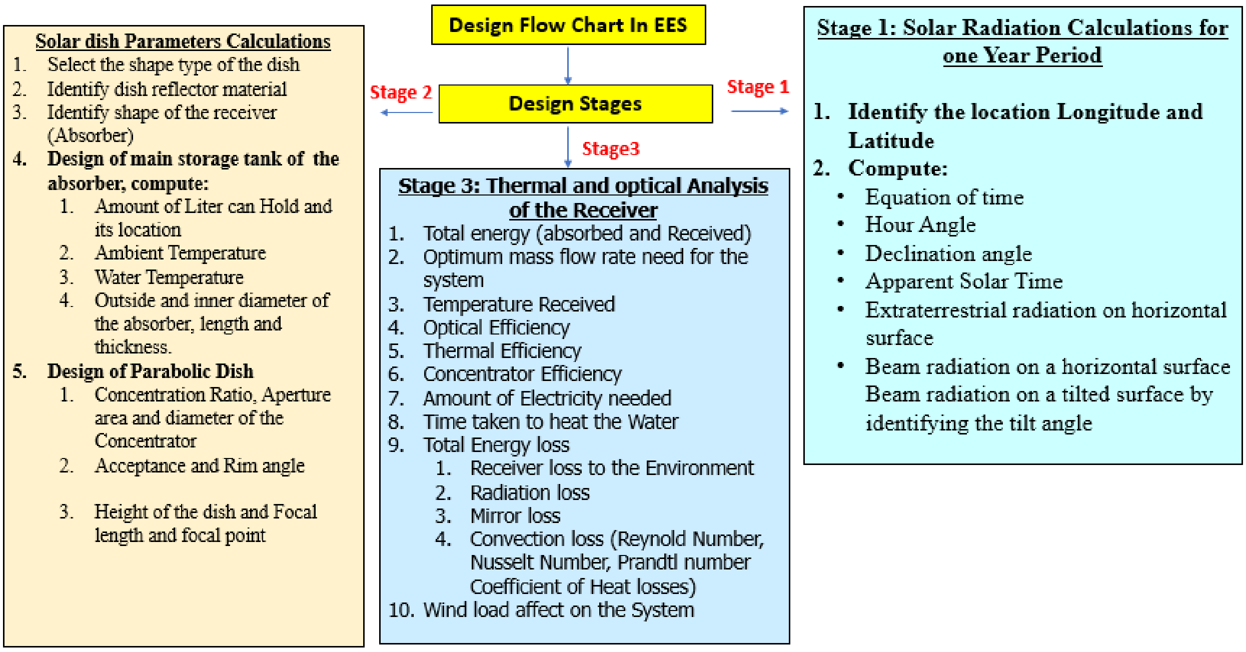

Figure 3. Parabolic solar dish design stages on ESS flow chart.

4.1. Model Validation

The current model was validated by applying the input data from K.K. Sharma et al. (2018) as input data for the current model, and the results were compared to the current model as shown in Table 2.

Table 2. Variation of the temperature received throughout the day for current model as compared to K.K. Sharma Model (2018)[21].

Time [hour]	Temperature (˚C)	
	Present Model	K.K. Sharma Model
10	47	46
11	62	60
12	67	65
13	64	62
14	60	58
15	50	47
16	47	44

4.2. Simulation Results and Discussion

The variation of the tilted surface beam radiation located at the northern part of Jordan (32.49° N- latitude, 35.9° E-longitude) for August 2has been plot in figure 4from 7:30 AM to 5:00 PM. The results show that the peak beam solar radiation occurs between 11:00 A.M. and 2:00 PM and was recorded as1328W/m^2. Then, after2:00 PM, the beam radiation starts to decrease as the time of the day reaches 5:00PM.

The potential of solar radiation for a one-year period has been plotted at 12 noon in figure 5. It is clear that the maximum solar radiation potential throughout the year occurs during June to August with peak value of 1267W/m^2 on the day of 139 (July). It's also clear that the maximum. Figure 6 shows that the output temperature increases linearly with beam radiation on a tilted surface.

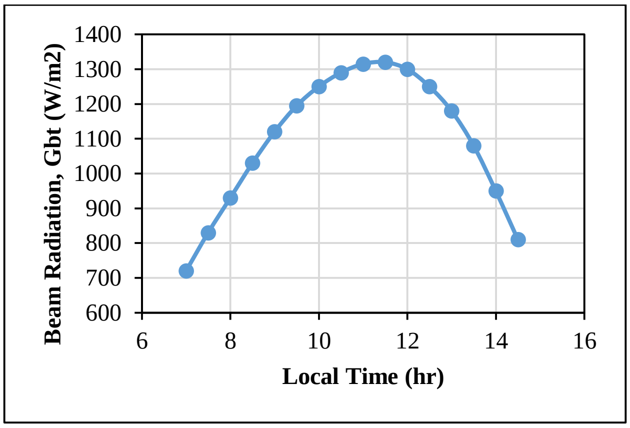

Figure 4. Variation of the tilted surface beam radiationfor one day period.

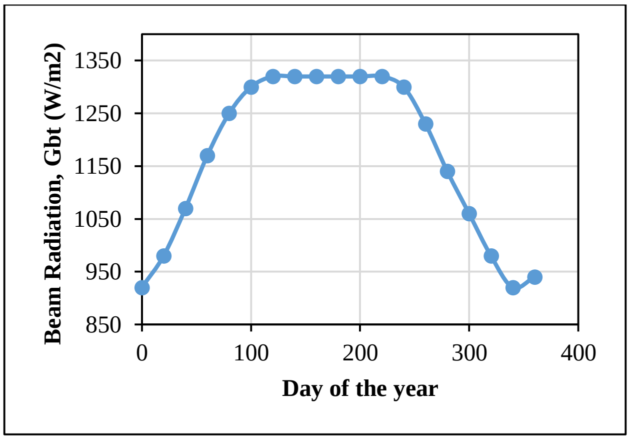

Figure 5. Variation of the solar radiation at 12 noon for one-year period.

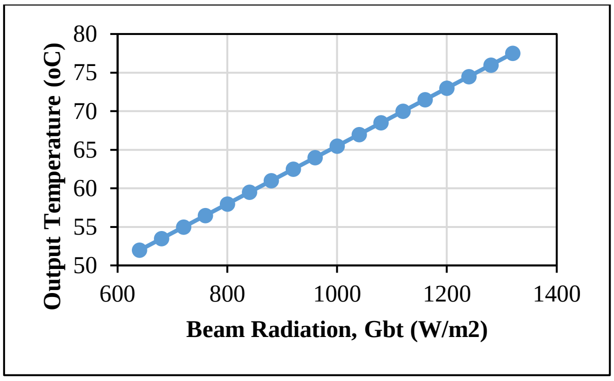

Figure 6. Variation of output temperature with the tilt surface solar radiation.

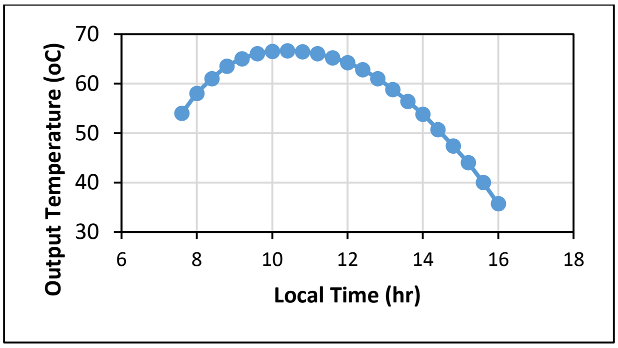

Figure 7. Variation of the temperature received throughout the day.

The variation of the temperature received throughout the day of simulation at a concentration ratio of 10 from 7:30 A.M till 5:00 P.M is presented in figure 7.The results shows that the temperature increases to peak value of67.3℃for a mass flow rate of 0.03624 kg/sec at time between 11:00 to 13:00. Then, after that the temperature received starts to decrease till 5:00 PM since the intensity of beam radiation decay. The output temperature seems to decrease at the afternoon period more rapidly due to increase in losses of received energy due to increase in demand (heat removal) and wind speed.

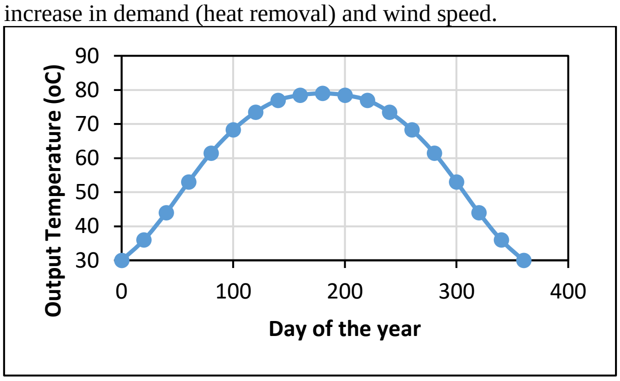

Figure 8. Predictedoutput temperatures throughout a year.

At a concentration ratio of 10 and mass flow rate 0.03786 kg/sec the variation of the output temperature with time for one year was shown in figure 8. The predicted results show that the maximum output temperature was found to reach 79.78ºC at 11:30 AM on the day of 183 in July. The variation of both output temperature and mass flow rate with concentrator thickness was shown in figure 9. The simulation results obtained show that the maxmium output temperature can be achieved a thickness of 0.003758 m while the maximum mass flow rate of 0.03635kg/sec was obtained at 0.0046 m thickness. The optimum operating point was found to be around 0.004 m thickness, at which the corresponding output temperature and mass flow was 66.5 ºC and 0.355 kg/sec respectively.

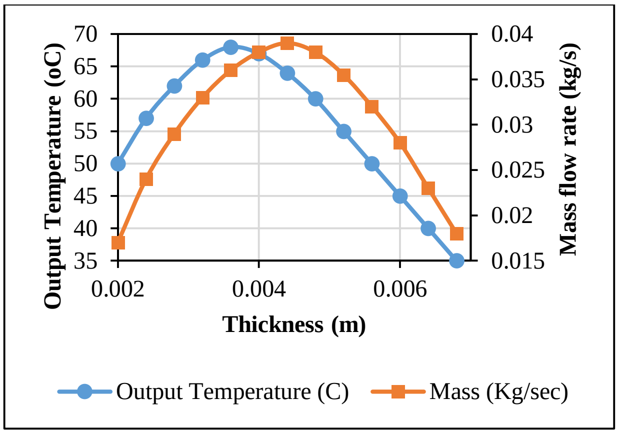

Figure 9. Optimum mass flow rate, thickness with respect to the output temperature.

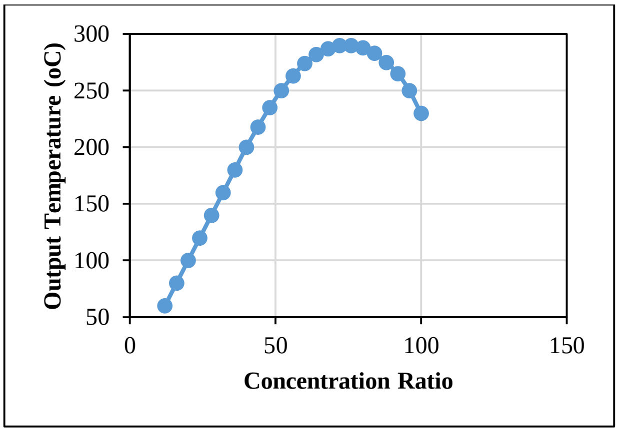

Figure 10. Variation of output temperature with concentration ratio.

The concentration ratio was varied in the simulation from 10 to100to show its effect on the receiver output temperature as shown in figure 10. The results show that as the concentration ratio increases, the output temperature received increases at the receiver until it reaches its maximum value of 289 ºCat a concentration ratio of 75.5 after which the output temperature starts to decrease. The temperature reached can be used to generate superheated steam in steam turbine power plants. The power absorbed by the receiver increases linearly with output temperature as shown in figure 11. Figure 12 shows the effect of reflectivity on the dish performance. Results show that the output temperature increases with enhancing surface reflectivity of the dish up to 0.92 after which the output temperature almost reaches its steady value.

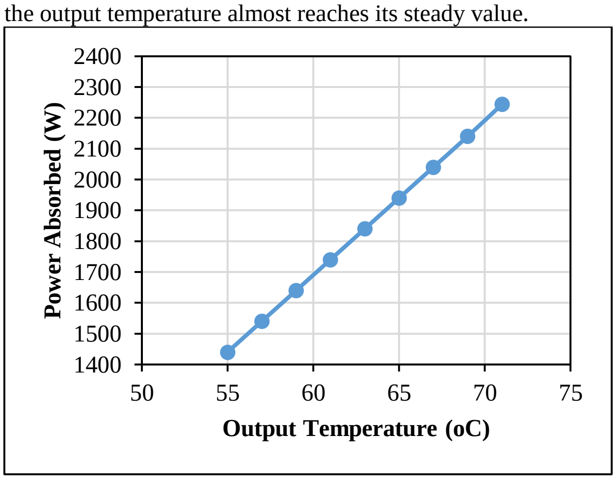

Figure 3. Variation of power absorbed with output temperature.

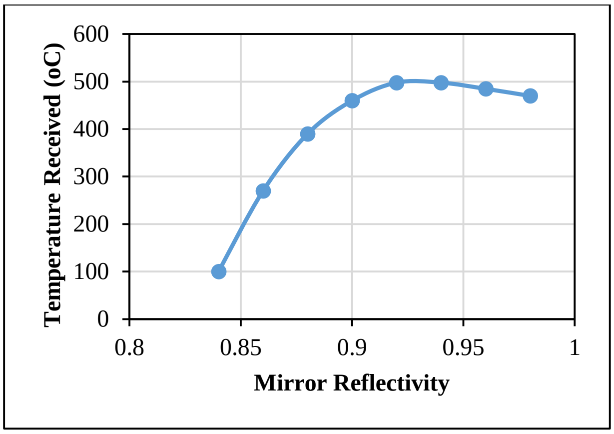

Figure 4. Variation of output temperature with mirror reflectivity.

The receiver output temperature increases with time since the water circulated more in the dish solar heating system. The results presented in figure 13 show that it took about 6.5 hours for to output water to reach a temperature of 250 ºC. The lower the temperature required, the lower the time needed.

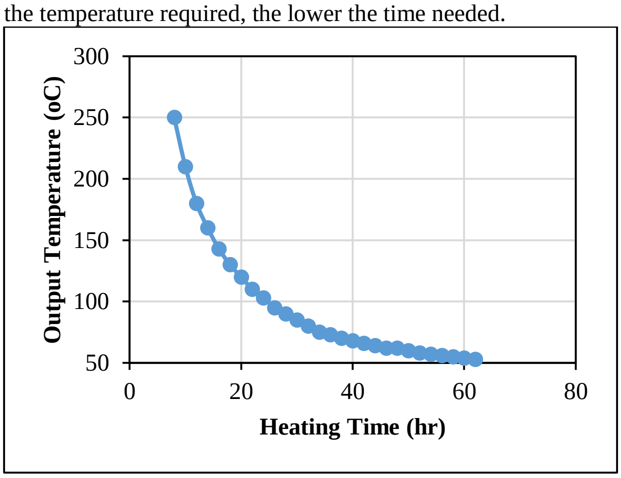

Figure 5. Variation of output temperature with time taken to heat water.

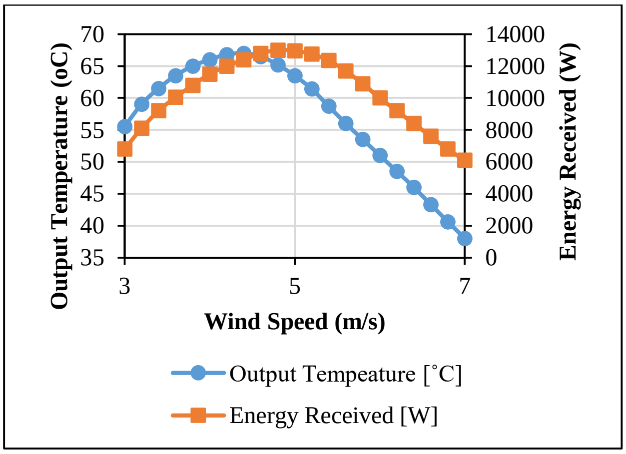

Figure6. Effect of the wind speed on the performance of the parabolic dish.

Wind speed strongly affects both the output temperature and total energy received by the dish system. Figure 14 shows that maximum values of output temperature and energy received occurred at different wind speeds and the optimum operating point for both is the speed corresponding to the intersection point which was around 4.6 m/s.

5. Conclusion

A small-scale parabolic dish solar for domestic hot water application and thermal processes was designed and its performance was analyzed at the northern region of Jordan (32.49o N, 35.9o E). The Engineering Equation Solver software was used to run the performance simulation. The water tank delivers 96 liters of hot water per day at peak efficiency with sun tracking. The system has been subjected to performance analysis to investigate the optimum rim angel, mass flow rate, direct solar radiation throughout the year, the effect of the material and shape on the concentrator, maximum temperature received and its relationship with concentration ratio, maximum power absorbed at the receiver, thermal analysis, and wind effects on the system. The optimum operating thickness, reflectivity, and wind speed were discovered to be 0.004 m, 0.92 m, and 4.6 m/s respectively. The maximum output temperature was obtained at 75.5 concentration ratio.

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