Design and fabrication of a solar-dish concentrator with 2-axis solar tracking system

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Abstract
This paper presents an economical parabolic solar collector including design analysis, fabrication, and testing of the solar concentrator with a dual-axis solar tracking system. The design goals of the solar dish are high concentrating temperature and power density but low weight and cost. To achieve a high-efficiency dish, minimizing loss is important therefore the design focuses on high reflectability, low heat absorption with an optimum dish profile. The dish is a parabolic shape with two layers of different materials. Three reflector materials, an emergency blanket, PET-Mirror, and Mirror are introduced on the top layer as the solar reflectance. The second layer, fiberglass that is lightweight, easy to shape up in various features, and cheap, is used as a dish structure. The dish is installed with a 2-axis solar tracking system and supported by a steel column. The ¼ inch copper tube is coiled as a receiver. The receiver is placed at the focal point of the solar dish. To evaluate the heat at the focal point, water is pumped through the receiver coil to absorb the heat from the focal point. The heat output of the solar dish is calculated from the temperature difference of the water inlet and outlet of the receiver coil. The temperature at the focal point was presented along with the heat power output, and solar dish efficiency.

Keywords: Solar concentrator, Parabolic dish, Solar tracking

1. Introduction
Global warming is a serious environmental problem because it wildly affects the climate around the world. Causing many parties to take this issue seriously. The rise in global temperatures is caused by ozone in the atmosphere, which reflects some of the solar radiation, being destroyed by CFCs, NOx, CO₂ [1]. One of the main sources of these gases is energy production from non-renewable fossil fuels. However, we cannot cut down on the amount of energy we use because the various economic activities tend to require more energy. Therefore, the sustained solution to energy demand and global warming is to find clean energy sources that can be circulated back and forth unlimitedly.

Solar energy is the most potent and abundant permanent renewable energy source. The amount of sunlight that is continuously hitting Earth's atmosphere is about 1.75×10⁵ TW, around 60% or 1.05×10⁵
TW transmission through atmospheric reaching the Earth's surface continuously [2].

There are two main categories of technology to utilized solar radiation: solar thermal and solar photovoltaics (PV). For solar thermal, solar radiation is converted to heat by thermal collectors, while PV produces directly electricity. The advantages of solar thermal energy over PV are higher efficiencies, lower investment costs, and solar thermal can store thermal energy efficiently and may use other fuels such as natural gas or biogas as a backup to ensure continuous operation [3]. The solar collector working as a heat exchanger that harvests the solar radiation and converts it to heat, then transfer to a fluid flowing through the collector [4]. The solar collector technologies can be divided by tracking type as non-tracking, single-axis tracking system, dual-axis tracking system as in figure 1 [5]. The dual-axis tracking system, which concise of a linear Fresnel reflector, solar tower receiver, and parabolic dish concentrator (PDCs), provides the highest efficiency [6].

The PDCs are a compact focal point that can achieve very high concentration ratios up to 1000. At temperatures exceeding 1,000°C, they can produce power efficiently by utilizing high energy conversion cycles [7]. The PDCs can couple with various applications such as water heating receiver, Stirling engine, etc. [8]. The PDCs that are coupled with the Stirling engine with the typical cycle efficiency of ~38% may behave annual solar-electric efficiency of ~25% [6].

For the study and experiment of PDCs, many researchers study the operation of the system by building and experimenting. Bianchini et al were presented the performance assessment of a solar parabolic dish for domestic use. They evaluate the performance of a small-scale commercial parabolic dish of 11.5 kW and shown the result in different environmental conditions [9]. Pavlovic et al. have presented the experiment of a prototype solar dish collector. A mathematical model was used to evaluate the system performance of the collector in many operating cases [10]. Mavire and Taole studied the thermal performance of the cavity receiver for parabolic dish concentrator namely SK-14. Different types of receivers and focal lengths of parabolic dishes were also tested with the experimental setup [11]. Hijazi et al. were presented the mechanical design of a low-cost parabolic solar dish concentrator. One of the highlights of their study is the optimum size of the reflector to be cut to reduce both cutting cost and sheets cost [12].

Several related papers on the parabolic concentrator dish were shown that the solar dishes are high-cost devices and very heavy [9, 10, 12]. They need very large nearly perfect curve mirrors to effectively concentrate solar radiation. In order to build a dish prototype for study and experiment requires a considerable amount of budget for the whole dish structure and reflective material. Therefore, this research is to investigate the feasibility of fabricating a prototype of the solar dish system at the lowest cost and weight, while maintaining at high the efficiency of the solar collector system.

**Figure 1.** Type of solar collector.
2. Background and theory

2.1 The sun
This section provides the background theory, radiation from the sun, and its position observation from the earth, to understand the physics of solar radiation for the analysis of solar energy systems.

2.1.1 Heat and radiation from the sun
The sun is a 13.9 × 105 km diameter sphere composed of many layers of gases. At its surface, the fusion reaction is continuously reacted and releases the energy of 3.8×1023 kW in form of an electromagnetic wave, only a tiny fraction approximately 1.7x1014 kW, is intercepted by the earth which is located approximately 150 million km from the sun [1]. The sun radiates energy to the earth is referred to as solar radiation. As the solar electromagnetic energy passes through the atmosphere of the earth, while the solar energy levels are around 1 kW/m2 when it reaches the surface of the earth [2]. The amount of solar energy per unit area received is normally define as irradiance, qs which varies with geographical position on the earth, the orientation of the collector, meteorological conditions, and the time of day [3].

For concentrating systems, the net solar energy, Qs is proportional to the collector area Aa and the proportionality of the solar energy falling on the reflector, qs (W/m2)[3]. The thermal efficiency is defined as the ratio of the useful energy delivered to the energy incident on the collector aperture. Therefore, the radiation falling on the receiver q0 is a function of the optical efficiency, which accounts for all errors [3].

2.1.2 The Sun Position
According to the earth move around the sun and rotates daily about its polar axis, it is important for the parabolic dish concentrator system to mathematically calculate the position of the sun [2]. The coordinates of the location of the sun at any instant of time can be expressed by two variables, Azimuth and Elevator angle as shown in Figure 2. Both angles are the function of the site location and time as Equations 1 and 2 respectively [2].

![Figure 2. Azimuth and elevator angle.](image)

\[
\phi = \cos^{-1}\left(\frac{\sin(\delta)\cos(\varphi) - \cos(\delta)\sin(\varphi)\cos(\omega)}{\cos(\alpha)}\right)
\]

\[
\alpha = \sin^{-1}\left(\sin \delta \sin \varphi + \cos \delta \cos \varphi \cos \omega\right)
\]
2.2 Collector

Solar thermal collectors are classified into different tracking structural designs and working principles as shown in figure 1. The parabolic dish concentrator (PDC) is a single focal point type so that it provides the highest temperature compare to other collector structure. The detail of the PDC and the thermal analysis were presented in this section.

2.2.1 Parabolic dish

The equation of a parabolic in the x-y coordinate and focal point is given in Equations 3 and 4 respectively[1].

\[ y = \frac{x^2}{4f} \]  \hspace{1cm} (3)

\[ f = \frac{D^2}{16d} \]  \hspace{1cm} (4)

Where f is the focal point of the dish, D is the diameter of the dish and d is the depth of the dish as detail in Figure 3. The rim angle \( \phi_r \) is the angle between the sunray and a line from the focus to the concentrator dish edge. The rim angle affects the radiation ray of the sun and the manufacturing of the parabolic dish. The rim angle of a parabolic can be written as Equation 5.

\[ \phi_r = \tan^{-1}\left(\frac{D/2}{f-d}\right) = \tan^{-1}\left(\frac{4fD/2}{4f^2-(D/2)^2}\right) \]  \hspace{1cm} (5)

![Figure 3. Schematic of the parabolic curve.](image)

Another parameter that indicates the solar dish is the concentrating ratio. Due to the flux density of solar radiation is estimated at not over 1000 W/m\(^2\). Therefore, it needs to concentrate to obtain higher solar radiation. So that the solar concentration ratio is an important concept for the solar collector. The concentration ratio, C is defined as the ratio of the aperture area to the receiver area as written in Equation 6.

\[ C = \frac{A_a}{A_r} \]  \hspace{1cm} (6)

2.2.2 Thermal analysis

As mention in section 2.1.1 that the amount of heat obtained from the dish is the radiation intensity (qs) of light that hits the light multiplied by the aperture area (Aa) as in Equations 7 and 8. To analyze the concentrator efficiency, we consider the heat loss, (Q\(_{\text{loss}}\)) from the receiver to ambient temperature as follows.
\[ Q_s = q_s A_u \]  

(7)

\[ q_0 = n_0 q_s = \frac{n_0 Q_s}{A_u} \]  

(8)

\[ Q_{loss} = Q_s - Q \]  

(9)

\[ Q_{loss} = U_r A_r (T_r - T_0) \]  

(10)

Where \( U_r \) is the overall heat transfer coefficient and \( A_r \) is the receiver area.

From equation 10, if all heat loss to the ambient then the maximum temperature occurs at the receiver[3] and the temperature can be write in dimensionless as equation 11.

\[ \theta_{max} = \frac{T_{r, max}}{T_0} = 1 + \frac{Q_s}{U_r A_r T_0} = 1 + \frac{q_s A_u}{n_0 U_r A_r T_0} = 1 + \frac{q_s C}{n_0 U_r T_0} \]  

(11)

The collector efficiency is

\[ \eta_c = \frac{Q}{Q_s} = 1 - \frac{\theta - 1}{\theta_{max} - 1} \]  

(12)

3. Design and Manufacture

3.1 Design and Manufacturing the Parabolic Dish

This section provides the design information and fabrication technique of parabolic solar dishes. The solar dish collector designed with a diameter of 1 meter, and a rim angle of 45°, and other specifications are shown in Table 1. The diameter of 1 meter was constrained by the size of 1.2mx2.4m of the emergency blanket.

Table 1. The design parameter of a parabolic dish.

| Specification     | Value   |
|-------------------|---------|
| Diameter          | 1 m     |
| Rim Angle         | 45°     |
| Depth             | 0.01 m  |
| Focal point       | 0.06 m  |
| Aperture area     | 0.785 m²|
| Receiver area     | 0.00785 m²|
| Concentrating ratio| 100     |

3.1.1 Parabolic mold

In order to fabricate a fiberglass parabolic dish, it is necessary to create a parabolic mold. In this research, a highly reflective and flexible emergency blanket was applied as a mold. The emergency blanket was stretched by the wood frame as shown in Figure 4 (left). The stretched blanket was glued in a circle with a diameter of 1 meter onto the PVC sheet.

To forming a parabolic shape of the blanket, a pressurized technique was used. Air was compressed slowly into the cavity between the PVC sheet and the blanket to push the blanket to be inflated until achieving the design curve as Figure 4 (right). Note that, parabolic moles with different depths can be easily created by increasing or decreasing the amount of compressed air.
3.1.2 Fiberglass and resin
Once the parabolic mold is obtained, the fiberglass sheet no.450 was used to strengthen the resin no. CPS-515 PTW. As shown in Figure 5 (left), the fiberglass sheet was placed on the emergency blanket mold, and Figure 5 (right) was shown the resin is poured over the fiberglass to achieve the desired parabolic shape.

3.2 The reflector
The reflector material should be excellent reflective to reflect a direct beam efficiently into the receiver. However, the material must be available, low cost, and quality. In this paper, three reflector materials, emergency blankets, PET-mirror, and mirrors were studied.
Three resin dishes obtained from the casting process in section 3.1 are attached to three reflective materials: emergency blanket, PET-mirror, and mirror. Dish 1 is a cast resin plate with an existing emergency blanket as a reflective material. Dish 2 and 3 are attached PET-mirror and mirrors over the emergency blanket, respectively as in Figure 7. The data of the 3 dishes are shown in Table 2.

3.3 The tracking system

3.3.1 Tracking structure

The parabolic concentrator is a point-focus optical system, it is, therefore, necessary to have a dual-axis solar tracking system for the highest efficiency. In this research, three dishes with a diameter of 1 m need to test simultaneously to maintain the same condition. Thus, a two-axis sun tracking system as show in Figure 7 was built. The structure is built to be lightweight and easy to transport. Hence, the elevator and azimuth can be disassembled.

| Data         | Dish 1       | Dish 2       | Dish 3       |
|--------------|--------------|--------------|--------------|
| Diameter(m)  | 1            | 1            | 1            |
| Reflector material | Emergency blanket | PET-Mirror | Mirror       |
| Mass(Kg)     | 4.04         | 4.82         | 6.31         |
| Cost(THB)    | 550          | 1,250        | 2,325        |
3.3.2 Tracking programming
To control the tracking system, the Arduino Mega board was used along with a real-time clock (RTC) to calculate the real-time position (azimuth and elevator angle) of the sun. Two absolute encoders were used to measure the real value of azimuth and elevator angle. The program in the Arduino board is comparing both angles from calculation and encoder to drive azimuth and elevator motor to track the sun as a closed-loop system.

4. Experimental setup
The experimental setup was placed in the Department of Mechanical Engineering, Faculty of Engineering, King Mongkut’s Institute of Technology Ladkrabang on 14th September 2020. In order to investigate the performance of the solar dish with different reflector material, the experiment was set up as shown in Figure 8-9. The water pump was used to pump water pass through the receiver to absorb heat. The rotameter with a range of 0.4-2.4 LPM was used to indicate the flow rate of water through the receiver of each dish.

To test all dishes with the same condition, all three dishes were placed on the 2-axis tracking system as in Figure 8. The tracking control box calculates and tracks the sun’s position every minute to turn the dish to face the sun. The 12VDC battery was used as the power source of the tracing system.

In each dish, three K-type thermocouples were used. Two of them were used to measure the temperature of the water inlet and outlet of the receiver, respectively. Another one was placed at the focal point of the dish as shown in figure 9 to measure the temperature of the focal point. Nine thermocouples were used for three dishes. All of the thermocouples were wired to the Wisco AI 210 data locker to collect the value of all thermocouple temperature. The useful power output from the receiver or receiver power is given by Equation 13 [4].

\[
Q_{heat} = mc_p (T_{out} - T_{in})
\] (13)
5. Result and discussion

The efficiency of three solar parabolic dishes with a diameter of 1 meter and a rim angle of 45° was tested. The reflector material of each dish was made from an emergency blanket, PET-Mirror, and Mirror, respectively. The temperature of the focal point of each dish was shown in Figure 10.

In Figure 10, during the experiment period from 9.00 am-3.00 pm, the temperature at the focal point of all dish was ranged between 200 and 875°C depend on the weather condition. The maximum temperature of dish 1, 2, and 3 are 817°C, 724°C, and 874°C, respectively. The average temperature of dish 1, 2, and 3 are 582°C, 506°C, and 643°C, respectively.

Figure 11 shows the temperature of the water outlet from the receiver of each dish. The maximum water outlet temperature of dish 1, 2, and 3 are 42.4°C, 41.5°C, and 43.4°C, respectively. The average water outlet temperature of dish 1, 2, and 3 are 38.1°C, 37.1°C, and 39.0°C, respectively. The heat power of dish 1, 2, and 3 are 389W, 361W, and 420W, respectively.
Figure 10. The focal point temperature of each dish.

Figure 11. The temperature of the water outlet from the receiver of each dish.

Table 2. was shown the data and experimental results of the three dishes. Besides the maximum temperature and heat power, other interesting ratios are mass and cost of each per its heat power. The result was shown that dish 1 with an emergency blanket has the lowest mass per heat power and cost per heat power of 1.04 x10^{-3} k/W and 1.41 THB/W, respectively.

Table 3. Summarize experimental results of each dishes.

| Data                      | Dish 1       | Dish 2       | Dish 3       |
|---------------------------|--------------|--------------|--------------|
| Diameter (m)              | 1            | 1            | 1            |
| Reflector material        | Emergency blanket | PET-Mirror      | Mirror       |
| Mass (Kg)                 | 4.04         | 4.82         | 6.31         |
| Cost (THB)                | 550          | 1,250        | 2,325        |
| Maximum focal point temp. (C) | 817          | 724          | 874          |
| Maximum heat power (W)    | 389          | 361          | 420          |
| Mass per heat power (x10^3 k/W) | 1.04          | 1.34         | 1.50         |
| Cost per heat power (THB/W) | 1.41          | 3.46         | 5.54         |
6. Conclusion

First of all, this paper presents the parabolic dish fabrication technique. Forming a resin parabolic dish from an emergency blanket mold is a flexible technique. This technique allows the fabrication of a dish of various sizes and rim angles at which low cost. Therefore, it is ideal to create a parabolic dish for research purposes.

The performance of three solar parabolic dishes with different reflector material (Emergency blanket, PET-Mirror, and Mirror) were investigated by experimental test. The dish was designed with a diameter, focal point, and rim angle of 1m, 0.6m, and 45° respectively. The dual-axis tracking system was used to turn the tested dish to the sun so that the solar dish can be performed at the highest efficiency.

The experimental result was shown that the maximum temperature of the dish with an emergency blanket, PET-Mirror, and Mirror are 817°C, 724°C, and 874°C, respectively. The heat power of the dish with an emergency blanket, PET-Mirror, and Mirror are 389W, 361W, and 420W, respectively.

In addition, other parameters that were present are the mass of each dish per its heat power and fabrication cost per its heat power. The result was shown that the dish with an emergency blanket has the lowest mass per heat power and cost per heat power of 1.04 ×10-3 k/W and 1.41 THB/W, respectively. This shows that the fabricating technique is worthwhile in terms of efficiency and price.

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References

[1] Kalogirou S A 2004 Progress in Energy and Combustion Science 30 231-295
[2] Goswami D Y 2015 Principles of Solar Engineering 3rd ed (CRC Press)
[3] Faraz T 2012 Proc. 2nd International Conference on the Developments in Renewable Energy Technology 1-5
[4] Gorjian S Ebadi H Calise F Shukla A and Ingroa C 2020 Energy Conversion and Management 222 113246
[5] Suman S Khan M K and Pathak M 2015 Renewable and Sustainable Energy Reviews 49 192-210
[6] He Y L Qiu Y Wang K Yuan F Wang W Q and Li M J 2020 Energy 198 117373
[7] Barlev D Vidu R and Stroeve P 2011 Solar Energy Materials and Solar Cells 95 2703-2725
[8] Loni R Askari E Areh A Ghobadian B Kasaeian A B Gorjian S and Najafi G 2020 Renewable Energy 145 783-804
[9] Bianchini A Guzzini A Pellegrini M and Saccani C 2019 Renewable Energy 133 382-392
[10] Pavlovic S Daabo A M Bellos E Stefanovic V Mahmoud S and Al-Dadah R K 2017 Journal of Cleaner Production 150 75-92
[11] Mawire A and Taole S H 2014 Energy for Sustainable Development 19 162-169
[12] Hijazi H Mokhiamar O and Elsamni O 2016 Alexandria Engineering Journal 55 1-11
[13] Prinsloo G and Dobson R 2015 Solar Tracking (South Africa: Prinsloo, Dobson)
[14] Venkatachalum T and Cheralathan M 2019 Renewable Energy 139 573-581