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Investigation of Reflective Effect on a Solar Power Collector

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Abstract

This paper presents design and investigation on reflective surfaces of a solar concentrated dish. The parabolic dish is controlled by tracking system to move and adjust the dish precisely for optimal solar power concentration. The parabolic dish surface should be an excellent reflector directing sun beam to concentrate as a spot of power aggregation at the focal point when the dish is perpendicular to the sun. The proposed solar collector has rim diameter, focal point, and surface area of 1.5 m, 0.57 m and 1.95 m², respectively. In order to evaluate reflective effect on solar collective performance, the analysis and experiment were conducted by using the reflective materials including acrylic mirror, PET aluminum and aluminum foil were attached neatly on the satellite dish. The temperature variation on the focal point were instrumented and recorded during sun shine period. The maximum temperature at the focal point of the acrylic mirror dish was obtained in the range of 700-800 °C.

Keywords: solar, collector, reflective

1. Introduction

Fossil fuels in various phrases such as oil, gas, and coal are increasingly utilized and continuously decreased resulting insufficient use and depletion in the near future according to the limitation of such natural resources. However, the utilization of fossil fuels are mostly burned for energy conversion which emits carbon dioxide and toxic gases causing global warming and pollution Solar energy is a renewable and free energy that can be converted to heat or electricity. Since Thailand is located in the tropical areas having good solar potential. The solar potential area is 14.3% of overall area and 19-20 MJ/m² of solar intensity. The solar direct radiation in Thailand is approximately 1350-1400 kWh/ m² covering 4.3% of the country's area [1]. The solar thermal systems are emerging to produce electricity from many technologies [2].

Parabolic dish has the highest efficiency in covert of solar energy to electricity with an efficiency of 29.4% [3]. Kaushika and Reddy [4] proposed the development and performance of a low cost solar steam generating system by modified receivers and, thermally optimized. The experimental results showed that a solar to steam conversion efficiency of 70-80% at 450 °C and cost estimates is 8000-9000 Rs/ m² (US$1 = 400 Rs). Lovegrove el at [5] had built a parabolic dish solar concentrator of an area 400 m² in 1994. They also, developed the design of a 500 m² parabolic dish solar concentrator later in 2010. The design process is, although, successful, but it is costly and area consuming. Gwani et al. [6] presented design and fabrication of solar parabolic dish concentrator that can be used for cooking and drying in rural areas. The satellite dish was adapted to be the solar parabolic dish attached by mirror plates as the reflective materials. From their experiment, the focal solar concentrator can be heated of 100 °C and 180 °C for boiling water and frying oil, respectively. Hijazi et al. [3] presented design a low cost of a parabolic solar dish concentrator by structural simulation with computer program in order to calculate the size of the solar dish concentrator. In the analysis, the focal point to dish diameter ratio is 0.3 and three diameters of the dish of 5, 10 and 20 m are investigated. Autodesk inventor is used for stress analysis of the dish structure frame. From the study, the 10 m of diameter is robust and durable for sustaining wind force and weight.

In Thailand, Sookaramoon et al. [7] presented the two-stage parabolic dish Stirling engine. It is characterized by 2-stage heat source. The first stage, solar is concentrated on the focal point by a solar collector made from the satellite dish as a frame covered by aluminum foil as a reflector. The second stage, mini satellite dish attached on the focal point of the first stage is used to reflect solar energy on such focal point to the Stirling engine. The maximum concentrator efficiency of their concentrator is 26.29%.

The most important of solar collector is reflective surface and position tuning. The excellent reflective material on dish is the key factor. Therefore, this research aims to investigation of reflective the materials on solar dish collector. Mechanical and electrical systems for control and adjust the dish are also described. The aperture area, focal temperature and dish efficiency will be observed

2. Design Methodology

2.1 Solar Power Investigation

Thailand is located in the tropical area and excellent solar power. The direct radiation in Thailand is approximately 1,350 – 1,400 kWh/m² per year. [1] Fig. 1 show the average solar radiation, Bangkok. The global average, diffuse average and direct average were 14.76 MJ/m², 6.14 MJ/m² and 10.25 MJ/m², respectively [8].

The solar radiation a surface generally can be classified in three components, the direct (beam) solar radiation (I_D), the diffuse solar radiation (I_d), and the reflected solar radiation (I_R). The total solar flux is derived from Eq. (1), [9].

$$I = I_D + I_d + I_R \tag{1}$$

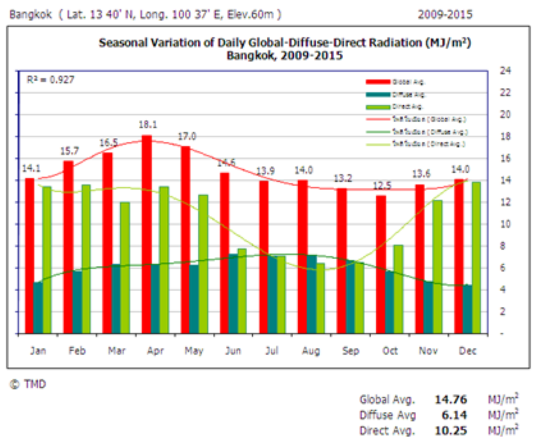
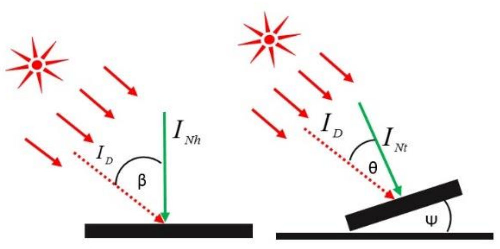


Fig. 1 Diurnal variation of solar radiation in Bangkok during 2009-2015 [8]

2.1.1 Solar beam radiation, I_D

The direct incidence of solar radiation, I_D, is an extraterrestrial solar ray which reaches the earth's surface as depicted in Fig. 2. The angle of direct beam and normal beam radiation on horizontal or tilted surface of β and θ is shown in Fig. 2(a) and (b), respectively.



(a) Horizontal surface (b) tilted surface

Fig. 2 radiations on horizontal and tilted surfaces

Hence, the normal beam irradiation on either horizontal (I_{Nh}) or tilted surface (I_{Nt}), therefore, can be evaluated in Eq. (2) and Eq. (3), consecutively.

$$I_{Nh} = I_D \cos\beta \tag{2}$$

$$I_{Nt} = I_D \cos\theta \tag{3}$$

The ratio of normal beam irradiation on horizontal surface to that on the tilted surface is calculated by Eq. (4).

$$R_B = \frac{I_{Nh}}{I_{Nt}} = \frac{\cos\theta}{\cos\beta} \tag{4}$$

The beam radiation for any surface (I_B) can be defined as in Eq. (5).

$$I_B = I_{Nt} = I_{Nh} R_B \tag{5}$$

2.1.2 Diffuse solar radiation, I_d

Sun ray that has been scattered in the atmosphere but still touched the earth surface is called diffuse solar radiation. The diffuse solar radiation on the tilted surface, I_{dt} can be derived in form of that on the horizontal surface, I_{dh} as in Eq. (6).

$$I_d = I_{dt} = I_{dh}\left(\frac{1+\cos\psi}{2}\right) \tag{6}$$

when ψ is the angle of tilted surface.

2.1.3 Reflected solar radiation, I_R

The reflected ray of solar radiation from surrounding surfaces that then strikes a surface is called the reflected solar radiation. The reflected solar radiation can be approximated by Eq. (7) [10] if the surface is horizontal and the reflection is also diffuse when ρ_g is a solar reflectance of the ground (varies with the type ground) and I_H is the total solar flux striking the horizontal surface.

$$I_R = \rho_g I_H \frac{1-\cos\psi}{2} \tag{7}$$

2.2 Design of the solar parabolic dish concentrator

A parabolic dish is one of the most efficient solar collectors function as both reflector and concentrator. When the solar beam impinges on the parabolic surface, such solar ray will be reflected and concentrated on the focal point [11]. Design of the solar dish collector must consider dish dimension, reflective surface, tracking system and mechanical adjustment.

2.2.1 Dish dimension

Dish feature can be determined from desired solar power which can be achieved by the solar collector depending on solar incident power and area of reflective surface. Dish geometry and a focal point are shown in Fig. 3.

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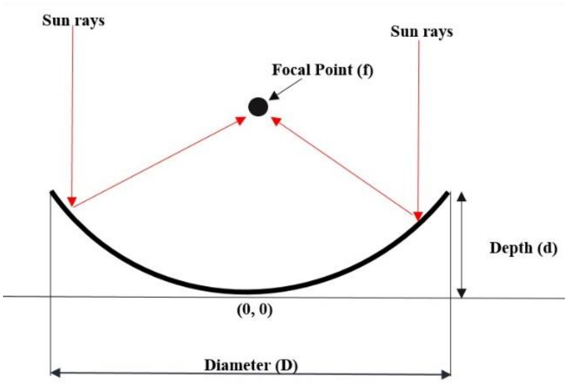

Fig. 3 shows the parabolic dish concentrator parameters

The focal point (*f*) of the concentrator can be calculated by equation:

$$f = \frac{D^2}{16d} \quad (8)$$

The full surface area (A) of the parabolic dish concentrator can be calculated by equation [12]:

$$A = \frac{8\pi f^2}{3}\left\{\left[\left(\frac{D}{4f}\right)^2 + 1\right]^{3/2} - 1\right\} \quad (9)$$

where D is diameter of the parabolic dish concentrator, d is depth of the parabolic dish concentrator and A is full surface area of the parabolic dish concentrator.

2.2.2 Material Selection

The used satellite dish frame, however, is an excellent and preferred choice converting to a solar parabolic dish according to accessibility, standard shape and economic reason.

The reflective material should be an excellent reflector. However, the material considered use should be accessible, cheap and proper. The Table 1 shows the characteristic of some typically materials.

Table 1. The characteristic of materials

Materials/ Properties	Acrylic mirror [13]	PET Aluminum [14]	Aluminum foil [15], [16]
Reflectance (%)	98-99	95-97	88-90
Tensile strength (MPa)	76.04	79.289	□50
Thickness(mm)	1.00-20.00	0.15 -0.20	0.009 -0.04
Cost$/Area(m²)	17.36	14.40	0.64

*1U.S.dollar =35.02 Baht (online: 28/10/2016)

Before manufacturing the prototype dish, the preliminary observations were conducted in order to select reflective material for the collector. Therefore the parabolic models are made equally with the dimension shown in Table 2.

Table 2. Parameter of simulation structure of parabolic

Parameter	Values
Diameter	400 mm
Depth	100 mm
Focal point	100 mm

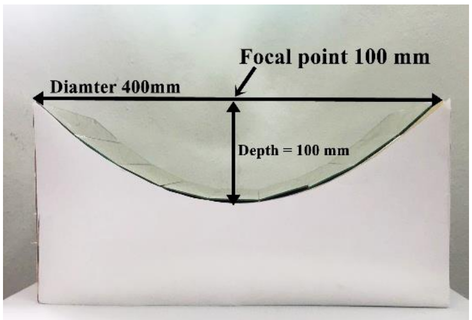

Fig. 4 Parabolic model

In order to investigate reflection of materials, three types of common reflective materials were cut into identical size of 50x150 mm attached on parabolic curve model. The experiments were performed at department of mechanical engineering of King Mongkut's Institute of Technology Ladkrabang, Bangkok. Temperature at focal point of each model was measured by thermocouple and recorded as in Table 3.

Table. 3 Temperature of materials

Materials	Temperature
Acrylic mirror	60 °C
PET Aluminum	54 °C
Aluminum foil	48 °C

Fig. 5 Acrylic mirror

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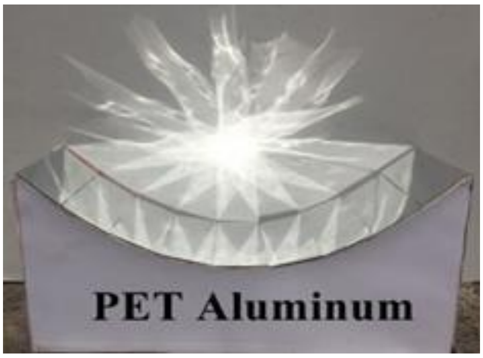


Fig. 6 PET Aluminum

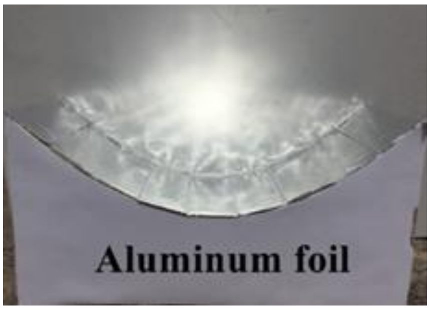


Fig. 7 Aluminum foil

From the preliminary tests, temperature at the focal point of acrylic mirror, aluminum foil, and PET aluminum was 60°C, 54 °C and 48 °C, respectively. It is obvious that the temperatures at the focal point of three materials were corresponding to the reflective performance as listed in Table 1. The acrylic mirror provides the best reflectance of 98-99% while aluminum foil gives the lowest performance of 88-90% reflectance.

Characteristics of light reflection were also taken as in Figs. 5-7. Lights that reflected on acrylic mirror are uniform stripes concentrated at the focal point with clearly white spot as illustrated in Fig. 5. While reflected lights on PET aluminum are fairly deformed and refracted stripes, the focal point can be observed as the moderate white sport in Fig. 6. However Fig. 7 shows that the reflected lights characterized differently on aluminum foil and diffused resulting in the big and blur spot of light concentration.

2.2.3 Thermal efficiency of the solar parabolic dish concentrated

Heat gain of the dish collector can be calculated and considered losses of conduction, convection and radiation in Eq. (10) [17].

$$q_u = IA_{app}\eta_0 - A_{rec}\left[h\left(T_H - T_A\right) + \varepsilon\sigma\left(T_H^4 - T_A^4\right)\right] \quad (10)$$

where I is the direct solar flux intensity, A_{app} is the aperture area , and A_{rec} is the absorber area at the focal point, respectively, η_0 is the collector optical efficiency, h is the conduction/convection coefficient, T_H and T_A are the absorber, the ambient temperature, respectively, ε is the emissivity factor of the collector, and σ is the Stefan-Boltzmann constant.

Thermal efficiency η_s of the solar collector dish is:

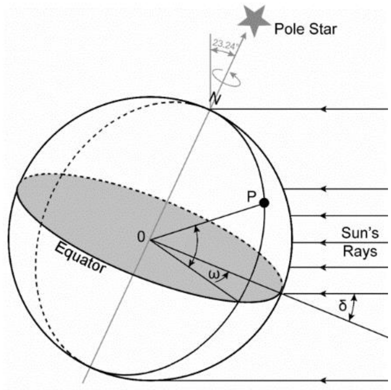
$$\eta_s = \frac{q_u}{IA_{app}} = \eta_0 - \frac{1}{IC}\left[h\left(T_H - T_A\right) + \varepsilon\sigma\left(T_H^4 - T_A^4\right)\right] \quad (11)$$

where c is the collector concentrating ratio.

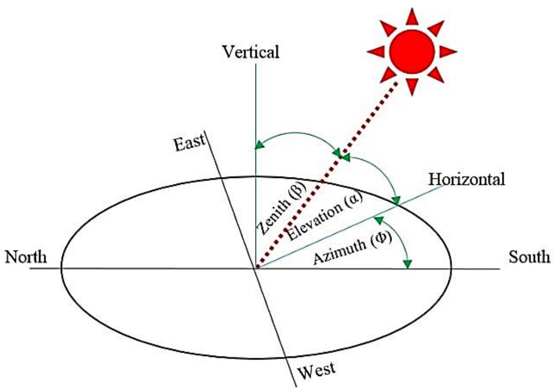
2.3 Sun position and tracking system design

2.3.1 Sun position

In order to achieve efficient solar concentration, solar tracking system, therefore, is necessary component to perceive exact position of the sun. However, sun position cab be evaluated as a function of both the time during the day and the time of year. Solar angle and hour angle are characterized by Fig. 8.



(a) Declination angle & Hour angle [18]



(b) Motion of the sun

Fig. 8 Solar angle

2.3.1.1 Solar hour angle

The angle motion of the sun from local meridian to east (or west), which is 0° at solar noon. Since the Earth rotates 15° per hour. The hour angle, (ω) is calculated as the following equation.

$$\omega = 15°(t_0 - 12) \quad (12)$$

2.3.1.2 Declination Angle

The declination angle (δ) is the angle of a sun's ray in north (or south) measured from the equator as shown in Fig 7(a). The declination angle is calculated as follows: [19]

$$\delta = 23.45 \sin\left[360\left(\frac{284+n}{365}\right)\right] \qquad (13)$$

where n is date i.e. the number of days since 1 January

2.3.1.3 Elevation angle

The elevation angle, (α) is the angle measured from horizontal plane to the position of the sun which can be found from Eq. (14) [19]:

$$\alpha = \sin^{-1}(\sin\delta \sin\varphi + \cos\delta\cos\varphi\cos\omega) \qquad (14)$$

If φ is latitude of the interested location.

2.3.1.4 Zenith Angle

The zenith angle is the angle between the sun and the vertical direction that can be determined from Eq. (15).

$$\beta = 90° - \alpha \qquad (15)$$

2.3.1.5 Azimuth Angle

The azimuth angle (ϕ) is the angle between due south and the observed position, which varies with the latitude and time of year [19] and verified in Eq. (16).

$$\phi = \cos^{-1}\left(\frac{\sin(\delta)\cos(\varphi) - \cos(\delta)\sin(\varphi)\cos(\omega)}{\cos(\alpha)}\right) \qquad (16)$$

Table. 4 Parameter of sun position.

Experiment Date: May 24th 2016 at 10:00 am	
Day number (n)*	144 Days
Latitude	13.844 degree
Longitude	100.508 degree
Hour angle	-30.00 degree
Declination angle	20.730 degree
Elevation angle	60.550 degree
Azimuth angle	108.240 degree
Zenith angle	29.45 degree

*n is date i.e. the number of days since 1 January

2.3.2 Dish controlling systems

The systems used to control the solar collector are cooperated by solar tracking system and mechanical system.

2.3.2.1 Solar tracking system

In order to adjust solar dish collector correctly, electronic circuit including microcontroller was programed to control motor powering the mechanical system precisely. Date, time of the day and the year and location must be firstly input to the microcontroller for evaluation of sun position and angles and then switching motor relay. Figure 9 shows schematic electronics circuits of the tracking system.

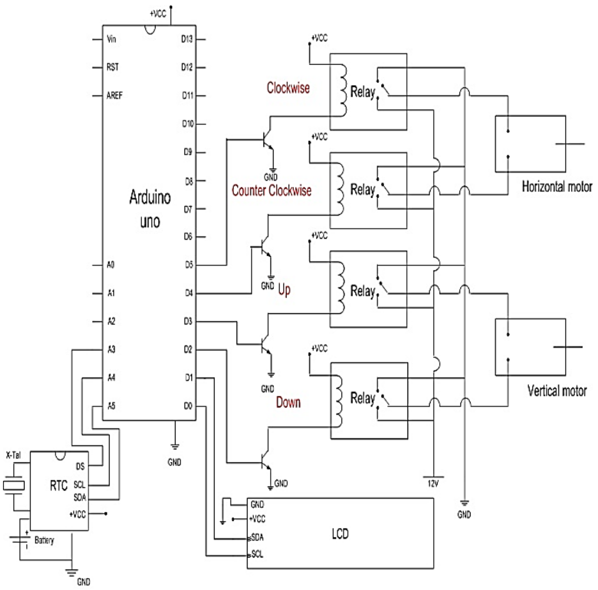
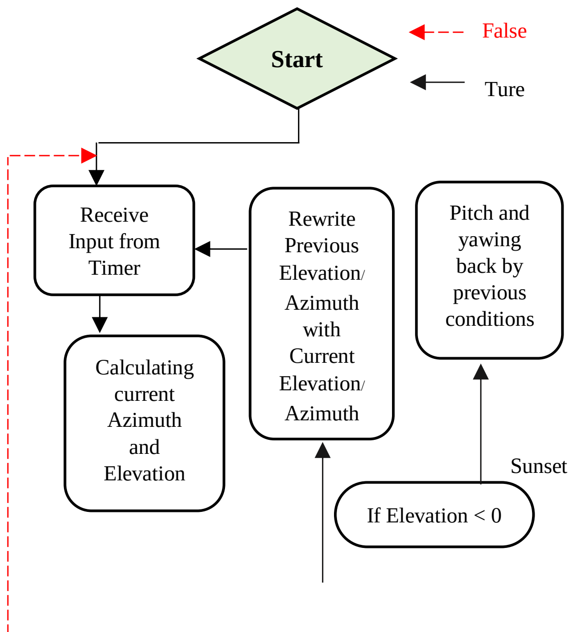


Fig. 9 Electronic circuits schematic sun tracking system

2.3.2.2 Mechanical system

The driving mechanism of solar dish is used to adjust dish position as demonstrated in Fig. 11. Two sets of worm gear reduction are designed for driving dual axis, vertical axis and horizontal axis depending on azimuth angle and elevation angle of the sun, respectively. Driving motor is selected regarding power input, gear ratios, load, torque and speed. Power supply and mechanical system are described in Table 5.



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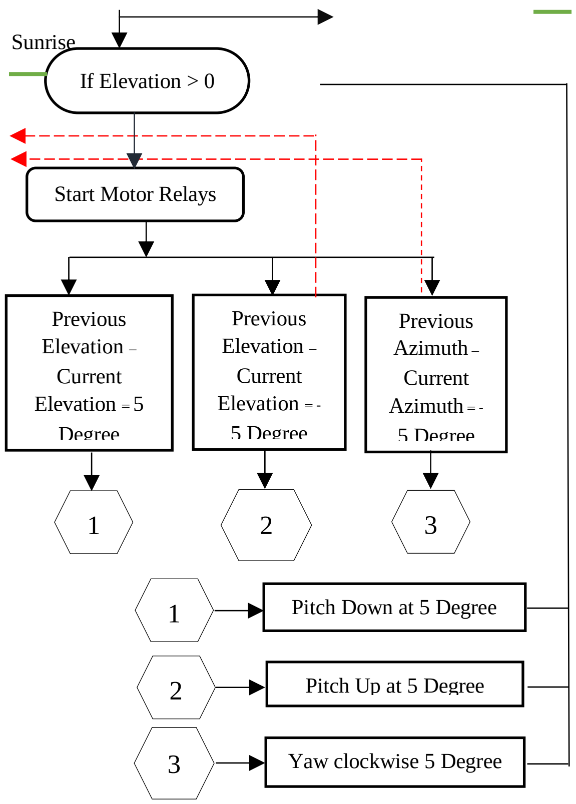

Fig. 10 The diagram a processing of tracking system.

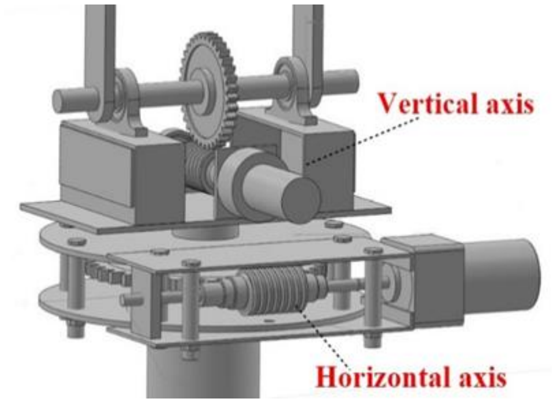

Fig. 11 Schematic diagram the driver mechanism of dish

Table. 5 Description of the transmission system

Description	Value
Power input of motor	12V ,3 A
Power output of motor	6.87 N·m at 5 RPM
Gear ratio of vertical axis	12 : 1
Gear ratio of horizontal axis	15 : 1
Maximum Torque Output of vertical axis	83 N·m
Maximum Torque Output of horizontal axis	103 N·m
Vertical Gear Diameter	150 mm
Horizontal Gear Diameter	200 mm

The gear ratio is defined as the input speed of a driving worm to the output speed of the driven gear as in Eq. (17) [20] where m_{GW} is the gear ratio, ω_W is angular speed of worm pinion, ω_G is angular speed of worm gear, N_G is number of teeth of a worm gear and N_W number of teeth of a worm pinion.

$$m_{GW} = \frac{\omega_W}{\omega_G} = \frac{N_G}{N_W} \qquad (17)$$

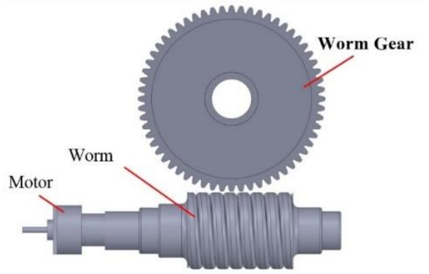

Fig. 12 Worm gear set

3. Experimental Setup

The schematic of the experimental setup is represented in Fig. 13. Thermocouple is installed to measure temperature of the focal point. Battery is used as a power supply for electronic circuit and motor in the remote testing site.

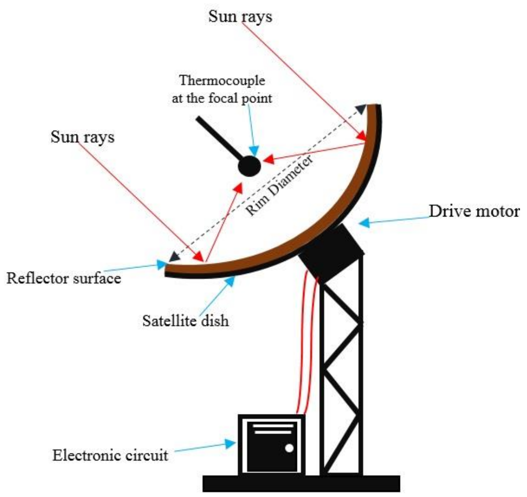

Fig.13 The experimental setup

4. Results and Discuss

The results for testing efficiency a reflective of materials at Department of Mechanical Engineering, Faculty of Engineering, King Mongkut's Institute of Technology Ladkrabang, Bangkok.

Table. 6 Data of location at date experimental.

Location: Department of Mechanical Engineering, Faculty of Engineering, King Mongkut's Institute of Technology Ladkrabang, Thailand

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The local longitude	100.772
The local latitude	13.728
Date	24th may 2016
Time	10:00 AM – 15:30 PM

From the preliminary investigation, three samples of reflective materials were tested and found that the acrylic mirror and PET aluminum provided the focal temperature of 60 °C and 54 °C, respectively. Therefore acrylic mirror and PET aluminum were used and laminated on dish surface as shown in Fig. 14 and 16, respectively. The prototype dimension of solar dish is presented in Table 7.

Table 7. The dimension of solar collector

Parameter	The material was acrylic mirror	The material was PET aluminum
Diameter	1.50 m	2.00 m
Depth	0.25 m	0.20 m
Focal point	0.57 m	1.25 m
Surface area	1.95 m²	3.26 m²
Frame of dish	Satellite dish	Satellite dish

The experiments were conducted during the sunny day in May 2016. The variation of temperature at the focal point versus diurnal time of the acrylic mirror dish is plotted in Fig. 15 while that of the PET aluminum dish is presented in Fig.17.

The acrylic mirror dish gave significantly higher maximum temperature at the focal point of 938 °C than that of 69°C at the focal point on the PET aluminum dish collector. The average temperature of the focal point on the acrylic mirror and PET aluminum dish was 804.5 °C and 52°C, consecutively.

Fig. 14 the material on solar collector was acrylic mirror

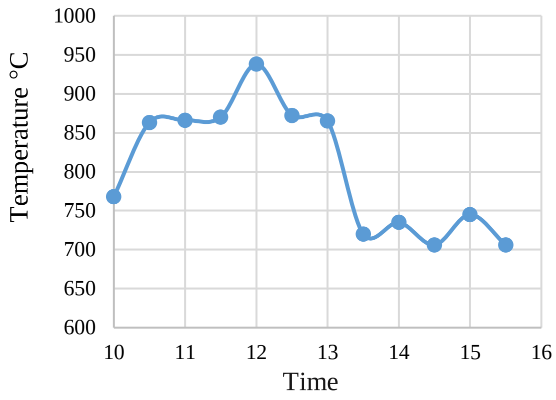

Fig.15 The temperature at the focal point of the materials was acrylic mirror.

Fig. 16 the material on solar collector was PET aluminum

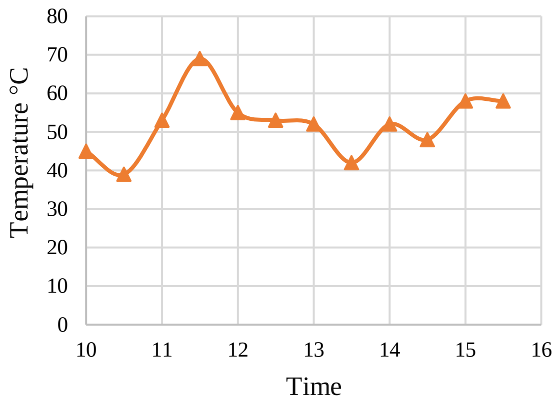

Fig. 17 The temperature at the focal point of the materials was PET aluminum.

5. Conclusion

The reflective materials on solar collectors were investigated experimentally. The test site was located at KMITL in Bangkok, Thailand. From the preliminary observation of reflective materials including acrylic mirror, PET aluminum and aluminum foil on the same parabolic curve profile was found that acrylic mirror surface gave the highest value of the maximum temperature at the focal point while that of PET aluminum surface was comparatively lower. Each prototype dish, therefore, was neatly attached by acrylic mirror and laminated PET aluminum sheets. Temperature at the focal point on each dish was measured. The acrylic mirror dish is the best reflective material compared to PET aluminum and aluminum foil.

6. Acknowledgement

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