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Applied Research Concerning the Selection of Track Modes of Parabolic Trough Collectors in Sub-tropical Area

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Abstract

The optical performance of Parabolic Trough Collectors (PTCs) for various tracking modes in sub-tropical area (for latitude of 25.02°) were investigated with Hottel model, incidence angle and daily irradiation during equinoxes and solstices, as well as annual incident irradiation were all compared. Results show that, the mode of tracking affects the amount of incident radiation falling on the collector surface, for four tracking modes, PTCs obtain much more irradiation in summer and much less in winter, and the optimum period for solar thermal application is between March and October. Besides, for two axes rotating tracking, polar E-W tracking, horizontal E-W tracking and horizontal N-S tracking, the relative proportion of yearly irradiation yield are 100%, 95.93%, 91.32% and 73.67% respectively. The selection of tracking mode for PTCs should not only take into consideration of temperature delivered, heat demand level, but also all the costs for manufacture, the auxiliary energy required for tracking drive, and other overheads.

Keywords: *parabolic trough collector, solar energy, solar radiation, irradiance, tracking*

1. Introduction

Energy is a key factor in determining the economic development. Limited fossil resources and severe environmental problems require new sustainable options, solar thermal applications with optical concentration technologies are therefore important alternatives for providing the clean and renewable energy needed in the future.

PTCs are made by bending a sheet of reflective material into a parabolic shape. Metal black tubes, covered with a glass tube to reduce heat losses, are placed along the focal line of the receiver. When the parabola is pointed towards the sun, parallel rays incident on the parabolic trough reflector are reflected onto the receiver tube on the focal line (Figure 1).

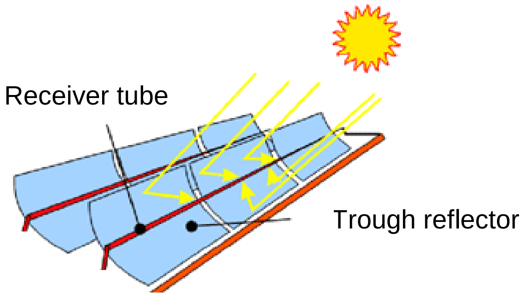

Figure 1. Schematic of Parabolic Trough Collector

PTCs are widely used to generate heat for the temperature range between 50℃ and 400 ℃ for solar thermal power generation or process heat applications, such as heating, drying, chemical, desalination, distillation and evaporation, *etc.*, as in [1, 2].

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With more than two-third of land receiving radiation of more than 5.02×10^3 MJ/m^2/yr (Figure 2), China is well endowed with solar energy as a low-carbon and pollution renewable alternative and is trying to exploit it fully. As a result, solar thermal application is underemphasized in China's renewable energy plan.

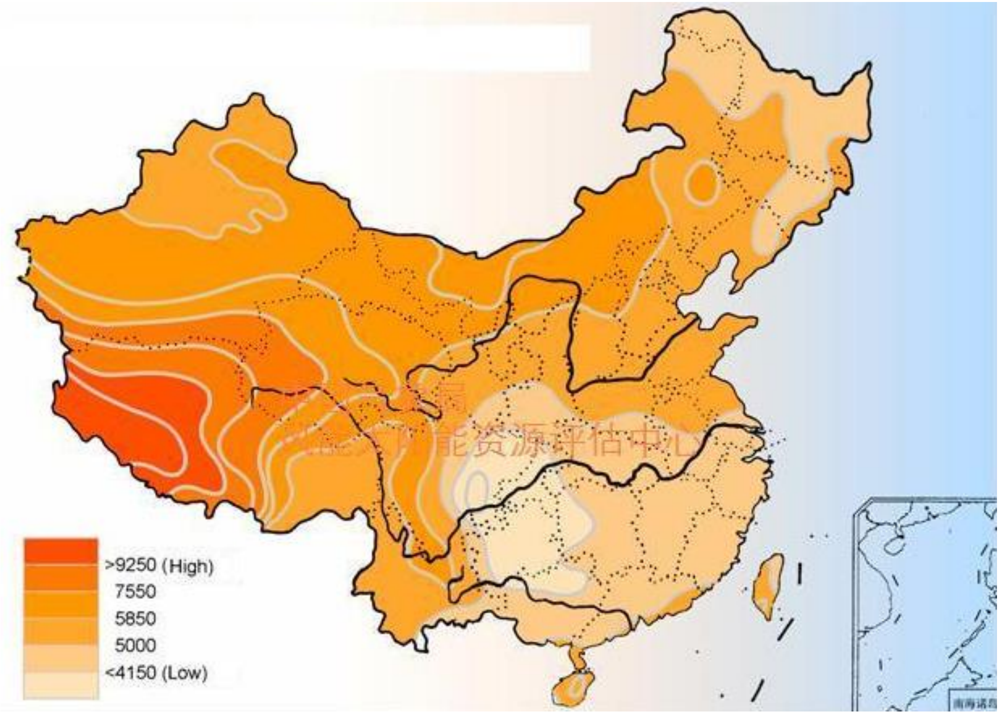


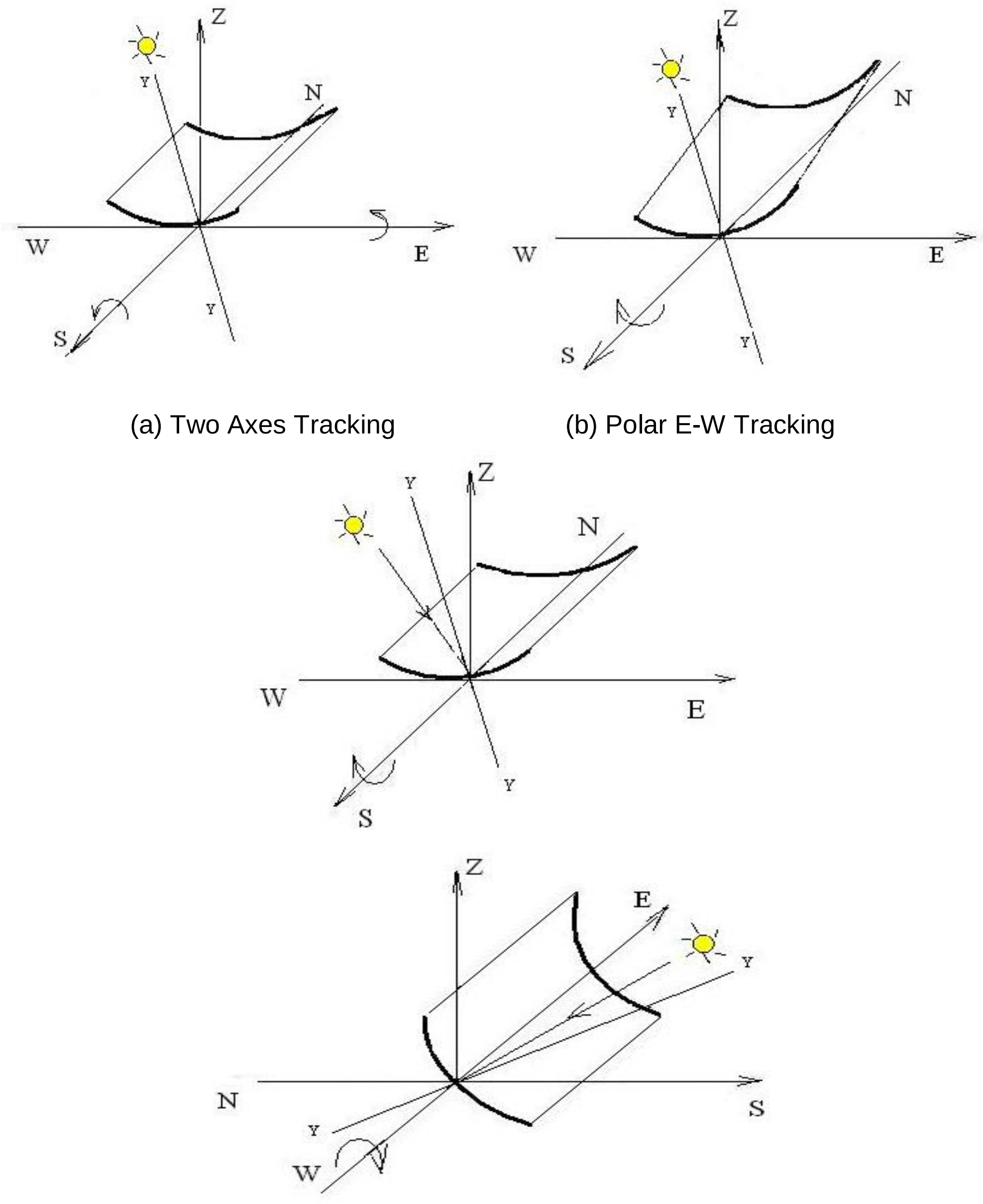
Figure 2. Solar Radiation Resource in China

In this paper, the optical performance of PTCs for various tracking modes is investigated with Hottel model in sub-tropical area (for latitude of 25.02°), the selection of tracking modes is therefore discussed, and some useful results are obtained.

2. Concentration Performance of PTCs for Various Tracking Modes

2.1. Tracking Modes

Generally, the modes of tracking for PTCs can be divided into a single axis tracking or two axes tracking, as shown in Figure 3. Two axes tracking follows not only the sun's changing altitude, but also the sun's changing azimuth, so as to concentrate the parallel rays incident on the reflectors right onto the receiver tube, while for single axis tracking, the collectors can be orientated in a north-south direction and track the sun from east to west (horizontal E-W tracking), and can be orientated in an east–west direction, track the sun from north to south (horizontal N-S tracking), or be installed and tilted at an angle equal to the latitude of the installation site facing directly to the sun and track the sun's east–west movement (polar E-W tracking), as in [3-8].



(a) Two Axes Tracking (b) Polar E-W Tracking

(c) Horizontal E-W Tracking (d) Horizontal N-S Tracking

Figure 3. Schematic of Various Tracking Modes of PTCs

2.2. Incidence Angle

As in [9], solar altitude angle α_s, solar azimuth angle γ_s and solar declination δ can be calculated by

$$\alpha_s = \arcsin(\sin\varphi \sin\delta + \cos\varphi \cos\delta \cos\omega) \tag{1}$$

$$\gamma_s = \arccos\left(\frac{\sin\alpha_s \sin\varphi - \sin\delta}{\cos\alpha_s \cos\varphi}\right) \tag{2}$$

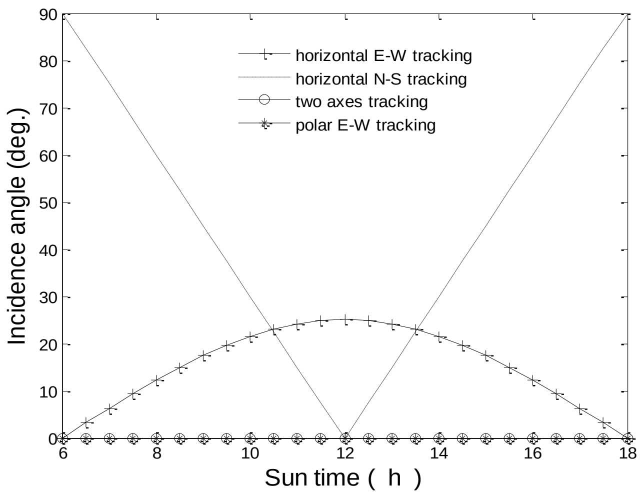
$$\delta = 23.45 \sin\left(2\pi \times \frac{284 + n}{365}\right) \tag{3}$$

Where n is the day number, ω is hour angle, φ is latitude.

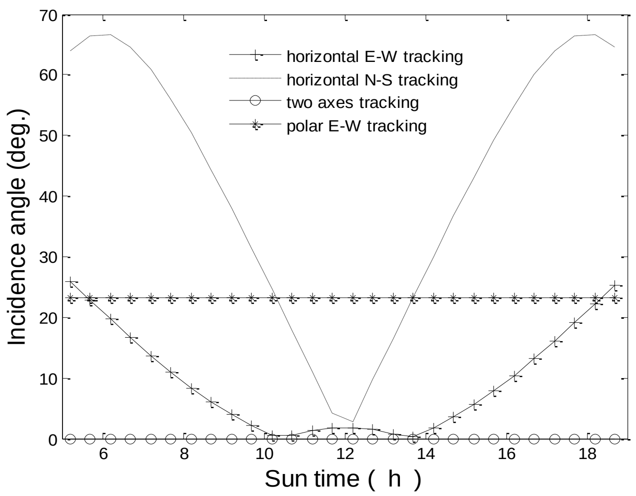
The incidence angle between the sun beam and the main normal direction of PTCs, affects the amount of incident irradiation obtained on the reflectors (cosine loss), which is relied on the mode of tracking, as shown in Table 1 [9]. Incidence angles during solstices and equinoxes for latitude of 25.02° in the sub-tropical area of the northern hemisphere for various tracking mode are shown in Figure 4.

Table 1. Incidence Angle for Various Tracking Modes

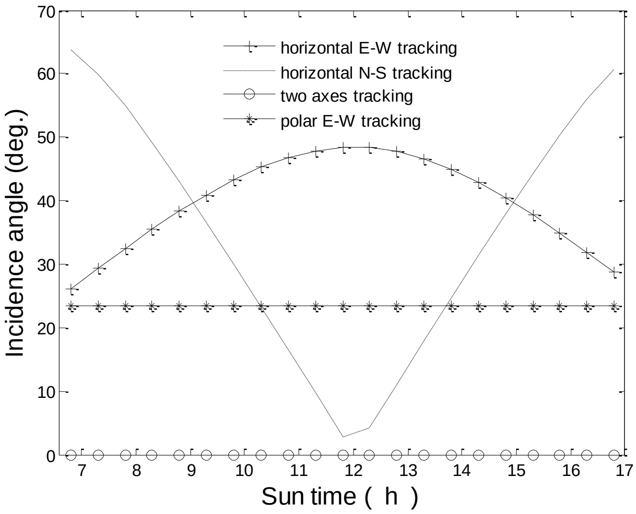
Mode of tracking	Incidence angle
two axes tracking	0°
collector axis in N-S axis polar E-W tracking	δ
collector axis in N-S axis horizontal E-W tracking	$\arccos \sqrt{1 - \cos \alpha_s^2 \cos \gamma_s^2}$
collector axis in E-W axis horizontal N-S tracking	$\arccos \sqrt{1 - \cos \alpha_s^2 \sin \gamma_s^2}$



(a) Equinoxes



(b) Summer solstice



(c) Winter solstice

Figure 4. Incidence Angle for Various Tracking Modes of PTCs

It can be seen for two axes tracking, the incidence angles of PTCs remain 0° due to full movement tracking of the sun, while for polar E-W tracking, incidence angles follow only the change of solar declination, which are minimum at equinoxes and maximum at solstices. For horizontal E-W tracking, the incidence angles are more than 26° at winter solstice, which are relatively larger compared with those at equinoxes and summer solstice, which are varying between 0° and 27°. Compared with horizontal N-S tracking, whose incidence angle reaches its lowest value of 0° at noon and varies remarkably from morning to the afternoon, the incidence angle of that of horizontal E-W tracking generally reaches its peak at noon during equinoxes and solstices.

2.3 Incident Irradiation

As in [9], Hottel model for estimating the beam radiation transmitted through clear atmospheres $G_{b,n}$ is used for sub-tropical area (at latitude of 25.02°) with 23km visibility, which is given by

$$G_{b,n} = 1367\left(1 + 0.033\cos\frac{2\pi n}{365}\right)\tau_b \qquad (4)$$

Where τ_b is the atmospheric transmittance for beam radiation, can be given by the following equation

$$\tau_b = a_0 + a_1\exp(-k/\cos\theta_z) \qquad (5)$$

The constants in this equation are given by

$$a_0 = 0.95a_0^*, \quad a_1 = 0.98a_1^*, \quad k = 1.02k^* \qquad (6)$$

Where,

$$a_0^* = 0.4237 - 0.00821(6 - A)^2 \qquad (7)$$

$$a_1^* = 0.5055 + 0.00595(6.5 - A)^2 \qquad (8)$$

$$k^* = 0.2711 + 0.01858(2.5 - A)^2 \qquad (9)$$

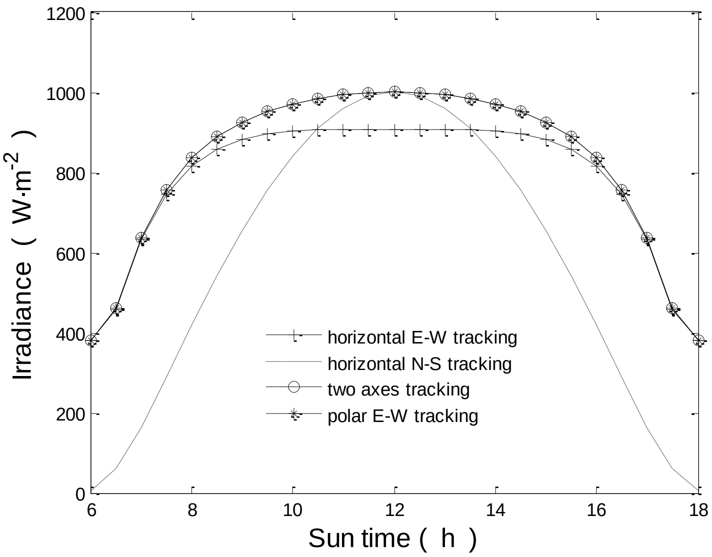
Where A is the altitude of the observer in kilometers, and is given by 2.0 km.

Operating time for PTCs is assumed to be from sunrise to sunset. As in [9], sunset hour angle ω_s and the number of daylight hours S_0 can be solved by the following equations

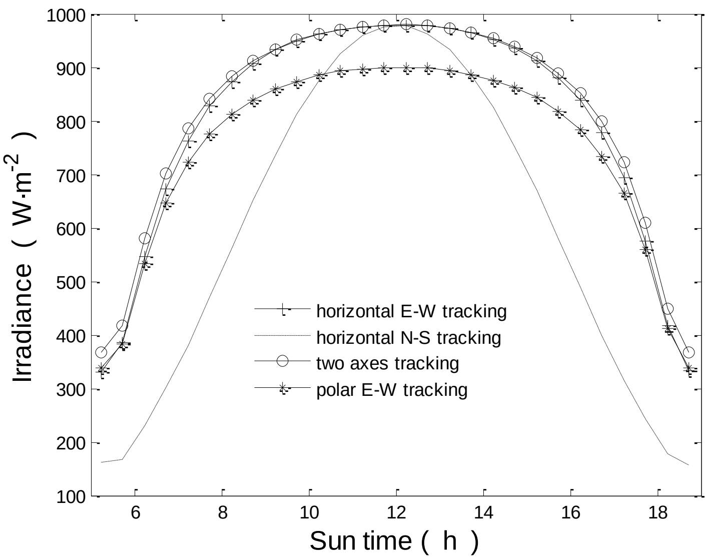
$$\omega_s = \arccos(-\tan\delta\tan\varphi) \tag{10}$$

$$S_0 = \frac{2}{15}\omega_s \tag{11}$$

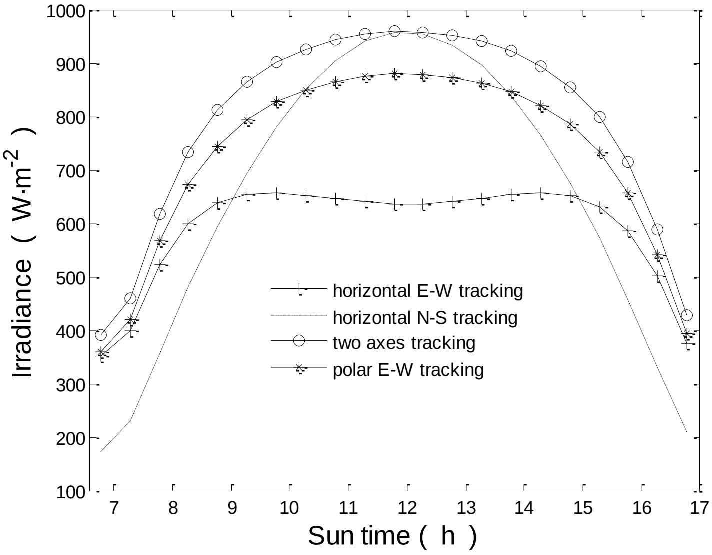
Incident irradiation falling on the collector surface is in proportion to the cosine of the incidence angle. The incident irradiance for various tracking modes during equinoxes and solstices is given in Figure 5.



(a) Equinoxes



(b) Summer solstice



(c) Winter Solstice

Figure 5. Incident Irradiance for Various Tracking Modes of PTCs

It can be seen corresponding to the characteristics of sun radiation, incident irradiance for various tracking modes is larger at about noon, and smaller in the early morning and the late afternoon. The irradiance is the largest for two axes tracking and the polar E-W tracking during equinoxes among them. However, the performance of polar E-W tracking during solstices decreases a little bit. During the period from 8 a.m. to 16 p.m., for horizontal N-S tracking, the variation of incident irradiance on the collector surface is quite larger, with its highest value presenting in the middle of day, while on the contrary, the variation of incident irradiance for horizontal E-W tracking is quite smaller, with 2 peaks occurring at about 3 hours before and after noon. While it can also be seen the collector performance during the early and late hours of the day is greatly reduced due to large incidence angles for horizontal N-S tracking. On the contrary, horizontal E-W tracking troughs have their highest cosine loss at noon and the lowest in the mornings and evenings.

Energy absorbed for various tracking modes during solstices and equinoxes is shown in Table 2.

Table 2. Comparison of Energy Absorbed for Various Tracking Modes

Mode of tracking	Percent to two axes tracking,%			Daily irradiation,MJ/m^2		
	E	S S	W S	E	S S	W S
two axes tracking	100%	100%	100%	37.02	40.75	29.89
Polar E-W tracking	100%	91.9%	91.9%	37.02	37.46	27.43
horizontal E-W tracking	94.8%	98.4%	74.5%	35.10	40.09	22.26
horizontal N-S tracking	68.9%	73.2%	81.8%	25.51	29.82	24.45

Note: E: equinoxes, SS: summer solstice, WS: winter solstice.

Two axes tracking, which collects the maximum amount of solar radiation, is defined as 100%, in this case, the performance of other tracking modes can be compared to it. For polar E-W tracking, the irradiation obtained will be lowered to 91.9% at solstices. As for horizontal E-W tracking, the incident irradiance is comparatively larger during equinoxes and summer solstice, daily irradiation is therefore more than 94.8%, while this value decreases to 74.5% at winter solstice due to larger incidence angle. On the contrary, the performance of horizontal N-S tracking is worse during equinoxes and summer solstice, which is at about 70%, but is better to be 81.8% at winter solstice.

As shown in Figure 6, daily irradiation for various tracking modes is comparatively larger in summer and smaller in winter. Among them, the variation is the largest for horizontal E-W tracking, while smallest for horizontal N-S tracking. In other words, horizontal N-S tracking collects more radiation in winter and less in summer than those of horizontal E-W tracking, providing a more constant annual output.

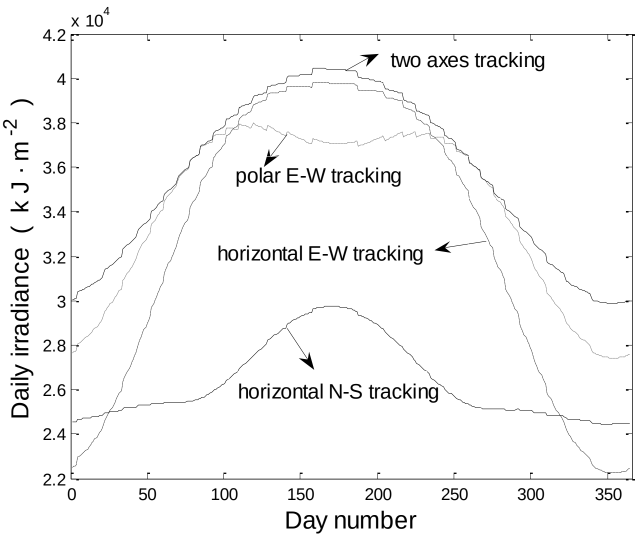


Figure 6. Daily Incident Irradiation for Various Tracking Modes

Monthly incident irradiation for various tracking modes is shown in Figure 7.

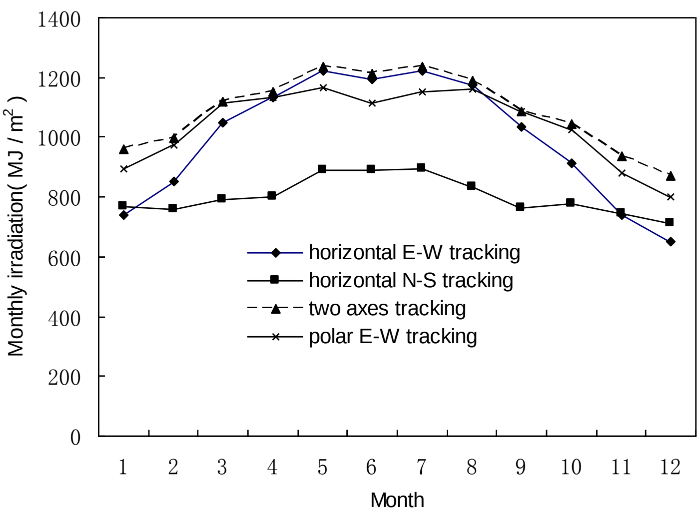


Figure 7. Monthly Incident Irradiation for Various Tracking Modes

For monthly incident irradiation, it can be seen, the performance of four tracking modes is much better during the period from March to October, while is worse between

November and February. Therefore, the better period for solar radiation collection in sub-tropical area should be from March to October.

As for annual incident irradiation for various tracking modes, as shown in Table 3, two axes tracking leads the first, obtaining about 13.03 GJ per square meter of PTCs, and then polar E-W tracking, after that, horizontal E-W tracking, with horizontal N-S tracking in the very end. Compared with that of two axes tracking, their relative proportions of yearly irradiation yield, are 100%, 95.93%, 91.32% and 73.67% respectively. Over the period of one year, horizontal E-W tracking collects more solar radiation than horizontal N-S tracking.

Table 3. Annual Incident Irradiation for Various Tracking Modes

Mode of tracking	Annual irradiation,GJ/m^2
horizontal E-W tracking	11.9
horizontal N-S tracking	9.6
two axes tracking	13.03
polar E-W tracking	12.5

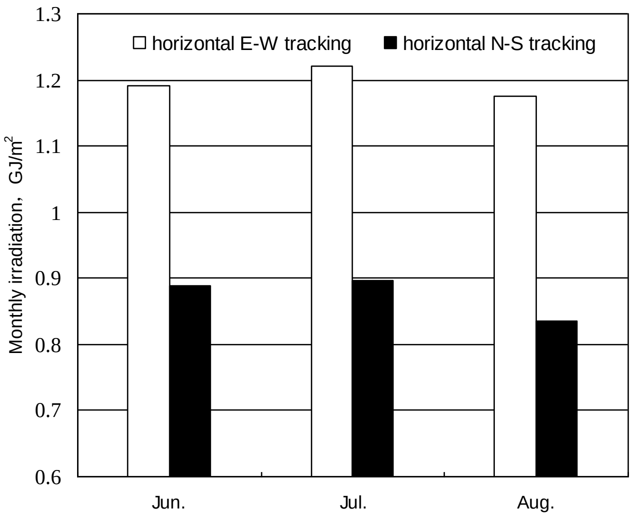
3. Selection of Tracking Mode of PTCs

Industrial processes using solar heat at different temperature levels generally range from 60℃ to 260℃ [8]. As for the application of solar energy in sub-tropical area, the optical performance of PTCs varies with various tracking modes. As for annual incident irradiation for various tracking modes, two axes tracking leads the first, and then polar E-W tracking, after that, horizontal E-W tracking, with horizontal N-S tracking in the very end. To meet the same level of heat demand, the covered land of corresponding solar field will decrease accordingly for these four tracking modes.

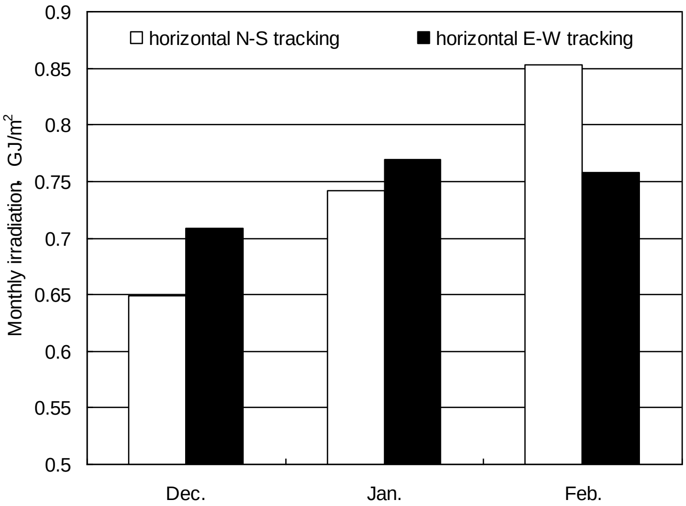
While the fact should be noticed that the performance of PTCs depends largely on their tracking mechanism, which must be reliable and able to follow the sun with a certain degree of accuracy, and return the collector to its original position at the end of the day or during the night. The capital costs of PTCs should not only take account of the costs for the reflective surface, shell, supportive frame, but also the costs for gears, motors and other components of the assemble. All the costs should be estimated for materials, labor, and overheads. Overheads include such items as transportation from manufacturing plants to field sites, field rental, pipe supports, foundations, maintenance and operation fees [10].

The main advantage of two axes tracking is its higher efficiency, because of having a zero incidence angle, however, it also has several important disadvantages in its greater mechanical complexity, less rigidity, higher maintenance costs and more auxiliary pipes. Therefore, two axes tracking can be only used especially in higher temperature applications as in power generation system. Generally it is sufficient to use a single axis tracking for industrial process-heat application. For the difficulty of driving tilted axis, horizontal axis tracking is commercially employed for PTCs.

It can be seen from Figure 7, compared with horizontal N-S tracking, horizontal E-W tracking system is superior with respect to the incident irradiation falling on the collector surface and the useful energy extracted which results in a higher annual irradiation collected and smaller auxiliary energy required, however the variation of horizontal E-W tracking during the year is larger, which collects more radiation in summer and much less in winter, switching from high temperature level in summer to low temperature level in winter may also make the solar heating system much more complicated. Therefore, the choice of tracking normally depends on the application and whether more energy is needed during summer or during winter.



(a) Summer



(b) Winter

Figure 7. Seasonal Comparison for Horizontal Tracking Modes

Other factors are also needed to be considered when more than one collector is needed. Although the horizontal tracking can benefit quite a lot from less shadowing when more than one collector is used, shadowing is still present in the first and last hours of the day for horizontal E-W tracking and at winter solstice for horizontal N-S tracking [2].

4. Conclusion

This paper presents the configuration of PTC and its various tracking modes. With trough reflector with a parabolic shape concentrating the direct solar radiation onto the receiver tube located in the focal line of the parabola, the collector can be orientated in an east–west direction, tracking the sun from north to south, or orientated in a north–south direction or parallel to the earth's axis and tracking the sun from east to west, or even moved in two axes for full tracking the sun in order to deliver high temperatures with good efficiency required.

The mode of tracking affects the amount of incident radiation falling on the collector surface. This paper presented a comparison of the optical performance for various tracking modes of PTC. The total amount of energy falling on the surface of PTC is the largest for two axes tracking and the polar E-W tracking over the period of one year, and it is slightly larger for a horizontal E-W tracking than that of a horizontal N-S tracking, while the former collects more energy in summer but less in winter, and the latter provides a more constant annual output but reduces its performance during the early and late hours of the day due to large incidence angles.

The selection of tracking modes made here allows a comparison between the cost of different tracking systems and different heat demand. It is the fact that the mode of tracking affects the amount of incident radiation falling on the collector surface, as a result, the selection of tracking mode for PTCs should take into consideration of the temperature delivered, heat application demand, and all the costs for the solar field. For industrial process-heat application, horizontal axis tracking is commercially employed. If heat demand exists in winter, then horizontal N-S tracking is recommended, while if heat demand exists in summer, then horizontal E-W tracking will be superior in spite of much more rainy days in sub-tropical area for latitude 25.02° and the better period for solar radiation collection should be from March to October.

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