

Tracking mechanism and cosine effect study of Module-Heliostat Solar Collector

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Keyword: solar collector, tracking mechanism, cosine effect.

Abstract. Concentrated solar power is one of the most promising technique for significantly reducing the consumption of fossil fuels. In this paper, a quasi-two-dimensional tracking solar concentrator- module heliostat (M-H) collector and its tracking mechanism are discussed. Comparing to the traditional two-dimensional tracking method, the M-H system only track the azimuth angle of the sun in real time, while the other dimension, the elevation angle, is changed once a day. This tracking method make it possible to achieve low cost, precise, and robust tracking. To quantitatively determine the efficiency, the cosine loss of this system is calculated. The result indicates that the cosine loss of M-H collector is as low as 1%.

Introduction

Concentrated solar power generation uses mirrors or lens to condense large areas of low-density sunlight into small areas of high-density sunlight, then electricity is generated by photovoltaic or photothermal action [1]. Unlike traditional thermal power, solar energy cannot provide sustained and stable output, resulting in solar energy is difficult to transfer to the current power grid. This requires that solar power must be able to be stored. Compared to electricity storage, thermal storage technology is suitable for large-scale applications and has a cost advantage. Therefore, concentrated solar power is considered an ideal solution for the energy crisis [2,3].

The difficulty of concentrating solar energy technology is how to precisely track the movement of the sun. Among the many tracking methods, two-dimensional disc tracking has the highest accuracy and the smallest cosine loss. However, this method relies on a heavy tracking mechanism, and its own energy consumption and cost are also factors that cannot be ignored. In this paper, tracking mechanism of a new type of tracking technique- Module heliostat (M-H) is discussed. The M-H concentrator can achieve more than 200 times focus ratio with a quasi-two-dimensional tracking mechanism. Calculation of cosine loss indicates that Module heliostat (M-H) can achieve energy efficiency closed to two-dimensional tracking.

Tracking mechanism of the M-H collector

The general two-dimensional tracking collector has two tracking axes. One is for tracking the azimuth angle (referred to herein as hour angle), while the other axis to tracking the declination angle (referred to herein as season angle). In the M-H concentrator system, the polar axis is used to track the hour angle, while another axis, season axis, is used to track the season angle. As is shown in Figure 1, the polar axis is parallel to the polar axis of the earth and the season axis is perpendicular to the polar axis.

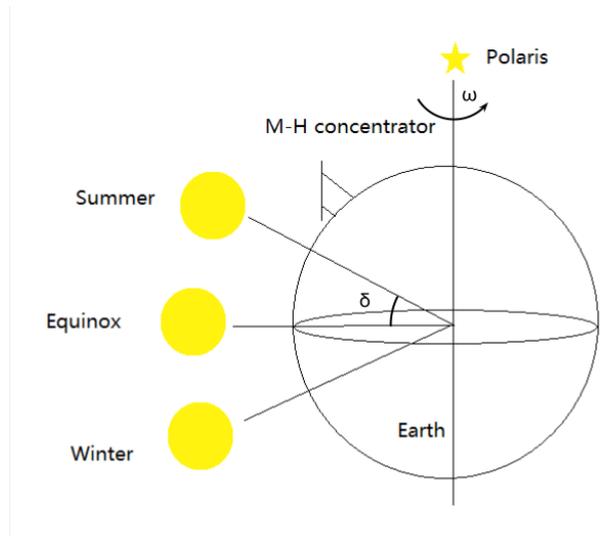


Figure 1. The alignment illustration of the M-H concentrator. δ and ω is the season angle and hour angle, respectively.

It is equivalent to that the M-H collector is laid in the horizontal plane of the equator. Because the season angle changes less than 0.3 degrees each day, it is approximately constant in a single day. The panel rotates around the polar axis to track the hour angle in real time, while season axis only need to rotate a small degree once a day, which significantly reduce the tracking mechanism and cost. Based on the principle of optical reflection, when the season angle changes δ , the season axes rotate $\delta/2$ to achieve tracking.

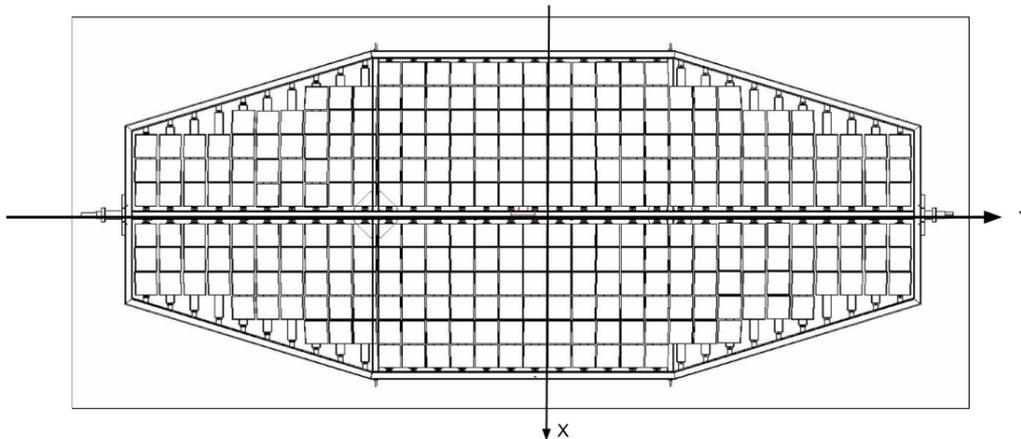


Figure 2. Top view schematic drawing of the M-H concentrator panel.

As shown in Fig. 2, there are 300 mirrors in one panel of the M-H collector, which is similar to a Fresnel lens being divided into 300 parts. Each mirror is 10 cm by 10 cm and the distance between two adjacent mirrors is 6 mm. The direction of the incidence ray is perpendicular to the panel on spring (or autumn) equinox and on that day the reflection ray is directly to the collector target. On solstice the angle between the sunlight and the normal of the panel, the season angle, is 23.5 degrees. Figure 3 shows the schematic diagram of season angle tracking.

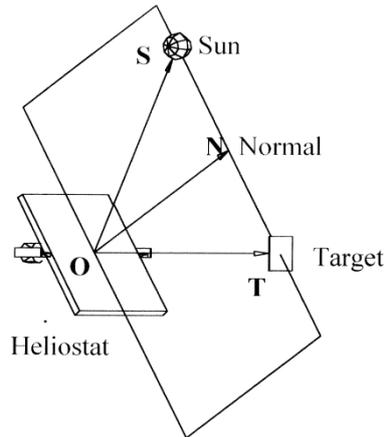


Figure 3. Schematic diagram of season angle tracking.

Definition of cosine effect

Cosine effect is defined as the reduction of the receiving area caused by the cosine angle formed between the solar radiation and the normal line, as shown in Fig. 4. Cosine effect is an extremely important concept as it is one of the main reasons that causes the energy loss in solar energy concentration system [4]. As is shown in Figure 4, the angle α is the angle between the incidence line and the normal line of the mirror, so $\cos\alpha$ represents the ratio of the effective area to the real area.

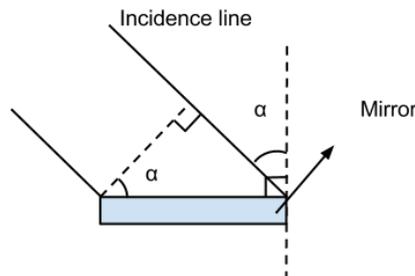


Figure 4. Definition of cosine effect. α is the angle formed between the incident line and the normal line, so the cosine loss is derived as $(1-\cos\alpha)$.

Calculation of cosine effect of M-H collector

The variation of season angel is given by equation. (1)[5], and the diagram is shown in Fig. 5.

$$\sin \delta = 0.39795 \cos [0.98563(N - 173)] \quad (1)$$

The argument of the cosine here is in degrees and N is the day number. For example, January first corresponds to N=1, December thirty-one to N=365, and the spring equinox corresponds to N=79, respectively.

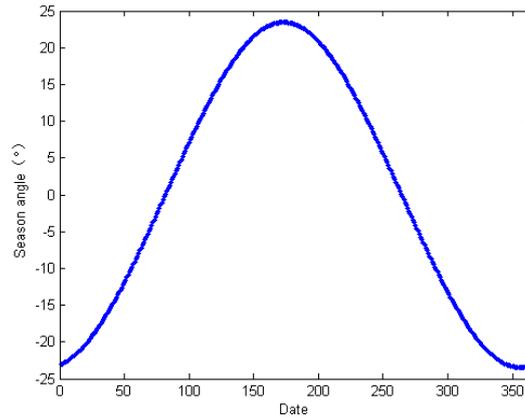


Figure 5. Diagram of the variation of season angle

Taking the Albuquerque (New Mexico, United State) as an example [5], the average radiation (S) from 8 a.m. to 4 p.m. of every day is summarized and plot as a function of the day number (N), as is shown in figure 6.

Fig. 7 illustrates the relationship between incidence, reflection and normal line of the mirror on the equinox and that one particular day when the season angle is δ .

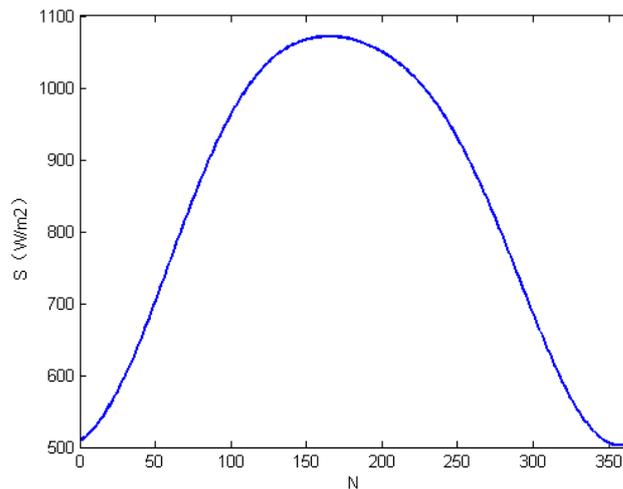


Figure 6. Annual average daily radiation of Albuquerque

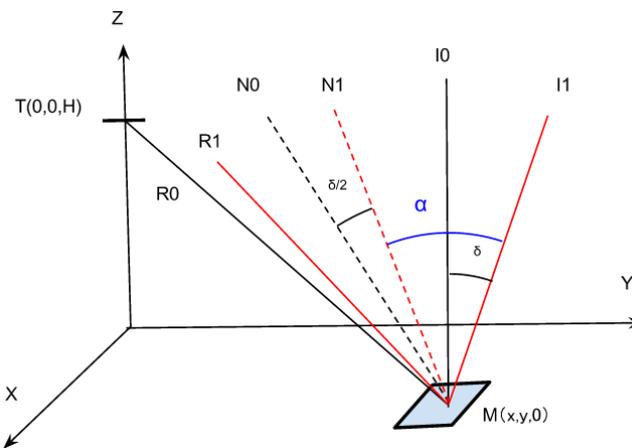


Figure 7. \vec{I}_0 , \vec{N}_0 , \vec{R}_0 is the vector of incidence line, reflection line and the normal line of the mirror on the equinox, respectively. When the season angle is δ , the vector of incident line, reflection line and the normal line change to \vec{I}_1 , \vec{N}_1 , \vec{R}_1 , respectively. $T(0, 0, H)$ and $M(x, y, 0)$ are the coordinate of hot target and mirror.

On the equinox, the vectors of incidence line and reflection line are:

$$\begin{aligned}\vec{I}_0 &= (0, 0, 1) \\ \vec{R}_0 &= (-x, -y, H)\end{aligned}$$

After normalized, the \vec{R}_0 form to

$$\vec{R}_0 = \left(\frac{-x}{|\vec{R}_0|}, \frac{-y}{|\vec{R}_0|}, \frac{H}{|\vec{R}_0|} \right)$$

Where $|\vec{R}_0|$ is the module of \vec{R}_0 and

$$|\vec{R}_0| = \sqrt{x^2 + y^2 + H^2}$$

The normal vector of the mirror is:

$$\vec{N}_0 = \vec{I}_0 + \vec{R}_0 = (0, 0, 1) + \left(\frac{-x}{|\vec{R}_0|}, \frac{-y}{|\vec{R}_0|}, \frac{H}{|\vec{R}_0|} \right) = \left(\frac{-x}{|\vec{R}_0|}, \frac{-y}{|\vec{R}_0|}, \frac{H + |\vec{R}_0|}{|\vec{R}_0|} \right)$$

After normalized, the \vec{N}_0 comes to the form:

$$\vec{N}_0 = \left(\frac{-x}{|\vec{R}_0| * |\vec{N}_0|}, \frac{-y}{|\vec{R}_0| * |\vec{N}_0|}, \frac{H + |\vec{R}_0|}{|\vec{R}_0| * |\vec{N}_0|} \right)$$

Where the $|\vec{N}_0|$ is the module of \vec{N}_0 and

$$|\vec{N}_0| = \sqrt{\left(\frac{-x}{|\vec{R}_0|} \right)^2 + \left(\frac{-y}{|\vec{R}_0|} \right)^2 + \left(\frac{H + |\vec{R}_0|}{|\vec{R}_0|} \right)^2}$$

The variation of season angle, which corresponds to the vector of incidence line rotating around the season axis here, can be proceeded as a vector multiplies a matrix in mathematics. The matrix is:

$$M(\delta) = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \delta & \sin \delta \\ 0 & -\sin \delta & \cos \delta \end{pmatrix}$$

We define here that when the vector rotates anti-clockwise, δ is positive, otherwise negative. Thus, when the season angle is δ , the vector of incidence line changes to

$$\vec{I}_1 = \vec{I}_0 * M(\delta) = (0, 0, 1) * \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \delta & \sin \delta \\ 0 & -\sin \delta & \cos \delta \end{pmatrix} = (0, -\sin \delta, \cos \delta)$$

And the normal vector is

$$\vec{N}_1 = \vec{N}_0 * M\left(\frac{\delta}{2}\right) = \left(\frac{-x}{|\vec{R}_0| * |\vec{N}_0|}, \frac{-y}{|\vec{R}_0| * |\vec{N}_0|}, \frac{H + |\vec{R}_0|}{|\vec{R}_0| * |\vec{N}_0|} \right) * \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \frac{\delta}{2} & \sin \frac{\delta}{2} \\ 0 & -\sin \frac{\delta}{2} & \cos \frac{\delta}{2} \end{pmatrix}$$

Thus the cosine value is

$$\cos \alpha = \xi = \frac{|\vec{N}_1 \bullet \vec{I}_1|}{|\vec{N}_1| |\vec{I}_1|}$$

The average cosine value of the 300 mirrors can be described in the form:

$$\chi = \frac{\sum_{i=1}^{300} \xi_i}{300}$$

Where i is the serial number of the mirror. After normalized by the cosine value on equinox, the cosine loss can be obtained in the form:

$$\eta = 1 - \frac{\sum_{N=1}^{365} \chi_n * S_N}{\sum_{N=1}^{365} S_N} = 0.9970\%$$

Where N is the number of the day and 79 corresponds to spring equinox.

Conclusion

Tracking mechanism of a quasi-two-dimensional tracking technique, Module-Heliostat is discussed in this paper. Compared to the traditional two-dimensional tracking method, only one axis of Module-Heliostat track movement of sun in real time, which make it possible to achieve simple tracking mechanism. Calculation of cosine loss indicates that the Module-Heliostat system can achieve cosine efficiency close to real two-dimensional tracking.

Acknowledgments

This work was financially supported by the National Natural Science Foundation of China [grant number 51472044].

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