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Cross linear solar concentration system for CSP and CPV

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Abstract

The novel concentration system, Cross Linear (CL) system has been newly invented by Tokyo Institute of Technology. From a simulation study on how cosine effect varies with latitude, declination angle, hour angle, and tan μ (the ratio of the receiver height and the distance from mirror position to the receiver position for the receiver/mirror configuration of the CL system), it was found that the cosine factor of CL system increases with an increase in the latitude. The higher cosine factor with around 0.95 in winter months is obtained by CL system even at high latitudes. The CL system can eliminate the end loss and increase the optical efficiency compared to Trough and LFR (Linear Fresnel Reflector system). This seems to solve the problems in the concentration systems of Trough and LFR; the lower concentration efficiency (lower cosine factor) in the winter months. In addition, a higher temperature around 650 °C can be obtained with the CL system, due to the high concentration degree of CL solar reflection method. Thus, the CL system can achieve both high concentration temperature and high collection efficiency in both winter and summer seasons, even at high latitudes. Therefore the CL system seems to be the only CSP system suitable for the CSP-sites at high latitudes such as Mongolia (outer and inner), southern areas of Spain and Australia, and northern area of India. Due to the promising CL system, a joint collaboration between Japanese and Indian industries, institutes and universities has been launched to build solar plant based on CL technology. Also, the CL system also seems to be applicable for the CPV, because the coma tic aberration is very small during 9am to 3pm during the sunlight duration.

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1. Introduction

In the existing solar concentration systems of parabolic trough (Trough), linear Fresnel reflector (LFR) and power tower (PTower), the optical efficiency drastically goes down in winter months, especially at higher latitude [1-2]. The optical efficiency of PTower is higher than Trough and LFR in winter months, but lower in summer months [1]. These variations with season months come from the cosine factor change in the optical concentration systems. For LFR, the optical efficiency of horizontally rotating mirrors suffers from the cosine factor due to the north-south inclination of the sun. This becomes worse when the mirrors are installed in geographic zones with high latitude. This situation is the same as Trough. Also, this cosine factor effect is accentuated by the end loss, which is caused by the reflected light going beyond the end of the receiver due to the inclination of the sun in the direction of the axis of the receiver. As a result, the output of the solar power plant becomes significantly lower during the winter than during the summer [1-3]. These effects are called “declination penalties”, which can be felt right from latitude 20° or so, and becomes more important as the latitude increases [2]. For geographic zones with latitude over 40°, the penalties are so severe that the installation of a horizontally mounted concentrator is not recommended [4]. It is proposed that large scale solar fields can be installed in North African countries, and then long distance power transmission lines can be drawn to transport the generated solar power to Europe [5]. North African regions near Europe are of latitude near 35°, therefore the declination penalties are already significant.

To solve these problems on the declination penalties, a new solar concentration system, CL system, has been invented. This paper will describe the optical principles of CL system and the simulation results for the reduction of the declination penalties by CL system. For a practical development of the CL system, we have started the construction of 30kW pilot plant in India. This paper includes an optical examination on the joint collaboration between Japanese and Indian industries, institutes and universities, which has been launched to build solar plant based on CL solar concentration technology. Furthermore we have slightly examined to find out another application of the CL system for CPV, because the CL system has a unique characteristic on the coma tic aberration; it is very small during 9am to 3pm during the day time.

2. Cross Linear concentration system

Figure 1 shows the sketch of the CL system which consists of linear mirror lines and receiver lines. The both lines are crossed each other at right angles; the mirror lines are aligned on a north-south axis, and the receiver lines, on an east-west axis.

![Fig. 1. Conceptual sketch of CL-system](image)

In Fig. 1, the mirrors are placed in a mirror line set up in North-South direction, and can be rotated along the mirror line axis. Each mirror situates at the center of the horizontal line and celestial sphere. All the incidents are in the same direction for each mirror, therefore apparently we may say that we could concentrate the sun light with
these mirrors by using a different elevation angles for each mirror at a nearly the same rotation angle. Exactly saying, we have to control the rotation angle for each mirror, because the rotation angles are different for each mirror position, but several mirrors located at some distance from receiver can be rotated together within a required error range; we can operate several mirrors within some error range by adaptation of the same rotation angle for each mirrors. Thus, we can track the sun and make a solar concentration by adjusting the (1) rotation angle of the north-south axis and (2) elevation angle. Figure 2 shows the solar concentration concept of the CL-system using several mirrors (three mirrors are shown in Fig. 2) which can be operated by adjusting the rotation and elevation angles. The three mirrors 1, 2, and 3 are placed on the same OO’ axis (North-South), and can be rotated along the axis. Each mirror situates at the center of the horizontal line and celestial sphere. All the incidents are in the same direction for each mirror, therefore apparently we may say that we could concentrate the sun light with these mirrors by using a different elevation angles for each mirror at a nearly the same rotation angle. Exactly saying, we have to control the rotation angle for each mirror, because the rotation angles are different for each mirror position, but several mirrors located at some distance from receiver can be rotated together within a required error range; we can operate several mirrors within some error range by adaptation of the same rotation angle for each mirrors.

![Fig. 2 Solar concentration concept of CL system using multi mirrors by operating rotation and elevation angles](image)

Figure 3 shows geocentric frame for understanding CL concentration system. Circle a is the celestial sphere. N, W, S and E indicate north, west, south and east, respectively. N’ is the celestial north pole. Circle FEGW and circle NWSE are celestial equator and horizontal line. Point O, where a mirror is placed, is center of the horizontal line NWSE, respectively. The Sun light from the point S’ on the celestial equator FEGW reaches the point O and reflected by the mirror. In the CL system, the reflected light goes toward the receiver R, which is placed on the north-south axes. The OS’ and OR are direction vectors pointing toward the positions of the Sun and the receiver R, respectively. The corresponding angles for OS’ are Azimuthal angles (A) and solar altitude (P). The Azimuthal angles (A) are measured clockwise on the horizontal plane, from the north-pointing coordinate axis to the projection of the sun’s central ray. The corresponding angles for OR are elevation angles (P) from the ground level at the mirror position O. In the CL concentration system, the receiver is just on the line of the mirror line which is perpendicular to the receiver line placed in the east-west direction. Therefore, only the one angle of elevation angles (P) is given for the direction vector OR. The sun’s declination angle, which is limited to the range of \(-23.45 \leq \delta \leq 23.45\), is indicated by \(\delta\) in Fig. 1. The hour angle \(\omega\) varies between -180 and 180°, with \(\omega = 0\) at solar noon and \(\omega > 0\) after noon. The latitude angle is shown in Fig. 1 by \(\phi\).

The direction vector OS’ in terms of \(\alpha\) and \(A\) in the geocentric coordinate frame is related to vector components \(S_z, S_e, S_n\) in a rectangular Cartesian frame (Fig. 1) (subscripts z, e, and n denote the z, e, and n axes toward zenith, east, and north, respectively), and they are given by

\[
\begin{align*}
S_z &= \sin \alpha \\
S_e &= \cos \alpha \sin A \\
S_n &= \cos \alpha \cos A
\end{align*}
\]
The vector components of the unit vector of the direction vector $\overrightarrow{OR}$ are given by

\[
R_z = \sin \mu, \\
R_e = 0, \\
R_n = -\cos \mu.
\]  

(2)

The cosine factor for each reflection mirror is given by

\[
\text{CosEffct} = \sin (\text{arch} \sin \left(\frac{\overrightarrow{OS'} \cdot \overrightarrow{OR}}{|\overrightarrow{OS'}| \cdot |\overrightarrow{OR}|/2}\right))
\]

(3),

where $\overrightarrow{OS'} \cdot \overrightarrow{OR}$ is the scalar product, and $|\overrightarrow{OS'}|$ and $|\overrightarrow{OR}|$ are lengths of the vectors. They are written by

\[
\overrightarrow{OS'} \cdot \overrightarrow{OR} = \sin \alpha \sin \mu + \cos \alpha \cos A (-\cos \mu)
\]

(4),

\[
|\overrightarrow{OS'}| \cdot |\overrightarrow{OR}| = 1
\]

(5).

Since $\sin \alpha$ and $\cos \alpha \cos A$ in eq. 4 can be given by

\[
\sin \alpha = \sin \delta \sin \phi + \cos \delta \cos \omega \cos \phi
\]

(6)

\[
\cos \alpha \cos A = \sin \delta \cos \phi - \cos \delta \cos \omega \sin \phi
\]

(7),

the eq.4 can be rewritten by

\[
\text{CosEffct} = \sin \delta (\sin \phi \sin \mu - \cos \phi \cos \mu) + \cos \delta \cos \omega (\sin \phi \cos \mu + \cos \phi \sin \mu)
\]

(8).

3. **Comparison on solar concentration efficiency between Cross Linear and Trough**

Figure 4 shows the simulation results on the comparison of solar concentration efficiency (cosine factor) between CL and Trough (Curve A; CL, B; Trough). The simulation was carried out by assuming that the site is Almeria in Spain (latitude 35°N) and the date is winter solstice. For the calculation of cosine factor in Fig. 4, we have used eq.(8) for CL system and the equation in reference [6] for the calculation of cosine factor for Trough system. For both of the CL system and Trough system, those are aligned on a North-South axis. The shadowing loss factor for Trough system was estimated from the eq.(4.3) given in the literature [7]. The same shadowing loss factor was
applied for the calculation of the CL system, assuming that the same shadowing effect takes place. This assumption seems to be reasonable, because the mirrors surfaces face to the sun light direction by rotating the north-south axis in both of the Trough and CL systems. For the calculation of the CL system, the mirror ray-out, the ratio of the receiver height and the distance between the receiver position and mirror position, and mirror/mirror distance were designed to eliminate the blocking effect during the operation. In this sample geometry, 15 number mirrors (width 1.8m x length 1.5m) are arrayed on the same mirror line with North-South direction (one mirror line; mirror numbers are from one to 15). The mirrors from 11 to 15 are placed on the same mirror line with an inclined angle of 15°.

As can be seen from Fig. 4, the cosine factor of TR (Curve B) reaches peak value at 9:30am, significantly decreases, and then increases back to peak value at 2:30pm. In case of CL system (Curve A), the cosine factor almost keeps constant as it reaches peak value from 9:30am to 2:30pm during sunshine duration. The cosine factor for Trough system is lower than that for the CL system from 8am to 4pm during sunshine duration. The difference in cosine factor reach maximum at 12:00 clock, and the cosine factor of CL. This difference comes from the fact that the cosine factor for the CL system can be determined by eq. 8, which gives a higher values for the higher latitude. On the other hand, the cosine factor for the Trough system decreases with an increase in the latitude. Thus, the higher value of the CL in winter season (high value of declination) is the unique characteristic for the CL system.

Figure 5 displays the calculation results, which describes the dependence of cosine effect on time in daytime for CL and trough systems at Almeria in Spain. For the CL system (Fig. 5 a), the cosine effect first goes up in morning and then goes down in afternoon. Once it reaches peak top, the value of cosine effect keeps constant with time until
the cosine effect drops. There is no obvious difference in the value of cosine effect among different months. The difference in the cosine effect among different months is only the solar collection time period; it is shorter in winter months than in summer months. For the trough system (Fig. 5 b), the cosine effect also first goes up in morning and then goes down in afternoon. The peak value of cosine effect is almost constant in May and June, but it significant drops in April, March, February and January and reaches peak bottom at 12 clock. Comparing CL system (Fig. 5a) and trough system (Fig. 5b), it is obvious that the cosine effect of trough is greatly influenced by month (declination angle). The CL system can keep the value of cosine effect as high as 0.95 even in winter months. When compared to the conventional systems which set the heliostat in the north field of tower system, the cosine factor of some of heliostats can’t keep the cosine factor above 0.8 all the time. Therefore, the advantage of CL solar collection system is prominent.

Figure 6 depicts the comparison of daily collected solar energy (DSE) and cosine factor during sunshine duration (DayAv Cos.) of CL and Trough systems for each month in a year at Almeria (latitude 35° N) in Spain. The calculation parameters are the same as aforementioned. As shown in Fig. 6, the cosine factor of CL system (CL-DayAv Cos.) does not vary much with month in a year, and almost keep the same value greater than 0.75. This means that even in winter season, the CL system can collect the maximum amount of solar energy. This is the overwhelming advantage of CL system comparing with conventional solar collection technologies, which is shown by Curve of TR-DayAv Cos (the cosine factor of Trough system). TR-DayAv Cos. drops as winter months come, and then goes up when summer months come. In winter months, the solar energy collection efficiency of Trough system (TR-DayAv Cos.) is much lower than that of CL system (CL-DayAv Cos.). Thus, the CL system exhibits high performance for solar energy collection every month in a year. The collected solar energy per day (DSE) for CL and Trough systems is also given in Fig. 6. The DSE’s of both CL system and Trough system (CL-DSE, TR-DSE) show the same trend that DSE decreases in winter months and then increases in summer months. For the CL system, even the cosine factor (CL-DayAv Cos.) keeps almost the same, the collected energy per day (CL-DSE) greatly decreases in winter season. This is because the collected solar energy depends on the sunlight duration; in winter season, the sunlight duration becomes significantly shorter than that in summer season. This means that the CL system can collect the maximum amount of solar energy even in winter seasons at high latitude by keeping the cosine factor at a high level. Saying, we can operate the CL-system plant under the same operating condition for the constant DayAv Cos. throughout year. However, for Trough system, the collected solar energy value (DSE) drops fairly largely compared to the CL-system in winter season. This large drop of the Trough system comes from both of the decrease in cosine factor (DayAv Cos.) and the sunlight duration in winter season.
Figure 7 compares the simulation results of solar concentration efficiency (cosine effect) at Bhopal in India between CL and Trough systems (Curve A; CL, B; Trough). The latitude of Bhopal is 23° N, and the date is winter solstice. For the calculation of cosine factor of CL system, eq.(8) was used, and for that of Trough system, the equation of cosine effect of the Trough system with axis oriented North-South [5].

The configurations of CL and Trough are the same as those used in Fig. 3. From Fig. 7, it can be seen that the daily trend of the cosine effect varies with time is nearly the same to that in Fig. 3. But the values of the cosine effect are different, for CL system, the value of cosine effect at Bhopal (23° N) in India (Fig. 7) is almost the same to that at Almeria (35° N) in Spain (Fig. 3). This suggests that the concentration efficiency of CL system does not change much with latitude; therefore this novel concentration system, CL system, is more suitable for collecting solar energy at high latitudes. This is a promising advantage of CL system, which overcomes the obstacle (the cosine effect is too low in winter season as shown in Fig. 3 and Fig. 7) of existing concentration systems such as Trough and linear Fresnel system. In the case of trough system, the cosine effect of Almeria in Spain (Fig. 3) significantly drops, as compared to that of Bhopal in India (the cosine effects of Bhopal and Almeria are 0.69 and 0.50, respectively). This indicates that the concentration efficiency of trough system is greatly influenced by the latitude and it is not suitable to use at high latitudes to collect solar energy for solar power plant.

The CL solar concentration system (CL-system) for 30kW pilot plant is planned to be constructed in RGVP (Rajiv Gandhi Technical University) in India (Rajiv Gandhi CSP Project). Fifteen numbers of the mirrors (one mirror size; 1.8x1.5m) in one mirror line will be placed, and four mirror lines will be set-up. The mirrors are controlled to track the sun by adjusting the rotation angle along the mirror line and elevation angle of the mirror. The height of the receiver line is nearly 15m and the length of the mirror line, 25m. The solar concentration degree is 50-150; therefore a high temperature around 650 °C can be obtained for thermal fluids using a cavity-type receiver suitable for a linear receiver.

4. Advantage of the Cross Linear system

In the CL-system, we can place a number of mirrors in one mirror line, and select any heliostat number. This enables us to take a wide range in the concentration degree from lower one of 50 to higher one of 300-500. Therefore, we can get a wide temperature range from 200 to 650 °C of the thermal fluids of air, steam and molten salt. When we apply a higher concentration degree, we can reduce the numbers and length of the receiver lines, which gives an advantage for lowering the investment cost and power generation cost compared to trough and Linear Fresnel systems.

Another interesting advantage is that with the CL-system, a higher sun light collection efficiency can be obtained at higher latitudes compared to the existing conventional concentration systems. One of our simulation results...
shows that the amount of collected solar energy by CL-system is about 2 times larger than that obtained by trough system in winter season (Ulan Bator in Mongolia). As mentioned above (Fig.6), we can get the same amount of collected solar energy during 10-14 hour in daytime and in winter season as that of in summer season.

The main differences between the Fresnel concept and the parabolic trough collector include: 1) LFCs use cheap, flat mirrors (6–20 €/m²) instead of expensive parabolic curved mirrors (25–30 €/m²); furthermore, flat glass mirrors are a standardized mass product. 2) LFCs require less heavy steel material, using a metal support structure with limited or no concrete (making for easier assembly). 3) On-site installation of LFCs is predicted to be faster. For our CL-system, we can use a one way -curved mirror which can be more readily mass-produced with a high accuracy. CL-system also requires less heavy steel material, and On-site installation can be achieved for a faster construction. Also, when compared with parabolic trough, we can reduce the receiver pipe length by 1/50-1/100, which clearly reduce the plant construction cost drastically. As mentioned above, the gear numbers can be reduced compared with the conventional tower heliostat. And, we can use a usual motor with a low torque. This will be a very strong factor to reduce the heliostat cost.

The CL-system seems to be applicable for the CPV, because the comatic aberration is very small during 9am to 3pm during the day-time. For CPV, we can select any scale of the power in 10-100kW by changing the mirror line number and length. This is preferable for hospitals in the district near the Sunbelt in India, because they need a clean and hot water, and electricity with a wide range of power depending on the bed numbers of the hospitals. We are going to apply the CL-system for CPV in the hospitals in India.

5. Conclusion

Cosine effect of CL-system, which can be represented by \( \sin \delta = \sin \phi \sin \mu - \cos \phi \cos \mu \) + \( \cos \delta \cos \omega \sin \phi \cos \mu + \cos \phi \sin \mu \), can be kept constant at around 0.9 for all seasons. This overcomes the obstacle that the cosine factor for the existing solar concentration systems such as trough and Linear Fresnel is too low in winter season. And, the cosine factor of CL-system becomes higher at the higher latitude, which is reverse relation for the conventional solar concentration system, i.e., cosine factor becomes smaller at the higher latitudes. Thus, CL-system is suitable for collecting solar energy at high latitudes.

When compared between CL- and Trough systems, the CL system can collect the maximum amount of solar energy even in winter seasons by keeping the cosine factor at a high level. However, for Trough system, the collected solar energy value drops largely compared to the CL-system in winter season, which is caused by decrease in cosine factor and the sunlight duration in winter season.

CL-system can provide a wide range in the concentration degree from lower one of 50 to higher one of 300-500, and that in the temperatue of 200-650°C.

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