# EFFECT OF PARABOLIC TROUGH SOLAR COLLECTOR ORIENTATION ON ITS COLLECTION EFFICIENCY

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ABSTRACT

Parabolic trough solar collector PTC is often oriented with its axis horizontally in the North-South or East-West direction. However, it may be set in a position where its axis makes an angle $\Psi$ with the south direction. The main objective of the present work is to study the effect of this angle on the collection efficiency. An algorithm for calculating the collection efficiency for any time period has been developed. The results obtained by using this algorithm show that the maximum daily collection efficiencies $\eta_{c,d}$ all over the year are obtained for the N-S orientation at sites having latitude angles $\phi \leq 15°$. For latitude angles $\phi > 15°$, $\eta_{c,d}$ are much higher in summer days than in the winter days for N-S orientation. In the case of orienting the collector with an angle $70° < \Psi \leq 90°$, $\eta_{c,d}$ are higher in winter days than in summer ones This orientation is preferable to obtain almost constant output of PTC through the whole year. The results show also that a trough oriented with an angle of 70 ° from N-S direction has almost a constant daily collection efficiency all over the year of 82% when considering the reflectivity of the collector surface equal to unity. Also, the effect of orientation on yearly collection efficiency $\eta_{c,y}$ are minor at latitude angle $\phi$ between 30° and 40° while the effect of orientation becomes important outside this range.

## INTRODUCTION

Parabolic trough solar collectors (PTCs) have shown to be advantageous over other collecting systems for producing heat energy at moderate temperatures ( 100 - 400 °C) such as the provision of industrial process heat and solar cooling [1-8]. They have been considered for total energy applications [9] because of their simplicity, reliability and lower unit cost.

To produce a big amount of heat energy, individual collectors are connected together in series and parallel. For easier construction and operation they are set with their axes in a horizontal position. In this setting way it has been shown in [10, 11] that the North-South orientation leads to high collection efficiencies during the summer days whereas the collection efficiencies become relatively lower during winter days. In contrast to that, the East-West orientation shows to have its highest collection efficiencies in winter days and the lowest ones in summer days.

The question that may arise , is there an optimum orientation at which the horizontal parabolic trough can give the highest amount of the reflected rays to the absorber? . This is the aim of the present work. Consequently, in the work reported herein, an algorithm for calculating the energy collected by a horizontal PTC oriented at any angle between N-S and E-W is presented. This algorithm allows to study the effect of the PTC orientation on its collection efficiency for different seasons of the year as well as all over the year.

## ANALYSIS

Figure (1) shows a schematic representation of a horizontal PTC with width w and length l. The collector is oriented with its axis (a) at an angle $\Psi$ to the South direction. The angle $\Psi$ progresses in counter-clockwise direction. A cartesian coordinate system (x,y,z) is set at the vertex of a collector contour (b); it is chosen for the drawn collector to be the right-hand one. The x-axis coincides with the collector axis and the z-axis runs vertically. Seen from the surface of the earth, the solar disc is located within a radiation cone. For simplicity, the central ray of such a cone is shown in Figure (1), whose direction is determined by the latitude angle $\alpha$ and the azimuth angle $\gamma$. These two angles can be easily calculated for any site and solar time [10, 11]. A unit vector $\vec{s_i}$ in the direction of the incident central ray can then be obtained from Figure (1) in component notation as:

$$\vec{s_i} = [\, s_{i,x} \,,\, s_{i,y} \,,\, s_{i,z} \,] \\ =[-\cos\alpha\cos(\gamma-\psi),\, -\cos\alpha\sin(\gamma-\psi),\, -\sin\alpha] \tag{1}$$

In order that the incident central ray is reflected by the collector surface and intersects the collector focal line (c), the collector central plane $\lambda$ -composed of the collector axis (a) and focal line (c)- should incorporate the vector $\vec{s_i}$. In this case the collector is to be rotated around its axis (a) so that the plane $\lambda$ makes an angle $\omega$ with the vertical plane. The angle $\omega$ progresses in counter-clockwise direction. The component of the unit vector $\vec{n_\lambda}$ normal to the plane $\lambda$ is given from Figure (1).

$$\vec{n_\lambda} = (n_{\lambda,x}, n_{\lambda,y}, n_{\lambda,z}) = (0, -\cos\omega, -\sin\omega) \tag{2}$$

For the vector $\vec{s_i}$ to lie in the central plane $\lambda$, the following condition must be fulfilled:

$$\vec{s_i} \cdot \vec{n_\lambda} = (\, s_{i,x}\, n_{\lambda,x} + s_{i,y}\, n_{\lambda,y} + s_{i,z}\, n_{\lambda,z} \,) = 0 \tag{3}$$

From Eq. (3) and with the help of Eqs. (1) and (2), one can obtain the following expression for the angle $\omega$

$$\omega = \tan^{-1}\left[ -\frac{\sin(\gamma-\psi)}{\tan\alpha} \right] \tag{4}$$

For calculating the solar power incident on the collector surface, it is necessary first to be able to determine the incident angle $\theta$ between the vector $\vec{s_i}$ and the normal to the collector surface. A unit vector $\vec{n_a}$ in the direction normal to the collector surface is given in components from Figure (1) as:

$$\vec{n_a} = (n_{a,x}, n_{a,y}, n_{a,z}) = (0, -\sin\omega, \cos\omega) \tag{5}$$

The angle $\theta$ can then be calculated with the help of Eqs. (1) and (5) from :

$$\cos\theta = -\vec{s_i} \cdot \vec{n_a} = -\cos\alpha\sin(\gamma-\Psi)\sin\omega + \sin\alpha\cos\omega \quad (6$$

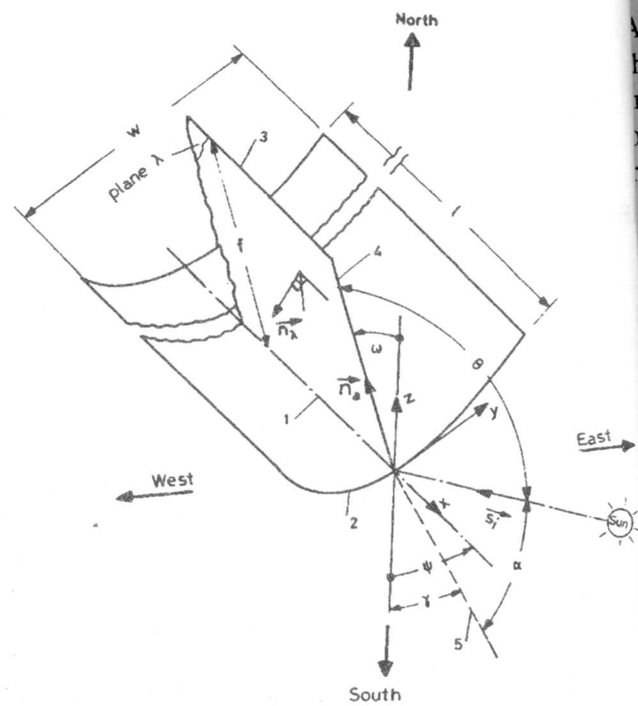


**Figure 1**. Parabolic tough collector
1- collector axis 2- collector contour
3- facal line 4- optical axis
5- projection of sun ray xy-plane.

The solar radiation power received by the collector surface may be given by:

$$\dot{Q} = q_s\, A_c \cos\theta \tag{7}$$

where, $q_s$ is the direct normal solar flux and $A_c$ is the projected sunny collector area ($A_c$ = l (w - d)), where d is the absorber tube diameter (see Figure (2)).
If the reflectivity of the collector surface for short-wave solar radiation is represented by $\rho_r$, the following fraction is reflected from the collector surface toward the absorber.

$$\dot{Q}_r = \rho_r\, q_s\, l\,(\,w - d\,)\cos\theta \tag{8}$$

It should be borne in mind that there is a portion of the absorber tube named $\ell_s$ will not be lighted by the reflected radiation, see Figure (2). The length $\ell_s$ may be calculated as given in [10] from the following equation:

$$l_s = f \tan\theta \tag{9}$$

Assuming that the absorber diameter is large enough that the intercept factor $\gamma$ (it is the ratio of the power intercepted by the absorber to the reflected one in case of very long absorber) equals a unity. Then the power received by the absorber tube is given by:

$$\dot{Q}_a = \rho_r\, q_s\, (w-d)(1-f\tan\theta)\cos\theta \tag{10}$$

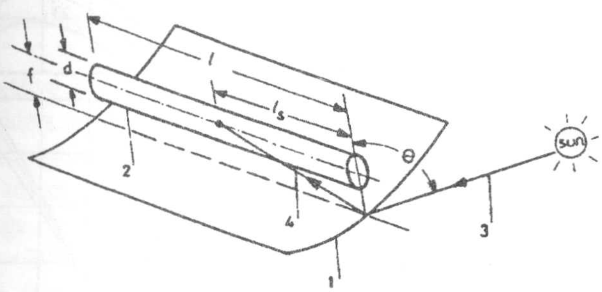


Fig. 2 Unlighted length of the absorber

**Figure 2.** Unlighted length of the absorber.

The instantaneous collection efficiency $\eta_c$ is defined as the ratio of the actual radiation power received by the absorber, given by Eq. (10), and the solar radiation power that would be received by the collector surface when it is oriented normal to the incident sun rays. Accordingly and with aid of Eq. (10), $\eta_c$ may be given as:

$$\eta_c = \rho_r \left[ 1 - \frac{f/w}{l/w} \tan\theta \right] \cos\theta \tag{11}$$

The radiation energy intercepted by the absorber through a time period $\Delta t$ from $t_1$ to $t_2$ is calculated by integrating Eq. (10) over that time.

$$Q_{a,\Delta t} = (w-d) \int_{t_1}^{t_2} \rho_r q_s (1 - f\tan\theta)\cos\theta\, dt \tag{12}$$

Hence, the collection efficiency $\eta_{c,\Delta t}$ through a time interval $\Delta t$ is given by:

$$\eta_{c,\Delta t} = \frac{\int_{t_1}^{t_2} \rho_r q_s \left[ 1 - \frac{f/w}{l/w} \tan\theta \right] \cos\theta\, dt}{\int_{t_1}^{t_2} q_s\, dt} \tag{13}$$

## RESULTS AND DISCUSSIONS

It is clear From Eq. (13) that the value of the collection efficiency of a PTC in a certain period depends on both the collector geometrical and optical parameters. The geometrical parameters are the focal ratio f/w and the length ratio l/w while the optical parameters are the collector surface reflectivity and the incident angle of the sun rays relative to the collector surface, which is mainly dependent on the collector orientation. For an existing collector, the only parameter one can adjust is the collector orientation which in turn affects the incident angle.

Concerning f/w, most of the commercially constructed PTCs have values of f/w around 0.25 [4-8] since the PTC has the highest concentration ratio at this value. Therefore, all the following results have been obtained for a PTC having f/w = 0.25. The reflectivity of the collector surface has been taken to be 1.0. To determine the collection efficiency at a specified day, it is first necessary to find out the rotation routine of the collector through that day. Such routines are shown in Figure (3) for a site having a latitude angle of 30°. The diagrams of this figure are for values of the angle $\Psi$ = 0° (N-S), 30°, 60° and 90° (E-W). In each diagram, the curves represent the declination angles $\delta$ = -23°, -11.5°, 0°, 11.5° and 23°. Each value of $\delta$ represents a pair of days. Figure (3) shows that the East-West orientation ($\Psi$ = 90 °) needs the least care of adjusting the collector, especially for the most effective 6 hours around the solar noon. These hours have a big influence on the collector performance since the sun irradiance has its highest intensities at these hours.

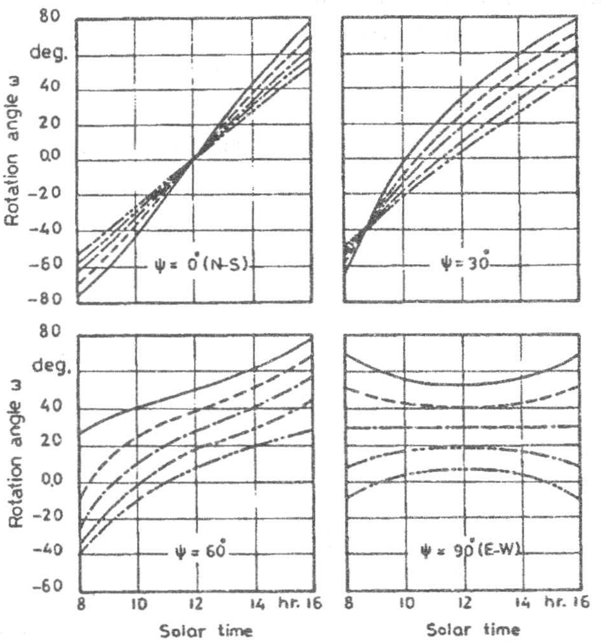


Fig. 3 Rotation routines of a Parabolic Trough collector (φ = 30°)

δ = -23.0° ; δ = 0.0° ; δ = 23.0° ; δ = -11.5° ; δ = 11.5°

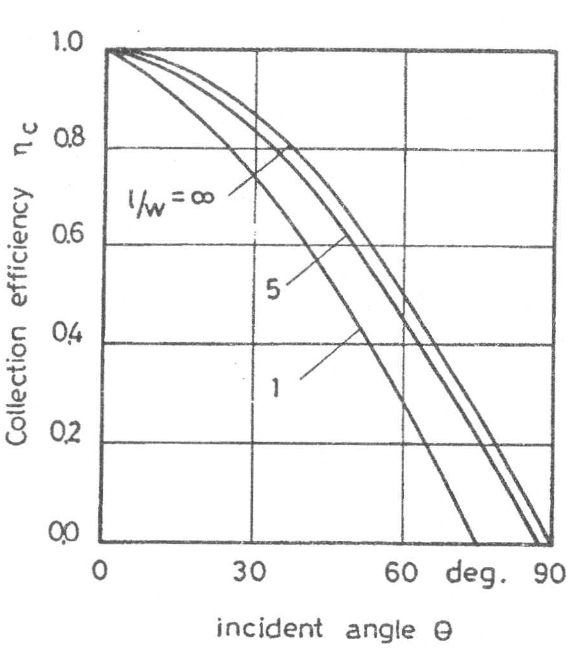


**Figure 4.** Dependence of collection efficiency on incident angle (f/w = 0.25).

Figure (4) shows the effect of the incident angle on the instantaneous collection efficiency $\eta_c$ evaluated at three different values for l/w of 1, 5 and $\infty$. It is clear from the figure that $\eta_c$ decreases with the increase of $\theta$ where the rate of decrease of $\eta_c$ gets remarkably high for values of $\theta$ greater than 30°. The effect of the unlighted absorber length becomes smaller as the ratio l/w increases and it nearly diminishes for l/w> 5.

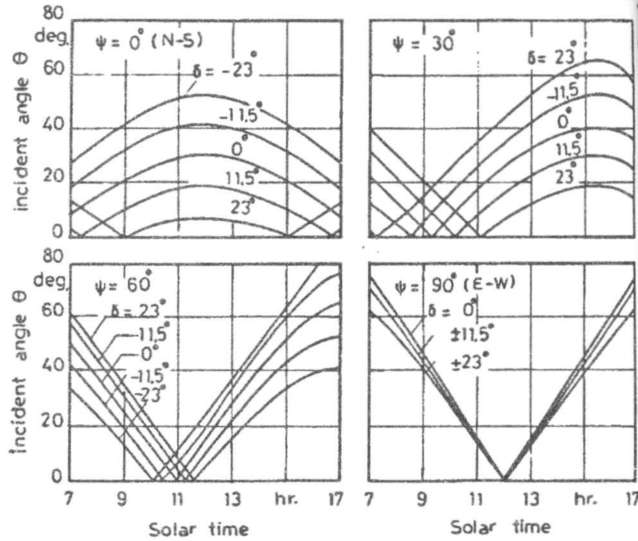


**Figure 5.** Variation of the incident angle with solar time ($\phi$ = 30°).

In Figure (5) the values of the incident angle $\theta$ obtained from Equation 6 are plotted versus the solar time and for a site having a latitude angle of 30° and for the values of the angle $\Psi$ = 0°, 30°, 60° and 90°. The curve parameter is the declination angle $\delta$ which has the value of -23°, -11.5°, 0°, 11.5° and 23°. It is clear from this figure that the angle $\theta$ has its highest values at solar noon for the N-S orientation ($\Psi$ = 0°). As $\Psi$ increases the maximum values of $\theta$ are shifted away from solar noon . $\theta$ reaches zero value at solar noon for all days of the year (all possible declination angles ) when $\Psi$ equals 90° (E-W orientation). Consequently in the N-S orientation, $\eta_c$ has relatively low values at the effective six hours around the solar noon. $\theta$ is relatively high, and in turn, $\eta_c$ is low when the declination angle $\delta$ is negative whereas $\theta$ becomes smaller and $\eta_c$ increases when $\delta$ is positive.

Figure (6) shows the effect of the angle $\Psi$ on the daily collection efficiency $\eta_{c,d}$ for sites having latitude angles $\phi$ of 0°, 15°, 30° and 45° respectively . The curves of this figure represent five values of the declination angle $\delta$; i.e. -23°, -11.5°, 0°, 11.5° and

23°. Also, the intensity of the incident solar radiation $q_s$ has been estimated using the equations given in [12]. Figure 6 reveals clearly that the N-S orientation ($\Psi$ = 0°) generally gives the highest daily collection efficiency all over the year when the latitude angle $\phi$ lies between 0° and 15°. As $\phi$ increases over 15°, $\eta_{c,d}$ keeps its highest values for days having positive values of $\delta$ (summer time), at the N-S orientation. In contrast to that when $\delta$ becomes negative (winter time) the smallest values of $\eta_{c,d}$ occur when the collector is oriented N-S ($\Psi$ = 0°) and the greatest values of $\eta_{c,d}$ are obtained at the E-W orientation ($\Psi$ =90°). It is interesting to mention that, for the orientation range 70° < $\Psi$ ≤ 90° $\eta_{c,d}$ becomes higher in winter ($\delta$ is negative ) than in summer ( $\delta$ is positive). Since the incident solar radiation energy on a PTC surface is much less in winter than in summer, it is advantageous to orient the collector within the above mentioned range. In this connection, the E-W orientation ($\Psi$ =90°) is preferable for its simplicity in tracking the sun. However, if there is a space limitation problem, the collector may be oriented with an angle 70° ≤$\Psi$≤ 90° without considerable decrease in daily collection efficiency $\eta_{c,d}$ . Also, it is clear from Figure 6 that, the PTC can be oriented in such a way to get a constant collection efficiency all over the year. This constant efficiency equals to 82% at an orientation angle laying between 60° and 70 °. The variation of the daily efficiency between this range of orientation becomes zero at $\phi$ = 0 and increases as $\phi$ increases reaching almost 5% when $\phi$ = 45°.

Table 1 shows the effect of the angle $\Psi$ on the collection efficiency $\eta_{c,y}$ over the year for different latitude angle $\phi$ (between 0° and 60° ). Concerning $\eta_{c,y}$ , it is obvious from the table that the N-S orientation ($\Psi$ = 0°) is advantageous for 0 °≤ $\phi$ ≤ 30° since $\eta_{c,y}$ has its maximum values. For latitudes having angle $\phi$ greater than 30°, the greatest values of $\eta_{c,y}$ are obtained in case of the E-W orientation ($\Psi$ = 90°). From Table 1, the difference in the yearly efficiency can reach up to 13% at latitude $\phi$ =0° or 60°, and becomes as small as 2% at a latitude of 40°. One can conclude that the change in $\Psi$ in the range of 30 to 40 has the least influence on $\eta_{c,y}$ . Clearly, for 75° < $\Psi$ ≤ 90°, the collection efficiency is almost invariant with the change of the latitude.

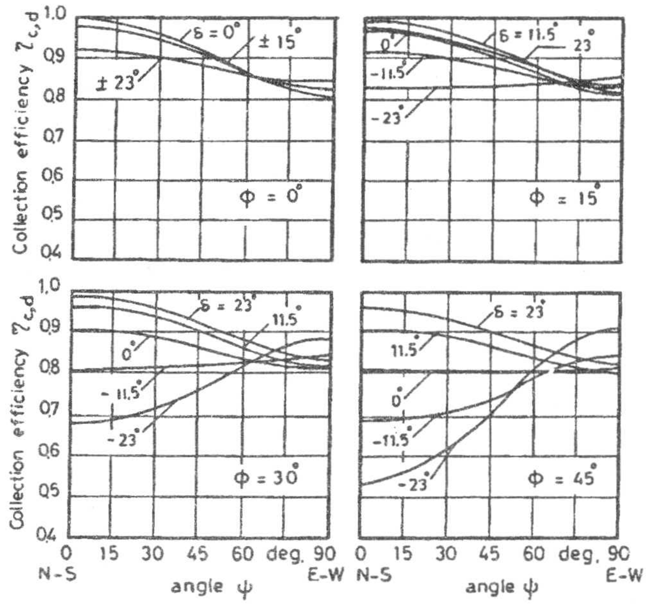


**Figure 6.** Effect of the orientation angle $\Psi$ on daily collection efficiency $\eta_{c,d}$.

**Table 1.** Effect of angle $\Psi$ on the yearly collection efficiency $\eta_{c,y}$ for different latitude angles.

| $\Psi$ degrees | Latitude angle $\phi$ (degrees) | | | | | | |
|---|---|---|---|---|---|---|---|
| | 0 | 10 | 20 | 30 | 40 | 50 | 60 |
| 0 | .9521 | .9413 | .9116 | .8644 | .8034 | .7333 | .6569 |
| 5 | .9511 | .9405 | .9100 | .8633 | .8032 | ..7355 | .6578 |
| 10 | .9482 | .9377 | .9086 | .8622 | .8027 | .7343 | .6603 |
| 15 | .9434 | .9332 | .9047 | .8589 | .8018 | .7354 | .6648 |
| 20 | .9370 | .9270 | .8994 | .8556 | .8006 | .7372 | .6709 |
| 25 | .9288 | .9193 | .8931 | .8520 | .7992 | .7394 | .6788 |
| 30 | .9191 | .9102 | .8857 | .8467 | .7979 | .7424 | .6886 |
| 35 | .9082 | .9000 | .8774 | .8411 | .7966 | .7462 | .7000 |
| 40 | .8966 | .8891 | .8687 | .8367 | .7957 | .7508 | .7134 |
| 45 | .8843 | .8778 | .8597 | .8311 | .7952 | .7566 | .7282 |
| 50 | .8720 | .8663 | .8509 | .8267 | .7957 | .7637 | .7324 |
| 55 | .8600 | .8553 | .8431 | .8222 | .7973 | .7721 | .7591 |
| 60 | ..8488 | .8451 | .8551 | .8189 | .8001 | .7818 | .7746 |
| 65 | .8386 | .8359 | .8286 | .8173 | .8034 | .7911 | .7892 |
| 70 | .8289 | .8281 | .8232 | .8159 | .8068 | .7994 | .8021 |
| 75 | .8229 | .8219 | .8191 | .8149 | .8097 | .8064 | .8126 |
| 80 | .8178 | .8167 | .8156 | .8142 | .8119 | .8116 | .8204 |
| 85 | .8148 | .8147 | .8143 | .8138 | .8132 | .8148 | .8252 |
| 90 | .8137 | .8138 | .8138 | .8138 | .8138 | .8159 | .8288 |

## CONCLUSION

The following conclusive remarks can be mentioned:

1- The N-S orientation at latitude less than 15° gives the highest daily collection efficiency all over the year.

2- For sites having latitude angle $\phi > 15$, it is preferable to orient the collector in the range $70° \leq \Psi \leq 90°$ to obtain higher daily collection efficiency in winter days of lower sun irradiiance.

3- There is an orientation at which the PTC gives nearly a constant daily collection efficiency all over the year. This orientation is in between 60° to 70° measured from south direction. Its accurate value depends on the site latitude angle.

4- For $0° < \phi < 30°$ the maximum yearly efficiency is obtained for N-S orientation, While E-W orientation gives the maximum yearly efficiency at latitude angle $\phi > 30°$

5- The effect of orientation on $\eta_{c,y}$ are minor at latitude angle $\phi$ of 30 -40° while the effect of orientation becomes important outside this range.

## NOMENCLATURE

| | | | |
|---|---|---|---|
| $A_c$ | : | sunny area of the collector | $m^2$ |
| d | : | diameter of absorber tube | m |
| f | : | focal length | m |
| l | : | collector length | m |
| $l_s$ | : | unlighted length of the absorber tube | m |
| $\vec{n}_a$ | : | unit vector normal to the collector surface | |
| $\vec{n}_\lambda$ | : | unit vector normal to the plane λ | |
| $q_s$ | : | directed normal solar flux | $W/m^2$ |
| $\dot{Q}$ | : | solar radiation power incident on collector surface | W |
| $\dot{Q}_a$ | : | solar radiation power received by the absorber surface | W |
| $\dot{Q}_r$ | : | solar radiation power received by the absorber surface | W |
| $\vec{s}_a$ | : | unit vector in direction of the incident central ray | |
| w | : | collector width | m |

*Greek Letters*:

| | | | |
|---|---|---|---|
| $\alpha$ | : | altitude angle | rad |
| $\gamma$ | : | azimuth angle | rad |
| $\delta$ | : | declination angle | rad |
| $\eta_c$ | : | collection efficiency | |
| $\rho_r$ | : | reflectivity of the collector surface for solar radiation | |
| $\phi$ | : | latitude angle | rad |
| $\theta$ | : | Incident solar angle | rad |
| $\lambda$ | : | collector central plane | |
| $\Psi$ | : | collector orientation angle | ra |
| $\omega$ | : | Collector rotation angle | ra |

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