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Optical performances of a solar parabolic trough collector for various solar tracking modes under climatic conditions of Maroua

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ABSTRACT: Detailed simulations in aim to evaluate optical performances of a solar parabolic trough collector for various solar tracking modes under climatic conditions of Maroua have been investigated by using the empirical model of Capderou, incidence angle, day of the year, solar direct radiation, legal time, incident angle modifier and global energy absorbed by the heat collection element during the sunniest and the least sunny month. The performances of the three tracking modes assumed compare to full tracking mode during a typical sunny day in Maroua, lead to percentages 98%, 99.98% and 69.25% in the sunniest month and 91.2%, 81.45%, and 62.85% in the least sunny month for East-West polar tracking, East-West horizontal tracking and North-South horizontal tracking respectively. Besides, the results show that, the East-West horizontal and East-West polar solar tracking modes are more suitable and getting closer with full tracking compared the North-South horizontal tracking mode. The optical efficiency reached at about 74% according to the East-West horizontal and East-West polar solar tracking mode and maximum temperatures of 180°C for air and oil and 90°C for water were reached by applying East-West polar and East-West horizontal tracking modes in a typical day of the sunny month.

KEYWORDS: Optical efficiency, parabolic trough collector, solar tracking modes, Maroua.

1 INTRODUCTION

Access of energy is poor in Cameroon Sahelian zone and particularly in Maroua. Furthermore, most of the global energy consumption in Maroua is produced from fossils fuels. But fossil fuel resources are being depleted at an incredible speed and their combustion contributes significantly to greenhouse effect and indirectly to depletion of the ozone layer. Faced with shrinking fossil fuel resources, growing global energy demands and increasing level CO_2 in the earth atmosphere, Maroua urgently needs to reassess how it generates and consumes power. Located on the sun-belt regions, where the most abundant component of solar radiation falling on the ground level is solar direct radiation, the site possesses high solar direct irradiation which is considered the fuel of solar parabolic trough collectors. Thus, solar energy is a very promising alternative to meet Maroua energy needs and solar parabolic trough collectors are the most proven widespread and commercially tested solar energy technologies available for solar harnessing [1]-[2] to explore. Also, solar parabolic trough collector is a very interesting solution near term option for countries with high solar irradiation levels and small resources of fossil fuels like Cameroon. Furthermore, solar parabolic trough collector offers interesting large-scale applications of solar energy in the context of Maroua such as air conditioning, distillation, industrial process heat, domestic heat water, electricity production.

To operate, a solar parabolic trough collector required a continuous solar axis tracking system as shown in Figure 1. The orientation of the tracking axis has a significant influence on the sun's incidence angle onto the aperture plane of the collectors which, in turn, affects the collector's performances. Once the physical characteristics of the collector are known, the optical performances and even the energy gained can be calculated in order of some configurations, tracking modes and meteorological conditions.

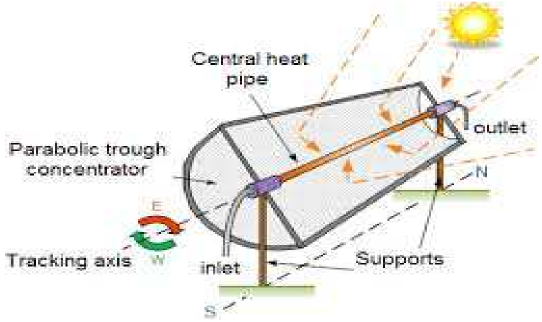


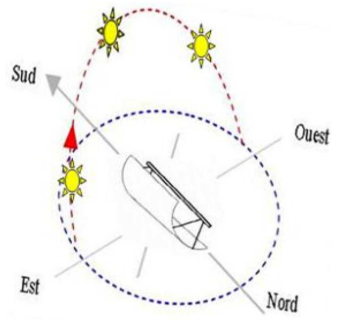
Fig. 1. Solar parabolic trough collector with tracking axis

Cunxu Wang, Hongli Zhang and Shuqun Wang [3] investigated optical performances of a parabolic trough collector for various tracking modes in Sub-tropical Area. By using the Hottel model in equinoxes and solstices, the results show that, for two axes tracking, polar East-West tracking, horizontal East-West tracking and horizontal North-South tracking, the relative proportion of yearly irradiation yield are 100%, 95.93%, 91.32% and 73.67% respectively. Yogender Kumar and Avadhesh Yadav [4] devoted experimental investigation of various tracking configurations of a solar parabolic trough collector and the results show that a two axis tracking mode along East-West direction performs better as compared to other cases and the maximum temperatures of heat collecting element obtained are found to be 139.5 °C, 184.4 °C and 162.4 °C in right-end, in the middle and left-end respectively. By comparing various tracking modes of a solar parabolic trough collector in the site of Ouargla, Yacine Marif, Hocine Benmoussa, Hamza Bouguettaia, Mohamed Mustapha Belhadj and Moussa Zerrouki [5] show that, in the case of full tracking mode, the parabolic trough collector absorbed maximum amount of energies and the optical efficiency of the collector is found to be 73.92%. Furthermore, the one axis East-West polar and East-West horizontal tracking systems are sufficient for a parabolic trough collector in the summer, spring and autumn. The North-South horizontal tracking system is more suitable in summer than East-West horizontal tracking. Y. Marif, M. Zerrouki, M. Belhadj and H. Ben Moussa [6] studied optical and thermal performances of a solar parabolic trough collector. The results obtained show that for various tracking solar modes the East-West polar mode-based one axis solar tracking is suitable. Kalogirou gathered relations for estimation of the angle of incidence for various tracking mode. By applying a radiation model in equinoxes, 100%, 100%, 73.8% and 89.1% amount of energy falling on surface of 1 m^2 of collector for full tracking, East-West polar, North-South horizontal and East-West horizontal, respectively were obtained. By comparing the performance of the various tracking modes with the full tracking which collects the maximum amount of solar radiation, the percentages obtained are 91.7, 74.0 and 97.7 in summer solstice and 91.7, 86.2 and 60.9 in winter solstice, respectively for some trackers [1]-[2]. More recently, Joseph Kessel Pombe, Camelia Stanciu, Haman-Djalo, Viorel Badescu and Beda Tibi [7] investigated energy balance of heat collecting element of a solar parabolic trough collector by using air as heat transfer fluid. The maximum temperature of air obtained at the outlet of heat collecting element is found to be 590 K and this was expected to study the global performances and relevant areas pertaining of a solar parabolic trough collector in Sahelian zones such as Maroua.

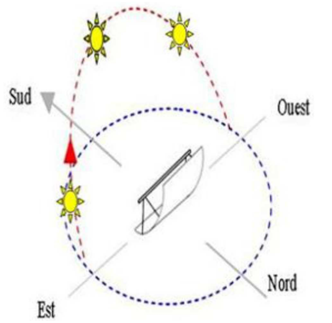
Many researchers have worked and analyzed performances of solar parabolic trough collectors in different countries and for several applications. But none of them worked on effect of various tracking modes on optical performances of solar parabolic trough collectors in Sahelian zones. Furthermore, to date, no solar parabolic trough collector has been installed in Sahelian zones and particularly in Maroua and none is under construction. Moreover, no study in order to evaluate solar direct radiation, solar parabolic trough collector performances and relevant areas pertaining to the central African sun-belt countries has ever been investigated. This work aims at filling that gap by analyzing optical performances of solar parabolic trough collectors in climatic conditions of Maroua for various solar tracking modes.

2 METHODOLOGY OF THE WORK

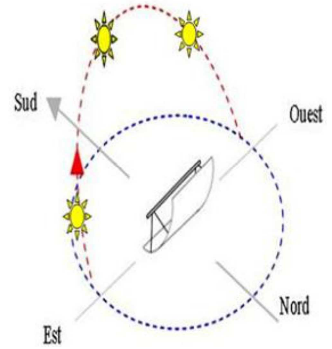
Three major solar tracking modes as displayed in Figure 2 were examined to show the effect of tracking techniques on the amount of direct normal solar radiation collected in Maroua. The configuration of those three major solar tracking modes consists to maintain the plane of the incident solar radiation so that it is always normal to the collector aperture. For the East-West horizontal tracking mode, the collector is orientated in a North-South direction and then, tracks the sun from East to West while for the North-South horizontal tracking mode, the collector is orientated in an East-West direction and then, tracks the sun from North to South and at least for the East-West polar tracking mode, the collector is orientated facing the sun with a titled at an angle according the latitude of the site location and then, tracks the sun from East to West. Thus, the direct solar radiation from different points of the parabolic trough-reflecting surface is collected on the heat collecting element. Then, daily direct normal radiation in Maroua was generated by using the empirical model of Capderou after implementing the numerical model which was also used to plot optical efficiency, amount of energy absorbed by heat collecting element and to estimate yearly irradiation yield for various tracking configurations. The model simulated compares the solar direct radiation during the sunniest month on a typical sunny day of 21st March 2014 and the least sunny month on a typical day of 21st August 2014 for various tracking modes. In another hand, optical efficiency and energy absorbed by the heat collecting element are comparing in the sunny and least sunny months for various tracking modes.



(a) East-West horizontal tracking



(b) North-South horizontal tracking



(c) East-West polar tracking mode

Fig. 2. Solar tracking mode configurations, adapted from [4]

2.1 ESTIMATION OF THE SOLAR DIRECT RADIATION

Daily a large flux of solar energy received on Earth is not completely that issued from the sun. The power of this radiation is based on several criteria such as weather, atmospheric diffusion (dispersion phenomena, reflection and absorption) and aerosols. This can reduced solar technologies performances. Then, knowledge of solar direct radiation is essential for the calculation of various performance-related solar technologies such as solar parabolic trough collectors and the energy gained by the system depends on the tracking modes. Maroua is known of an arid climate with irregular rainfall, low cloudiness of the atmosphere, hot and dry air, permanent aerosols, almost ten sunny months and two less sunny months. Under these climatic conditions, the empirical model of Capderou [8] based clear sky seems suitable to explore in order to estimate solar direct radiation received on a collector surface located in Maroua.

The equation used by Capderou to estimate the direct solar radiation received on any surface is given:

$$I_{dir}\left(W.m^{-2}\right)=I_0\times\varepsilon_0\times\cos(\theta)\times\exp\left(-T_L\times m_A\times\delta_{Ra}\right) \tag{1}$$

In this study, the mean value of the solar constant flux received on the ground is assumed to be set:

$I_0\left(W.m^{-2}\right)=1367$.

The correction coefficient of the Earth-Sun distance can be calculated by the equation:

$$\varepsilon_0(-)=1+0.034\times\cos\left(\frac{360}{365}\left(N_j-2\right)\right) \tag{2}$$

Where N_j is the day number of the year, ranging from 1 on 1 January to 365 on 31st December.

According to equation (3), the absorption and diffusion caused by the atmospheric constituents can be expressed by the Linke turbidity factor, which is calculated, based clear sky as given:

$$T_{Lf}(-) = T_0 + T_1 + T_2 \tag{3}$$

The turbidity factor of gaseous absorption based only on geo-astronomical parameters is given by the following expression:

$$T_0(-) = (2.4 - 0.9\sin\varphi) + 0.1 \times Ah_e(2 + \sin\varphi) - 0.2z - (1.22 + 0.14 \times Ah_e)(1 - \sin h_s) \tag{4}$$

The turbidity factor of absorption by atmospheric gases (O_2, CO_2 and O_3) is calculated by the following formula:

$$T_1(-) = (0.89)^z \tag{5}$$

The turbidity factor caused by aerosols is calculated by the formula below:

$$T_2(-) = (0.9 + 0.4 \times Ah_e) \times (0.63)^z \tag{6}$$

With $z(m)$ is the altitude of the site location.

The parameter which characterize seasons is calculated as follow:

$$Ah_e(-) = \sin\left(\frac{360}{365}(N_j - 121)\right) \tag{7}$$

The atmospheric mass given by [9] represents the atmospheric mass trough the solar direct radiation to reach the ground and depends of the local pressure and the sun elevation angle:

$$m_A(-) = \frac{P}{101325}\left[\sin(h_s) + 0.15(h_s + 3.885)^{-1.253}\right]^{-1} \tag{8}$$

Where the pressure is calculated as follow:

$$P(Pa) = 101325 \times (\exp(-0.0001184z))$$

The sun elevation angle is calculated as follow:

$$h_s(°) = \cos\varphi\cos\delta\cos\omega + \sin\varphi\sin\delta \tag{9}$$

The atmospheric thickness optical also called the integral Rayleigh optical thickness recommend by [10] is calculated as follow:

$$\delta_R(-) = \left[6,6296 + 1,7513m_A - 0,1202m_A^2 + 0,0065m_A^3 - 0,00013m_A^4\right]^{-1} \tag{10}$$

The direct solar radiation on a horizontal plane can be estimated as follow:

$$I_{dir\_h}(W.m^{-2}) = I_0 \times \varepsilon_0 \times \sin(h_s) \times \exp(-T_L \times m_A \times \delta_{Ra}) \tag{11}$$

2.2 Solar Tracking Modes

Solar tracking mode affects the amount of direct solar radiation received on the reflector and then throughout the day, allows minimizing the angle of incidence of solar radiation on a plane with the solar parabolic trough collector. Indeed, the angle of incidence varies with the optical efficiency of the solar parabolic trough collector. Thus, the optical efficiency of the solar parabolic trough collector is as important as the angle of incidence is small. Usually, the plane of the angle of incidence of solar radiation is heat collecting element or the collector itself. The principle of tracking mode by movement around an axis is to guide in each moment the receiver plane by rotation around the axis so that the normal plane is constantly in the plane formed by the axis and the sun's path (figure 2). Solar tracking systems are classified according the number of axes and tracking modes. The solar tracking mode with two degrees of freedom can track the sun's path so that the incidence is constantly normal. In applications using solar parabolic trough collector, solar tracking modes based on one or two axis are generally interesting. In this work, we assume the solar tracking modes on one axis based the cosine of incidence angle $\cos(\theta)$ as well as proposed by Capderou in Table 1:

Table 1. Estimation of the Cosine of Incidence Angle Trough the Solar Tracking Mode

Tracking modes	Heat collecting element orientation	Cosine of incidence angle
East-West polar	Along the earth axis	$\cos\theta = \cos\delta$
East-West horizontal	Parallel to the North-South axis	$\cos\theta = \left(1-\left(\cos(\delta)\sin(\varphi)\cos(\omega)-\sin(\delta)\cos(\varphi)\right)^2\right)^{\frac{1}{2}}$
North-South horizontal	Parallel to the East-West axis	$\cos\theta = \left(1-\cos^2(\delta)\sin^2(\omega)\right)^{\frac{1}{2}}$ o

2.3 SOLAR ENERGY ABSORBED

For a solar parabolic trough collector, the incident solar radiation absorbed per unit of area by the heat collecting element is given:

$$Q_{abs}(W) = A_0 \times I_{dir} \times \rho_0 \times \alpha_0 \times \gamma \times K \tag{12}$$

For a solar parabolic trough collector, the incident solar radiation absorbed per unit of area by the glass envelope is given:

$$Q_{ver}(W) = A_0 \times I_{dir} \times \rho_0 \times \alpha_{ver} \times \gamma \times K \tag{13}$$

The aperture area of a solar parabolic trough collector is calculated as follow:

$$A_0(m^2) = W \times L \tag{14}$$

The transmittance-absorptance factor is calculated in the following form:

$$\alpha_0(-) = \frac{\tau_{ver} \times \alpha_{abs}}{1-(1-\alpha_{abs})(1-\tau_{ver})} \tag{15}$$

The shape factor is calculated as follow:

$$\gamma(-) = \prod_{i=1}^{6} \gamma_i \tag{16}$$

The incident angle modifier is calculated:

$$K(-) = 1 - 0{,}00384(\theta) - 0{,}000143(\theta^2) \tag{17}$$

The solar parabolic trough collector optical efficiency is then defined in the following form:

$$\eta_{opt} = \frac{Q_{abs}}{A_0 \times I_{dir}} = \rho_0 \times \alpha_0 \times \gamma \times K \tag{18}$$

3 RESULTS AND DISCUSSION

2.3.1 Optical performances of solar parabolic trough collectors for various solar tracking modes under climatic conditions of Maroua were performed in this work. Solar direct radiation, optical efficiency, energy absorbed by the heat collecting element, was plot and estimated in this work for various solar tracking modes by using the empirical model of Capderou based clear sky and results were compared for a typical sunny day of the sunniest month and for a typical least sunny day of the least sunny month. Also, maximum temperatures of three heat transfer fluid obtained in right-end of heat collecting element for a typical day of the sunny month was compared and displayed in the case of East-West Polar mode which seems to be, according to this study the suitable solar tracking mode.

3.1 SITE LOCATION

Maroua is situated in the far north region of Cameroon which is located in Cameroon Sahelian zones. The physical characteristics of the site are given in Table 2.

Table 2. Geographical Coordinates of the Studied Location

Position studied	Latitude (°)	Longitude (°)	Altitude (m)	Climate	Albedo
Maroua	5.15	13.58	718	Sahelian	0.6

3.2 MODEL TESTING

We have used the optical characteristics (Table 3) of the Sandia National Laboratory experimental collector installed in the Mojave Desert in South of California located on Sun-Belt countries to analyse optical performances of a solar parabolic trough collector under climatic conditions of Maroua.

Table 3. Optical Characteristics of the Sandia Experimental Collector [11]

	Symbol	Physical parameters	Value	Unit
Collector	L	Length	7.8	m
	W	Aperture	5	m
	F	Focal length	1.840	m
Reflector	C_{refl}	Specific heat	581	J/kg K
	ρ_{refl}	Density	2400	kg/m^3
	e	Thickness	0.005	m
	α_0	Transmittance-absorptance factor	0.864	-
	ρ_0	Reflectivity	0.93	-
	γ	Shape factor	0.92	-

The Sandia National Laboratory experimental tested collector is displayed in Figure 3.

Fig. 3. Sandia experimental collector installed in desert Mojave in South California, 39m² adapted from [12]

3.3 Performances of Parabolic Trough Collector for Various Tracking Modes

3.3.1 Direct Solar Radiation Estimated

Results show that the empirical model of Capderou gives a good estimate of direct solar radiation during the sunniest month compared to the least sunny month. By comparing Figure 4 and Figure 5 it is shown that, the East-West horizontal and the East-West polar modes are more getting closer with full tracking mode on a typical sunny day of the sunniest month than the least sunny month. Furthermore, the North-South horizontal mode is not advantageous during those periods.

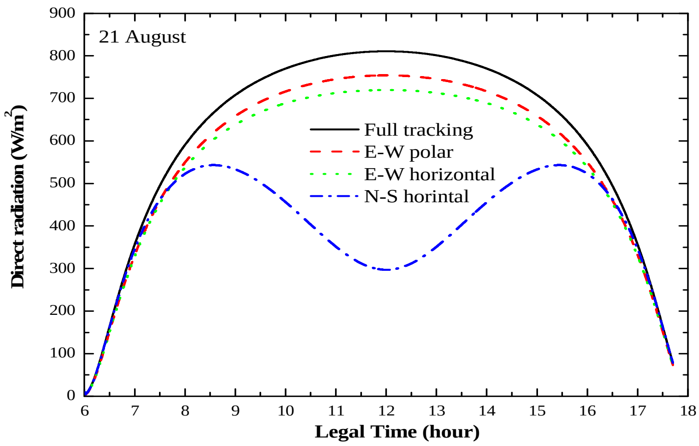


Fig. 4. Direct Solar Radiation for Various Tracking modes on a Typical less Sunny Day

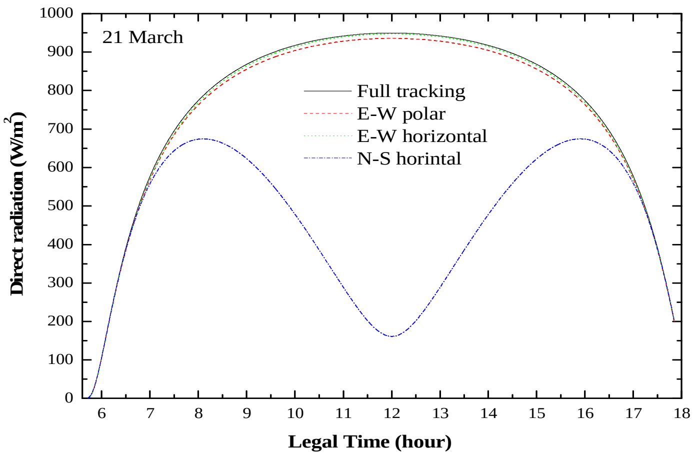


Fig. 5. Direct Solar Radiation for Various Tracking modes on a Typical Sunny Day

3.3.2 Optical Performances

The daily annual average of optical efficiency is displayed (Figure 6) for various tracking modes. The maximum of efficiency obtained during the day of the year is around 74% for both the East-West horizontal and the East-West polar mode while the maximum is around 65% for the North-South horizontal tracking mode.

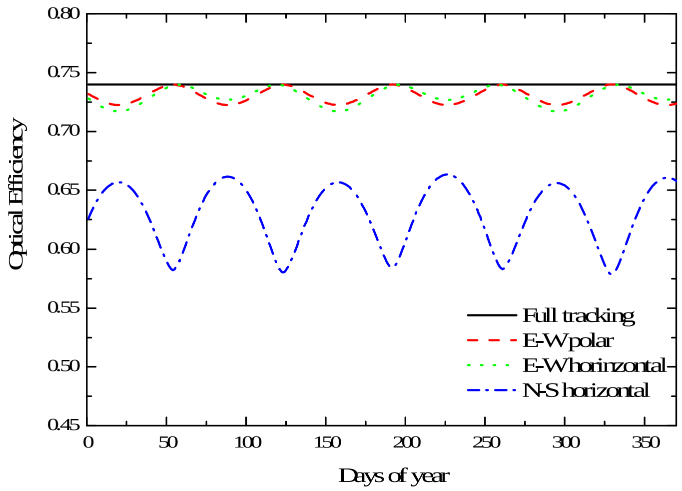


Fig. 6. Daily Annual Average of Optical Efficiency for Various Tacking modes

The optical efficiency for various tracking modes is displayed (Figure 7 and Figure 8) for the sunny and the less sunny months. It is observed that, the full tracking collectes the maximum amount of energy with about 74% of optical eficiency. In addition, the optical performances from East-West horizontal and East-West polar modes are getting closer with full tracking mode for both the sunniest and the least sunny months.

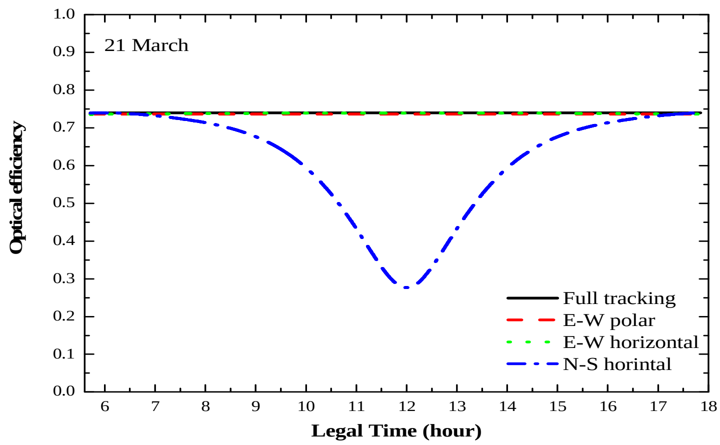


Fig. 7. Optical Efficiency for Various Tracking modes on a Typical Sunny Day

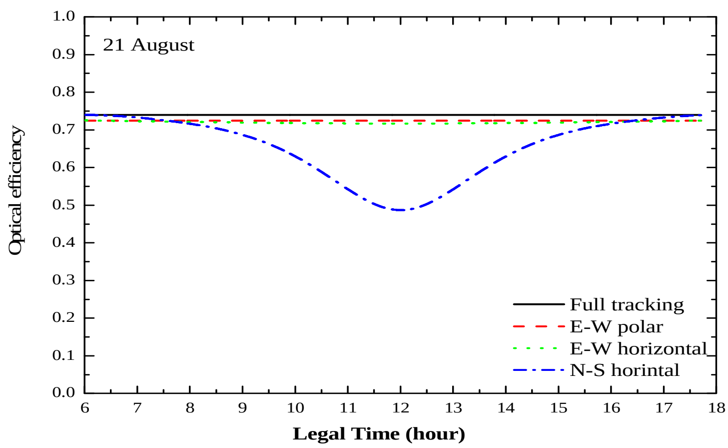


Fig. 8. Optical Efficiency for Various Tracking modes on a Typical Less Sunny Day

The optical efficiency depends on incident angle modifier. The result displaying (Figure 9), show that the optical efficiency and the incident angle modifier decrease substantially with increasing incidence angle. The optical efficiency reached at about more than 74% for both the sunniest and the least sunny months. Hence, coupling tracking mode with a solar parabolic trough collector is necessary for the operation of a solar parabolic trough collector.

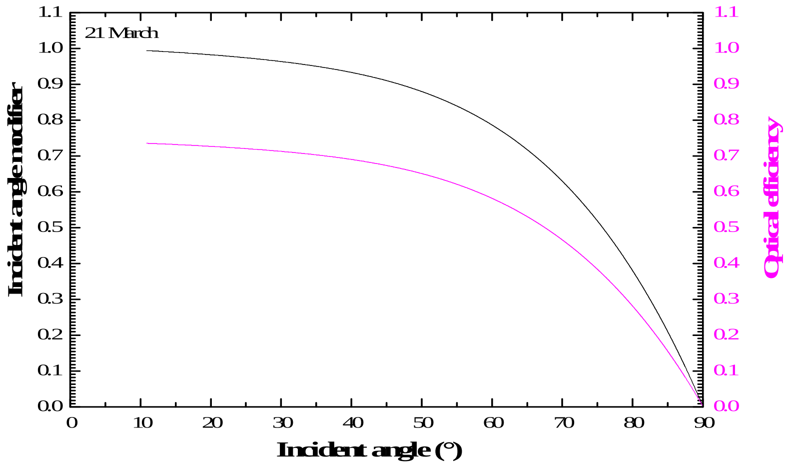


Fig. 9. Variation of Incident Angle Modifier in order with Optical Efficiency and Incident Angle

In those cases (Figure 10 and Figure 11), for East-West horizontal mode, daily energy absorbed is of maximum amount and getting closer with full tracking during the sunny month compared to East-West polar tracking mode during the less sunny month. Furthermore, the North-South horizontal mode consumes less energy during the year compared to the other tracking modes.

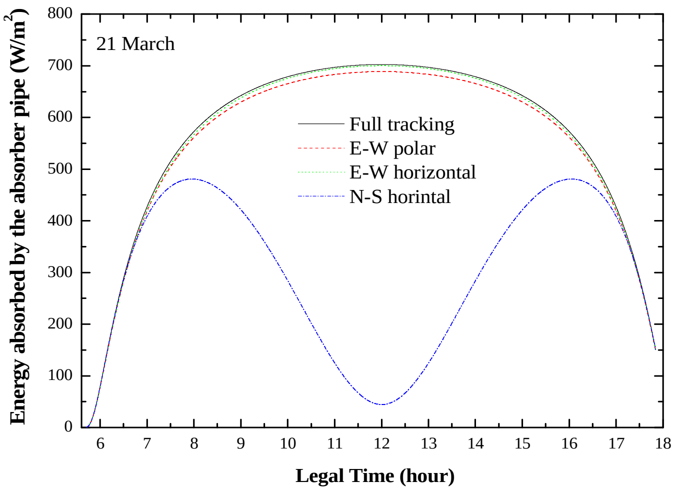


Fig. 10. Energy Absorbed by Heat Collecting Element for Various Tracking modes on a Typical Sunny Day

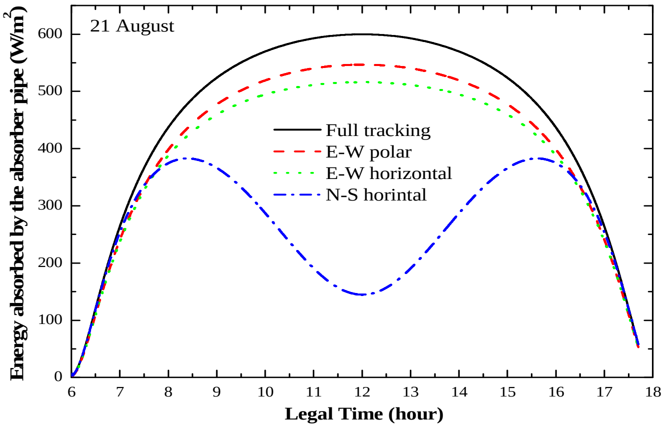


Fig. 11. Energy Absorbed by Heat Collecting Element for Various Tracking modes on a Typical Less Sunny Day

According to Table 4, the energy absorbed by the heat collecting element during the sunny and the less sunny months in the case of the three various tracking modes is compared with the full tracking mode which collects the maximum amount of solar radiation. It is shown, that, the performances of East-West polar and East-West horizontal tracking mode are more suitable and getting closer with full tracking mode during the sunny month while the East-West polar tracking mode performances is comparatively larger than the East-West horizontal tracking mode during the less sunny month. Besides, the performance of North-South horizontal tracking mode is worse during the less sunny and sunny months compared to the other tracking modes. However, this mode consumes less energy during the whole year.

Table 4. Comparison of Energy Absorbed in Maroua for Various Tracking Modes

Tracking mode	Absorbed energy (kWh/m^2)		Percent to full tracking (%)	
	Sunny months	**Less sunny months**	**Sunny months**	**Less sunny months**
Full tracking	8.50	6.55	100	100
East-West polar	8.33	6.1	98.03	91.2
East-West horizontal	8.5	5.41	99.98	81.45
North-South Horizontal	5.89	4.13	69.25	62.85

According to Table 5, full tracking mode compared to East-West horizontal mode, East-West polar mode and North-South horizontal tracking modes lead at about 14.24 GJ/m^2 of the annual incident irradiation of solar parabolic trough collector surface.

Table 5. Annual Incident Irradiation for Various Tracking Modes

Mode of tracking	Annual irradiation, GJ/m^2
Full tracking	14,24
East-West horizontal	13,32
East-West polar	12,85
North-South horizontal	9,97

By applying under climatic conditions of Maroua, the East-West polar and East-West horizontal mode which is more suitable and getting closer with full tracking than the North-South horizontal mode, we have obtained (figure 12) for a typical day of the sunniest month, maximum temperatures of three heat transfer fluid in the right-end of heat collecting element as well as 180°C for air and oil and 90°C for water.

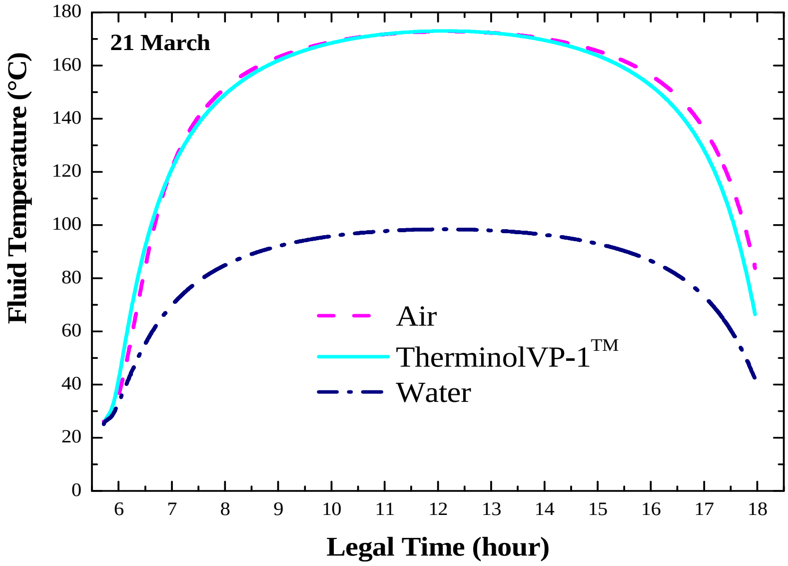


Fig. 12. Temperature Variation of Various Heat Transfer Fluids According the East-West Solar Tracking Mode on a Typical Sunny Day

4 CONCLUSION

In this paper, optical performances of the Sandia National Laboratory experimental collector under climatic conditions of Maroua were performed and compared for various solar tracking modes. The total amount of energy falling on the aperture of solar parabolic trough collector in the case of East-West Horizontal and East-West polar tracking modes is getting closer with full tracking mode than that of the North-South horizontal tracking mode which leads to consume less energy than the others tracking mode during the sunny and the least sunny day. However the East-West polar and the East-West horizontal provide a more constant annual output. In the case of heat application during less sunny months due of abundant rain (June, July, August), the North-South horizontal mode is recommended while the East-West polar and East-West horizontal is preferable during the sunny months (September to May). In another hand, the better period for solar radiation collection is covered from September to May. The maximum of daily annual average of optical efficiency devoted for various tracking modes show that, the East-West horizontal is better for a solar parabolic trough collector field with several collectors due to the low power losses of field's shadow while the East-West polar tracking mode is preferred for individual installation because of the small surface of the reflector.

Further work is ongoing for determining the predictive model control of a solar parabolic trough collector under climatic conditions of far North Cameroon region by using different types of fluids transfer.

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