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Research Paper

Yearly performance of low-enthalpy parabolic trough collectors in MENA region according to different sun-tracking strategies

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HIGHLIGHTS

- Detailed thermo-optical model of PTCs with MATLAB code is presented.
- Climatic conditions affect significantly the PTC overall performance.
- Best yearly heat generation (154.57 MWh) is predicted in Ouarzazate, Morocco.
- Polar E-W is the most cost effective tracking technique for such applications.

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ABSTRACT

Solar parabolic trough collector (PTC) is a very popular system in solar concentration technology, which is widely used for electric production and heat generation in industrial processes. In this paper, a validated mathematical model has been proposed to evaluate the performance of low-enthalpy PTC in five sites of the MENA region: Ouarzazate (Morocco), Gafsa (Tunisia), Jeddah (Saudi Arabia), Amman (Jordan) and Aswane (Egypt). A MATLAB program was developed to simulate the hourly thermal performance of the PTC under fluctuating climatic conditions. A particular attention has been given to the effect of the sun-tracking technique on the collector's performance. The model validation was carried out in two phases: first, by comparison with the results generated by the System Advisor Model software, and second by comparison with experimental data. In both cases, a very close agreement is obtained. The results have shown clearly that the tracking technique, climate and season of the year have a significant impact on the PTC performance. The best site for implementing such technologies was found to be Ouarzazate (Morocco) with a useful annual energy generation potential varying from 104.85 to 154.57 MWh. On December 24, the PTC operating in Ouarzazate using 0.2 kg/s mass flow rate, the outlet water temperature can achieve a maximum temperature of 70 °C using the full-tracking and N-S tracking techniques, while the outlet temperature does not exceed 46.5 °C using the E-W tracking. This temperature can reach 82 °C on July 07, by using the full-tracking and E-W tracking modes. From a general aspect, it was also concluded that the optimal cost-effective tracking strategy for the annual heat generation is the E-W polar tracking one independently of the geographical location.

1. Introduction

In a world where awareness about the damage caused by climate change is growing, the smooth transition toward a more sustainable energy system has become a first global challenge [1–3]. The Middle East and North Africa (MENA) region is not an exception and is primarily concerned with this challenge for many reasons [4]. In fact, the MENA region is often referred to as the lung of the international energy market, retaining the largest part of the world's oil and gas reserves evaluated to 52% and 42%, respectively [5,6]. Nevertheless, it also represents the highest energy consumption among all the world regions. During the period 2000–2011, primary energy and electricity demand have increased by about 8% each [7]. The fast growth of energy demand and the strong dependency on fuel-based energy generation have caused high levels of pollution in MENA that is considered as the second

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Nomenclature

N	day number in the year [dimensionless]
$LONG_{local}$	Local longitude [degree]
$LONG_{sm}$	standard meridian longitude [degree]
LT	local time [hours]
AST	apparent solar time [hours]
E_t	equation of time [minutes]
h	hour angle [degree]
z	zenith angle [degree]
α	solar altitude [degree]
δ	solar declination [degree]
θ	incidence angle [degree]
k_θ	incident angle modifier [dimensionless]
ε_{ci}	outer glass cover emittance [dimensionless]
ε_{co}	emittance of the external surface of the glass cover [dimensionless]
ε_r	receiver emittance [dimensionless]
G_{bh}	beam radiation on a horizontal surface [W/m^2]
G_{bt}	beam radiation [W/m^2]
c_{pf}	specific heat of the working fluid [J/kg K]
h_{fi}	convective heat transfer coefficient inside the receiver tube [W/m^2 K]
h_w	convective heat transfer coefficient between the external surface of the glass cover and the ambient air [W/m^2 K]
U_0	heat transfer coefficient between the surroundings and the fluid [W/m^2 K]
k_f	thermal conductivity of the working fluid [W/m K]
k_c	thermal conductivity of the glass cover [W/m K]
LAT	latitude of the concerned location [degrees]
Nu	Nusselt number [dimensionless]
Pr	Prandtl number [dimensionless]
Re	Reynolds number [dimensionless]
T_a	ambient temperature [°C]
T_{ci}	inside of the cover the temperature [°C]
T_{co}	outer glass cover temperature [°C]
T_i	inlet fluid temperature [°C]
$T_{o\text{-}assumed}$	Outlet temperature [°C]
T_r	receiver temperature [°C]
T_{sky}	sky temperature [°C]
U_L	loss coefficient [W/m^2 K]
V_{air}	wind speed around the glass cover [m/s]
V_f	working fluid speed [m/s]
γ	intercept factor [dimensionless]
η_0	optical efficiency [dimensionless]
τ	absorbance of the receiver [dimensionless]
α	transmittance of the receiver [dimensionless]
r_m	reflectance of the mirror [dimensionless]
μ_{air}	air dynamic viscosity [kg/m s]
μ_f	working fluid dynamic viscosity [kg/m s]
ρ_{air}	air density [kg/m^3]
ρ_f	working fluid density [kg/m^3]
σ	Stefan–Boltzman constant ($\sigma = 5.67 \cdot 10^{-8}$) [W/m^2 K^4]
$\dot{Q}_{loss}$	convection and radiation heat losses between the glass cover to the environment [W]
$\dot{Q}_u$	useful energy rate to the working fluid in receiver tube [W]
$\dot{m}$	fluid mass flow [kg/s]
F_R	the heat removal factor [dimensionless]
F’	collector efficiency factor [dimensionless]
D_{ro}	receiver outer diameter [m]
D_{ci}	glass envelope inner diameter [m]
D_{co}	glass envelope outer diameter [m]
W_a	width of the collector [m]
L	length of the collector [m]
D_{ri}	receiver inner diameter [m]
A_a	collector aperture area [m^2]
A_r	receiver area [m^2]
C	concentration ratio [dimensionless]

most polluted area in the world after South Asia [8,9]. From another perspective, MENA also confronts pressures to accelerate its economic and social development, especially with the high youth unemployment rate (22% according to 2010 statistics) [10]. Moreover, due to the limited fresh water resources in several countries around the region, the energy-intensive process of water desalination is indispensable for water security causing additional financial expenditures especially with the high-subsidization allocated [11]. Against all these issues, MENA has fixed a renewable energy policy target to reduce its dependency on fossil fuels and therefore has initiated significant investments in renewables evaluable to USD 2.9 billion in 2012, 40% higher than 2011 [12]. Along with this, attempts to modernize the legal infrastructure are deployed to assist the ongoing projects across the MENA region [13]. Among renewable sources, solar energy has the potential to notably contributing to sustainable development in MENA owing to [14,15]: (i) the huge available solar radiation, particularly in the desert zones, (ii) the suitable land-use features and accessible decommissioning and (iii) decreasing costs of solar systems. In the recent years, solar, whether thermal, photovoltaic or thermodynamic, has started to be more intensively installed across MENA countries profiting from the emerging market of solar equipments and the rapid technological advancement they are presently experiencing [16].

Among solar energy options, concentrating solar collectors have the potential of generating clean, renewable and grid-scale energy with the best opportunities for commercial exploitation in MENA. In addition to power generation [17], they can be used for other applications such as hot water and steam production for industrial use [18], solar heating and cooling [19,20], and water desalination [21,22]. The currently available concentrating collectors can be distinguished according to their focus geometry that can be either a point or a line, operating temperature levels and sun-tracking options. The five main technologies are solar towers [23], parabolic trough collectors [24], Fresnel collectors [25], compound parabolic collectors [26] and solar dish collectors [27].

Parabolic trough collectors (PTCs) have the advantage of being the earliest concept in solar concentration technology and the most mature technology currently [28]. This technology permits the exploitation of solar energy for a wide range of temperatures between 50 and 400 °C [29]. Furthermore, it is recommended for low/mid-temperature solar thermo-chemical reactions.

As shown in Fig. 1, a PTC comprises a receiver tube where the heat transfer fluid circulates, a transparent cover and a parabolic mirror. The receiver (or absorber) is upheld continuously at the focus of the parabolic mirror. The transparent cover, concentric with the absorber is used to reduce heat losses to surroundings by keeping a vacuum pressure in the space between the absorber and cover. In some configurations, to decrease the product cost, unshielded absorbers were proposed [30]. A rigid structure containing the solar tracking mechanism is employed to withstand exterior extreme conditions. The role of the tracking mechanism