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# Daily performance of parabolic trough solar collectors

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ABSTRACT

Parabolic trough collector (PTC) is the most mature concentrating technology which is used in a great variety of thermal applications. In this study, the daily performance of a PTC is investigated for all the year period. The module of Eurotrough parabolic trough collector is examined with various storage tanks from 3 $m^3$ to 15 $m^3$ and the collector performance is investigated in energetic and exergetic terms. An Input/Output method is applied for the daily evaluation of the solar thermal system, something innovative for concentrating solar collectors. According to the final results, different storage tank volumes lead to similar thermal outputs but to extremely different exergetic outputs because of the high dependence of the mean storage tank temperature with the storage tank volume. For the storage tank of 9 $m^3$, the mean thermal efficiencies in December and in June are found to be 37.1% and 68.7% respectively, while the mean exergetic efficiencies 2.0% and 8.5% respectively. Moreover, it is proved that the Input/Output performance method in concentrating collectors has to take into consideration the solar incident angle at solar noon in order high accuracy to be achieved.

## 1. Introduction

Solar energy utilization is one of the most promising ways to face numerous modern energy problems, such as the global warming, the fossil fuel depletion and the increasing rate of electricity cost (Tiwari and Tiwari, 2016; Reddy et al., 2015; Tripathi and Tiwari, 2016). Solar energy ability to be converted either to useful thermal or electricity renders it a suitable energy source for a great variety of applications. The most usual applications which exploit the solar thermal energy are space heating (Mahian et al., 2013), domestic hot water production (Duomarco, 2015), desalination (Sharshir et al., 2016), solar cooling (Bellos et al., 2016), as well as many industrial processes (Kumar and Kumar, 2016). Moreover, the last years a lot of research has been focused on the concentrating solar power plants which use concentrating solar collectors for producing electricity (Tzivanidis et al., 2016; Loni et al., 2016).

The concentrating collectors are usually selected in applications which demand temperature levels over 150 °C (Shirazi et al., 2016), because the conventional flat plate technologies cannot operate at medium and high temperatures. The most usual CSP technologies are parabolic trough collectors (PTCs) Bellos et al., 2016a, linear Fresnel reflectors (Bellos et al., 2016b), solar dish collectors (Hafez Ahmed Soliman et al., 2016) and solar towers (Abu-Hamdeh and Alnefaie, 2016). Among them, parabolic trough collector is the most mature technology (Chacartegui et al., 2016) which has been commercialized some decades before and at this time it can be supplied to the consumers at a reasonable cost close to 200 €/$m^2$ (Salgado Conrado et al., 2017).

In this direction, a lot of research has been focused on the improvement of solar collectors in order to make them a more sustainable technology (Sandeep and Arunachala, 2017). In the literature, many ideas such as the use of nanoparticles dispersed in the working fluid (Mwesigye et al., 2016), the use of internal fins in the absorber (Huang et al., 2015; Bellos et al., 2017; Gong et al., 2017), as well as the use of inserts in the flow have been examined. All these techniques aim to enhance the heat transfer between the absorber and the working fluid in order the thermal efficiency of the system to be increased. Mwesigye et al. (2016) examined the use of Cu nanoparticles with Therminol VP1 as the base fluid. They examined the LS-2 collector and they found thermal enhancement up to 12.5% for high nanoparticles concentrations. Different kinds of internal fins in the absorber have been examined by Huang et al. (2015). According to their results, the mean Nusselt number can be increased up to 60% and the enhancement is higher when the fins have deeper depth and narrower pitch. Mwesigye et al. (2014) examined the use centrally placed perforated plate inserts in the PTC absorber. They finally found thermal enhancement from 2% to 8% for different Reynolds numbers.

The next important research field is about the daily performance of

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## Nomenclature

| | |
|---|---|
| A | parameter of solar direct beam intensity, W/m$^2$ |
| $A_a$ | collecting area, m$^2$ |
| $A_T$ | storage tank zone outer surface, m$^2$ |
| B | parameter of solar direct beam direction, – |
| $c_p$ | specific heat capacity under constant pressure, J/kg K |
| D | daily energy, kWh |
| $D_{l,calc}$ | daily useful thermal energy calculated with the developed model, MJ |
| $D_{l.meas}$ | daily useful thermal energy measure in the literature study, MJ |
| $D_T$ | storage tank diameter, m |
| DR | daily range, °C |
| Ex | exergy flow, W |
| $F_1$ | 1st coefficient of characteristic I/O equation, m$^2$ |
| $F_2$ | 2nd coefficient of characteristic I/O equation, kWh/K |
| $F_3$ | 3rd coefficient of characteristic I/O equation, kWh |
| $G_b$ | solar direct beam radiation, W/m$^2$ |
| $G_{b,max}$ | maximum daily solar beam radiation in horizontal surface, W/m$^2$ |
| $G_T$ | solar irradiation on titled surface, W/m$^2$ |
| $H_{avail}$ | daily solar energy on the collector surface, kWh/m$^2$ |
| $H_b$ | daily solar direct beam energy, kWh/m$^2$ |
| $H_T$ | daily solar energy on the titled surface, MJ/m$^2$ |
| i | intermediate zone of storage tank ($1 < i < n$), – |
| K | incident angle modifier, - |
| $L_T$ | storage tank height, m |
| m | mass flow rate, kg/s |
| $N_D$ | day duration, h |
| $N_L$ | draw-off duration, h |
| n | number of storage tank mixing zones, – |
| Q | heat flux, W |
| t | time, s |
| $t_h$ | time, hours |
| T | temperature, °C |
| $T_{sun}$ | sun temperature in its outer layers, K |
| $U_T$ | thermal loss coefficient of storage tank, W/m$^2$ K |
| V | storage tank volume, m$^3$ |
| Z | daily exergy, kWh |

*Greek symbols*

| | |
|---|---|
| $\delta$ | solar declination angle, ° |
| $\Delta t$ | time step, s |
| $\eta$ | efficiency, – |
| $\theta$ | solar incident angle, ° |
| $\theta_z$ | zenith angle, ° |
| $\rho$ | density, kg/m$^3$ |
| $\varphi$ | local latitude, ° |
| $\omega$ | solar time angle, ° |

*Subscripts and superscripts*

| | |
|---|---|
| am | ambient |
| am,m | ambient mean |
| c | collector |
| c,in | collector inlet |
| c,out | collector outlet |
| ex,c | collector exergy |
| ex,sys | system exergy |
| fm | mean fluid |
| hmax | hour of maximum ambient temperature |
| l | load |
| m | mean |
| s | storage tank |
| s(i) | storage tank in "i" mixing zone |
| sol | solar |
| sun | sun |
| s0 | initial storage tank |
| s,end | end day storage tank |
| th,c | collector thermal |
| th,s | system thermal |
| u | useful |

*Abbreviations*

| | |
|---|---|
| CSP | concentrating solar power |
| DD | day of the year |
| E–W | east–west direction |
| N–S | north–south direction |
| PTC | parabolic trough collector |

the PTCs. In the literature, the studies are mainly focused on the evaluation of solar thermal collectors coupled to other thermal devices inside a greater system (Mahmoudimehr and Loghmani, 2016). The daily performance of a PTC field operating with molten salt (60% $NaNO_3$ - 40% $KNO_3$) with two storage tanks (cold and hot tank) was examined by Maccari et al. (2015). They focused on determining the operating time period of the system in order to be able to feed a power plant for electricity production. Another interesting study about the daily performance of PTC is performed by Kumar and Kumar (Kumar and Kumar, 2015) for the climate conditions of India. They examined the LS-2 PTC module for one characteristic day of each month. They did not use storage tank in their analysis and they applied the same inlet temperature during the daily performance. According to their results, the highest useful heat output is achieved in April with the collector in an inclined plane and in May for the collector in a horizontal plane.

However, there is a lack of detailed studies which examine the daily performance of PTC coupled to a storage tank with an Input/Output method. In flat plate technologies, the Input/Output method is usually applied (Belessiotis et al., 2013) which is associated with (ISO 9459-2, 1995). This Input/Output method calculates the daily yield of the solar field using the total daily irradiation, the average ambient temperature and the energy level of the storage tank at the start of the day. According to Ref. (Belessiotis et al., 2013), three coefficients are calculated experimentally in order to define the system performance in various operating conditions. Belessiotis et al. (2010) calculated these coefficients theoretically and they validated their results with experimental data from large solar thermal systems. However, there are not literature studies in this direction which have been focused on the evaluation of integrated PTC fields with a systematic methodology, as Input/Output. One study which is close to this concept is performed by Frank et al. (2014). They tried to depict the daily thermal output of a solar thermal system with PTC for different solar potentials, for process heat integration in Dairies.

In this study, the module of the commercial PTC Eurotrough is examined in a solar thermal system with a storage tank. The analysis is performed on daily basis, applying an Input/Output performance methodology as in Ref. (Belessiotis et al., 2013) with the proper modifications which are needed due to the solar concentration. To our knowledge, there is no other study evaluating the parabolic trough solar collectors with an Input/Output method and thus the present study can be characterized as innovative. Various storage tanks are examined in order to perform a parametric analysis which covers a great variety of applications. The final results are focused on the thermal and exergetic performance determination of the integrated