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MAPPING THE PERFORMANCE OF A SOLAR PARABOLIC TROUGH COLLECTOR USING A NEW EVALUATION TECHNIQUE

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Abstract. *The present paper is devoted to a new concept regarding the solar collector efficiency map, which is a two-dimensional depiction of the performance of a solar collector. This depiction shows thermal efficiency on the horizontal axis and exergy efficiency on the vertical axis. Specifically, this depiction includes results for various mass flow rates and inlet fluid temperatures in order to investigate the collector's performance in different operating conditions. The main objective of this depiction is to present in a simple and direct way the optimum operating area of the collector in order for the system designers to select the proper application for every type of solar technology. The present work investigates a Eurotrough commercial parabolic trough solar collector, with a validated thermal model developed in EES under steady-state conditions. Optimum operating conditions were found for inlet temperatures between 450 K and 650 K, while mass flow rate has to be over 1 kg/s, according to the developed efficiency map. The maximum found exergy efficiency was 42.4% and the respective thermal efficiency was 73.1% for the inlet temperature of 650 K and mass flow rate of 5 kg/s. This map can be used to quickly determine both thermal and exergy efficiency and to know in which cases the collector has to be used for thermal or electricity applications.*

Key words: *Performance map, Solar thermal efficiency, Exergy efficiency, Parabolic trough collector, Parametric study*

1. INTRODUCTION

Solar irradiation is one of the most appropriate candidates among renewable energy sources. Solar thermal collectors are devices that capture the incident solar irradiation and convert it into useful heat at various temperature levels. The suitable evaluation of these devices, which are usually characterized as heat exchangers, is vital for the broader adoption of this technology.

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In the literature, there are numerous studies and regulations for the thermal evaluation of solar collectors which were well-established several decades ago. Rojas et al. [1] described in detail the methodology for evaluating the thermal performance of a solar collector. Moreover, the following standards are usually used: ASHRAE 93 [2], ISO 9806-1 [3] and EN12975-2 [4]. On the other hand, the exergy evaluation of solar thermal collectors has gained more and more attention recently because this procedure aids in the optimization of solar collectors by minimizing irreversibilities. This has been stated by Sciubba and Wall [5], as well as other numerous studies in the literature with the exergy evaluation of solar collectors, such as Farahat et al. [6], who examined and optimized a flat plate collector with exergy analysis. Padillia et al. [7] examined a solar parabolic trough collector (PTC) exergetically in various operating conditions. More specifically, they examined various inlet temperature levels, various mass flow rates and wind velocities in order to determine the optimum operating conditions for the examined PTC. Recently, Kalogirou et al. [8] stated the importance of exergy analysis in solar thermal collectors by giving an extended review.

The previous brief literature review shows the most recent research in the field of solar thermal collector performance evaluation. However, there are no literature studies that examine the thermal and exergy performance of solar thermal collectors simultaneously. The objective of this work is to present a methodology for evaluating thermal and exergy efficiency at the same time. The efficiency map of a solar collector is introduced as a depiction of the operation of the solar collector in all the possible operating conditions. This depiction can be used for a deep and detailed evaluation of solar thermal collectors, as well as a decision tool for the selection of a suitable collector in real applications.

2. MATERIALS AND METHODS

Firstly, it is important to define the basic parameters of the present study which are associated with the efficiency indexes. The thermal efficiency (η_{th}) of the collector is defined as the ratio of the useful heat (Q_u) to the available solar irradiation (Q_s):

$$\eta_{th} = \frac{Q_u}{Q_s} \quad (1)$$

The exergy efficiency (η_{ex}) can be written as the ratio of the useful exergy (E_u) to the available exergy of the solar irradiation (E_s).

$$\eta_{ex} = \frac{E_u}{E_s} \quad (2)$$

The useful exergy in a solar heating process (E_u) with a liquid working fluid is written as [9]:

$$E_u = m \cdot c_p \cdot (T_{out} - T_{in}) - m \cdot c_p \cdot \ln \left[\frac{T_{out}}{T_{in}} \right] \quad (3)$$

The exergy flow of the undiluted solar irradiation (E_s) is calculated by the Petela formula [10], which is the most accepted model:

$$E_s = Q_s \cdot \left(1 - \frac{4}{3} \cdot \frac{T_{am}}{T_{sun}} + \frac{1}{3} \cdot \left[\frac{T_{am}}{T_{sun}} \right]^4 \right) \quad (4)$$

The sun temperature (T_{sun}) can be taken as equal to 5770 K, which is a representative value for the outer layer of the sun. The temperature levels in the previous equations are given in Kelvin.

In this work, the module of a commercial parabolic trough collector (Eurotrough [11]) is examined for operation with Therminol VP-1 [12], which is depicted in Figure 1. The developed thermal model is presented briefly in Figure 2 and this model has been also used and validated in other literature studies [9, 13]. All the inputs, the outputs and the used equations are given in Figure 2. The simulation tool is EES (Engineering Equation Solver) by F-Chart [14].

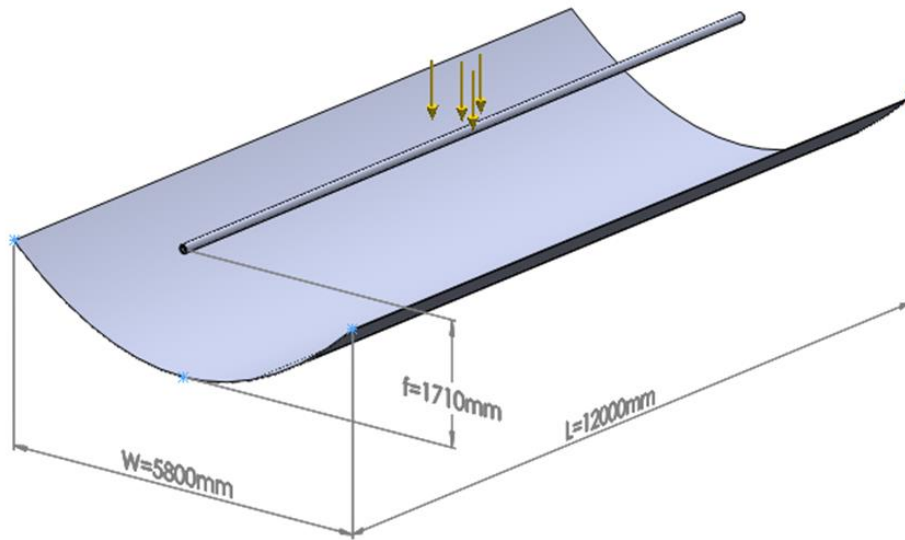


Fig. 1 The studied module of Eurotrough PTC

In the developed model, different combinations of mass flow rates and inlet temperature levels are inserted as outputs for thermal and exergy efficiency for every case. The results are firstly evaluated using the usual techniques in figures, with the usual parameter ($[T_{in}-T_{am}]/G_b$) in the horizontal axis. The next step is the creation of an efficiency map by using thermal efficiency on the horizontal axis and exergy efficiency on the vertical axis. Also, the operation points of the same inlet temperature level are depicted in this figure. It is essential to state that the inlet temperature ranges from 300 K to 650 K for the collector to operate at the allowed temperature levels. Lastly, it is important to state that the solar beam irradiation was selected to be vertical to the collector aperture and the analysis was performed in steady-state conditions.

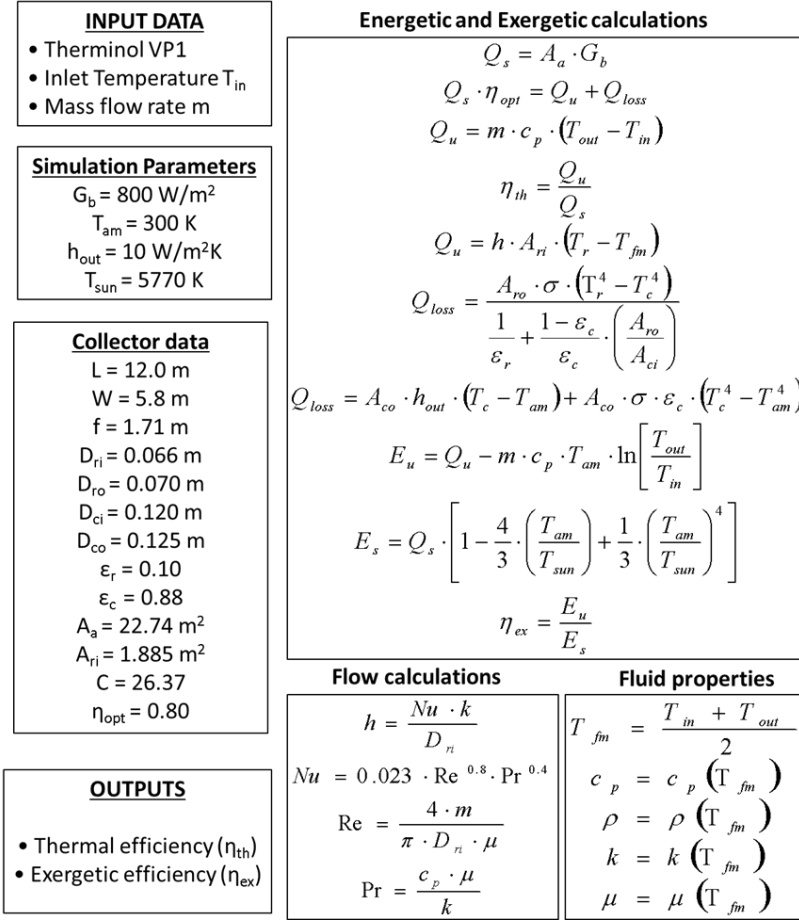


Fig. 2 The basic mathematical equations of the present modeling and the input data

3. RESULTS AND DISCUSSION

In this section, the results are presented in Figures 3 to 5. Figure 3 shows the thermal efficiency of the solar collector and Figure 4 the exergy efficiency for the examined cases. It is obvious that a higher mass flow rate leads to higher thermal efficiency and a higher inlet temperature level to lower thermal efficiency. On the other hand, a greater inlet temperature leads to higher exergy efficiency. In low temperatures, the optimum mass flow rate is the lowest examined, while in higher temperature levels the highest examined mass flow rate is the optimum. The maximum found exergy efficiency was 42.4% and the respective thermal efficiency was 73.1% for the inlet temperature of 650 K and mass flow rate of 5 kg/s.

Figure 5 is the efficiency map of the examined solar collector, which is a PTC. This depiction is innovative and indicates the thermal and exergy efficiency of the solar

collector for all the examined cases. This depiction is similar to the “compressor map” or other engineering device maps, and illustrates in a brief way the collector's performance. Especially for concentrating collectors, which are usually used in power production applications or polygeneration systems, exergy evaluation is vital for designing sustainable systems. Observing this efficiency map, the designer can select the optimum operating area by considering both energy/thermal and exergy performance. For the present case in Figure 4, the optimum area seems to be from 450 K to 550 K and for mass flow rates of over 1 kg/s. Moreover, it could be said that this depiction can show how the increase in exergy efficiency is conjugated with a penalty in thermal efficiency. So, by determining the optimum operating area of the examined collector, the system designer can know the applications in which the examined collector has to be used.

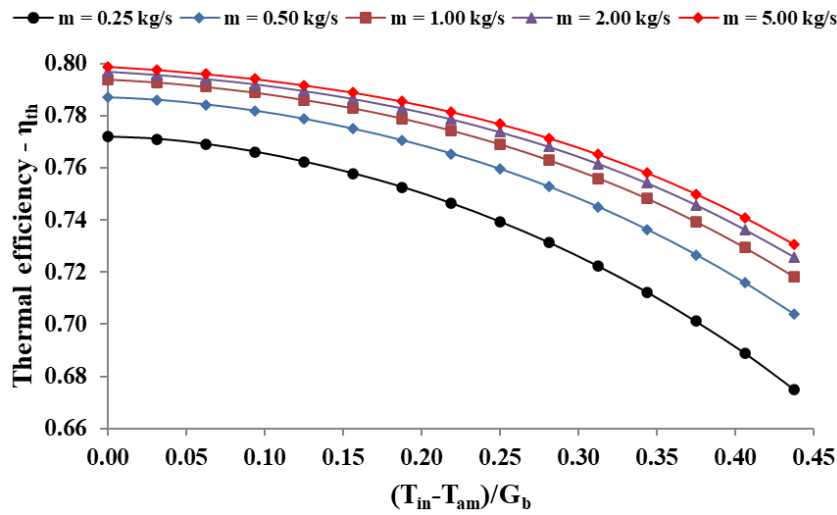


Fig. 3 Thermal efficiency of the examined solar collector

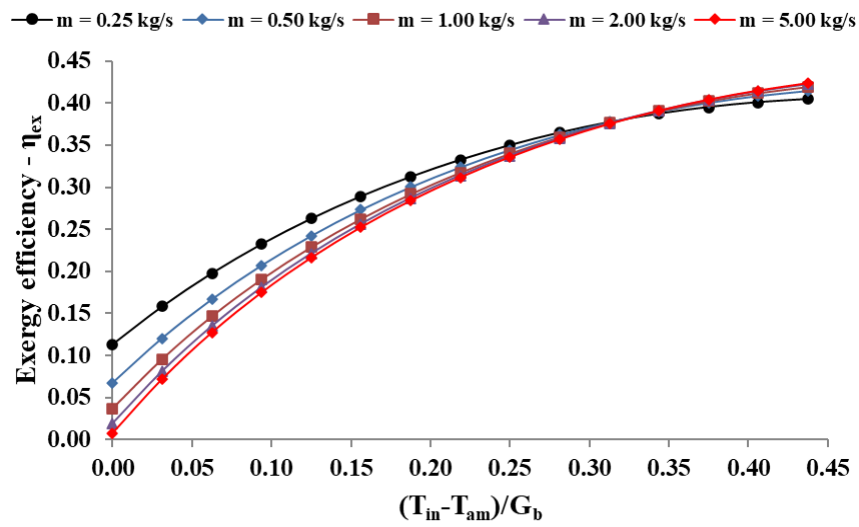


Fig. 4 Exergy efficiency of the examined solar collector

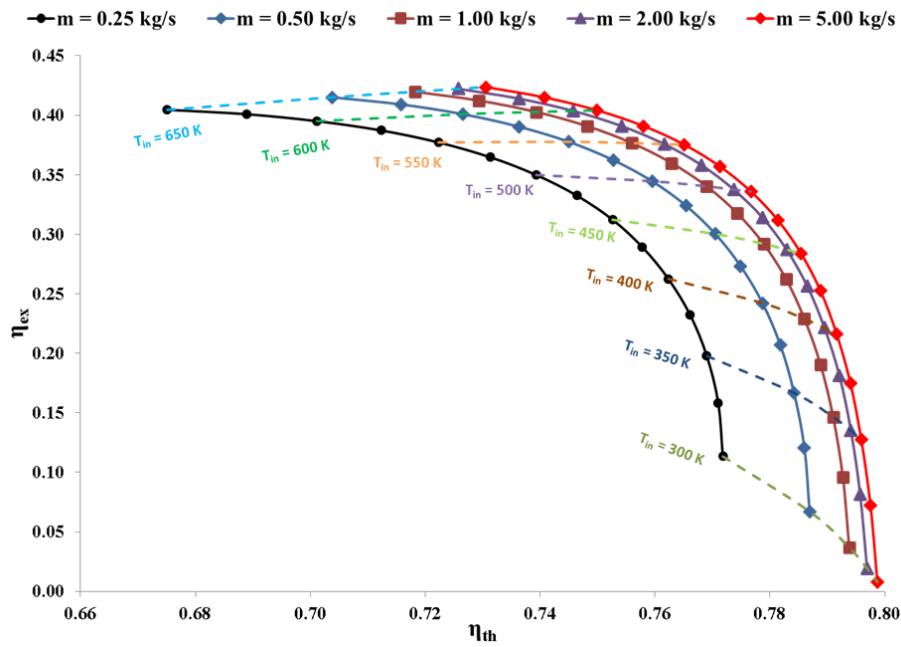


Fig. 5 The efficiency map of the studied solar collector

4. CONCLUSIONS

This paper presents a novel way of evaluating the performance of solar thermal collectors, which is the solar collector efficiency map. This tool is a two-dimensional depiction of thermal and exergy efficiency of solar collectors. This chart aids the designer to quickly determine the optimum region and decide the applications in which this collector can be used. More specifically, the cases with thermal efficiency correspond to designs for heating production (e.g. industrial heating) and the cases with high exergy efficiency correspond to applications of electricity production (e.g. with Organic Rankine Cycle or Stirling Engine). For the examined solar collector (Eurotrough), the optimum operating area was estimated to be for inlet temperatures between 450 K and 550 K, while the mass flow rate had to be greater than 1 kg/s. These results indicate the optimal operation region, and they can be used for selecting this collector in applications that need to operate close to the optimal conditions, mainly regarding the temperature levels. Moreover, it is valuable to add that the present efficiency map can be used as a decision tool for the selection of a suitable collector in real applications. In the future, the efficiency map can be extended for different values of the solar beam irradiation and the incident solar angle. Also, the efficiency maps can be developed for other collector types such as solar dish collectors and linear Fresnel reflectors.

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Nomenclature

| | |
|------------------|--|
| A | Area, m ² |
| C | Concentration ratio, - |
| c _p | Specific heat capacity under constant pressure, J/kg K |
| D | Diameter, m |
| E | Exergy flow, W |
| f | Focal length, m |
| G _b | Solar beam radiation, W/m ² |
| h | Convection coefficient, W/m ² K |
| h _{out} | Convection coefficient between cover and ambient, W/m ² K |
| k | Thermal conductivity, W/mK |
| L | Tube length, m |
| m | Mass flow rate, kg/s |
| Nu | Mean Nusselt number, - |
| Pr | Prandtl number, - |
| Q | Heat flux, W |
| Re | Reynolds number, - |
| T | Temperature, K |
| W | Width, m |

Greek symbols

| | |
|---|---------------|
| α | Absorbance, - |
| ε | Emittance, - |

| | |
|----------|--|
| η | Efficiency, - |
| μ | Dynamic viscosity, Pa s |
| ρ | Density, kg/m ³ |
| σ | Stefan–Boltzmann constant [= 5.67 · 10 ⁻⁸ W/m ² K ⁴] |

Subscripts and superscripts

| | |
|------|----------------|
| a | aperture |
| am | ambient |
| c | cover |
| ci | inner cover |
| co | outer cover |
| ex | exergy |
| fm | mean fluid |
| in | inlet |
| loss | thermal losses |
| opt | optical |
| out | outlet |
| r | receiver |
| ri | inner receiver |
| ro | outer receiver |
| s | solar |
| sun | sun |
| th | thermal |
| u | useful |

Abbreviations

| | |
|-----|----------------------------|
| EES | Engineer Equation Solver |
| PTC | Parabolic trough collector |

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