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Experimental Analysis of Heat Transfer Characteristics of a Parabolic Solar Collector

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Abstract

The parabolic trough collectors are the most used in different areas such as generation, heating, cooling, among others; in the same way, it is one of the technologies of greater object of study for the generation of clean energy. The purpose of this document is the presentation of mathematical equations that allow to quantify the amount of heat received by the circulating fluid inside the absorber tube, the maximum temperature that will reach the working fluid through the heat transfer modes present and finally, the thermal efficiency of the parabolic solar collector.

Keywords: Solar collector, heat transfer, heat losses

1 Introduction

A solar collector is a device that helps to take advantage of the radiation that comes from the sun and converts it into a useful form of energy [1]. Among several solar collectors, the parabolic trough collector (PTC) is considered the best option for medium temperature $(150 - 400°C)$ heat requirements [2], which is employed for electricity generation, industrial process heating, steam generation,

refrigeration and air conditioning, hot water production, etc. [3]. Currently, the electrical energy generated by solar technologies has increased at a rate of 20% per year, from 2000 to 2011 [4], with parabolic trough collectors covering 90% of the total concentrated solar system (CSP) [5] because this set of techniques are the most mature among concentrating collectors, it leads to light-structure systems and has been applied for several decades [6]. In recent years, a significant sum of heat transfer studies has been performed in the PTC experimentally and numerically [7]. De Oliveira et al. developed and implemented a mathematical model to calculate the flow parameters and the heat transfer applied to the PTC [8]. Similarly, Liang et al. were focused on one-dimensional mathematical models (1-D) under different assumptions and details for PTC, considering all heat transfer processes and adopted a simple algorithm to easily solve nonlinear control equations [9]. Hachicha et al. presented a numerical model based on the finite volume method for heat transfer in the aforementioned devices [10]. Also, authors have used computational tools that include computational fluid dynamics (CFD) for the design and modeling of parabolic trough collectors. Salami et al. simulated and described the heat losses by radiation and convection associated with the heat collection element (HCE) of the parabolic solar collector by the representation in ANSYS of the parabolic cylinder absorber [11]; for its part, Tzivanidis et al. took the commercial software SolidWorks to design and simulate a PTC model for different operating conditions, with this they tried to predict the efficiency of the model and to analyze the phenomena of heat transfer that take place there [6].
The main objective of this work is the development of mathematical models for the study of the heat transfer in a parabolic trough solar collector that includes the losses by radiation and convection, the efficiency factor, heat removal and flow, as well as its thermal performance. With this, the PTC implementation is sought in low enthalpy processes and, in turn, the experimental evaluation of its performance.

2 Methodology

2.1 Heat transfer in the parabolic trough collector

To quantify the heat acquired by the fluid, a one-dimensional energy balance is performed in the absorber tube, taking as a boundary the internal surface of the absorber that is in contact with the fluid and assuming a steady state. In this model heat flows, temperatures and thermodynamic properties are assumed to be uniform around the circumference of the tube. The solar radiation taken by the parabolic surface is absorbed by the external wall of the tube, transferred to the inner surface by conduction and then this is taken advantage for the working fluid (water) by forced convection inside the absorber. Part of this energy on the outer surface of the receiver returns to the environment in form of convection and radiation losses, and is calculated as

$$\dot{Q}_{useful} = \dot{Q}_{radiation} - \dot{Q}_{losses}, \tag{1}$$

where $\dot{Q}_{useful}$ is the heat transmitted per unit time to the fluid, $\dot{Q}_{radiation}$ is the heat rate capted by the reflecting surface and transmitted to the absorber tube and $\dot{Q}_{losses}$ is the total value of the loss rate presented by convection, radiation and conduction. Figure 1 shows the heat output of the absorber tube [12].

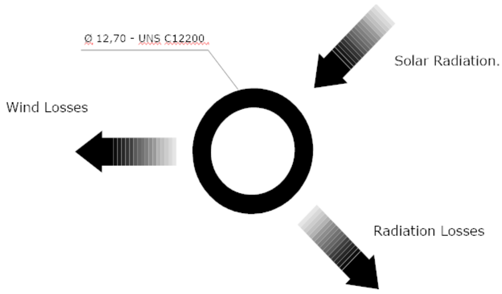

Figure 1. Scheme of losses in the absorber tube [12].

The conditions under which this energy balance will be done are: steady state, there is no work in the system, kinetic and potential energy are considered zero. When these conditions are applied, the energy balance is presented as follows [12]

$$\dot{Q} = \dot{m}(h_{out} - h_{in}), \tag{2}$$

Considering that the properties of the fluid depend on temperature, the amount of heat per unit of time that must be transferred to bring the working fluid to the required conditions, $\dot{Q}_{useful}$ is determined by the following mathematical expression [12], [13]

$$\dot{Q}_{useful} = C_p\dot{m}(T_{out} - T_{in}), \tag{3}$$

where C_p is the specific heat of the water at the average inlet temperature T_{in} and T_{out} is the outlet temperature of the absorber tube at a mass flow $\dot{m}$. The amount of heat required is directly proportional to the difference in temperatures at the ends of the absorber tube.

2.2 Heat losses in the absorber tube

Heat losses in the absorber tube are related to the characteristics of the working fluid as the characteristics of the tube itself, also by the heat transfer mechanisms that are present and due to the difference between the surface of the tube. The heat rate ceded to the environment Q_{losses} is defined by the following equation [14]

$$Q_{losses} = U_L A_r(T_s - T_a), \tag{4}$$

where U_L is the total heat transfer coefficient between the tube and the ambient obtained from the sum of the heat transfer coefficients for every phenomena present, A_r is the area of the absorber that is in contact with the outside , T_s is the average temperature of the absorber outer surface, which can be assumed to be identical to the inner surface by the material properties and the dimensions of the absorber tube, and the ambient temperature T_a, this heat transfer coefficient is calculates from the following expression [14]

$$U_L = h_w + h_r \; + \; U_c, \tag{5}$$

the corresponding coefficients of each phenomenon are calculated by analyzing that the conduction is a mechanism of heat transfer produced by direct contact between bodies [13]. The convection is defined as a case of forced external convection because the air currents present in the environment collide with the outside of the absorber, this heat transfer coefficient is calculated as follows [13]

$$h_w = 0.193 Re^{0.618} Pr^{1/3}, \tag{6}$$

where Re is the Reynolds number of the air passing over the absorber, Prandtl number (Pr) and the kinematic viscosity of the air must be taken at the average temperature between the ambient temperature and the average temperature of the tube outer surface [13], the above formula is only valid for the following intervals $4000 < Re < 40000$. The value of Re is calculated using the following expression [13]

$$Re = \frac{D_o V_w \rho_a}{\mu}, \tag{7}$$

where V_w is the wind speed, D_o is the outer diameter of the absorber, ρ_a is the air density and the quotient μ is the air kinematic viscosity [29]. For the radiation mechanism the heat transfer coefficient is calculated as follows [14]

$$h_r = \frac{\varepsilon\sigma(T_s^4 - T_{sky}^4)}{T_s - T_a}, \tag{8}$$

ε is the emissivity of the absorber tube material, σ is the Boltzman constant, T_{sky} is the estimated temperature of the sky, which is assumed to be the same as the ambient temperature, since it does not present a large alteration in the forecast made from of the collector performance model [13].

2.3 Parabolic trough collector efficiency factor ($\boldsymbol{F'}$)

The relation between the amount of useful energy gained and the amount collected in the condition in which the temperature of the absorber is equal to the average temperature of the working fluid [15]

$$F' = \frac{U_o}{U_L}, \tag{9}$$

where U_o is calculated by equation

$$U_o = \left[\frac{1}{U_L} + \frac{D_o}{h_f D_i} + \frac{D_o \ln D_o/D_i}{2k}\right]^{-1}, \tag{10}$$

the variable U_o represents the total coefficient of heat transfer. In order to increase the efficiency factor of the collector, the dimensions of the components must be selected by trying to find a relation D_o/D_i near the unit, a high coefficient of heat transfer by forced internal convection h_f and a high thermal conductivity of the material k [16].

2.4 Heat removal factor, flow factor, and thermal efficiency of the parabolic trough collector

The heat removal factor F_R is defined as the ratio between the amount of useful energy and the energy taken from the sun if the entire absorber tube is at the same inlet temperature of the working fluid [28]

$$F_R = \frac{C_p \dot{m}}{U_L A_r}\left[1 - \exp(-\frac{U_L A_r}{C_p \dot{m}})\right], \tag{11}$$

the flow factor F'' is a relation between the heat removal factor F_R and the efficiency factor F' [28]. The thermal efficiency of the parabolic solar collector (η_{ptc}) can be obtained by a simple relation between the useful heat and the radiation captured from the sun [28]

$$\eta_{ptc} = \frac{Q_{useful}}{I_b A_c} = \frac{Q_{useful}}{Q_{radiation}}, \tag{12}$$

where A_c is the area of the collector and the direct solar radiation is the variable I_b.

3 Results and discussion

3.1 Ambient temperature and wind speed

Air temperature and wind speed are fundamental parameters in the heat transfer to the working fluid and the losses to the ambient, so it was observed the change in their values throughout the day. Based on the values delivered by the weather station on the day of the test, as shown on

Figure 2.

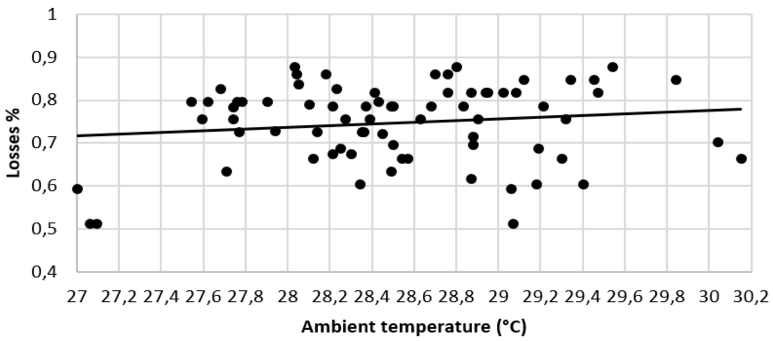

Figure 2. Relation between losses and ambient temperature.

It is observed in the graph that most of the temperature values are in the range of $27{,}8°C$ and $29{,}2°C$. Although the losses increased by almost 10%, the relationship between the increase in ambient temperature and the losses can not be described with a linear relationship. Wind speed behavior did not show a predictable trend, ranging between about $0{,}2$ and $3\ m/s$. The smallest loss was obtained at wind speeds between $0{,}25$ and $0{,}75\ m/s$ as shown in Figure 3.

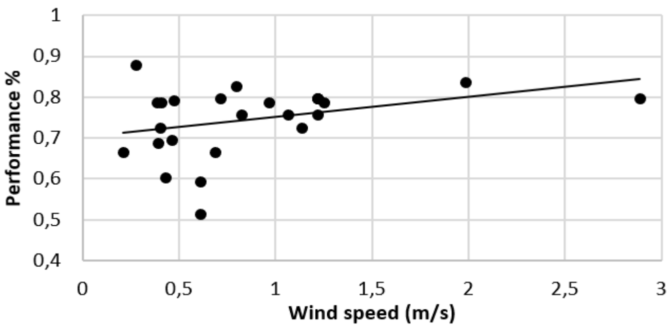

Figure 3. Relation between performance and wind speed.

It is possible to analyze the low correlation between the wind speed and the increase of the losses by the way the data were distributed, there are data of high losses in relatively low speeds and vice-versa.

3.2 Solar radiation during the test

In order to estimate the solar radiation of Barranquilla city during the day in question, the transmissibility model was used, taking into account the geographical position of the city ($10°\ 57'\ 42''$ north latitude and $74°\ 46'\ 54''$ western length) and the angle of inclination of the reflecting surface of the solar collector (11°) as shown on Figure 4.

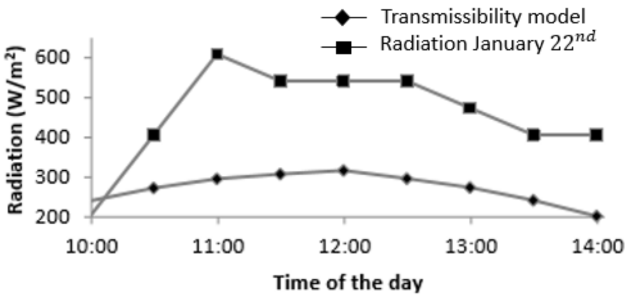

Figure 4. Comparison between the prediction and the data obtained.

3.3 Thermal performance (η) with inclination and flow variables

In this section will be analyzed the variation of the performance of the parabolic trough collector during the day using equation 13. It is important to mention that the values obtained are slightly lower than expected, as there are many factors that could influence this variation, among them can be mention the misalignment of the mirrors, the absorber tube, low heat absorption by the copper tube, slight deviation in the location of the collector, among others. The results for each slope, according to the established flows are shown in Figure 5.

It is possible to appreciate that with this inclination the values of the independent variable were distributed closer to zero, in a very limited range, marking a maximum performance of 30%. The influence of the volumetric flow used on the collector performance is evident in the graphs shown below, making it clear that working at relatively low flow rates can achieve better performance in the equipment.

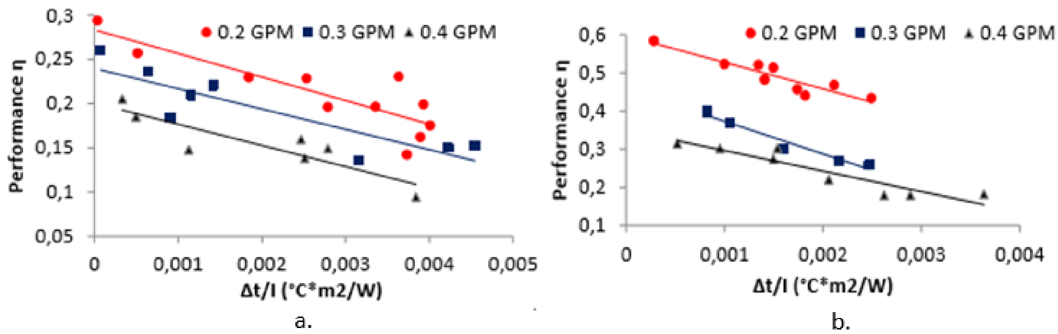

Figure 5. Collector performance with a. 5° inclination, b. 11° inclination.

References

[1] R. Vasquez Padilla, G. Demirkaya, D. Y. Goswami, E. Stefanakos and M. M. Rahman, Heat transfer analysis of parabolic trough solar receiver, *Applied Energy*, **88** (2011), 5097-5110. https://doi.org/10.1016/j.apenergy.2011.07.012

[2] G. Kumaresan, P. Sudhakar, R. Santosh and R. Velraj, Experimental and numerical studies of thermal performance enhancement in the receiver part of solar parabolic trough collectors, *Renewable and Sustainable Energy Reviews,* **77** (2017), 1363-1374. https://doi.org/10.1016/j.rser.2017.01.171

[3] D. Kumar and S. Kumar, Simulation analysis of overall heat loss coefficient of parabolic trough solar collector at computed optimal air gap, *Energy Procedia*, **109** (2017), 86-93. https://doi.org/10.1016/j.egypro.2017.03.057

[4] V. C. Pigozzo Filho, A. B. de Sá, J. C. Passos and S. Colle, Experimental and numerical analysis of thermal losses of a parabolic trough solar collector, *Energy Procedia*, **57** (2014), 381-390. https://doi.org/10.1016/j.egypro.2014.10.191

[5] M. Binotti, G. Zhu, A. Gray, G. Manzolini and P. Silva, Geometric analysis of three-dimensional effects of parabolic trough collectors, *Solar Energy,* **88** (2013), 88-96. https://doi.org/10.1016/j.solener.2012.10.025

[6] C. Tzivanidis, E. Bellos, D. Korres, K. A. Antonopoulos and G. Mitsopoulos, Thermal and optical efficiency investigation of a parabolic trough collector, *Case Studies in Thermal Engineering*, **6** (2015), 226-237. https://doi.org/10.1016/j.csite.2015.10.005

[7] J. Jin, Y. Ling and Y. Hao, Similarity analysis of parabolic-trough solar collectors, *Applied Energy*, **204** (2017), 958-965. https://doi.org/10.1016/j.apenergy.2017.04.065

[8] A. M. de Oliveira Siqueira, P. E. Neves Gomes, L. Torrezani, E. Oliveira Lucas and G. M. da Cruz Pereira, Heat transfer analysis and modeling of a parabolic trough solar collector: an analysis, *Energy Procedia*, **57** (2014), 401-410. https://doi.org/10.1016/j.egypro.2014.10.193

[9] H. Liang, S. You and H. Zhang, Comparison of different heat transfer models for parabolic trough solar collectors, *Applied Energy*, **148** (2015), 105-114. https://doi.org/10.1016/j.apenergy.2015.03.059

[10] A. A. Hachicha, I. Rodríguez, R. Capdevila and A. Oliva, Heat transfer analysis and numerical simulation of a parabolic trough solar collector, *Applied Energy,* **111** (2013), 581-592. https://doi.org/10.1016/j.apenergy.2013.04.067

[11] A. Salami Tijani and A. M.S. Bin Roslan, Simulation analysis of thermal losses of parabolic trough solar collector in Malaysia using computational fluid dynamics, *Procedia Technology,* **15** (2014), 841-848. https://doi.org/10.1016/j.protcy.2014.09.058

[12] M. J. Moran and H. N. Shapiro, *Fundamentos de Termodinámica Técnica*,

Reverté S.A., 1995.

[13] Y. A. Cengel and A. J. Ghajar, *Transferencia de Calor y Masa. Fundamentos y Aplicaciones*, McGraw-Hill, México, 2011.

[14] J. A. Duffie and W. A. Beckman, *Solar Engineering of Thermal Processes*, John Wiley & Sons, Inc., 2013. https://doi.org/10.1002/9781118671603

[15] S. A. Kalogirou, *Solar Energy Engineering: Processes and Systems*, Academic Press, 2013.

[16] Aceros industriales S.A., Tubería de cobre C12200-flexible, Available: http://www.acerosindustriales.com.co/sitio/index.php/component/content/article/41

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