ORIGINAL ARTICLE

Theoretical Bases for Exergetic Analysis of a Flat Plate Solar Collector with Forced Draft

Bases teóricas para el análisis exergético de los colectores solares de placas planas con tiro forzado

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ABSTRACT. In the present paper, theoretical basis for the exergy analysis of solar flat plate collectors with forced draft used in drying and dehydration of agricultural products are exposed. This analysis starts from the discussion of the theoretical elements that are included in the realization of the energy balance of solar flat plate collectors and forced draft. Later the elements to consider for implementing the exergy balance of these types of collectors were analyzed. The results allowed defining the methodological procedure for the realization of exergy analysis of solar collectors. In addition, the variables or factors that determine the energy efficiency were defined, as well as the causes and factors that cause energy losses. Finally, the method proposed by Pons (2012) was defined as the most suitable for determining the exergy of solar radiation reaching the earth's surface.

Keywords: energy balance, exergy balance, loss of exergy, exergy efficiency, drying, air heaters.

RESUMEN. En el presente trabajo se exponen bases teóricas que fundamentan el análisis exergético de los colectores solares de placas planas con tiro forzado, empleados en el secado y deshidratación de productos agrícolas. Dicho análisis parte de la discusión de los elementos teóricos que se incluyen durante la realización del balance energético de los colectores solares de placas planas y tiro forzado. Posteriormente se analizaron los elementos a tomar en cuenta para la realización del balance exergético de estos tipos de colectores. Los resultados permitieron definir el procedimiento metodológico para la realización del análisis exergético de los colectores solares, además se definieron las variables o factores que determinan la eficiencia energética de los mismos, así como las causas y factores que originan las pérdidas de energía. Finalmente se definió el método propuesto por Pons (2012) como el más adecuado para determinar la exergía de la radiación solar que llega a la superficie terrestre.

Palabras clave: balance energético, balance exergético, pérdidas de exergía, eficiencia exergética, secado, calentadores de aire.

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INTRODUCTION

Solar collectors are devices designed to collect solar energy. Once the sunlight is absorbed by the device, the energy collected is used in thermal or photovoltaic process. Generally, in thermal processes, solar energy is used to heat gas or liquid, for its storage or distribution. In the photovoltaic process, solar energy is transformed into electrical energy without the use of any mechanical device.

Although man has used solar energy since the beginning of his own existence, it was not until 1875 that the French Mouchont developed the first solar collector for steam production. From this, several collector prototypes were developed with dissimilar construction features and applications of transformed energy (Arellano-Escudero, 2015).

At the very beginning of the last century, the use of solar energy took special interest in the United States, especially in the state of California, where several prototypes of large collectors were developed (Díaz Marcano, 2012). At the beginning of 1913, the use of these collectors began to expand to other countries, achieving their introduction in several sectors of industry and private sector.

During the mid-twentieth century, a new stage in the use of energy was undertaken and, although the development of these means has been slowed down in several stages, due to the low prices of fossil or conventional fuels, in that context in general, a moderate increase is shown in the solar energy application and particularly the solar air collector.

One of the main applications that these solar collectors have had is the drying of products from the agricultural sector. At the end of 1940, a series of experimental works were developed whose objective was to take advantage of solar energy in the grain drying, although experimental theoretical studies had their beginnings in the decade of the 60s of the last century (López, 2012).

Since then, many variants of dryers have been built and introduced into the grain drying activity. They have a common element in their construction and it is that they have a solar collector with a plate or surface that absorbs solar energy (López, 2012). The characteristics of this plate vary according to the application of the dryer.

The applications of solar energy in the drying and dehydration of perishable products have increased and they have been conditioned mostly by the need to introduce alternative energies that make these processes sustainable and to reduce the polluting load that is emitted to the environment.

In addition to this problem, it is the fact that currently 10 to 40 % of harvested products never reach the consumer. This occurs mainly in developing countries due to the decomposition and contamination of the product (Llosas *et al.*, 2014).

These applications include the drying and dehydration of aromatic plants like coffee, cocoa, mango, among many other examples that can be cited (González *et al.*, 2012; López, 2012; Llosas *et al.*, 2014; Esteban, 2015).

During these thermal processes, the collectors capture the solar radiation in a plate (absorber) that then absorbs a fluid, which is called carrier fluid. That fluid, whether in liquid or gaseous state, is heated by heat transference from the absorption plate. The energy transferred by the carrier fluid, divided by the solar energy that falls on the collector and expressed in percentage, is called instantaneous efficiency of the collector.

According to González et al. (2012), studies on these collectors in a first stage were aimed at finding a better thermal efficiency-cost ratio, reaching efficiencies of 75% under normal operating conditions. Subsequently, the focus was on the increase of heat transferred to the carrier fluid from the creation of the turbulence, achieving efficiencies greater than 75% (Ammari, 2003, Moummi et al., 2004, Romdhane, 2007).

According to Kurtbas and Durmuş (2004), the effects of the material and the geometry of the absorber on the efficiency of the collectors are parameters that had been widely reported in the literature; however, the influence of the flow regime on the efficiency of the collectors had not been studied in details.

With the development reached by the computer media since the last decade of the last century, a series of studies begins. Models were developed by Computational Fluid Dynamics (CFD) method for the simulation of flow circulation processes and heat transference in solar collectors. Some looked for improving the energy efficiency and its optimization (Marroquín *et al.*, 2013; Salame *et al.*, 2014; Uppal *et al.*, 2014; Tapas *et al.*, 2015; Yadav *et al.*, 2015; Singh and Dhiman, 2016). Others studied Finite Differences (Durán and Condori, 2012; Marathe *et al.*, 2013) and the use Artificial Neural Networks (Esen *et al.*, 2009; Omojaro *et al.*, 2013; Abuşka *et al.*, 2015 and Liu *et al.*, 2015).

In the same way, a series of investigations have been developed to determine the useful work potential or the exergy of these collectors (Akpinar and Koçyiğit, 2010; Chamoli, 2013; Kalogirou, 2013; Oztop *et al.*, 2013; Bouadila *et al.*, 2014; Sahu and Prasad, 2016; Ghiami *et al.*, 2017). All these investigations have taken into account the constructive characteristics of the hot air collectors, their operating principles, and the operating conditions. Aspects that are included in the theoretical models for the calculation of energy or loss of useful energy.

Validations of these models have been carried out under different conditions and different environments from the typical regions of Ecuador, especially the provinces of the Ecuadorian Pacific coast.

METHODS

This work has the objective to expose the theoretical bases of the exergetic analysis of solar collectors of flat plates with forced draft, considering the importance of the introduction of solar energy in the drying and dehydration of agricultural products, the need of efficient solar collectors, as well as environmental conditions and operation requirements in Ecuador.

Theoretical Bases for Exergetic Analysis of a Solar Flat Plate Collector with Forced Draft

The performance of solar collectors is described as a balance that indicates the amount of incident solar energy that is transformed into useful energy, which includes an analysis of the irreversible facts that cause the destruction of exergy. Therefore, the exergy analysis of the collectors starts with a balance of energy of the system.

Energy Balance of a Flat Plate Solar Collector and Forced Draft

The energy that is received in the absorber is the difference between the incident radiation and the optical emissions, which means that it depends on the optical transmission of the receiving plate.

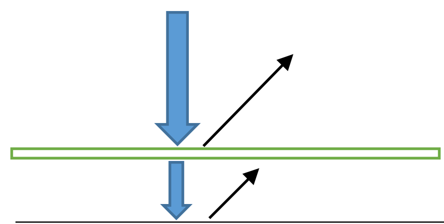

FIGURE 1. Transmissibility of the receiver plate and absorption effect of the absorber.

In this way, the useful heat will reach the absorber and will be affected by the optical performance of the collector (η_O) and the intensity of the solar radiation $I_{T,}$ and it is determined as:

$$S = (\tau_{\propto})I_T = \eta_o I_T \quad (1)$$

Where:

S, absorber radiation flow, W/m^2

τ, transmittance of the cover,

α, absorbance of the plate,

I_T, solar radiation, W/m^2;

η_o, collector optical performance.

The value (τ_α) will depend on the angle of incidence of the sunrays, although the variation is very small. When the rays strike perpendicularly on the receiving plate (I_T), it reaches its maximum value.

The useful energy gain by the working fluid is calculated with the following equation:

$$Q_u = \dot{m}C_p(T_{out} - T_{in}) \quad (2)$$

Where:

$Q_{u,}$ useful energy in the collector, *W;*

m, mass flow rate, *kg/sec*;

C_p, specific heat of the working fluid, *J/kg-K*;

T_{in}, fluid inlet temperature, *K*;

T_{out}, fluid outlet temperature, *K*.

Equation 2 represents the heat delivered by the absorber plate of the collector to the working fluid. However, it does not allow watching the effects of some parameters such as the heat loss coefficients and the optical efficiency of the collector (Jafarkazemi and Abdi, 2016).

According to Chamoli (2013), considering these elements and using Hottel-Whillier equation, the useful power will be determined, as:

$$Q_u = A_p F_R[S - U_l(T_{in} - T_a)] \quad (3)$$

Where:
Q_u, Useful power of the energy that reaches the collector, *W*;
A_p, area of the collector absorber plate, *m²*;
F_R, heat removal factor;
F', collector efficiency factor;
U_l, coefficient of heat losses of the collector, *W/m² K*;
T_a, room temperature, *K*.
The heat removal factor, F_R, is determined by equation 4:

$$F_R = \frac{\dot{m}C_p}{A_p U_l}\left[1 - exp\left(\frac{F' U_l A_p}{\dot{m}C_p}\right)\right] \tag{4}$$

Determining the useful heat, the energetic efficiency of the collector (η_t) can be obtained by means of equation 5:

$$\eta_t = \frac{\dot{Q}u}{A_p I_T} \tag{5}$$

Considering the correlations of temperature distribution in the collector Duffie & Beckman (2013), the temperature output component of the fluid can be omitted when equations 3 and 4 are replaced in equation 5, therefore, the energy efficiency of the collector can be reformulated according to equation 6:

$$\eta_t = \frac{\dot{m}C_p\left[\left(T_{in} - T_a - \frac{S}{U_l}\right)\left(exp\left(-\frac{U_l A_p F'}{\dot{m}C_p}\right) - 1\right)\right]}{A_p I_T} \tag{6}$$

Exergetic Balance of a Flat Plate Solar Collector

The calculation of the exergetic performance of a flat plate solar collector is not simple, because it depends on many factors such as the type of collector, characteristics of the components that comprise it, manifestations of solar radiation, and the environmental conditions to which it will be subjected.

Exergy is defined as the maximum amount of work that can be produced by a system before reaching equilibrium with a reference environment. The exergy balance in the collector is shown in equation 7.

$$\sum \dot{E}x_{in} - \sum \dot{E}\,x_{out} = \sum \dot{E}x_{dest.} \tag{7}$$

Where $\dot{E}x_{in}, \dot{E}x_{out},$ *and* $\dot{E}x_{dest}$, represent the input, output, and destroyed exergy rate, respectively.

As expected, the exergy rate of the collector entrance includes the exergy of the heat absorbed from the sun and the exergy of the input fluid. The ejection exergy of the collector coincides with the exergy of the output fluid. The difference between these two components represents the amount of exergy destroyed in the collector (Jafarkazemi and Abdi, 2016).

The rate of exergy of the working fluid can be obtained by means of equation 8:

$$\dot{E}x_f = \dot{m}C_p\left[\left(T_f - T_a\right) - T_a l_n\left(\frac{T_f}{T_a}\right)\right] \tag{8}$$

The difference between the exergies of the fluid at the outlet and at the entrance of the collector represents the increase of the exergy flow that the fluid experiences as it passes through the collector and is given by equation 9:

$$\dot{E}x_{f.out} - \dot{E}x_{f.in} = \dot{m}C_p\left[\left(T_{f.out} - T_{f.in}\right) - T_a l_n\left(\frac{T_{f.out}}{T_{f.in}}\right)\right] \tag{9}$$

The absorption plate, increasing its exergy, absorbs most of the input energy of the system by solar radiation. The exergy rate that accompanies a flow Q of heat transferred from a source at temperature T and considering the environment at temperature Ta, is obtained by equation 10:

$$\dot{E}x_{calor} = Q\left(1 - \frac{T_a}{T}\right) \tag{10}$$

The exergy rate of the incident solar radiation I_T on the collecting surface is determined by equation 11, (Petela, 1964).

$$\dot{E}x_{rad} = A_p I_T \left[1 - \frac{4}{3}\left(\frac{T_a}{T_s}\right) + \frac{1}{3}\left(\frac{T_a}{T_s}\right)^4\right] \tag{11}$$

Being T_s the temperature of the sun considered as a black body.

The amount of exergy absorbed by the absorber plate of the flat solar collector can be calculated with equation 12.

$$\dot{E}x_{abs.} = \eta_o A_p I_T \left(1 - \frac{T_a}{T_p}\right) \tag{12}$$

Where T_p, is the average temperature of the absorber plate, *K.*

To evaluate the destruction of the exergy, it must be considered that the process of transferring energy from the sun to the working fluid of the collector consists of two main parts: the absorption of solar radiation by the absorber plate and the transference of heat from the plate absorber to the working fluid (Suzuki, 1988).

The destruction of the exergy in the absorption process is due to the temperature difference between the absorber plate of the collector and the apparent temperature of the solar radiation. This part of the destruction of the exergy is obtained by subtracting equations 11 and 12.

$$\dot{E}x_{dest.s-p} = A_p I_T \left[1 - \eta_o + \eta_o \frac{T_a}{T_p} - \frac{4}{3}\left(\frac{T_a}{T_s}\right) + \frac{1}{3}\left(\frac{T_a}{T_s}\right)^4\right] \tag{13}$$

The loss of heat from the absorber plate to the surroundings is a source of exergy loss from the system. Such heat loss is given by equation 14.

$$Q_{alrr} = U_l A_p (T_p - T_a) \tag{14}$$

The loss of exergy due to the heat losses of the collector is obtained according to equation 15.

$$\dot{E}x_{p\acute{e}rd.alrr} = U_l A_p (T_p - T_a)\left(1 - \frac{T_a}{T_p}\right) \tag{15}$$

The second source of destruction of exergy in the process of conversion of solar energy into heat in the collector is in the transference of exergy from the absorber plate to the working fluid through a finite difference of temperature, obtained from equation 16.

$$\dot{E}x_{p-f} = \dot{m}_f C_p \left[(T_{fout} - T_{fin})\left(1 - \frac{T_a}{T_p}\right)\right] \tag{16}$$

Considering that the exergy destroyed in the process of heat transference between absorber plate and fluid is equal to the difference between the exergy delivered by the plate, given by equation 16, and the exergy that the fluid gains, given by equation 9, then subtracting both, the destroyed exergy is obtained. That is shown by expression 17.

$$\dot{E}x_{dest.p-f} = \dot{m}_f C_p T_a \left[\left(ln \frac{T_{fout}}{T_{fin}}\right) - \frac{T_{fout} - T_{fin}}{T_p}\right] \tag{17}$$

The exergetic performance of the collector is defined as the gain of exergy that was achieved in the work fluid divided by the total generation that reaches with the solar radiation to the collector (Jafarkazemi & Abdi, 2016). Substituting the values of the rate of exergy gained by the flow of the work fluid and the activity of the solar incident radiation in the collector, expression 18 is obtained, which allows evaluating the exergetic performance of the collector.

$$\eta_{ex} = \frac{\dot{m} C_p \left[(T_{f.out} - T_{f.in}) - T_a l_n \left(\frac{T_{f.out}}{T_{f.in}}\right)\right]}{A_p I_T \left[1 - \frac{4}{3}\left(\frac{T_a}{T_s}\right) + \frac{1}{3}\left(\frac{T_a}{T_s}\right)^4\right]} \tag{18}$$

RESULTS AND DISCUSSION

The model of section 2 has been applied considering approximate theoretical values of the variables involved in the process of heat transference in flat solar collectors, which will be adjusted later with real data to be obtained from experimental tests using CFD simulation.

To apply the model, the following requirements are considered: the constant of incident solar radiation at 1000 W/m^2, the collector area of 2 m^2, the collector optical efficiency 0,85 and the air temperature at the collector inlet at 26 °C.

Figure 2, shows the effects of the variation of the energy efficiency in the air outlet temperature, in this case a constant mass flow of 0,05782 kg/s has been considered. As a result, a linear increase of the outlet temperature is observed as the energy efficiency increases.

In Figure 3, for the same values of mass flow and elevation of energy efficiency the increase in the exergy gained by the air passing through the collector is appreciated. For an energy yield of 60%, the gained exergy is 0,05144 kW.

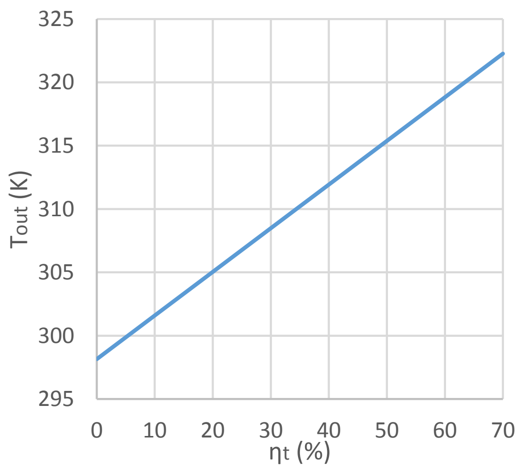

FIGURE 2. Variation of the temperature of the fluid outlet energy efficiency of the collector.

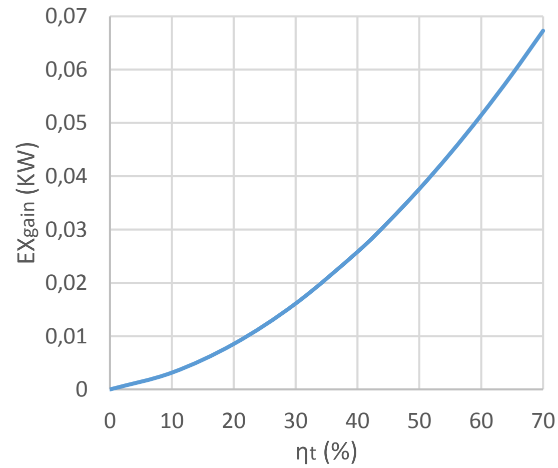

FIGURE 3. Variation of the exergy gained by the versus the fluid versus energy efficiency of the collector.

In Figures 4 and 5, the influence of the energy efficiency variation on the exergetic performance of the collector and the heat gained by the air passing through the collector are shown. For collectors with energy efficiency of 50%, an energy yield of 2 % and 1 kW of heat gained through the air are obtained.

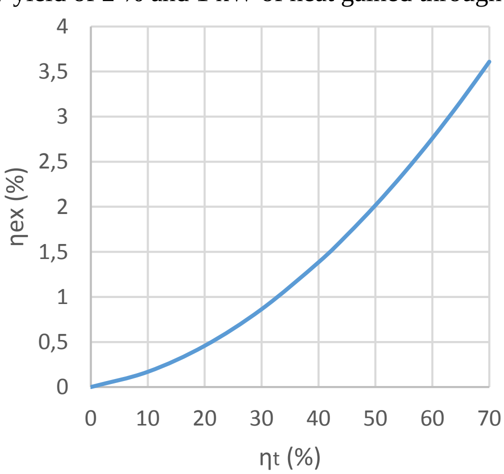

FIGURE 4. Variation of the exergetic efficiency versus the energetic efficiency of the collector.

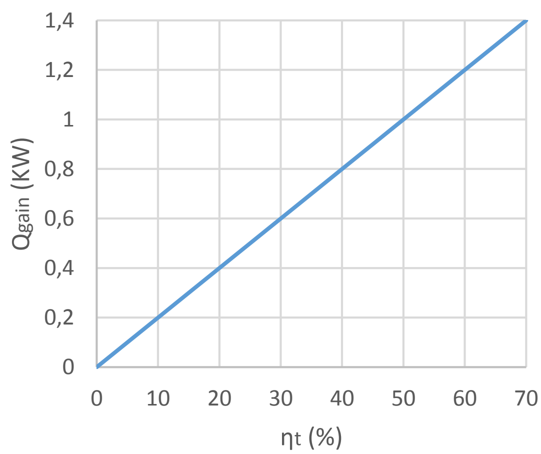

FIGURE 5. Variation of the heat gained by the work fluid versus energetic efficiency of the collector.

In Figures 6 and 7, the variations of the exergy gained by the air and the exergetic efficiency of the collector with respect to the variation of the ambient temperature are shown. In both cases, the mass flow and energy efficiency have remained constant. It can be appreciated that, the lower the ambient temperature, the greater the exergy gained by the fluid and the greater the exergetic efficiency of the collector.

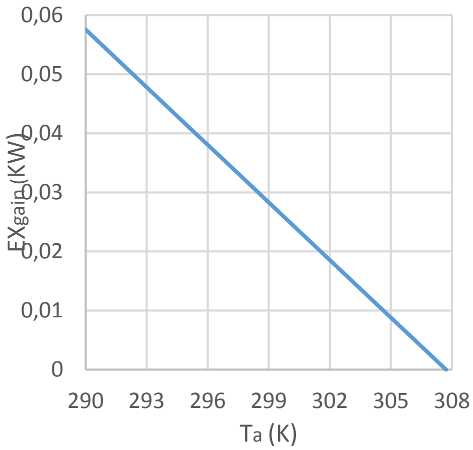

FIGURE 6. Variation of the exergy gained by the work fluid ambient temperature.

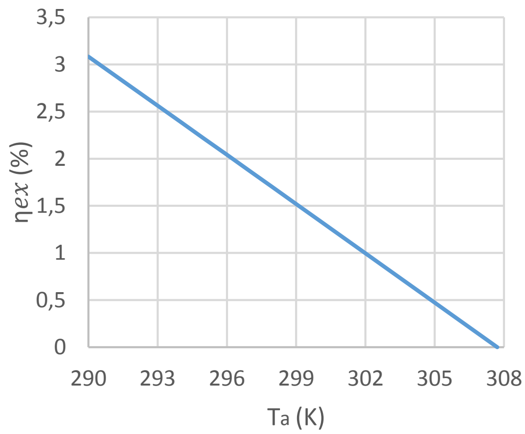

FIGURE 7. Variation of the exergetic efficiency of the versus the collector versus the ambient temperature.

In Figures 8, 9 and 10, the influence of the variation of the mass flow on the air outlet temperature, the exergy gained by the fluid and the exergetic efficiency of the collector are shown. The ambient temperature and the energy efficiency of the collector are kept constant. It is possible to see that, when increasing the mass flow, the three variables described decreases, being very important to consider relatively low mass flows.

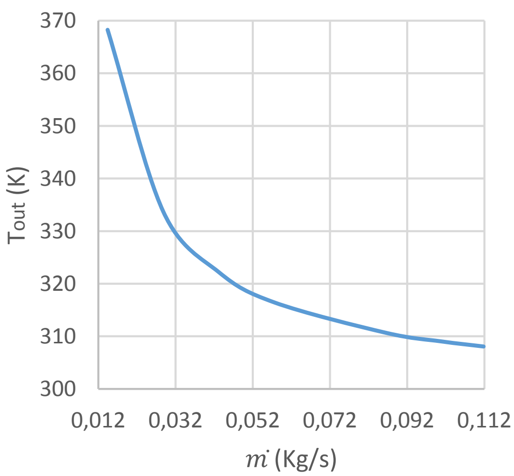

FIGURE 8. Variation of the temperature of the fluid outlet variation of the mass flow rate.

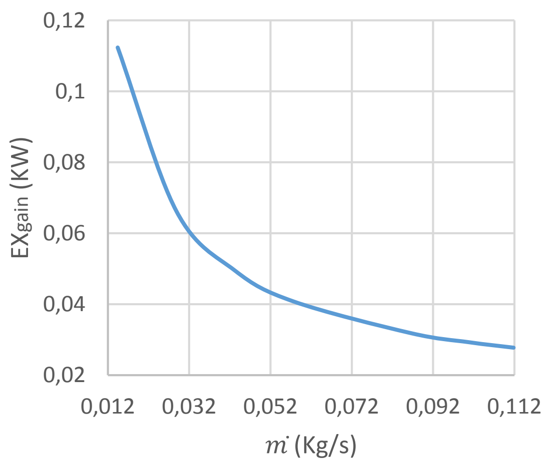

FIGURE 9. Variation of the exergy gained by the versus the fluid versus the variation of the mass flow rate.

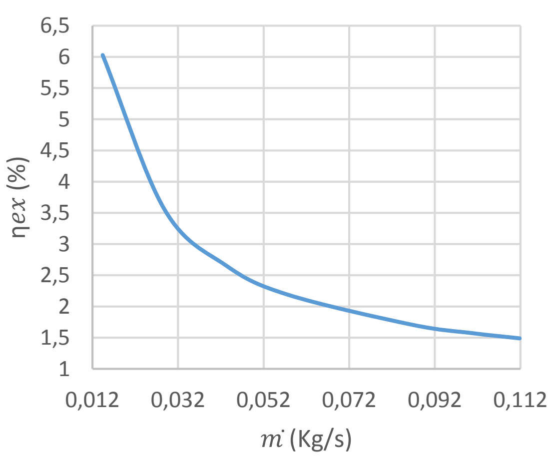

FIGURE 10. Variation of the exergetic efficient the collector versus the variation of the mass flow rate.

In Figures 11 and 12, the influence of temperature variation of the absorber plate on the exergy destroyed in the sun-plate heat transference and the exergy destroyed in the plate-fluid heat transference are shown. For this purpose, variable mass flow and constant ambient temperature are considered. It is observed that the destruction of the exergy in the sun-plate process decreases with the increase in the temperature of the absorber plate; on the contrary, the destruction of the exergy in the plate-fluid process increases with the increase in the temperature of the absorber plate.

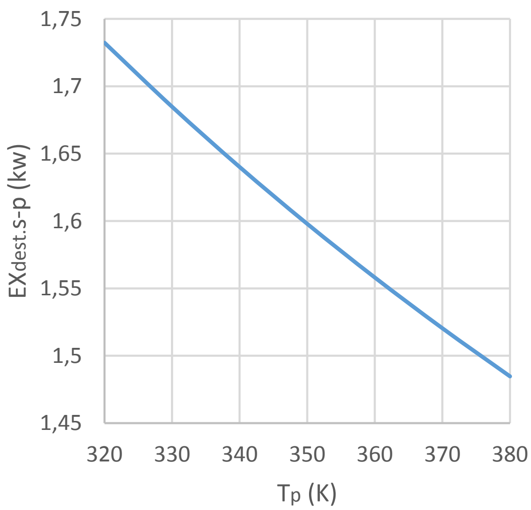

FIGURE 11. Variation of the exergy destroyed in the sun-plate transference versus the temperature of the plate.

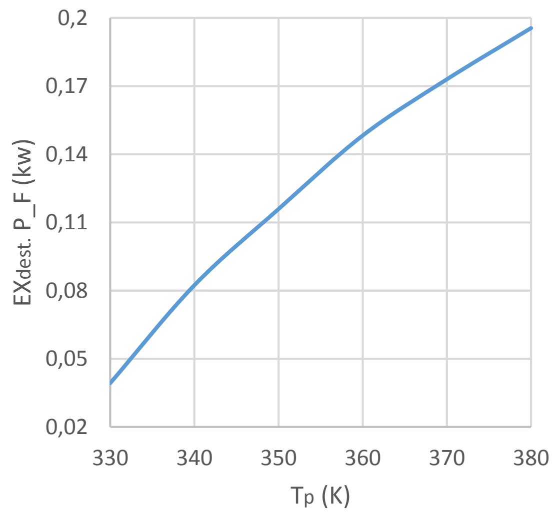

FIGURE 12. Variation of the exergy destroyed in the plate- heat fluid heat transference versus the temperature of plate.

CONCLUSIONS

Once exposed the theoretical foundations for the realization of the exergetic balance of solar collectors, the following conclusions are stated by the authors:

- The exergetic efficiency of solar collectors of hot air depends on the atmospheric conditions at the installation place (ambient temperature, intensity of solar radiation), the optical performance of the collector, as well as the dimensions of the absorber plate of the solar collector.
- The loss of exergetic in the system decrease with the increase of the collector efficiency, due the existence of an inverse relationship between loss of dimensionless exergy and heat transference;
- The parameters of greater incidence in the exergy loss of the hot air solar collectors are the efficiency of the collector and the differences in air temperature at the collector inlet and outlet;
- The exergetic performance of solar collectors decreases with the circulation of high mass flows.

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NOTES

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