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Thermal heating by photovoltaic solar energy

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Abstract

In this paper, we modeled the heating of thermal resistors photovoltaic solar energy. From the thermal models governing the thermal operation of the heating resistors and measuring equipment developed, we have shown, on the one hand, a very good agreement between experience and simulation, and, on the other hand, under a solar radiation of 800 W / m^2, electrical power of the order 144 W and ambient temperature of 35 °C, that temperatures and thermal efficiencies of the resistors reach 600 °C and 72%, respectively. All the obtained results show the good operation of the heating resistors with the electrical energy supplied by the photovoltaic panels. Therefore, there is a possibility of using these resistors in the appropriate applications requiring heating at high temperature (> 100 °C) (Solar oven and drying,…).

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Keywords: Heating resistance; Photovoltaic heating; Transitional regime; Thermal transfer; Electrical and Thermal Power; Efficiency.

1. Introduction

Currently, the international community has been mobilized to propose alternatives to mitigate the effects of climate change and to create innovation in ecological equipment [1]. This plays a vital role in the protection of environment and making it resistible to global warming [2-4]. The World Climate Conference (COP 22) that was

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organized in Marrakech (Morocco) in 2016 [5] has proposed certain solutions. Among the selected alternatives is the promotion of the use of renewable energy equipments, innovative, high-performance, low-cost and functioning by the solar energy [6-9].

In the framework of the program Cooperation Morocco-Wallonie Brussels (2018-2022), we propose in collaboration with the Faculty of Engineering of Mons (Belgium) (Project n° 4.2), the civil society of the eastern region 'Man and Environment Association of Berkane', the National Initiative for Human Development INDH (Province of Berkane) to find the design and production of innovative solar ovens. The latters are powered by photovoltaic solar energy [10-15]. The main objective is to contribute to the socio-economic development of the rural and urban world, and satisfy their domestic needs by using the electrical energy produced by the photovoltaic panels [16]. These types of applications require the control of the power supply of the heating resistors by photovoltaic energy, the operation at temperatures and efficiencies higher than 100 °C and 50% respectively [10]. Currently, in the literature, there is a very few works on the heating of resistors and their applications in the photovoltaic renewable energy domain.

In order to innovate in photovoltaic renewable energy applications and offer ecological equipments, we are conducting research on equipments that use the heating of thermal resistors by photovoltaic energy. The essential objectives are to exploit the electrical energy that is produced by the photovoltaic panels in order to reach temperatures of 600 °C and efficiency higher than 50%.

In this paper, we present the theoretical and experimental results concerning the in-depth analysis of the thermal heating of thermal resistors by photovoltaic solar energy. Moreover, we present the thermoelectric model of the transient temperature, the power and the thermal efficiency of the heating. Then, we introduce the obtained results from some numerical simulations and the experimental validation during sunny days and with variations of the solar irradiation.

2. Structure and models of thermal heating

2.1. Structure and operation

Figure1 represents a block diagram of the heating system using photovoltaic (PV) solar energy. The different equipments of this block are:

- PV generators formed by monocrystalline silicon panels,
- Adaptation control and supervision block whose role is to supply and manage the electrical energy produced by the photovoltaic generator. This block is sized for a power of 200 W in works presented in [16].
- Plate containing heating resistors supporting a current of 10A, power 500W and temperature of 800°C.

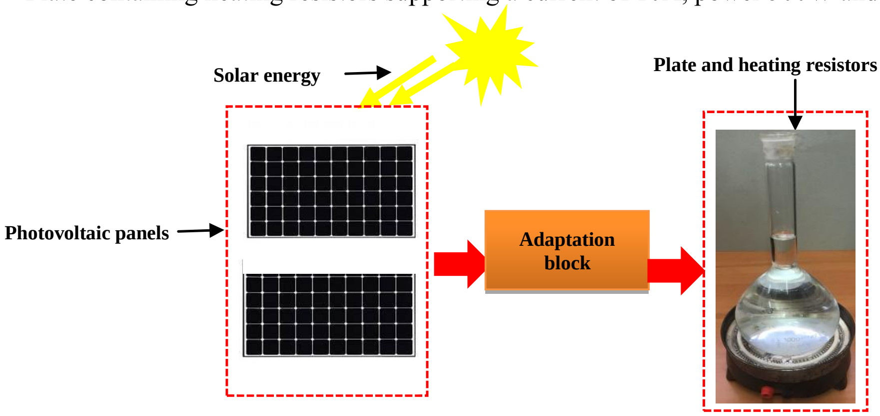

Fig. 1. Synoptic diagram of the system for heating the heating resistors (thermal) by solar photovoltaic energy.

2.2. Theoretical models

2.2.1. Heating resistance

The thermal model which is developed in this work, by supplying heating resistors with photovoltaic energy, is based on the principle of thermal energy balance [6, 17] of a temperature node of the heating resistor. Taking into account the electric power (P_{elc}) supplied by the photovoltaic generator and the heat losses by convection (P_{cv}) [18] and by radiative heat transfer (P_R) [19]. At this node, at a given solar irradiation and ambient temperature (T_{amb}), the transient temperature gradient of the resistance (Tr) is written in the following form:

$$
\begin{aligned}
m_r.Cp_r.\frac{dT_r}{dt} &= P_{elec} - P_{cv} - \mathrm{P}_R \\
&= Vs.Is - h_{r-amb}.A_{r-amb}.(T_r - T_{amb}) - A_r.\sigma.\varepsilon_r(T_r^4 - T_{amb}^4)
\end{aligned}
\tag{1}
$$

Where,

m_r : Mass of the heating resistor (m_r=0.01634kg),

Cp_r : Specific heat of the heating resistor (Cp_r=890 J/Kg-K)

Vs and Is : Voltage and current of the heating resistor,

A_{r-amb} : Coefficient of convective exchange between the heating resistor and the ambiance (h_{r-amb}= 50w/m^2.k^4),

A_r : Surfaces of the heating resistor (S=0.0025 m^2),

σ : Boltzmann constant (σ =5.669*10^{-5}w/m^2.k^4),

ε_r : Emissivity of the heating resistor (ε=0.9).

2.2.2. Thermal power and efficiency

In the literature [7, 20-21], generally, the boiling water is used to estimate the power and efficiency of the thermal heating. Recently, the authors of the reference [11], according to the international recommendations of the tests (ASAE-S580 JAN03) [21], for a quantity of water m = 0.385g and electric energy produced by solar batteries of a power Pel = 76.9W, follow the boiling of the water during intervals of time Δt = 10 min. Then, they deduce the thermal power Po and the efficiency η by the expressions:

$$
P_0 = \frac{m.cp.\Delta T}{\Delta t} = 32.2\,W
$$

$$
\eta = \frac{P_0}{P_{el}} = 43.6\% \tag{2}
$$

Where, Cp : Specific heat of water (Cp = 4180 J/Kg-K).

As part of our experiment, we used this method for a quantity of water m = 1 Kg.

2.3. Numerical code

The numerical resolution of equation (1) is performed by the Rung Kuta method of order 4 [6, 22] in the language C++. We have adopted this method since it has an accuracy and calculation stability [6, 22]. As shown in the flowchart of Fig. 2, the main calculation steps are:

- Declaration of dimensions, thermal data of resistor, time (tmax) and step calculation (h),
- Return of the parameters:
  - weather: ambient temperature (Tamb),
  - Electrical power by photovoltaic solar energy (Pel)
  - Time interval 15 min during operation.
- Initial conditions :

  Initial temperatures of the heating resistor (Tr (0)),
- Calculation :

  When t≤tmax, by incrementing the time by a step of h = 15min, the program optimally calculates the temperature of the node of the thermal heating resistor using Rung-kutta method. At this point, the calculations are performed:
  - ✓ When the ambient temperature (Tamb) and electric heating power (Pelc) are constant or variable with time.
  - ✓ By integration of the differential equations: once at the starting point (RK1), twice at the middle of the interval (RK2 and Rk3), and once at an estimated end point (RK4).

The calculations are stopped when t = 480 min. The program ends the execution and displays the results obtained for the temperatures with a fourth order accuracy (RK4).

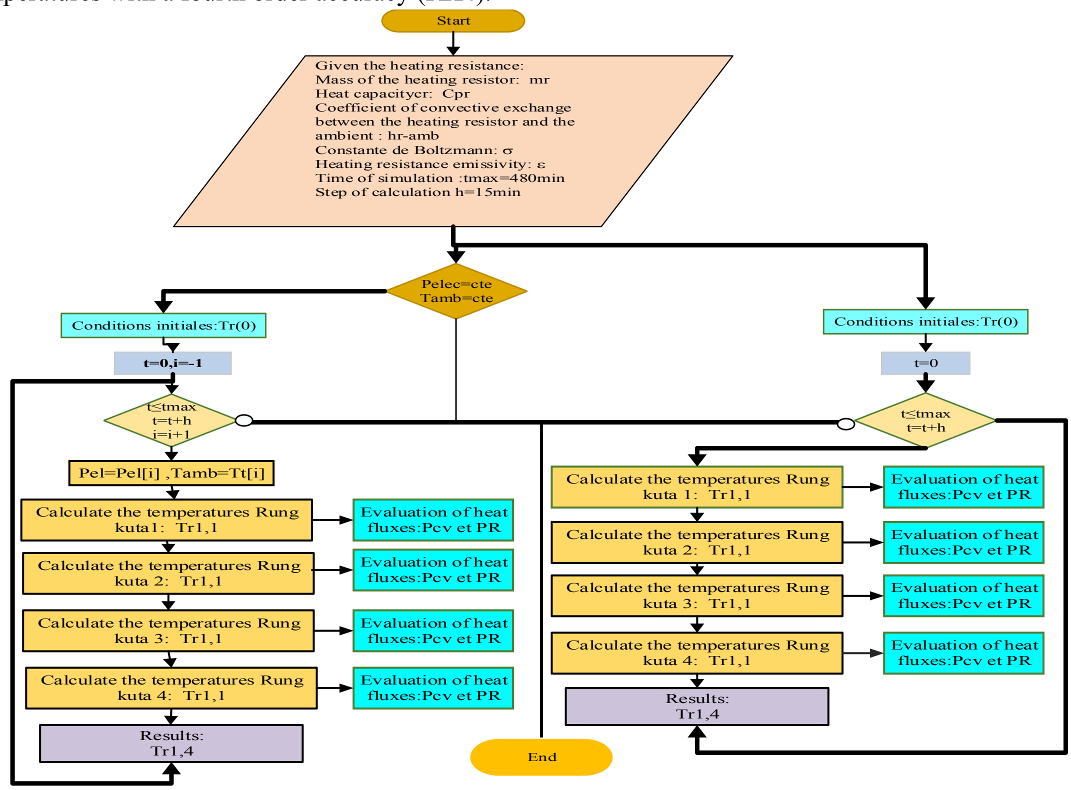

Fig. 2. Rung-kutta method of order 4 flowchart.

3. Experimental procedure

The system allowing the experimentation of the heating of a thermal resistor by photovoltaic renewable energy is represented in Fig. 3. This system, completely automated in the laboratory, is formed by:

- Photovoltaic generator formed by photovoltaic panels, power up to 300 W,
- Adaptation block formed by power and control circuits. Its role is to adapt the photovoltaic generator to the resistor and supervise the operation of the system [23,16].
- Resistance of the heating resistor 11.5 Ω, supporting a power of 800 W and a temperature of 600 ° C,
- PC acquisition and display of all electrical and thermal quantities,
- Digital Multimeter (Keithley model 2700), connected to the CM6 Pyranometer, temperature sensors and PC. Its role is to perform voltage measurements, on 40 different channels, and via the GPIB and RS232 interface, the PC deduces and displays the intensity of the irradiation, the ambient temperature and the different temperatures.

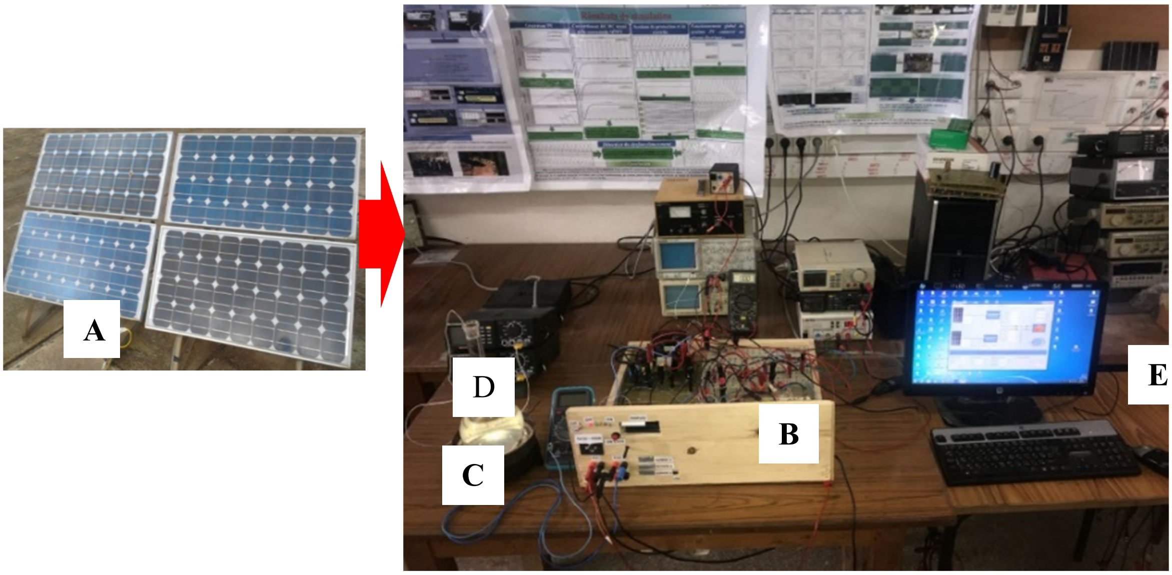

Fig. 3. Measurement bench set up in the laboratory.

A: Photovoltaic generator, **B**: Power block, controls, acquisition, and system management,
C: Plate and heating resistor **D**: Water to Heat**, E**: PC acquisition and display.

4. Results and discussion

4.1. Heating of the thermal resistor

In this paragraph, we have experimented the system of the paragraph 3.1, during a whole day, by measuring the intensity of the solar irradiation, the resistor heating temperatures, and the powers of the electric heating. The typical obtained results are shown in Figures 4, 5, and 6. In the same figure, concerning the temperature of the heating resistor, we reported the simulation results taking into account the meteorological conditions (solar irradiation and ambient temperature). The obtained results show that:

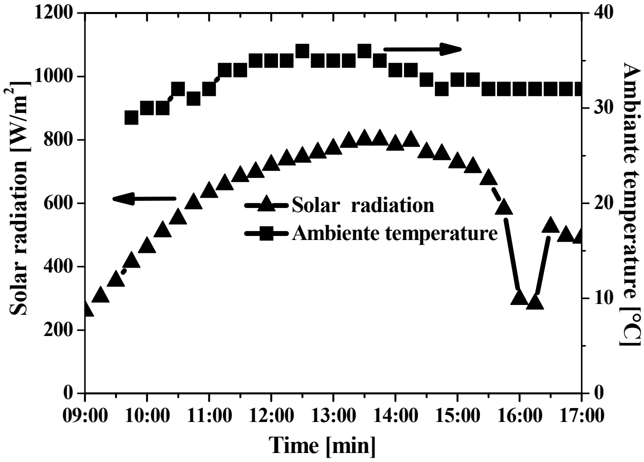

Fig. 4. Experimental plot of weather conditions (solar irradiation and ambient temperature).

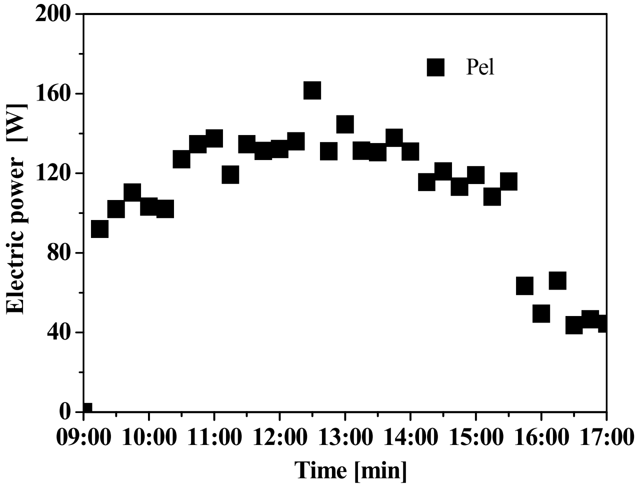

Fig. 5. Experimental plot of electrical power.

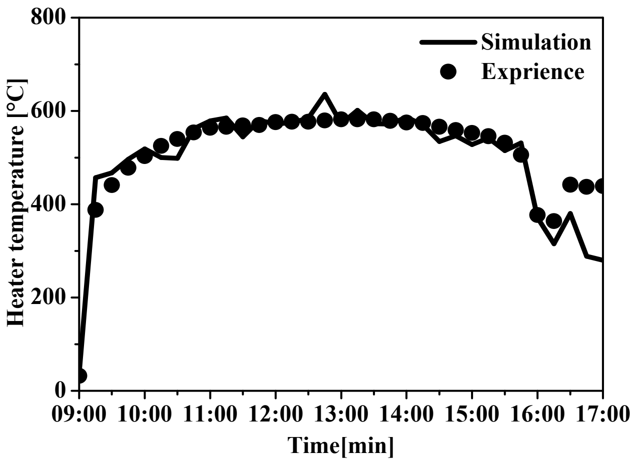

Fig. 6. Experimental and simulated temperature plot of the heating resistor.

- The solar irradiation reaches 800 W /m^2 and the ambient temperature 35°C around 13h30 min,
- The electrical power of the thermal resistor reaches the maximum value of 162 W at a solar irradiation of 746 W /m^2,
- The thermal resistor temperature varies from 32°C to 388°C (an increase of 91.75%) after 15 min,
- During the day, the temperature of the heating resistor is higher than 300 °C,
- When the solar irradiation varies from 450 W / m^2, the heating power varies from 90 W to 150 W (an increase of 36%), and the temperature of the heating resistor varies from 388°C to 582°C (an increase of 33%),
- Good agreement between experimental and simulated results.

In the literature, the best results published [15] show, when heated by solar batteries for an electric power of 65W, that the maximum temperature reached is 122 ° C. It should be noted that in these studies [15], no theoretical study is carried out. Therefore, the experimental and theoretical results obtained in the context of our work with photovoltaic energy are original and considered as an added value in the field of renewable energy applications.

4.2. Thermal efficiency and power

We have experimentally analyzed the power, temperature and thermal efficiency by following the boiling of the water using the expression (2) in section 2.2. To do this, we measured the meteorological conditions (solar irradiation and ambient temperature), electrical power Pelec, and water temperature. Based on these results, we deduced the thermal power Po and the thermal efficiency η. The obtained results (Figures 7, 8, 9 and 10), show:

- Solar radiation and ambient temperature reach 900 W/m2 and 20 °C.
- After 20 minutes of the water heating:

✓ the maximum heating resistor and water temperatures reach 502°C and 99°C, respectively,
✓ the maximum electric powers of the heating Pel and thermal resistor Po reach 167 W and 120 W, respectively,
✓ the maximum heating efficiency η reaches 72%.

In the literature, the best results obtained [11], by heating by the electric energy supplied by the batteries, show for a mass of water m = 0.385g and electrical power of 76.9 W, thermal power Po = 32.2 W and efficiency η=43.6%. In the framework of our experiment, using photovoltaic panels and a water quantity m = 1kg, we obtained, for an electrical power Pel = 167 W, very interesting results: a thermal power and efficiency of 120 W and 72%. As a conclusion, all the results obtained show very interesting performances and therefore the possibility of using photovoltaic energy to power, in renewable energy applications, thermal resistors with a very high efficiency.

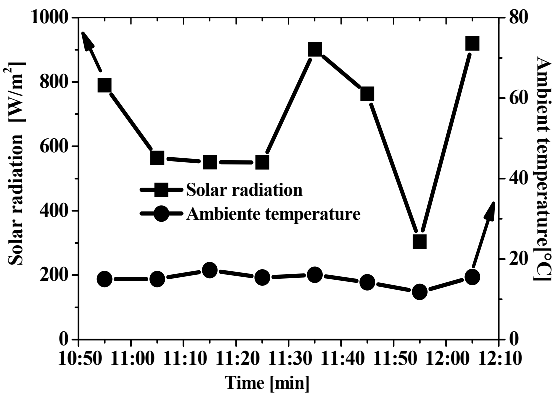

Fig. 7. Experimental plot of weather conditions (solar irradiation and ambient temperature).

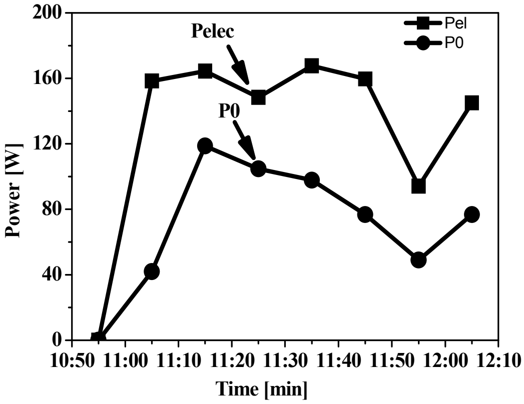

Fig. 8. Experimental plot of electrical and thermal powers.

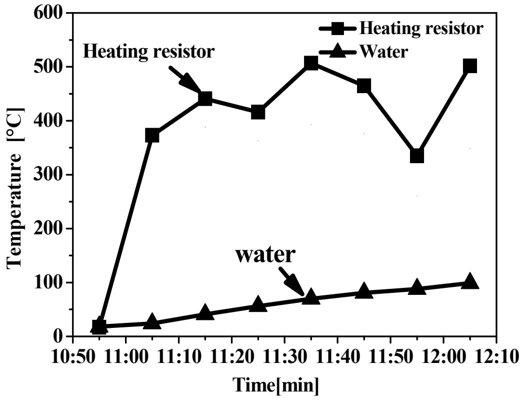

Fig. 9. Experimental plot of the heating resistor and water.

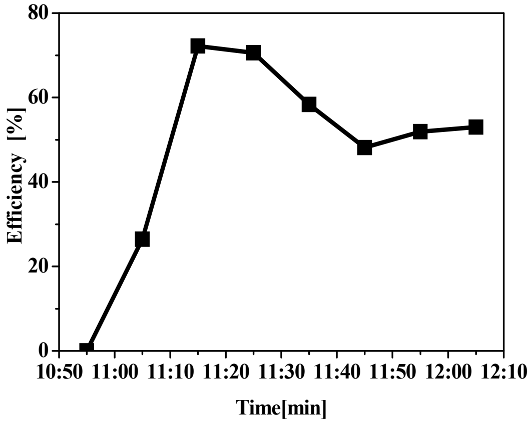

Fig. 10. Experimental plot of heating efficiency of one litre of water.

5. Conclusion

In this paper, we studied the thermal behaviour of heating resistors, powered by photovoltaic renewable energy. From a photovoltaic system as well as set-up and numerical calculation code, we analysed during a sunny day the temperature of the resistors and the heated water, the electric and thermal powers, as well as the thermal efficiency. The obtained results demonstrate:

- Concerning the temperature of the heating resistor, there is a good agreement between the simulation and the experiment,
- The electric heating of the resistors is very sensitive to the solar irradiation. When the solar irradiation increases by 450 W / m^2, the temperature of the heating resistor varies from 441°C to 582°C (an increase of 24.22%).
- Very satisfactory energy performances: After 20 minutes of heating, the intensity of solar irradiation varies from 790 W/m^2 to 551 W/m^2, the temperature of the heating resistors varies from 17 °C to 441°C, the electric and thermal power from 0W to 164.5W and 0W to 118.71W, respectively, and the thermal efficiency from 0% to 72%.

All the obtained results show the validation of the numerical code developed during this work, the electrical, the thermal and energy performances that reflect the possibility of using the thermal resistors, in the heating equipment by the photovoltaic renewable energy (solar oven, drying fruit and vegetable ...).

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- National Initiative for Human Development INDH, Berkane Province, Morocco,
- Company ‘EVES Energies’, Oujda, Morocco,
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