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Solar concentration using flat reflectors: parametric study and experimental investigation

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Abstract: A new design of a solar collector is proposed in this paper. The introduced novelty consists on using low cost flat reflectors with adjustable inclination. A detailed description of the solar collector as well as its functioning are also provided in the paper. Moreover, a mathematical model, that takes into account the variation of the heat transfer coefficients, is proposed and validated experimentally. Several experiments were also done in order to determine the influence of the new parameters that were induced by the use of reflectors. The parameters that were considered for this study are: the use or no-use of outer reflectors, the number of reflectors equipping the solar collector, and finally the reflectors inclination. The obtained results showed that the enhancement had a great effect on the performance of the solar collector. Indeed, the operating temperature range as well as the availability of the solar collector had increased. This allows the solar collector to work even during days with low solar radiation.

Keywords: New design; solar collector; flat outer reflectors; performance; experiment.

1. Introduction

During the last decades, a great interest has been accorded to renewable and clean energy-sources because of the increasing environmental problems that can affect the persistence of the remaining living species on earth [1].

These sources, despite the major solutions they give, still cannot attract industrials because of their random availability and repartition.

This led many researchers to work on improved technologies that can palliate these problems.

One of the most important solutions is the use of concentrating technologies in the solar field. In [2] for example, a compound parabolic concentrator was proposed in order to enhance the solar efficiency of a solar cooker. In spite of the high cost of manufacturing such concentrators, this solution gave better values of performance-indicators.

The use of paraboloid concentrators for solar cookers [3,4] and some of solar collector-technologies [5,6] also led to improved performances of their equipping devices. Inner mirrors were also employed in solar cooking technologies such as in [7,8]. This was a fructuous solution but with a light improvement of the thermal performance of the solar cookers, since the boosting mirrors are only capable of concentrating

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the solar radiation on the cooking vessel without improving the solar capture.

This paper, focuses the light on the influence of using four outer reflectors on the thermal performances of a solar collector that equips a solar refrigerator with intermittent adsorption-cycle.

In what follows, a detailed description of the utilized device will be provided. The prediction of the thermal performances is done by a dynamic mathematical model, that was implemented in a Matlab-program. The robustness of the mathematical model was then discussed according to the results that were obtained by an experimental investigation.

2. Design description and functioning

The proposed device over which the study was carried is a solar refrigerator with an intermittent adsorption cycle as depicted in Fig.1.

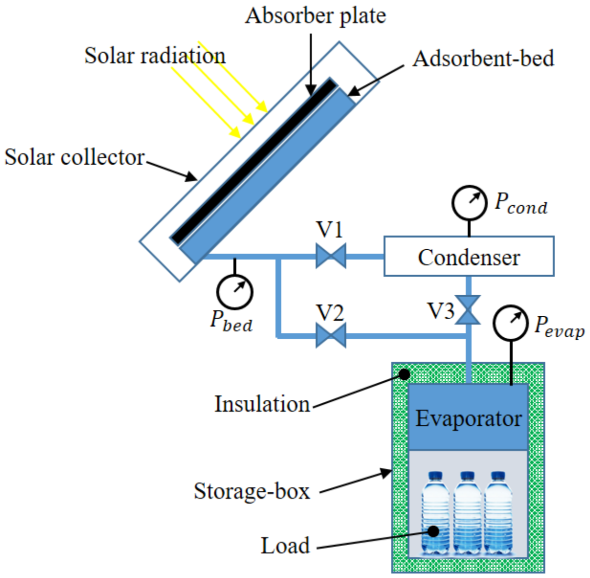


Fig. 1 Modeling of the solar refrigerator

The system uses a solar collector that provides heat to the adsorbent bed. This solar collector is the most important part in the proposed device since it governs the adsorption/ desorption process. Indeed, during the early hours of the day, the bed receives steam from the evaporator. The relatively cold adsorbent-grains which are filling the adsorbent-bed adsorb the steam particles. This process continues until the pressure equilibrium is achieved between the evaporator and the adsorbent-bed. At this precise moment, the adsorbent bed must be isolated from other parts of the refrigerator by closing the non-return valves V1 and V2. Under the effect of the rising solar radiation the temperature of the adsorbent-bed as well as the temperature of the whole collector starts to rise. The solar collector must be able to make the temperature of the adsorbent-bed exceed the desorption temperature T_{des}. Once this aim is achieved, the adsorbent-grains begin to release the adsorbed steam. This phenomenon is known as desorption process or regeneration process.

However, many of the proposed solar collectors failed face to days with low solar radiation, where they were not able to reach relatively high temperature.

In this work, a low-cost improvement, with four flat outer reflectors, is proposed for the solar collector which is depicted in Fig.2.

The main components of the solar collector are:

- A double glazing cover,
- An absorber plate,
- An air gap between the double glazing and the absorber plate,
- An adsorbent bed,
- Four removable reflectors with adjustable inclination.

The double glazing dimensions are chosen according to a study that was carried in order to determine the optimum spacing and thickness of two glass covers [9]. The adopted dimensions permit to lower heat loss by convection through the double glazing.

The air gap separates the double glazing from the absorber plate which creates a greenhouse effect. This allows to reach relatively high temperatures. The absorber plate is made of an aluminum plate with non-selective black matt paint. The absorber plate accumulates heat from the solar radiation and transfers it to the charge which is the adsorbent bed in our case.

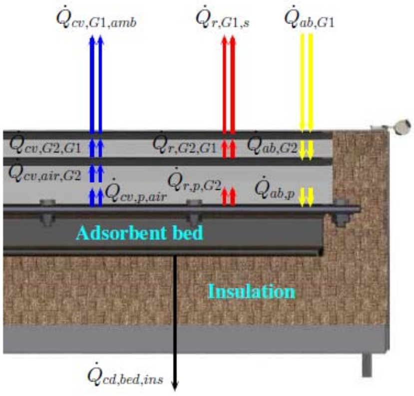
The adsorbent bed contains silica-gel grains and an amount of vapor. The goal of using the solar collector is to rise the temperature of the silica-gel from the temperature of adsorption T_{ads} to the temperature of desorption T_{des}.

Fig. 2 Pictorial views of the solar collector

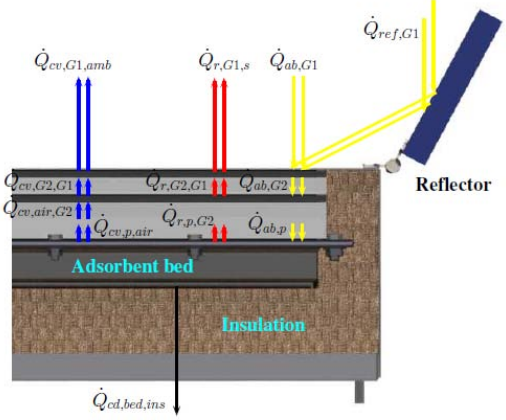
3. Mathematical model

The mathematical model is mainly based on thermal balances. The obtained equations are then discretized using finite differences method with backward differences. Newton-Raphson method is also adopted in order to solve the obtained equations and to correct the values of fluctuating coefficients.

In what follows, the thermal balance equations of the main components of the solar collector are developed. Both of the models of the two devices are presented in Fig.2.



a) Modeling of the solar collector without reflectors



b) Modeling of the solar collector with reflectors

Fig. 3 Modeling of the solar collector

The following mathematical model is developed with considering these assumptions:

- The incident solar radiation is normal to the surface of the double glazing cover.
- The thermal and physical properties of the components that are considered for this study are constant and independent from the system evolution in the considered temperature range.
- The main components temperatures are uniform but can vary with time.
- The temperature of the adsorbent-bed is assumed to be equal to the temperature of the absorber plate. This assumption is adopted since the thermal conductivity of the metallic parts constituting the adsorbent bed is relatively high.

- The heat transfer coefficients are time dependent and must be corrected several times until achieving convergence.

First glass thermal balance equation

The upper glass of the double glazing receives an amount $\dot{Q}_{ab,G1}$ of global solar radiation, a convective heat flow $\dot{Q}_{cv,G2,G1}$ and a radiation heat flow $\dot{Q}_{r,G2,G1}$ from the lower glass. A part of the energy received is accumulated inside the glass material with an accumulation rate of $\dot{Q}_{acc,G1}$, while the other part is rejected either by radiation towards the sky $\dot{Q}_{r,G1,sky}$ or by convection with the ambient air $\dot{Q}_{cv,G1,amb}$.

$$\dot{Q}_{ab,G1} + \dot{Q}_{cv,G2,G1} + \dot{Q}_{r,G2,G1} = \dot{Q}_{acc,G1} + \dot{Q}_{cv,G1,amb} + \dot{Q}_{r,G1,sky} \tag{1}$$

The previous heat rates are expressed in (W) and can be calculated using the following expressions:

$$\dot{Q}_{ab,G1} = \alpha_{G1}\,(4\,r_{ref}S_{ref}\,\sin(\theta) + S_{G1})\,I \tag{2}$$

$$\dot{Q}_{cv,G2,G1} = h_{cv,G2,G1}S_{G1}(T_{G2} - T_{G1}) \tag{3}$$

$$\dot{Q}_{r,G2,G1} = h_{r,G2,G1}S_{G1}(T_{G2} - T_{G1}) \tag{4}$$

$$\dot{Q}_{acc,G1} = m_{G1}C_{pG}\,\frac{dT_{G1}}{dt} \tag{5}$$

$$\dot{Q}_{cv,G1,amb} = h_{cv,G1,amb}\,S_{G1}(T_{G1} - T_{amb}) \tag{6}$$

$$\dot{Q}_{r,G1,sky} = h_{r,G1,s}S_{G1}\left(T_{G1} - T_{sky}\right) \tag{7}$$

Where, α_{G1} is the absorption coefficient of the glass, S_{ref} is the surface area of one reflector, r_{ref} is the reflectivity of the reflector's surface, θ is the reflector's inclination, S_{G1} is the glass surface area, I is the global solar radiation, h is the heat transfer coefficient, m is the mass, C_p is the specific heat capacity, and T is the temperature of the component.

The temperature of the sky can be expressed using [10]:

$$T_{sky} = 0.0552\,T_{amb}^{1.5} \tag{8}$$

Second glass thermal balance equation

The lower glass of the double glazing receives the transmitted part of the global solar radiation $\dot{Q}_{ab,G2}$ by the upper glass, a heat rate by convection $\dot{Q}_{cv,air,G2}$ from the air gap and a heat rate by radiation $\dot{Q}_{r,p,G2}$ from the absorber plate. On the other hand, it accumulates an amount of the received energy at a rate of $\dot{Q}_{acc,G2}$ while the remaining is wasted either by convection $\dot{Q}_{cv,G2,G1}$ or by radiation $\dot{Q}_{r,G2,G1}$ over the upper glass.

$$\dot{Q}_{ab,G2} + \dot{Q}_{cv,air,G2} + \dot{Q}_{r,p,G2} = \dot{Q}_{acc,G2} + \dot{Q}_{cv,G2,G1} + \dot{Q}_{r,G2,G1} \tag{9}$$

The previous heat rates are expressed as:

$$\dot{Q}_{ab,G2} = \alpha_{G2}\,\tau\,(4\,r_{ref}S_{ref}\,\sin(\theta) + S_{G2})\,I \tag{10}$$

$$\dot{Q}_{r,p,G2} = h_{r,p,G2}S_{G2}\left(T_p - T_{G2}\right) \tag{11}$$

$$\dot{Q}_{acc,G2} = m_{G2}C_{pG}\,\frac{dT_{G2}}{dt} \tag{12}$$

$$\dot{Q}_{cv,air,G2} = h_{cv,air,G2}S_{G2}(T_{G2} - T_{air}) \tag{13}$$

Where, τ is the coefficient of transmission of the lower glass.

Air gap thermal balance equation

A part of the released heat rate by convection by the absorber plate is accumulated in the air gap while the remaining is wasted towards the second glass. The air gap energy balance can be written as follows:

$$\dot{Q}_{cv,p,air} = \dot{Q}_{acc,air} + \dot{Q}_{cv,air,G2} \tag{14}$$

The expressions of the previous heat rates are calculated using the following expressions:

$$\dot{Q}_{cv,p,air} = h_{cv,p,air} S_p \left(T_p - T_{air}\right) \qquad (15)$$

$$\dot{Q}_{acc,air} = m_{air} C_{pair} \frac{dT_{air}}{dt} \qquad (16)$$

Silica gel bed thermal balance equation

To solve the silica gel bed energy balance equation, we assume that the temperature of the whole bed equals the temperature of the aluminum plate. The silica gel-bed energy balance is then expressed as follows:

$$\dot{Q}_{ab,p} = \dot{Q}_{acc,p} + \dot{Q}_{cv,p,air} + \dot{Q}_{r,p,G2} + \dot{Q}_{cd,bed,ins} \qquad (17)$$

Where, $\{\dot{Q}_{ab,p}\}$ is the dark aluminum plate absorption heat rate, $\{\dot{Q}_{acc,p}\}$ is the aluminum plate accumulation heat rate, and $\{\dot{Q}_{r,bed,ins}\}$ is the radiative heat rate rejected through the rock wool insulation. The previous heat rates can be calculated using the next expressions:

$$\dot{Q}_{ab,p} = \alpha_p \tau^2 (4\, r_{ref} S_{ref} \sin(\theta) + S_p)\, I \qquad (18)$$

$$\dot{Q}_{acc,p} = m_t C_{pg} \frac{dT_p}{dt} \qquad (19)$$

$$\dot{Q}_{cd,bed,ins} = h_{cd,bed,ins} S_{bed/ins} \left(T_p - T_{ins}\right) \qquad (20)$$

Where, m_t is the bed total mass that can be expressed as:

$$m_t = m_v + m_p + m_{sg} + m_{mp} \qquad (21)$$

m_v, m_p, m_{sg}, m_{mp} are respectively the mass of the vapor in the bed, the mass of the aluminum plate, the silica gel mass and the mass of the metallic parts that constitute the bed.

The global specific heat capacity of the bed C_{pg} can be expressed using the following expression:

$$C_{pg} = \frac{C_{pv} m_v + C_{pp} m_p + C_{psg} m_{sg} + C_{pmp} m_{mp}}{m_t} \qquad (22)$$

Heat transfer coefficients

The convective heat transfer coefficient at the interface between the first glass and the ambient air is expressed in term of the wind speed $\boldsymbol{V}$ as follows:

$$h_{cv,G1,amb} = 5.7 + 3.8\, V \qquad (23)$$

The convective heat transfer between the first glass and the second glass can be written as:

$$h_{cv,G2,G1} = \frac{Nu_{G2,G1} \lambda_{air}}{t_{G2,G1}} \qquad (24)$$

Where $\boldsymbol{t_{G2,G1}}$ is the thickness of the air gap between the first and the second glass.

The Nusselt's number is calculated the following expression:

$$Nu_{G2,G1} = 1 + 1.44 \left(1 - \frac{1708}{Ra_{G2,G1} \cos\beta}\right)^{*} \left(1 - \frac{1708(\sin(1.8\,\beta))^{1.6}}{Ra_{G2,G1} \cos\beta}\right) + \left(\left(\frac{Ra_{G2,G1} \cos\beta}{5830}\right)^{1/3} - 1\right)^{*} \qquad (25)$$

Where $\boldsymbol{\beta}$ is the inclination of the solar collector and $\boldsymbol{Ra_{G2,G1}}$ is the Rayleigh's number.

In the case where the terms $(-)^{*}$ are negative, they are set to zero.

The convective heat transfer coefficients $\boldsymbol{h_{cv,air,G2}}$ and $\boldsymbol{h_{cv,p,air}}$ are calculated the same way as in eq.(24) and eq.(25).

The radiative heat transfer coefficient of the absorber plate over the second glass is expressed as:

$$h_{r,p,G2} = \sigma \frac{\left(T_p + T_{G2}\right)\left(T_p^2 + T_{G2}^2\right)}{\frac{1}{\varepsilon_p} + \frac{1}{\varepsilon_{G2}} - 1} \qquad (24)$$

Where $\boldsymbol{\sigma}$ is the Stephan's number, $\boldsymbol{\varepsilon_p}$ is the absorber plate emissivity and $\boldsymbol{\varepsilon_{G2}}$ is the second glass emissivity.

4. Instrumentation and data recording

Several experiments were effectuated on the prototype of the solar collector. Where, two PTC sensors were placed in the middle of the upper and the lower glass of the double glazing. In addition to two Type-J thermocouples that were placed in the air gap and in the middle of the absorber plate. The employed PTC sensors can operate in a temperature-range of -40 to 140°C with an accuracy of 1%. While, the Type-J thermocouples can operate in a temperature-range of 0 to 760°C with an accuracy of 0.75%.

These sensors are connected to a serial 24bits analog to digital converter ADS1256 that converts the input signals which are read by an Arduino MEGA 2560 microcontroller. The acquired data is then stored in a .txt-file using Labview-Software.

This equipment has the main following advantages:

- Accurate readings of the thermocouple's signals with a resolution of 1µV.
- 835$ cheaper than using an Agilent 34970A for acquisition.
- Can be connected to a computer via Bluetooth, which permits safer control of the experiments.

5. Results and discussion

4.1. Influence of reflectors

Two tests over the solar collector were effectuated during 09-06-2017 and 24-06-2017. The first experiment consists on testing the solar collector without outer reflectors while the second experiment consists on using it with four outer reflectors. The weather data which correspond to the days during which the experiments were carried out are shown in Fig.4.

The obtained results,Fig.5, show that the use of outer reflectors had a huge impact on the thermal performances of the solar collector. Indeed, the maximum temperature of the adsorbent-bed passed from 91.8 °C at a global solar radiation of 835.5 W.m^{-2}when the solar collector is not equipped with reflectors to 167.4 °C at a global solar radiation of 828 W.m^{-2} when the solar collector is equipped with reflectors.

Hence, when not equipped with reflectors the solar collector was not able to reach the desorption temperature which is valuing 120 °C according to the manufacturer. While, it was able to do so when equipped with four outer reflectors and even better, the solar collector was allowed of approximately 8h 50min of desorption duration which permits to recuperate a maximum amount of vapor from the adsorbent.

It was also proven that the developed mathematical model is sufficiently accurate to predict the thermal behavior of the different components of the solar collector.

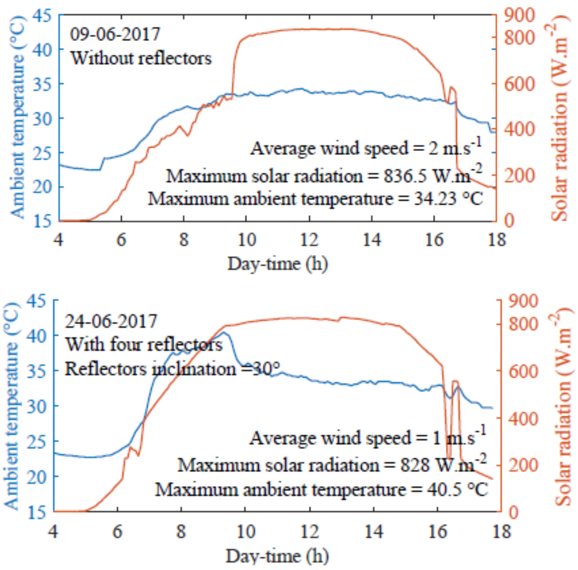


Fig. 4 Weather-data during 09-06-2017 and 24-06-2017

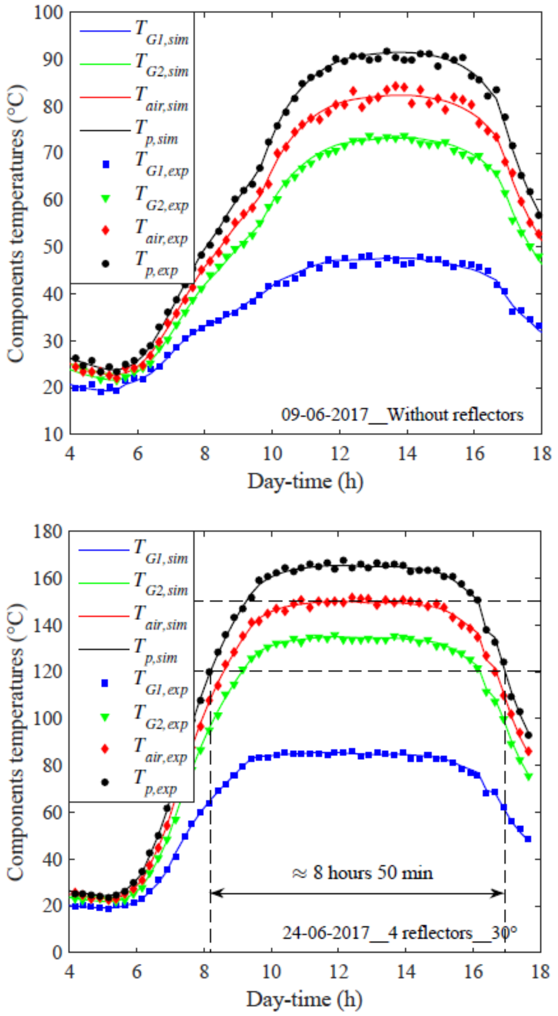


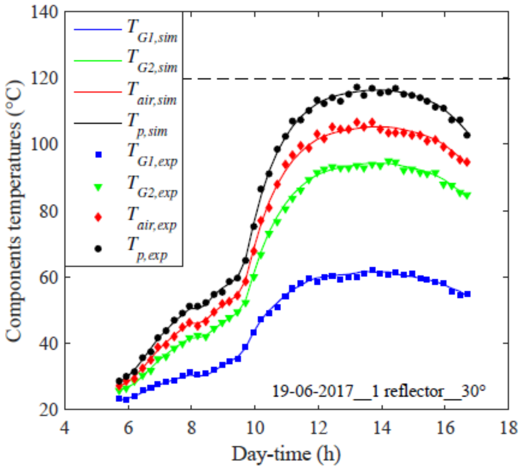
Fig. 5 Solar collector without reflectors vs solar collector with four outer reflectors

4.2. Influence of the number of reflectors

The number of reflectors as well as their disposition have a great impact on the thermal performance of the devices that are used in this study. Fig.6 shows the different configurations with which experiments were effectuated.

The obtained results Fig.7 show that the thermal performance increased with the number of the used reflectors. Indeed, during the one reflector test the maximum recorded temperature of the absorber plate was about 117 °C, while it was 134 °C during the two reflectors test and 150 °C during the three reflectors test. The desorption-period was about 5h 30min during the two reflectors test and 8h during the three reflectors test. But during the one reflector test the solar collector was not able to reach the desorption temperature which means that the desorption-phase did not occur.

Fig. 6 Solar collector with different reflectors configurations



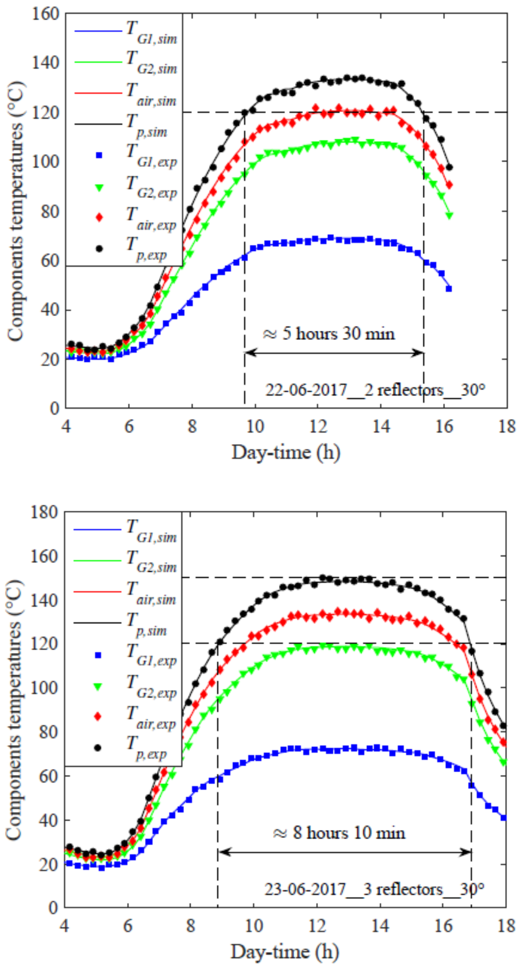


Fig. 7 Experimental and simulation results using different reflectors configurations

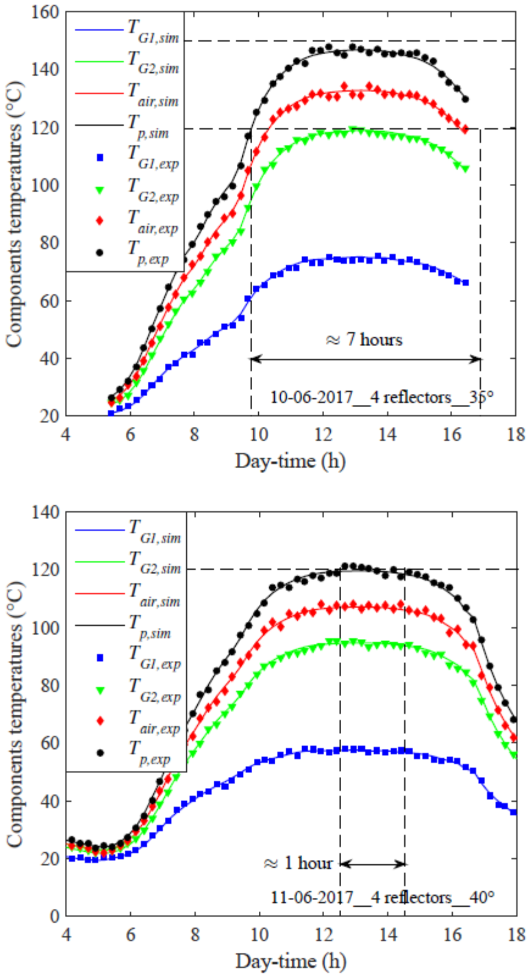


Fig. 8 Experimental and simulation results over the solar collector with different reflectors inclinations

4.3. Influence of the reflectors-inclination

Three tests were effectuated over the solar collector in order to highlight the influence of the inclination of the outer reflectors. These tests were effectuated during 10-06-2017, 11-06-2017 and 23-06-2017 with respective reflectors inclination of 35°, 40° and 30°.

The obtained results of the corresponding tests are shown in Fig.8.

These results showed that for a small fluctuation of the reflectors inclination the thermal performance can vary hugely. Indeed, during the first and the third test, the solar collector was able to reach relatively high temperatures 150 °C and 167 °C that exceeded the temperature of desorption. However during the second test, it was able to reach only 121.4 °C. During the first test the recorded desorption period was about 7 hours and during the third test the recorded desorption period was about 8h 50min. These periods are sufficient for the adsorbent to release the maximum of vapor. While during the second test the allowed time for desorption was only one hour. This period is not sufficient to obtain a satisfying amount of desorbed vapor in the vacant space of the bed.

6. Conclusions

This work consisted on experimenting over a new design of a solar collector equipping a solar refrigerator with intermittent adsorption cycle. The novelty was in the use of four flat outer reflectors with adjustable inclination in order to better solar capture. The reported results showed that this enhancement improved the thermal performance of the solar collector as expected and predicted in a theoretical study. Moreover, the parametric study that was carried out showed that the thermal performance of the solar collector is hugely affected by several parameters, besides the meteorological conditions, namely: the use or no-use of outer reflectors, the reflectors inclination, and the number of reflectors. Indeed, it was experimentally shown that when equipped with outer reflectors, the temperature of the charge, which is in our case the adsorbent-bed, passed from 91.8 °C to 167.4 °C. This means that the capability of the solar collector was improved by 82 %. In addition to that, tests that were effectuated with different outer reflectors numbers showed that higher the number of reflectors is, higher the temperature of the adsorbent-bed will be. Indeed, when passing from a configuration with only one reflector to a configuration with four outer reflectors, the maximum temperature of the adsorbent bed passed from 117 °Cto 134 °C to 150 °C to 167°C. This parameter had also an effect on the permitted desorption period where a desorption-period of 8h 50min was accorded to the adsorbent-bed to desorb the maximum quantity of steam. While, during the test with only one reflector the desorption-process couldn’t even start. Finally, a test with different reflectors inclinations is done. The obtained results revealed that the thermal performance of the solar collector vary as the reflectors inclination varies. The best performance was obtained for a 30° of inclination, with a maximum adsorbent-bed’s temperature valuing 167.4 °C. The thermal performance was altered as the reflectors inclination increased. Indeed, for an inclination of 35° the maximum obtained adsorbent-bed’s temperature was 150 °C, allowing a desorption period of approximately 7 hours. The same thing was noticed when the outer reflectors were inclined by 40°, where, the maximum recorded temperature was only 121.4 °C, allowing only 1 hour for the adsorbent bed to desorb the vapor which was contained on its surface.

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