

Parametrical study of the influence of the climatic data and the construction properties on the efficiency of a collector/storage solar water heater

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Abstract - A study was undertaken on the performance of an integrated collector-storage solar water heater consisting of a cylindrical water storage tank combined with a parabolic reflector, manufactured at the Laboratory of Energetic and thermal Processes (LEPT). The theoretical determination of the heat transfer phenomena which occur in the system was used to elaborate a numerical model, needed for a parametric evaluation of the system. The parametric study identified the parameters which have the higher influence on the system efficiency and allowed us to quantify the contribution of each of them. We can notice that for the climatic data, the cold water input temperature as well as the ambient temperature showed a major effect on the warm water output. For the construction characteristics, the most influencing factors are the transmissivity of the glazing and the painting of the tank.

Résumé - Une étude des performances a été menée sur un système de chauffe-eau solaire de type capteur stockeur cylindro-parabolique, fabriqué au Laboratoire d'Energétique et des Procédés Thermiques (LEPT). La détermination théorique des phénomènes de transfert de chaleur qui ont lieu au sein du système a été utilisée pour la réalisation d'un modèle numérique nécessaire à l'évaluation paramétrique du système. L'étude paramétrique a permis d'identifier les paramètres qui ont la plus forte influence sur le rendement du système et de quantifier la contribution de chacun d'entre eux. On note que pour les données climatiques, la température d'entrée de l'eau froide ainsi que la température ambiante ont présenté un effet majeur sur le rendement. Quant aux caractéristiques de construction, ce sont la transmissivité du vitrage et la peinture du réservoir qui ont le plus d'influence.

Keywords: Solar energy - Water heater - Integrated collector storage system - Numerical simulation
- Thermal efficiency - Optical efficiency.

1. INTRODUCTION

Solar heat applications, and mainly the production of hot water using solar water heaters, represent one of the most promising applications of solar energy in Tunisia.

There are various types of solar water heaters. The most known are, the classical flat-plate collector system, the vacuum tube system, the solar concentrating system and the collector /storage system [1-6].

Our objective was to investigate a less expensive not bulky solar water heater, which is easy to introduce on the Tunisian market. Consequently, we built an integrated collector/storage solar water heater at our laboratory with all the materials available on the Tunisian market; this type of water heater combines the solar collector and storage tank in one unit with lower cost and lesser maintenance requirement than other water heaters. In order to improve this system we focus on its parametrical study.

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After the description of the experimental setup and measurement techniques, we investigate essentially the theoretical part of this system and show the model used for the study. Then, we investigate the influence of the different climatic conditions and the construction properties relating to the daily thermal efficiency of this water heater.

2. DESCRIPTION OF THE INVESTIGATED WATER HEATER AND THE PERFORMANCE EVALUATION METHOD

The integrated collector/storage system (Fig. 1) incorporates a heat retaining cylindrical tank with a capacity of 200 l without a heat exchanger. The tank is painted in black (epoxy based paint) and placed inside a thermally isolated trunk with polyurethane foam. The insulation is covered by a parabolic stainless reflector. The unit is closed by a simple tempered glass glazing.

The system is monitored by a PC and an Agilent 34970A data acquisition unit, which measures the ambient condition and water temperature.

Incident solar radiation upon the system is measured by a pyranometer fixed at the same inclination as the unit. Water temperature is measured by Pt-100 probes placed at the inlet and outlet of the water heater.

The system daily efficiency is determined using the Input-Output method, which consists of making a draw-off early in the morning and then letting the integrated collector/storage system warm up during a period of 12 hours. At the end of the warm up period, the thermal energy stored in the tank is measured using a draw-off with a constant flow of 10 l/min.

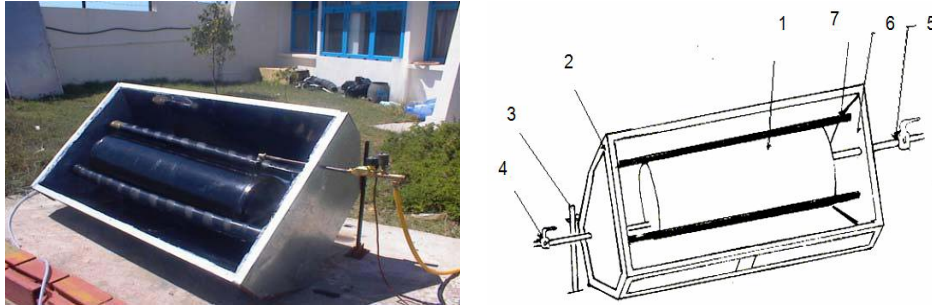


Fig. 1: Integrated collector/storage system manufactured at the LEPT

1. Steel storage tank (Volume 200 liters) - 2. Structure of the Case - 3. Fixing support,
4. Water inlet - 5. Water outlet - 6. Simple glass glazing - 7. Fixing arm

3. THEORETICAL INVESTIGATION

3.1 Thermal losses at the bottom of the collector

The heat losses by conduction and convection at the back of the collector are given by:

$$\phi_{\text{arr}} = U_{\text{tarr}} (T_s - T_a) \quad (1)$$

These losses are based on the storage to ambient temperature difference and the bottom heat transfer coefficient U_{tarr} which depends on the bottom isolation and the convection coefficient.

3.2 Thermal losses at the front of the collector

3.2.1 Heat transfer by convection

The heat losses by convection between the glass cover and the ambient media are:

$$\phi_{\text{conv}} = A_v h_{\text{ext}} (T_v - T_a) \quad (2)$$

where T_v and T_a represent respectively the temperature of the glass cover and the ambient media.

Here, we need to determine the convection coefficient h_{ext} which depends on the wind speed w [7] such as:

$$h_{ext} = 2.2 (T_v - T_a)^{0.25} + 4 w \quad \text{if } w < 4 \text{ m/s} \quad (3)$$

$$h_{ext} = 7.5 w^{0.8} \quad \text{if } w > 4 \text{ m/s} \quad (4)$$

For the heat transfer by convection between the storage tank and the reflector to the glass cover we use a mean heat transfer coefficient of $5 \text{ W/m}^2\text{.K}$.

3.2.2 Heat transfer by radiation

The net heat flux between the glass cover and the sky, can be described by the following equation:

$$\phi_{v-c}(\text{net}) = [\varepsilon_v \sigma T_v^4 + \sigma T_c^4 (1 - \varepsilon_v) - \sigma T_c^4] \cdot A_v \cdot F_{v-c} = h_{rv} A_v (T_v - T_c) \quad (5)$$

where h_{rv} represents the heat transfer coefficient by radiation such as:

$$h_{rv} = \varepsilon_v \sigma (T_v + T_c) \cdot (T_v^2 + T_c^2) \quad (6)$$

The heat transfer by radiation from the absorber and the reflector to the glass cover is:

$$\phi_{rint} = (K_1 A_r + K_2 A_s) (T_s - T_v) \quad (7)$$

Where K_1 and K_2 are two constants depending on the dimensions of the solar water heater.

3.3 Average optical efficiency

The average optical efficiency is determined by the formula of Rabl [8]:

$$\eta_0 = \tau \cdot \alpha \cdot \rho_{re}^{(N)} \cdot \gamma \quad (8)$$

with τ : transmittance of the glass cover, α : absorptance of the absorber (storage tank), ρ_{re} : reflectance of the reflector; N : mean number of reflexions; γ : intercepting factor.

3.4 Numerical simulation

We use the black box model for the daily simulation of our solar water heater. This simulation is based on the following heat balance:

$$Q_{sj} = Q_j - Q_{pj} \quad (9)$$

with Q_{sj} : energy provided by the system /day, Q_j : solar energy received by the system /day, Q_{pj} : energy losses /day.

The thermal losses, during the warming up period ($\Delta t = 12$ hours), are calculated using the overall heat loss coefficient U_t such as:

$$Q_{pj} = U_t \Delta t (T_{sj} - T_{aj}) \quad (10)$$

with the mean storage temperature:

$$T_{sj} = \frac{T_{CMj} + T_{fj}}{2} \quad (11)$$

and the storage temperature at the end of the warming up period:

$$T_{CMj} = \frac{Q_{sj}}{MC_p} + T_{fj} \quad (12)$$

where T_{fj} represents the inlet temperature of the cold water.

By combining the above equations the daily energy provided by the system can be expressed as follows:

$$Q_{sj} = \eta_0 H_j - U_t \Delta t (T_{fj} - T_{aj}) - \frac{Q_{sj}}{2 M C_p} U_t \Delta t \quad (13)$$

which can also be written as:

$$Q_{sj} = K_{1j} H_j - K_{2j} (T_{fj} - T_{aj}) \quad (14)$$

with

$$K_{1j} = \frac{2 M C_p \eta_0}{2 M C_p + U_t \Delta t} \text{ and } K_{2j} = \frac{2 M C_p U_t \Delta t}{2 M C_p + U_t \Delta t} \quad (15)$$

So, knowing the optical efficiency and the overall heat loss coefficient, it is easy to simulate the operation of the integrated collector/storage system.

4. PARAMETRICAL STUDY

4.1 Test of the validity of the model and reference conditions used

The daily thermal efficiency ‘ η ’ of the system is then deduced by the following equation:

$$\eta = Q_{sj} / H_j \quad (16)$$

The heat flux between the different constituents of this water heater and the ambient media depends essentially on their physical characteristics and the climatic data.

The model was tested under different experimental conditions and a good agreement between theory and experiment was obtained [9], as we can also see in table I where we chose two typical days which are respectively, a very cloudy day and a day with high solar radiation.

Consequently, this model gives a correct simulation and can be used for a parametrical study meant for the improvement of our system.

The reference conditions used for the parametrical study of our water heater are the following:

- $G = 22 \text{ MJ/m}^2$, - $T_a = 25^\circ\text{C}$, - $T_f = 18^\circ\text{C}$, - $w = 2 \text{ m/s}$.

Each time we vary only one parameter and observe its effect on the evolution of the system efficiency.

4.2 Effect of the climatic conditions on the system efficiency

4.2.1 Effect of the cold water inlet temperature

Figure 2 represents the evolution of the thermal efficiency of our system according to the cold water inlet temperature T_f for values varying from 10°C to 28°C . We also notice that T_f has a very strong influence on the collector efficiency, for the lowest cold water temperature we obtain the best efficiency.

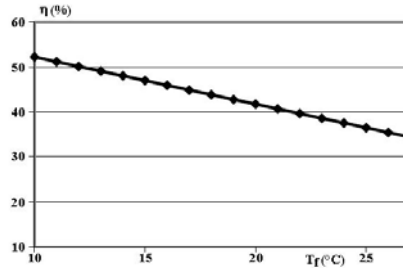


Fig. 2: Influence of the inlet cold water temperature on the system efficiency

We can as well notice that decreasing the water inlet temperature by 18 °C leads to increasing the system efficiency from 35 % to 53 %.

If we consider the stratification phenomenon which occurs within the storage tank, the water could be divided into several layers. The layer directly in touch with the top surface of the tank will be the hottest layer, this will affect the good working of the collector/storage system for two main reasons:

- The increase in losses caused by the increase in the surface temperature of the storage tank.
- The decrease in the heat transfer to water when the collector is sun exposed, since the heat transfer by conduction in the water is weak.

The stratification does not always have a bad effect. Indeed, when we need few hot water, it would be useful to have a good stratified water, thus we will have the hottest water at the top. But if we need a large amount of lukewarm water, it is better to destroy the stratification. In this case, we can easily imagine the addition of a pump (photovoltaic for instance) to homogenise the warm water temperature, and the lack of energy will be balanced by an auxiliary heat source.

4.2.2 Effect of the average ambient temperature

The effect of the average ambient temperature on the system efficiency is immediately perceptible as we see in Figure 3. This temperature represents a very important parameter for the collector.

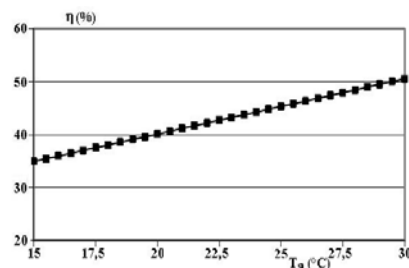


Fig. 3: Influence of the average ambient temperature on the system efficiency

We notice that the efficiency varies between 36 % and 50 % as the ambient temperature increases from 15 °C to 30 °C, in fact an increase in the ambient temperature leads to less losses by conduction convection and radiation.

4.2.3 Effect of the wind speed

Figure 4 shows the effect of the wind speed on the system efficiency. As expected, the efficiency decreases with the increasing of the wind speed, and this is due to the increasing of the global thermal losses of the system, and specially the losses by convection between the front side of the collector and the ambient media.

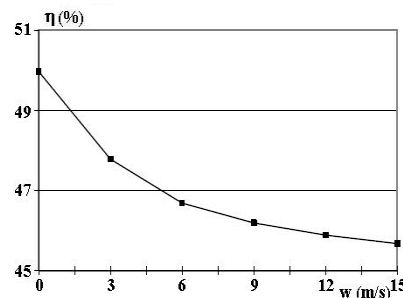


Fig. 4: Influence of the wind speed on the system efficiency

However, this kind of losses is not very high. Indeed, the evolution of the wind speed from 0 to 15 m/s generates a decrease in efficiency of 9 %.

4.3 Effect of the construction properties on the system efficiency

4.3.1 Effect of the isolation thickness

The rule of the isolation is to avoid the heat losses at the bottom and lateral sides. So it is necessary to know the influence of its thickness on the water heaters performance for a good optimisation of its conception and its cost.

Figure 5, shows that varying this thickness 'e' from 1 cm to 7 cm did not much influence the daily efficiency of the system, an horizontal asymptote is reached for $e = 5$ cm and increasing the thickness of the isolation after this point is worthless. But we must also keep in mind that the biggest losses occur at night and especially at the front side of the heater, and an ideal solution would be to cover it at night.

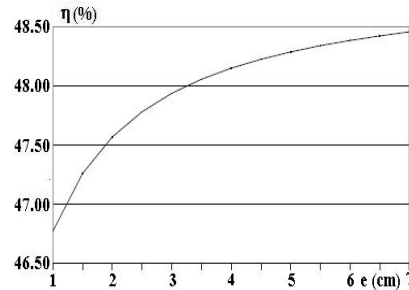


Fig. 5: Influence of the thickness of the isolation on the system efficiency

4.3.2 Effect of the glazing characteristics

The influence of the transmission coefficient of the glazing on the system efficiency represented in figure 6 shows that increasing this coefficient of 25 % results in a relative increase of the daily efficiency by 18 %.

The essential aim of the glazing is the realisation of a green house effect, but we must keep in mind that the glass cover decreases also the heat transfer by convection between the tank and the ambient media.

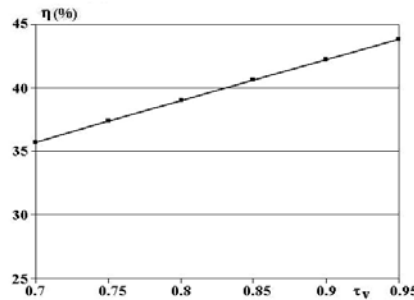


Fig. 6: Influence of the transmission coefficient of the glazing on the system efficiency

Moreover, we notice that this study was done using a simple glazing and it would be interesting to reinvestigate through a double glazing application. That will reduce the heat losses at night but involve a smaller transmission coefficient and an increasing the price of the water heater. This solution must be also investigated in terms of cost, optical characteristics and heat losses.

4.3.3 Effect of the tank painting

In order to improve solar radiation catching, selective paintings, with high absorption coefficient ' α ' are generally used on the absorber. That would lead to a better efficiency of the heater.

Figure 7 shows that the absorption coefficient has a big effect on the thermal efficiency of the heater and a variation of this coefficient from 0.7 to 0.95 results in an increase of the efficiency from 36 % to 44 %. However, good selective paintings are expensive and will increase the price of the heater.

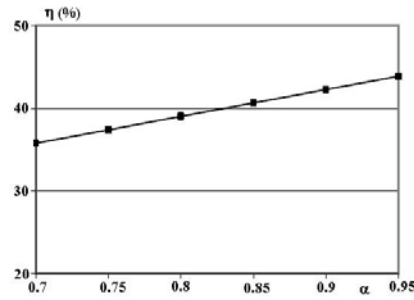


Fig. 7: Influence of the painting of the tank

5. CONCLUSION

The analytical investigation of the various phenomena of heat transfer which occur within the system was carried out. It aims at identifying a useful model for the analysis of the variation of the performances of the integrated collector/storage solar water heater depending on the climatic conditions and the construction properties.

The validity of the model was tested and showed good agreement between theory and experience.

For classical Tunisian climatic conditions, our model, based on the optical and thermal properties of the collector showed that the efficiency of the system varies by 30 % for the ambient temperature, 40 % for cold water temperature and 9 % for the wind velocity.

The variation of the construction properties, showed that it is worthless to increase the isolation more than 5 cm, but the use of good transmissive glasses and selective paints will considerably increase the performance of the water heater.

A meticulous study of the thermal stratification within the storage tank could lead to a further improvement of the design of our system.

To reduce the heat losses, it would be interesting to cover the collector at night, or to use a double glazing. But this last solution must be carefully studied because the double glazing will weakly lower the optical performance of the collector and increase its price.

The use of a less expensive storage tank must also be investigated.

NOMENCLATURE

| | | | |
|-----------|--|----------|--|
| A_v | Area of the glass cover, m^2 | Q | Solar energy received by the system /day, J |
| C_p | Specific heat of water, J/kgK | Q_p | Energy losses /day, J |
| e | Isolation thickness, m | T | Temperature, $^{\circ}C$ |
| F | Total exchange factor | T_a | Average ambient temperature, $^{\circ}C$ |
| G | Cumulative daily incident solar energy per unit area, J/ m^2 | T_{CM} | Storage temperature at the end of the warming up period, $^{\circ}C$ |
| H_i | Cumulative daily incident solar energy on aperture area, J | T_f | Cold water inlet temperature, $^{\circ}C$ |
| h_{ext} | Heat transfer coefficient by convection, W/ m^2K | T_s | Storage temperature, $^{\circ}C$ |
| h_{rv} | Heat transfer coefficient by radiation, W/ m^2K | U_t | Heat loss coefficient of the system, W/K |

| | | | |
|--------------------|--|----------------------|--|
| M | Mass of water, kg | U_{tarr} | Bottom heat transfer coefficient, W/K |
| N | Mean number of reflexions | V | Volume of water draw-off, m ³ |
| Q_s | Mean daily useful thermal energy, J | ω | Wind speed, m/s |
| Greek | | | |
| α | Absorptance of the absorber (storage tank) | Φ_{rint} | Heat transfer by radiation from the absorber and the reflector to the glass cover, W |
| γ | Intercepting factor | Φ_{arr} | Heat losses by conduction and convection at the back of the collector, W |
| Δt | Warm up period (12 hours), s | Φ_{couv} | Heat losses by convection between the glass cover and the ambient media, W |
| ε | Emissance | Subscripts | |
| η_0 | Average optical efficiency | a , c , | Ambient, Sky |
| η | Daily thermal efficiency | exp | Measured |
| ρ | Density of water | f | Cold |
| ρ_{re} | Reflectance of the reflector | j | Used in the numerical model for daily performance |
| α | Stefan-Boltzmann constant, W/m ² K ⁴ | r , re | Radiation, Reflector |
| τ | transmittance of the glass cover | s , v | Storage, Glass cover |

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