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Numerical simulations of meteorological data and parameters adopted for dynamic operation of a solar water heater

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***Abstract*— In this paper, the most specific problems related to solar radiation and its conversion are treated. A numerical study of the dynamic operation of a solar water heater is performed. We focused on the choice of the weather data in a given location with taking an interest in the theory. A MATLAB program was designed to model the system's operation.**

For this purpose, our approach consists in establishing the energy balance on each element of a solar water heater in dynamic operation. Then, we identify the weak points of the system and then looking for the parameters involved for a better design of the system adopted. Based on the different graphs, a good design of a solar water heater in a given location is made and this is done by selecting all critical parameters resulting in the highest efficiency or even when its variation is negligible so that the use of this parameter can save for the overall system.

We gave a theoretical analysis that can lead to tangible results by following a computer work and essentially by developing a numerical code able to calculate the solar radiation in a given location based on the values found for calculating efficiency, the storage power and other adopted parameters.

To improve the dynamic operation of the system as well as the economic aspect, the influence of different parameters on the efficiency of the overall system such as: the critical surface, the ratio of the mass of water to the surface of panel, the choice of flow of coolant, the coil length in the heat storage tank and the choice of coolant is investigated.

***Index Terms*— solar thermal panel, solar water heater, solar energy**

List

Ta	Ambient temperature	U	Conductance of sensor [W/m^{2}K]
T_{int}	Temperature around the balloon	M	Water mass into the balloon [kg]
T_u	Usable temperature	Gn	Global lighting[W]
T_0	Networks temperature	L	Usage rate [kg/s]
T_f	Temperature at the input of the panel	A	Area of panel
Te	Temperature at the output of the balloon	Rt	Thermal resistance of the tube [k/W]
T_i	Temperature at the input of panel	Rb	Thermal resistance of the coil [k/W]
T_s	Temperature at the output of the balloon	Qb	Power stored in the balloon [W]
T_b	Temperature of the storage tank	Qu	Useful power recovered by the balloon [W]
F'	Correction coefficient	Qp	Total lost power [W]
Fr	absorber	Qc	Consumed power [W]
	Conductance factor		
F	Efficiency of fin	α_0	Coef. absorption of the absorber
$(UA)_b$	Conductance coefficient of the balloon [W/K]	τ_0	coefficient of transmission of the glazing

I. INTRODUCTION

Solar energy has been used for a long time to produce heat. Although the expertise in this sector is considerable, nowadays an important renewal on the theoretical and experimental levels is known with the current technological development. Also, many studies have been conducted on the solar sensors by Sefeir et al [1] and Bernard [2].

For a long time, the specialists of solar thermal energy are interested by the modeling because it allows the performance of the facilities prediction. The numerical studies are fast, relatively cheap and can, in some circumstances, replace the experimental studies which are long and expensive. The majority of simulation softwares were developed to achieve the productivity of a solar water heater.

The main objective of this work is to develop a numerical code able to calculate the solar radiation at a given location. By using the values found, we can also calculate the efficiency, the storage power and other settings adopted for the best choice of elements of the system.

II. SIMULATION OF A SOLAR HOT WATER

The modeled system consists of a glazed flat-plate panel supplying heat to a storage tank (Figure 1).

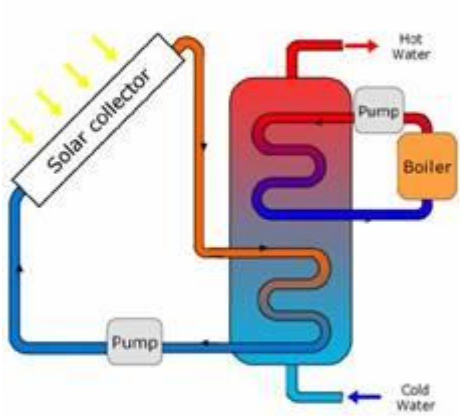

Figure 1 : Scheme of a system for producing hot water

Model adopted for the solar collector

In this study, we used a glazed flat plate sensor (Figure 2) and an absorber finned tubes (Figure 3). The absorber has a length

L_a, a width l_a, a thickness e, the outer diameter of the tube is D_e and "w" is the distance separating two successive tubes.

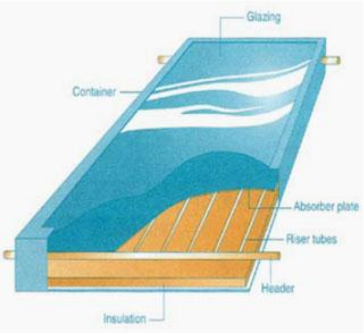

Figure 2 : Glazed flat panel

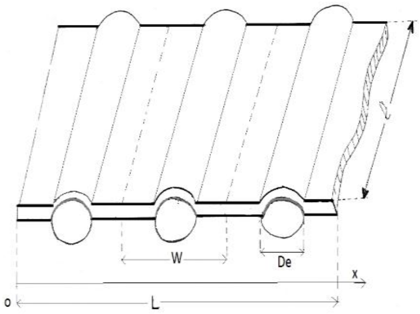

Figure 3 : Absorber finned tubes

III. HEAT BALANCE SYSTEM

A. At the sensor level

The Useful power Qu collected by the panels is given by the equations of HOTEL-WHILLER and BLISS [3].

$$\left.\begin{aligned} Qu &= A.\ Fr.\left[\tau\,\alpha_0.G_n - U\left(Ti - Ta\right)\right] \\ Qu &= m^{\bullet}.Cp.\left(Tf - Ti\right) \end{aligned}\right\} \quad [1]$$

$$Avec: Fr = \frac{GmCp}{U}\left[1-\exp\left(-\frac{U.F'}{Gm.Cp}\right)\right];$$

$$F' = \frac{\frac{1}{U}}{W\left[\frac{1}{U\left[(w-De).F+De\right]}+l.Raf\right]};$$

$$F = \left[\frac{th\left[m\left(\frac{W-De}{2}\right)\right]}{m\left(\frac{w-De}{2}\right)}\right] \quad ; \quad m = \sqrt{\frac{U}{\lambda t.e}}$$

B. At the pipe level

- At the level of a portion of length L_1 between the output of the sensor and the input of the balloon:

We isolate a portion of tube length dx and we establish the balance of the fluid. Between the times t and $t+dt$, after integration, we obtain:

$$\left(Te - T\,\mathrm{int}\right) = \left(Tf - T\,\mathrm{int}\right)\exp\left(-\frac{L1}{Rt.m^{\bullet}.Cp}\right)$$

As we can see, there are some losses corresponding to the fluid flow and its contact with the walls of the pipe.

- At the level of a portion of length L_2 between the output of the balloon and the input of panel:

$$\left(Ti - T\,\mathrm{int}\right) = \left(Ts - T\,\mathrm{int}\right)\exp\left(-\frac{L2}{Rt.m^{\bullet}.Cp}\right)$$

- At the level of length coil L_b in the balloon:

$$\left(Ts - Tb\right) = \left(Te - Tb\right)\exp\left(-\frac{Lb}{Rb.m^{\bullet}.Cp}\right)$$

- At the level of the storage balloon:

In such a system, the water in the storage tank will be generally laminated and the hot water is located in the upper part.

Therefore, the heat balance becomes: $Qu = Qb + Qp + Qc$

$$Q_b = \frac{M.C_p dT_b}{dt} = A.Fr.R\left[\tau\,\alpha_0.Gn - U\left(T_b - T_a\right)\right] - Q_p - Q_c \quad [2]$$

The amount $\frac{M.Cp.dTb}{dt}$ represents the power transferred to the continuous fluid into the balloon. R with the control function such as $R = 1$ when

$T_f > T_i$; $R = 0$ when $T_f \le T_i$

The lost power is expressed by:

$$Q_p = (U.A)_b\left(T_b - T_{\mathrm{int}}\right)$$

The consumed power is expressed by:

$$Qc = L.C_p\left(T_b - T_0\right)$$

IV. S0LVING EQUATIONS

In fact, the parameters Ti, Ti, Te, Tb, Ts, Fr, α, Gn, Ta et Tint depend on the time. In our study, F_r and α are assumed constant, although these two parameters depend on several parameters including: the nature of the glazing, the nature of the absorbing plate, the speed of wind and the external temperature. The value of Fr was taken equal to 0.8 and that of $\alpha = 0.46$.

To solve equations [2] which governing the dynamic operation of our system, the method of EULER is used. This method is characterized by the use of finite differences to give us sufficient accuracy. The integration of these equations is usually done with the time step on the order of the hour. Therefore:

$$T_b(i+1) = T_b(i) + \frac{\Delta t}{M.C_p}\left(\begin{aligned} &A.Fr.R\left[\tau\,\alpha_0\,Gn(i+1) - U\left(T_b(i) - T_a\right)\right] \\ &-L(i+1).C_p\left(T_b(i) - T_0\right) - (U.A)_b\left(T_b(i) - T_{\mathrm{int}}(i+1)\right) \end{aligned}\right) \quad [3]$$

With:

The index "i" specifies the variable's value at time $i.\Delta t$. We note from this equation that to find the temperature of the balloon at a given time, the conditions of weather at the considered instant and the temperature of the balloon at the moment $i\Delta t$ must be known, and other system temperatures are simultaneously calculated as follows:

$$T_s(i+1)=T_b(i+1)+\left(T_e(i)-T_b(i+1)\right)\exp\left(-\frac{L_b}{R_b.m^{\bullet}.C_p}\right) \quad [4]$$

$$T_i(i+1)=T_{\text{int}}(i+1)+\left(T_s(i)-T_{\text{int}}(i+1)\right)\exp\left(-\frac{L_2}{R_t.m^{\bullet}.C_p}\right) \quad [5]$$

$$T_f(i+1)=T_i(i+1)+\frac{A.Fr.\left[\tau\alpha_a Gn(i+1)-U\left(T_i(i+1)-T_a\right)\right]}{m^{\bullet}.Cp} \quad [6]$$

$$T_e(i+1)=T_{\text{int}}(i+1)+\left(T_f(i)-T_{\text{int}}(i+1)\right)\exp\left(-\frac{L_1}{R_t.m^{\bullet}.C_p}\right) \quad [7]$$

V. THE GLOBAL SOLAR FLUX

Any study or application of solar energy at a given site requires a complete knowledge and most detailed possible of the sunshine in site. This can be accomplished by the presence of a meteorological measuring station operating regularly for several years. In case of the absence of station, certain approximate methods for predicting characteristics of solar radiation are used.

In our work a program in MATLAB to calculate the global solar radiation (direct, diffuse and reflected) is established Depending on weather conditions and pollution (climate, altitude, ...) at any point on the Earth at every instant; the latitude of the place, date (day of the year) and time in the day and at the angle of the wall exposure to the sun at the time concerned.

The numerical code developed in MATLAB will be able to calculate the parameters involved using the values of solar radiation found in earlier calculations at a given location, for the best design of a solar heater namely influence of some parameters on the dynamic operation of the system by choosing the best settings according to the critical values of the efficiency of installation.

VI. DATA

A data file was selected from the database of our numerical code. The data come from daily weather measurements provides an annual file in hourly time.

This file is relative to a given location: it consists of the following information:

- The number of the day in each month when calculations are done.
- The calculation step.
- The Latitude of middle.
- The orientation of the sensor relative to the south.
- The solar flow.
- The coefficient of albedo.
- The proportion of insolation for 12 months.
- The dimensions of the panel (length, width).
- The thickness of the absorber.
- The diameter of the tubes in the panel.
- The coefficients of transmission, of absorption of the glazing.
- The heat capacity of the heating fluid.
- The dimensions of the storage balloon (radius, height).
- The power of the pump.
- The conductance between the balloon and the exterior of the absorber.
- The resistance of the tubes between the base of the fin and the tube due to the solid fluid contact.
- The length of the exchanger in the balloon and lengths of tubes between the balloon and the panel.
- The flow rate of the heating fluid in the panel.
- The flow rate of usage water.
- The temperature surrounding the storage, the ambient temperature and the temperature of network.

VII. RESULTS AND DISCUSSION

A. *Influence of the orientation of the panel*

Generally, the orientation of the sensor must be in a position which provides a perpendicular direction of the incident solar irradiance *'Gn'* on the panel plane. To determine the influence of the orientation of the panel, we varied the factor of this orientation "β", while other parameters are stabilized. For each β, we seek the efficiency of the installation η. In figure (4), we showed the efficiency of the installation η for different values of the angle of inclination of the panel.

In our case, we considered that the case of Beirut of Latitude 34,4°. This figure shows a maximum critical value for an efficiency orientation β ≈ 42°. According to the general rule, the optimum orientation of the panel is equal to the latitude of ± 10°. Generally, in Beirut an optimum orientation of 42 °is considered.

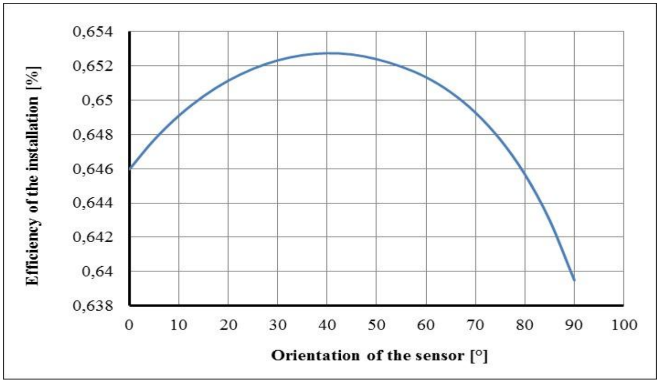

Figure 4: Evolution of efficiency for following the orientation of the panel.

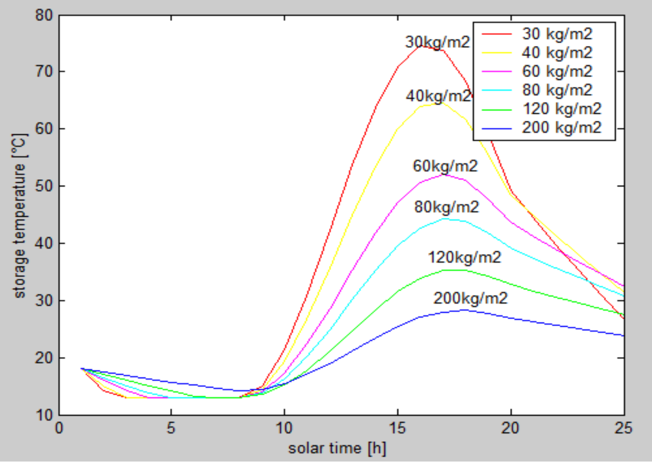

Figure 5 : Evolution of the storage temperature

B. . Influence of the ratio of the water mass of the balloon to the surface of panel (M/A) on the temperature of storage Tb

A good choice of the ratio of the water mass of the balloon to the surface of panel (M/A) has a beneficial interest in improving the temperature of storage tank.

In Figure (5), we show the evolution of the temperature of the storage during one day of the year for different values of the ratio [M/A]. We note that, from midnight, the temperature decreases due to heat loss through convection between the panel and the entourage then it increases with the sunrise and then it decreases after sunset.

For the same surface of the panel, when the mass of water in the storage tank increases the same amount of heat must be transferred to a larger mass, therefore the storage temperature decreases. Thus it is beneficial to consider a larger collector surface for a better storage temperature.

C. Influence of water mass ratio of the balloon on the panel surface

The choice of a sensor's surface depends highly on the mass of water in the heat storage tank. The evolution of the efficiency of installation η in function of ratio of water mass on the sensor surface is given in the figures (6 and 7). This evolution shows that for a given surface, when the mass of water increases, the sensor operates with a colder liquid thus it has a better efficiency till a critical value. Beyond this critical value, the efficiency improves only very few. In our case, the critical value $(M/A)_{\text{Critical}} = 170\ \text{kg} / \text{m}^2$. Using this critical value, for each panel's surface, the volume of the critical balloon can be obtained.

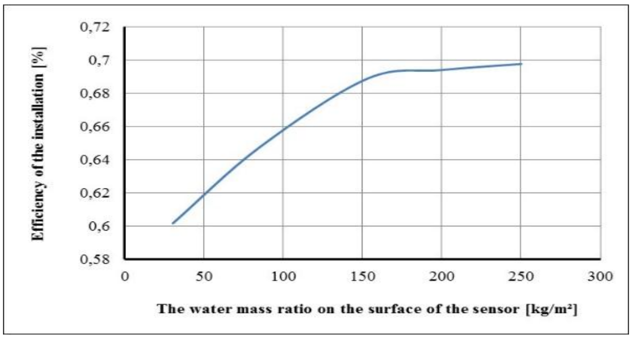

Figure 6 : Evolution of efficiency in function of M/A (A = 10m²)

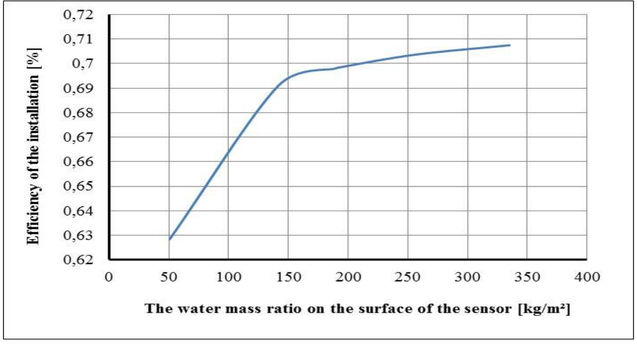

Figure 7: Evolution of efficiency in function of

M/A (A = 6m²)

D. Influence of the mass flow of heat transfer fluid in the panel

To determine this influence, the flow of heat transfer fluid in the sensor has been varied, while the other parameters are kept constant and then the efficiency of the installation η is calculated. In Figure (8), the evolution of the efficiency of the installation in function of the coolant fluid flow is shown. For a given diameter, the amount of heat absorbed by the fluid increases with thus the efficiency increases.

This evolution shows that the efficiency increases slightly for the values of flow less than 0,18 l/s then increases rapidly to a value 0,34 l/s and then increases slightly with the flow. Therefore, it is preferable to consider a flow rate of 0, 34 l/s.

E. Influence of the heat capacity of the coolant

As well to know the influence of the heat capacity of the coolant, this factor has been varied and then the efficiency of installation η is calculated. The figure (9) shows the evolution of efficiency of the installation for different values of the heat capacity of coolant. The amount of heat absorbed by the fluid increases with the heat capacity, therefore the efficiency increases .In addition, we notice that the water has the highest heat capacity (4180J / kg. ° C). This fluid is used despite the effects of corrosion and scaling which raises sustainable system operation problems. To solve the problems of corrosion effects, softeners or magnetic filters are used.

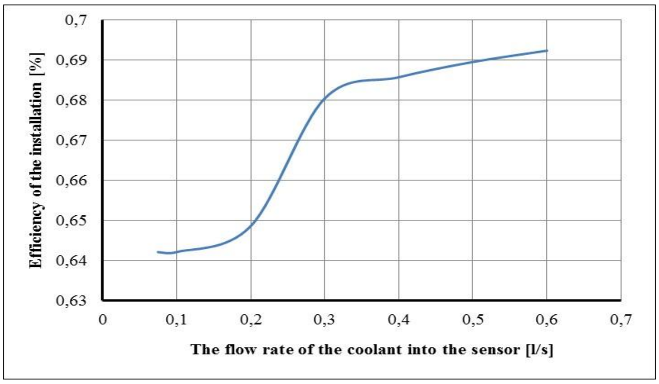

Figure 8: Evolution of the efficiency of the installation according of mass flow rate of coolant fluid.

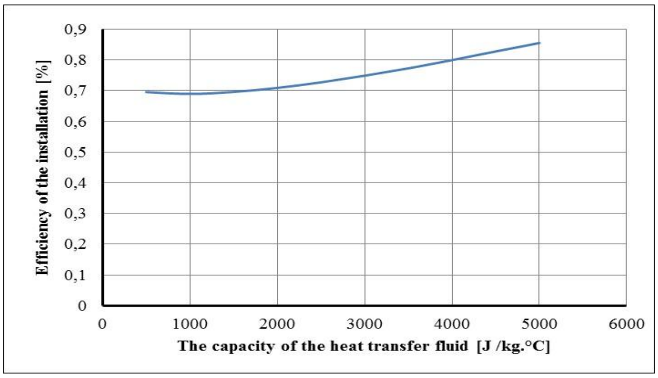

Figure 9: Evolution of the efficiency of the installation according to the heat capacity.

F. Influence of length of the heat exchanger in the storage balloon

The heat exchange between the primary and the secondary circuits takes place through the heat exchanger in the storage tank. The improvement of the heat exchange is linked directly with the contact area, therefore the coil length L_b should be precise to have a better efficiency of the installation. Obviously, this length depends on the volume of heat storage tank.

As well to know the influence of the length of the exchanger in the storage tank, we fixed a volume for the balloon and we vary L_b. The evolution of the efficiency of the installation in function to the latter brings us to a critical value of this length depending on the storage balloon volume. In the following, we give the coil length into the storage tank and the efficiency of the installation corresponding to five different values for the storage tank volume, which are: 150, 200, 250, 300, 350 liters Figures (10, 11, 12, 13, and 14).

The length of the exchanger in the storage tank increases as the energy transferred by the fluid to water is high, therefore the efficiency improves up until it reaches a critical value above which it becomes constant. In summarizing the five cases, a relationship can be concluded between the volume of the storage tank and the coil length:

$V[m^3]$	150	200	250	300	350
$L_b[m]$	30	34	36	40	42

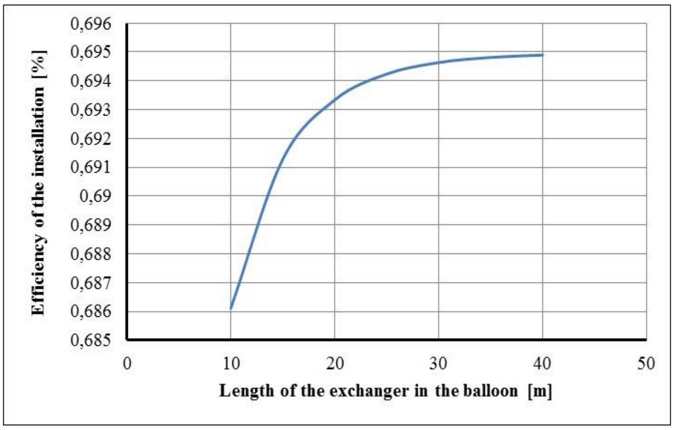

Figure 10: V= 150 liters

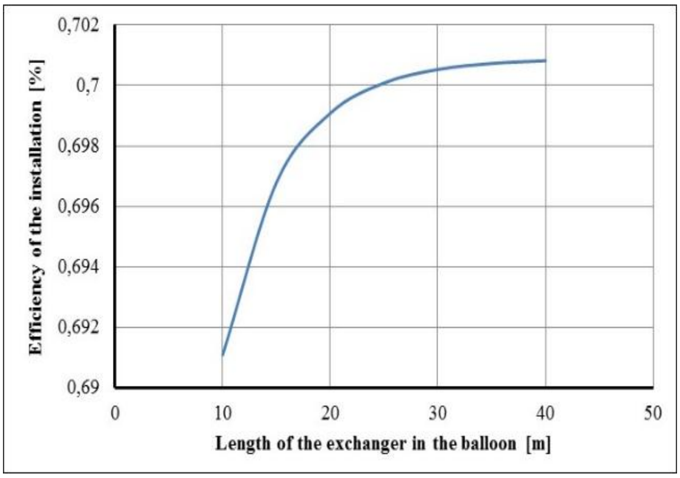

Figure 11: V=200 liters

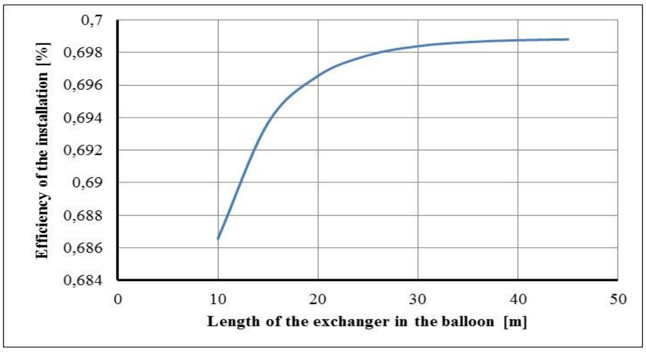

Figure 12: V= 250 liters

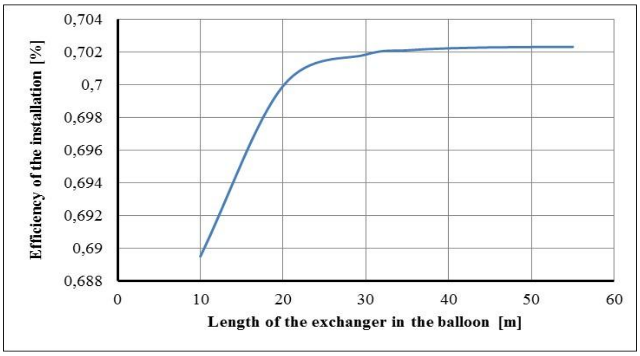

Figure 13: V=300 liters

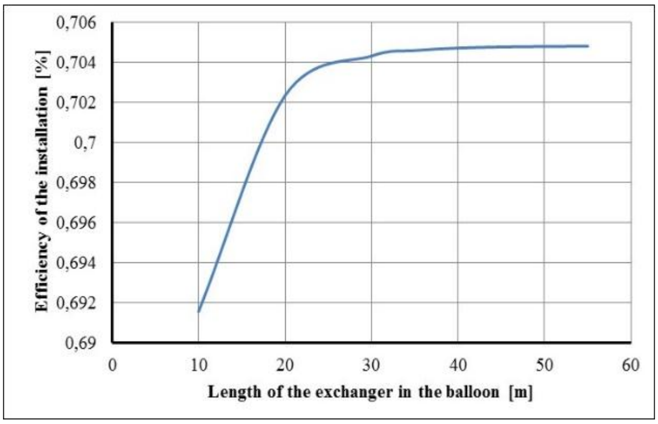

Figure 14: V=350 liters

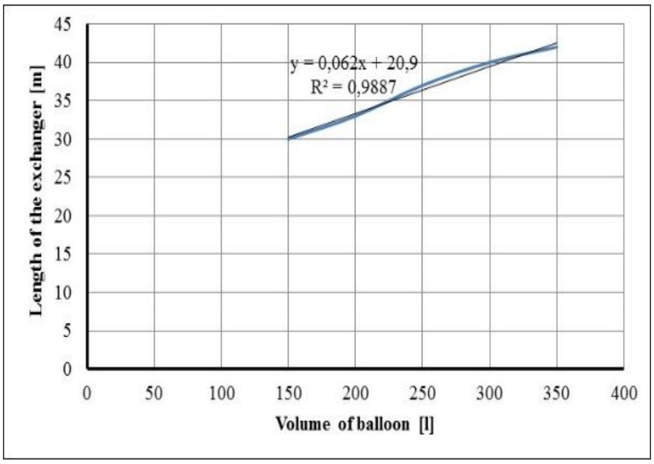

Figure 15: Variation of the length of the exchanger according to the volume of the balloon

Figure (15), shows the evolution of the length of the exchanger for different values of the volume of storage tank. Then from this figure, we can see an affine relation between the volume of the storage tank and the length of the exchanger by the following correlation:

$$\boxed{L_b \approx 0{,}06\ V + 21{,}4}$$

With L_b in [m] and V in [m^3]

G. *Critical panel surface*

The increasing of the sensor's surface has a beneficial interest on the amount of heat absorbed, but this increase is accompanied with an increase in thermal losses with the environment. Thus the search for a critical surface is essential to improve the dynamic operation of the system as well as the economic aspect. To determine the critical surface of the panel, in the figure (16), the evolution of the efficiency of the installation depending on the panel surface is showed. It is clear that this efficiency increases greatly with the panel surface to a critical value. Beyond this critical value the efficiency decreases slightly, the decrease is due to the increased heat loss by convection between the sensor and the entourage. From this figure, we conclude that the critical surface is 10 m^2. This critical value was found by Zelzouli et al [4].

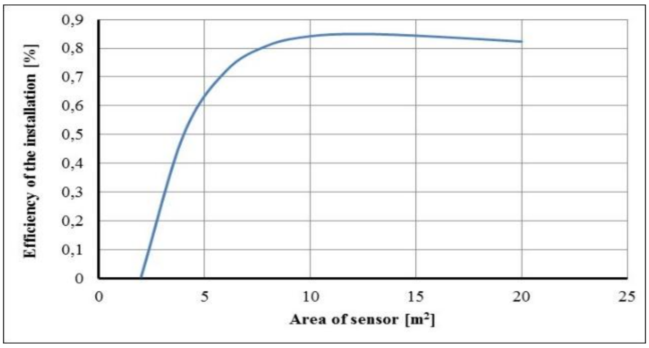

Figure 16: Evolution of the efficiency of the installation depending on the panel surface.

H. *Energy requirements during the year*

We notice that the energy needed for heating and domestic hot water and during the first four months of the year and for the last two months, are high because the temperature and the solar flow are low during these periods, while during the intermediate month requirements are lower as shown in figure (17). Thus it is advantageous to use the extra energy to cover the lack of sunlight during the cold period.

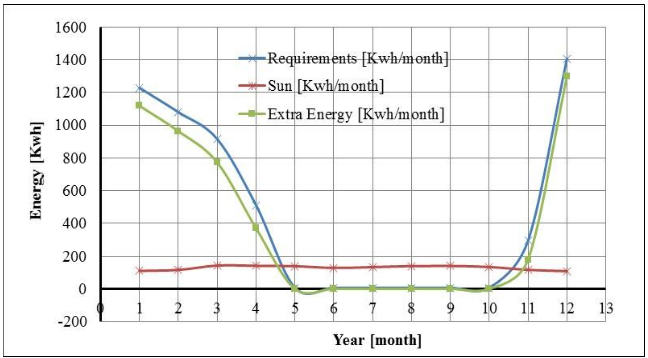

Figure 17: Evolution of energy requirements.(V=250 m^3)

VIII. CONCLUSION

In this study, the most specific problems related to solar radiation and its conversion are treated. Our work enabled us, from different graphs to make a good design of a solar heater in a given location and this by selecting all critical parameters resulting in the highest efficiency or even when its variation is very little that the use of this parameter can save.

We gave a theoretical analysis that can lead to tangible results following a work done on computer and essentially developed a numerical code able to calculate solar radiation in a given location, using the values found for calculating efficiency , storage power and other adopted parameters.

To improve the dynamic operation of the system as well as the economic aspect, we investigated the influence of parameters on the efficiency of system. These results can be useful for designers of solar systems.

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