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Long-term influence of external parameters on the storage of a solar water heater with thermosyphon

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Abstract

It is difficult to characterize the performance of a solar system in a simple manner; given the number of parameters that influence it. Some are related to the system itself (surface of sensors, storage volume and hydraulic system, etc...) and others are related to the setting up site (e.g., the outer temperature and the irradiation on the sensor) which are treated as random variables. A transient regime modeling allowed writing in a matrix form, the transfer matrix containing the data of all the components of a solar water heater with a thermosyphon and also an excitation vector which is given as a function of the above mentioned random variables. These variables are modeled using a database measured on a continuous way over a time interval of three years; treated and adjusted. The validation of this first work which the storage temperature is achieved due to experimental set up especially dedicated to this purpose. The temperature is significantly affected due to the change of climatic and radiometric parameters and it is around 70 ° C.

Keywords: *storage of a solar water heater, thermosyphon*

1. INTRODUCTION

The evaluation of long time performance of solar thermal conversion systems is commonly done by computer or Computer aided control. When compared with traditional deterministic methods, the stochastic modeling techniques are applied due to their enormous advantages. In particular, it allows reducing calculation time and its potential in simulation and evaluation of non-stationary behaviors which are related to weather conditions. These latter are fluctuating dramatically and therefore it is practical to use average monthly data in assessing solar conversion systems.

In the present paper the solar water heater is experimentally investigated whereby the effect of outdoor conditions on their performance has been analyzed. In the first part of the paper, a modeling of the solar system that comprises a thermosiphon flat plat collector, a storage system and piping system that links collector with storage has been described. Then, we have modeled the outdoor conditions as ambient temperature and solar radiation.

The first one is simulated using conditions using a stochastic method[1-5]and the second the Brichambautmodel [6]. The results of the mathematical model have been introduced on the developed model to to predict estimated the storage temperatures

2. MODELING OF THE SOLAR SYSTEM

The solar water heater in figure1,under study is composed essentially:

- A solar plane whose characteristics are given in Table 1.
- A cylindrical storage tank with a capacity equal to 190l,Insulated by a polyurethane layer thickness of 0.02m. [7]

Table 1: Characteristics of solar collector

Dimensions	1205 x 1950 x 105 (mm)
Casing	Aluminum
Thickness	0,35 mm
Radiator	Copper Number of tubes = 10 D = ½’’ x 0,48 L = 1800 mm
Absorber	Aluminum Surface 2, 07 m^2 Selective black
Isolation Bottom Sides	Glass wool 50 mm 20 mm
Glazing	Thickness4 mm Transmissivity = 0,83

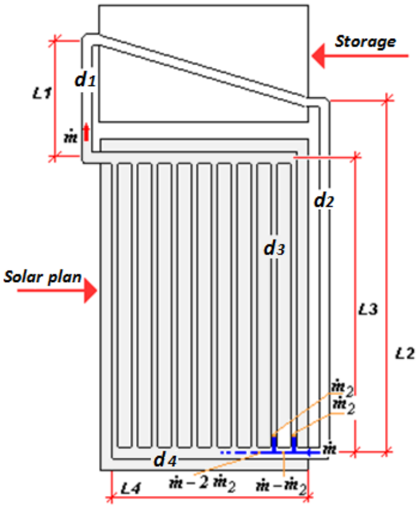

Figure 1: Schematic view of solar water heater

2.1 Collector modeling

The energy balance of a volume unit of a flat plat collector can be formulated by the following:

$$dQ_u = dQ_{ab} - dQ_p \qquad (1)$$

Where

dQ_U is useful thermal power, dQ_{ab} is absorbed thermal power and dQ_p is Thermal power lost.

The losses is function of the overall losses coefficient, which is given by :

$$U_g = \left[\frac{1}{h_w + h_{ry,v-a}} + \frac{1}{h_{cv,pl-v} + h_{ry,pl-v}}\right]^{-1} + \frac{k_{is-ar}}{e_{is-ar}} + \frac{k_{is-lt}}{e_{is-lt}}\frac{P_c e_c}{A_c} \qquad (2)$$

The convection heat transfer coefficient between the collector absorber and the glass cover can be given by:

$$h_{cv,pl-v} = Nu\frac{k_{air}}{e_{pl-v}} \qquad (3)$$

This coefficient can be estimated by the relation of Hollands et al. [8], function of the collectorslope.He air conductivity depends of the ambient temperature and can be expressed by the following equation [9]:

$$K_{air} = 0.02415 + 0.00008\,T \qquad (4)$$

We applied the energy balance of the tube wing to determine the heat transfer to the external wall of the tube per unit of area, figure2:

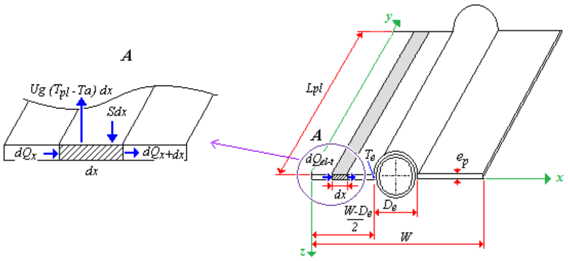

Figure 2: Heat balance on an absorber element

$$dQ_{el-t} + dQ_x - dQ_{x+dx} = 0 \qquad (5)$$

Replaces the various flows per length unit, the conditions at the end and the base of the absorber after calculation is required, the transmitted from the absorber to the external wall of of the tube power is expressed by:

$$dQ_u = F(W - D_e) + D_e\left[S - U_g(T_e - T_a)\right]dy \qquad (6)$$

An energy balance on a tube element, figure 3

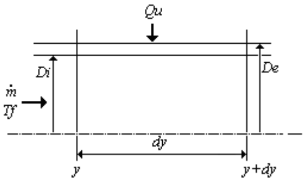

Figure 3: energy balanceon atube element

gives:

$$dQ_u = \frac{T_e - T_f}{\frac{De - D_i}{\pi D_i k_{pl}} + \frac{1}{\pi D_i h_f}} dy \qquad (7)$$

After treatment the calorific power will be:

$$dQ_u = WF'\left[S - U_g\left(T_f - T_a\right)\right]dy \qquad (8)$$

An energy balance of a fluid element, figure 4

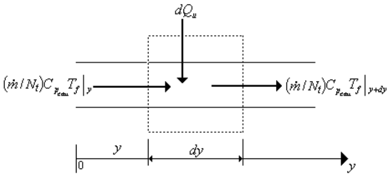

Figure 4: energy balance of a fluid element

After integration expression recover flow is:

$$\dot{m}Cp_{eau}\frac{dT_f}{dy}dy - N_t W F'\left[S - U_g\left(T_f - T_a\right)\right]dy = 0 \quad (9)$$

withT_i and T_0 the boundary conditions of inlet and outlet temperatures of the collector, after arrangement

In this contexte the total useful energy is given by:

$$Q_u = \frac{\dot{m}Cp_{eau}}{U_g}\left[S - U_g(T_i - T_a)\right]\left[1 - \exp\left(\frac{-A_c F' U_g}{\dot{m}Cp_{eau}}\right)\right](10)$$

2.2 *Modeling of the piping system*

The piping of solar systems is one of the major energy losses. The thermal energy losses to the ambient can be expressed by the following factor.

$$U_t = \left[\frac{1}{h_{cv,e-t}} + \frac{\frac{d_1}{2}log\frac{d_2}{d_1}}{k_{is}} + \frac{1}{h_{cv,t-a}}\right]^{-1} \quad (11)$$

With$T_1 = \frac{2\dot{m}Cp_{eau}T_o - U_1 A_1(T_o - 2T_a)}{U_1 A_1 + 2\dot{m}Cp_{eau}}$(collector-storage) (12) and$T_i = \frac{2\dot{m}Cp_{eau} - U_2 A_2(T_2 - 2T_a)}{U_2 A_2 + 2\dot{m}Cp_{eau}}$(storage - collector) (13)

2.3 *Modeling of the storage system:*

The following equation is determined from the energy balance of the storage system. [10]:

$$(MCp_{eau})_{st}\frac{dT_{st}}{dt} = Q_u{}' - Q_{p-cu} - ST \quad (14)$$

Where, the overall heat transfer coefficient is given by:

$$Q_{p-cu} = \frac{\pi d_{cu-is}}{2}\left(2L_{cu}U_{cu} + d_{cu-is}U_{pl,cu}\right)(T_{st} - T_a)(15)$$

3. MODELING OF THE SOLAR SYSTEM IN THE CASE TRANSIENT CONDITIONS:

The solar energy collected by the flat plat collector during a unit of time dt is:

$$dQ_u = A_c F_R\left[S - U_g(T_i - T_a)\right]dt = \dot{m}Cp_{eau}(T_o - T_i)dt \quad (16)$$

With $(T_o)_{i+1} = (T_i)_i + \frac{A_c F_R}{\dot{m}Cp_{eau}}\left[S_i - U_g((T_i)_i - (T_a)_i)\right]$ (17)

The energy balance between the piping collectors, collector-inlet heat exchanger can be expressed as follow:

$$\dot{m}Cp_{eau}(T_o - T_1)dt = A_1 U_1\left[\frac{T_o + T_1}{2} - T_a\right]dt \quad (18)$$

With$(T_1)_{i+1} = \frac{2\dot{m}Cp_{eau}(T_o)_i - U_1A_1(T_o)_i + 2(T_a)_i}{U_1A_1 + 2\dot{m}Cp_{eau}}$ (19)

The energy balance of the storage system allows formulating the equation bellow:

$$(MCp_{eau})_{st}dT_{st} + (UA)_{st}(T_{st} - T_a)_{dt} = \dot{m}Cp_{eau}(T_2 - T_1)dt \qquad (20)$$

The outlet temperature of the exchanger is:

$$(T_2)_{i+1} = (T_1)_i - \varepsilon(T_1 - T_{st}) \qquad (21)$$

If we introduce the above expression in the equations (21) and (14) respectively, we will have:

$$(T_{st})_{i+1} = \frac{\varepsilon\dot{m}Cp_{eau}}{(MCp_{eau})_{st}}((T_{st})_i - (T_1)_i)\Delta t - \frac{(UA)_{st}}{(MCp_{eau})_{st}}((T_{st})_i - (T_a)_i)\Delta t \qquad (22)$$

$$(T_i)_{i+1} = \frac{2\dot{m}Cp_{eau}(T_2)_i - U_2A_2((T_2)_i + 2(T_a)_i)}{U_2A_2 + 2\dot{m}Cp_{eau}} \qquad (23)$$

It is more practical to summing up the equations in matrix form.

$$T_{i+1} = A.T_i + B_i \qquad (24)$$

with

$$A = \begin{bmatrix} 0 & 0 & 0 & 0 & 1 - \dfrac{U_gA_cF_R}{\dot{m}Cp_{eau}} \\ \dfrac{2\dot{m}Cp_{eau} - U_1A_1}{2\dot{m}Cp_{eau} + U_1A_1} & 0 & 0 & 0 & 0 \\ 0 & -\dfrac{\varepsilon\dot{m}Cp_{eau}}{(MCp_{eau})_{st}}\Delta t & 0 & 0 & \dfrac{\varepsilon\dot{m}Cp_{eau} - (UA)_{st}}{(MCp_{eau})_{st}}\Delta t \\ 0 & 0 & 0 & \dfrac{2\dot{m}Cp_{eau} - U_2A_2}{2\dot{m}Cp_{eau} + U_2A_2} & 0 \end{bmatrix}$$

And $B = \begin{bmatrix} \frac{A_cF_RU_g}{\dot{m}Cp_{eau}}\left(S + U_gT_a\right) \\ \frac{2T_a}{U_1A_1 + 2\dot{m}Cp_{eau}} \\ \frac{(UA)_{st}}{(MCp_{eau})_{st}}T_a\Delta t \\ \frac{-2U_2A_2T_a}{U_2A_2 + 2\dot{m}Cp_{eau}} \end{bmatrix}$ (25)

$A$is the transfer matrix and B is the excitation vector that is a function of ambient conditions. This latter can be estimated using the probabilistic techniques or empirical methods. In this study, we have selected a new model based on experiments to estimate the excitation vector.

3.1 Modeling of ambient conditions random variables:

Solar radiation: a recorded data of four year (2003-2006) have been used to modeling the solar radiation. The record step has been five minutes to increase accuracy. The Brichambaut model [6] has selected for modeling the solar radiation as function of solar elevation angle:

$$I_g = f(h) = Z[sin(h)]^n \qquad (26)$$

The difference between theoretical values and experimental one can be given by.

$$(E_c)_i = \left(I_g\right)_i - Z\left[\left(sin(h)\right)_i\right]^n \qquad (27)$$

The quality of adjustment is expressed by the standard deviation [9]:

$$\sigma' = \sqrt{\frac{1}{n-1}\sum_{i-1}^{n}((E_c)_i)^2} \qquad (28)$$

We have analyzed the experimental data executively. This allows obtaining a model for solar radiation fluctuation. The cloud points for each month have been adjusted in order to find out the correlation type of experimental data. In figure 5, it is represented the cloud points of experiments and the adjustment of solar radiation for one month.

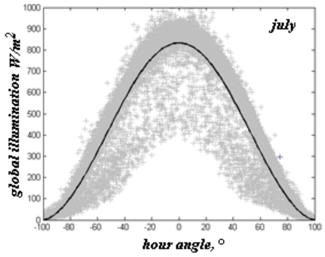

Figure 5: the average daily variation of solar irradiance with the data collected

The parameters *n*, *Z* and *Rc* (the non-linear correlation coefficient) are calculated for the days type of each month. In table 2 bellow, the parameters are represented.

Table 2: the value of coefficientsn, ZandR_c

Month	***N° of the day***	***Z***	***n***	***R_c***	***Measurements period***
Jan	17	1106.60	1.07	0.70	2005-2007
Feb	47	999.04	1.22	0.68	2005-2007
Mar	75	953.68	1.30	0.76	2005-2006
Apr	105	823.58	1.60	0.87	2005-2006
May	135	964.47	1.72	0.94	2003-2006
Jun	162	964.46	1.72	0.94	2003-2006
Jul	198	854.89	1.85	0.97	2003-2006
Aug	228	1013.80	1.43	0.86	2003-2006
Sep	258	876.11	1.66	0.82	2005-2006
Oct	288	1265.90	1.44	0.88	2004-2006
Nov	318	1242.80	1.23	0.76	2004-2006
Dec	344	1248.10	1.29	0.69	2004-2006

Ambient temperature: the ambient temperatures have been measured using metrological equipment at Bouzareah (**latitude 36°8’, longitude 3°12’ and altitude 345m**). The data have been recorded during five years (2003-2007) with a step time equal to 30 minutes.

Figure 6 is obtained considering a day schedule in which the data are divided into two different parts and modeled using two functions. The inflection point corresponds to average temperature

- A cosinus function for the time between 6a.m and 6 p.m it is given by:

$T_a(t) = a(cos p_1 t + p_2)$ (29)

The cœfficients,p_1 and p_2 and a are calculated using the non-linear least squares method.

The results of the first function are listed in table 3.

Table 3: the values of the coefficients p_1, $p_2$and a for each month as a function of cosines function

Month	***a***	***P_1***	***P_2***
Jan	1.7042	0.421	-3.166
Feb	1.2978	0.399	-2.701
Mar	1.79	0.381	-2.662
Apr	1.4357	0.383	-2.471
May	1.1451	0.379	-2.470
Jun	2.0457	0.375	-2.702
Jul	1.9139	0.382	-2.678
Aug	1.9523	0.379	-2.497
Sep	1.587	0.393	-2.587
Oct	1.3298	0.450	-2.692
Nov	1.2387	0.423	-2.639
Dec	1.0377	0.434	-2.805

- The second party is adjusted by the exponential function for the time period between 6 p.m and 6 a.m :

$$T(t) = C\left(1 - exp\left(-\left(\frac{t_o - t(i)}{b}\right)\right)\right) \qquad (30)$$

Appling the Method of non-linear least squares, we have found the average monthly values of the coefficient *b*. the value of these latter are listed in the table 4 below.

Table 4: the values of coefficient *b* for each month

	b		***b***	
January	6.7224		July	1.0001
February	1.8245		August	3.2958
March	5.0933		September	4.073
April	5.4234		October	5.9553
May	3.8759		November	5.0012
June	4.4594		December	3.8215

In the figure below, it is represented the experimental data (red color) and the predicted ambient temperature using the developed model in the present study.

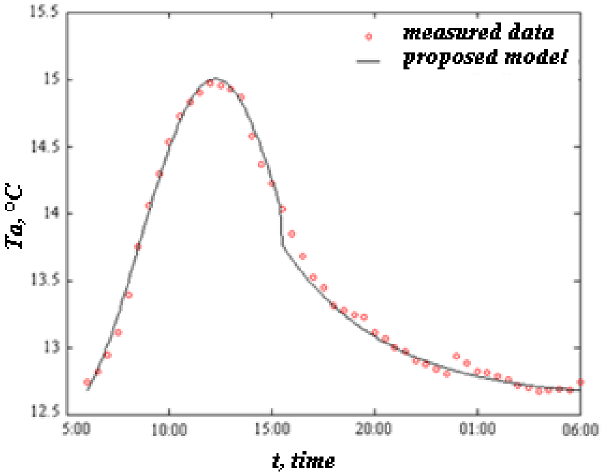

Figure 6 : Modeling of ambient temperature

It has been observed that the developed model is very accurate. moreover the curves in figure 5 can be adjusted by the Weibull law [11], but after a modification using the following equation :

$$T(t) = \overline{T}_{min} + \left(\frac{t}{P_3}\right)^{P_5} exp\left(-\frac{t}{P_3}\right)^{P_4} c \qquad (31)$$

Also, the constants$P_3, P_4, P_5$and $c$are a function of the hour of the day.

The ajustment results have been illustrated in table 5.

Table 5: modeling parameters of ambient temperature.

Month	c	P_3	P_4	P_5	$\overline{T}_{min}$
January	1.91	3.38	1.25	3.03	11.06
February	5.12	9.01	3.67	1.27	9.76
March	8.97	6.19	1.73	1.90	13.02
April	7.07	7.90	1.96	1.13	12.44
May	4.92	9.15	2.61	0.94	14.04
June	7.34	10.86	2.67	0.91	18.76
July	6.45	10.69	5.59	0.74	25.08
August	8.22	9.36	2.71	0.96	25.32
September	7.59	8.29	2.30	1.19	18.56
October	4.50	2.90	1.15	2.36	16.33
November	5.59	4.41	1.44	2.13	12.67
December	5.51	6.36	1.95	1.80	12.99

We have used a mathematical program developed in MATLAB of displaying the storage temperatures. It has been observed that our model is very accurate when compared with experiments, figure 7.

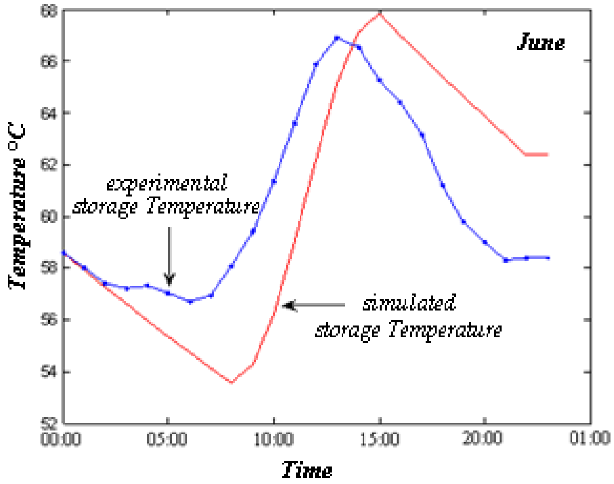

Figure 7 : Simulation and experimental storage temperature during June

4. Conclusion

We have analyzed the effect of ambient conditions on the performance of solar water heater. Therefore, we have developed a model for predicting the storage temperature for comparison to experiments, and we found good agreement. It has been observed that storage system strongly affected by ambient conditions, which include solar radiation and ambient temperature. For the collective solar water heater, a study is in progress to assess it long time performance.

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Nomenclature

A :area
Cp : specific heat
D, d : diameter
E_c : Difference between the values of the theoretical
F' : efficacy of the absorber
F_R : conductance factor of the absorber
h : Convective heat transfer coefficient
h_w : Convective heat transfer coefficient of the wind
I_g : global solar radiation incident
k : thermal conductivity
L : length
M : mass of the water in the storage tank
$\dot{m}$: mass flow
n, Z, p_1 and p_2 : Cœfficients
Nu : Nusselt Number
P : perimeter
P_3, P_4, P_5 and c :constant
Q : thermal power
Ra : number of Rayleigh
S : Solar illumination transmitted through the glazing and absorbed by the collector
ST : Energy extracted, per unit time
T: temperature
t : time
U : Loss coefficient
β : angle of inclination
σ' : standard deviation
ε : exchanger efficiency

Indices

1,2 : exchanger inlet and outlet
a: ambient
air: air
ar : rear
cu :tank
lt : lateral
pl : plate
ry : radiation
st: storage
t : tube
v : glazing
e :thickness
eau: water
is : insulation
cv : convection
c : collecton