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An Experimental Study of an Evacuated Tube Solar Collector Using the Response Surface Methodology (RSM)

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ABSTRACT

The purpose of this study is to investigate experimentally the performance of a solar hot water system with evacuated tube solar collector to obtain optimum process parameters by user-specified design. In these study parameters as solar radiation and fluid flow are optimized with the consideration of responses as outlet fluid temperature and bottom water temperature using the Response Surface Methodology (RSM). As a result, the optimal independent variables in the determined intervals are as follows: solar radiation is 850 w/m2 and fluid flow is 1, 36641 l/min; under these favorable conditions, the outlet fluid temperature can reach a maximum value of 75.9954 ° C whereas the bottom water temperature in the storage tank may attain a maximum value of 65.1443 ° C. It was found from the experimental design and ANOVA using the STATGRAPHICS Centurion (VERSION 18) program, that the solar radiation is the major parameter that influences of a solar hot water system performance.

1. INTRODUCTION

A solar water heating system is the conversion of sunlight into heat for water heating using a solar thermal collector such as flat plate systems, evacuated tube systems and thermosyphon systems. These systems are widely used in residential sector and some industrial applications.

In this study, we are interested in a heat pipe evacuated tube collector (HP-ETC) made up of a heat U-pipe inside a vacuum tube. The vacuum envelope reduces convection and conduction losses, so the collectors can operate at higher temperatures than flat plate collectors or thermosyphon collectors. The product IMEXSol 200L is intended for the production of domestic hot water using solar energy by heating a heat transfer fluid in a closed circuit. Vacuum tubes absorb solar radiation to turn it into heat. The heat is transported by a heat transfer fluid through the U-pipe in the vacuum tubes to a 200-liter storage tank through a coil finally to transfer heat collected by the solar collector to water inside the storage tank.

Hayek et al. [1] The authors investigated and compared the overall performance of two types of solar collectors (water in glass collector and heat pipe evacuated tube collector) under Eastern Mediterranean climatic conditions. They concluded that the heat pipe evacuated tube collector performs better than water in glass collector. In another work, Ayompe and Duffy [2] presented an analysis of a solar water heater system with a 3 m^2 heat pipe evacuated tube collector using data from a field trial in Dublin, Ireland.

Azimi et al. [3] studied the performance of evacuated tube solar collector in different climatic conditions in Iran using TRNSYS 16 software; they also improved instantaneous sensor yield using genetic algorithm in MATLAB software.

Laurence et al. [4] evaluated the performance of an evacuated tube solar hot water system installed on a domestic house of 5 persons in Dublin, they found that the system produced 1216 kW h of useful heating energy with a system efficiency of 62.8%.

Kabeel et al. [5] designed a modified coaxial heat pipes to improve the thermal performance of evacuated tube solar collector, the results show that the thermal efficiency can reach a maximum value of 67% at a mass flow rate of 0.009 kg/s.

Elsheniti et al. [6] presented the thermal performance of a heat-pipe evacuated-tube solar collector at a high inlet temperature by predicting the thermal efficiency as a function of operating parameters such as fluid flow, inlet temperature and number of evacuated tubes.

Evaluation of the overall performance of solar collectors is usually carried out experimentally using proven procedures according to international standards [7-10] and many correlations have been developed for the purpose of predicting the overall efficiency under various climatic conditions.

The response surface methodology (RSM) is a widely used mathematical and statistical method for modeling and analyzing a process in which the response of interest is affected by various variables [11] and the objective of this method is to optimize the response [12]. The parameters that affect the process are called dependent variables, while the responses are called dependent variables [13].

The RSM method was used in many fields such as optimizing the performance of thermal efficiency of the evacuated tube solar collector [14], optimizing parabolic mirror position in a solar cooker [15,16], optimizing extraction of plant materials [17], Optimization of hydrogen production [18] and the parameters of solar Drying [19, 20].

Our literature review shows that no one has used the response surface methodology in the domain of solar domestic hot water system, especially when combining the operating parameters to optimize the system. Accordingly, the present study focused on modeling the effect of the solar radiation and fluid flow (as independent variables) on the outlet fluid temperature and bottom water temperature in the vertical storage tank (as dependent variables) in a process of domestic hot water. The modeling was based on the Response Surfaces Methodology. The experiments were designed according to the user-specified design plan with two factors, each at five different levels.

2. MATERIALS AND METHODS

2.1 Experimental of a Solar Hot Water System

An experimental set-up was designed and installed on the workshop rooftop in the Applied Research Unit in Renewable Energies in Ghardaia region- Algeria. Figure 1 shows all the kit components of the product IMEXSol200L with a solar collector made up of 12 evacuated tubes and a vertical storage tank. The experimental set-up is a closed loop circuit with the required components and measurement tools as sketched in figure 1.

A vacuum solar collector consists of a series of 12 transparent glass tubes, the length of the tubes is 1.73 m and their diameter is 4 cm. In each tube there is an absorber for capturing solar radiation and a U-pipe type heat exchanger to allow the transfer of thermal energy. Vacuum sensors can reach high temperatures (150° C). The vacuum created inside the tubes makes it possible to reduce significantly the losses during rise in temperature.

The solar collector consists of 12 U-pipe collectors filled with a heat transfer liquid, which transports the calories captured by the solar collector to the hot water storage tank; this transport is carried out via a forced pipe (the solar pump). The solar collector is oriented towards the South and inclined by 32 °.

The regulator of RESOL type is an electronic device that controls the flow of heat transfer fluid through a solar pump that circulates the fluid within the closed circuit between the solar collector and the tank. The role of this control system is the adjustment and the control of the solar station (R_1) and electric auxiliary station (R_2). In this work, the operation of R_2 was cancelled.

The storage tank is equipped with several automatic control and protection means such as a thermostatic control, protection for high and medium temperatures and pressure protection (P / T valve and check valve), equipped with a supplementary electric heating element (auxiliary heater R_2) for safety. The storage tank transmits the calories provided by the heat transfer liquid to the water (through the exchanger located at the bottom of the tank).

The ImexSol 200L system consists of four probes: thermistors S_1 and S4which measure the temperature of the heat transfer liquid at the inlet and outlet of the solar collector respectively; S_2 and S3which measure the water temperature in the lower and upper level of the tank respectively.

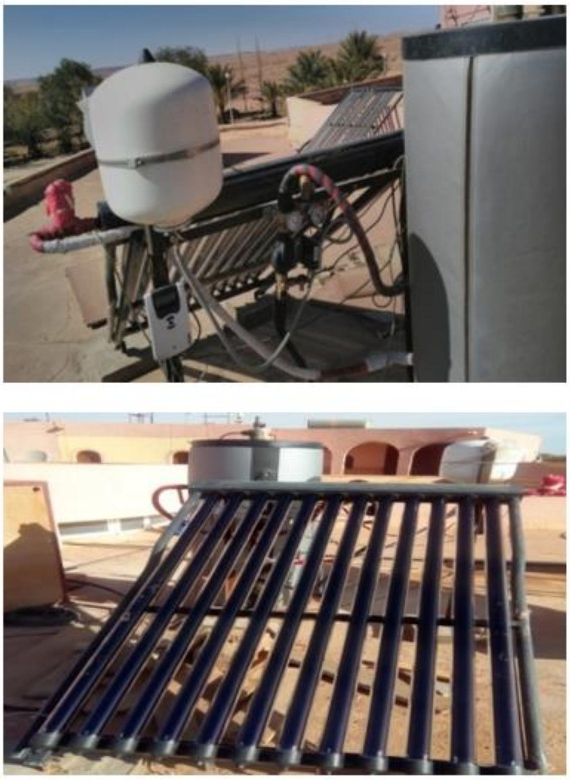


Figure 1. The product IMEXSol 200L installed in Ghardaïa region

The regulator calculates the temperature difference between thermistors S_1 and S_2, if this difference is greater than+1°C,the solar pump (R_1) is switched on; by contrast, the solar pump is switched off when the outlet fluid temperature is higher than the bottom water temperature by the predefined deactivation value of 0.5°C (DTF).

2.2 Method adapted for statistical analysis

The response surface methodology (RSM) has been proven to be a powerful tool for determining the effects of each factor and the interactions among them, thereby allowing for effective process optimization [21]. The response surface procedures involve experimental strategy, mathematical methods, and statistical inference, which, when combined, enable users to make an efficient empirical exploration of the system in which they are interested [22].

RSM can be applied to any system that has the following key elements: (1) a criterion of effectiveness, measurable on a continuous scale (extraction time), and (2) quantifiable independent variables (both controllable and uncontrollable) that affect the system’s performance (such as the extraction process, solvent, and drying method). Given these conditions, RSM offers techniques for finding the optimum response of the system in an efficient manner [22]. The major advantage of RSM is that the amount of data needed for evaluation, analysis and optimization significantly reduces the number of experiments required. RSM is a faster and more economical method for collecting research results than the classic one-variable at a time or full-factor experimentation [16].

The STATGRAPHICS Centurion software (VERSION 18) has been used for this purpose. RSM generates the table for the experimental design plan specified by the user. This experimental strategy has been widely used in production /

process development.

To study the effect of the operational parameters of solar water heating system, two operating parameters were favored and selected: solar radiation (between 250 and 850 w / m^2) and heat transfer fluid flow (between 0.6 and 3 l / min). After choosing the operating parameters that are the most influential and because of a large possible range of variation of each parameter, it was convenient to carry out a statistical study to identify, at the least cost of experimentation, the domain of exploitation of the parameters. Thus, during the present study, the surface response method was adopted; it is a user-specified design plan with two factors, each with five different levels.

The experimental design is presented in Table 1. The aim is to obtain samples adapted to the 25-point experimental design given in Table 2. The relationship between the independent variables, solar radiation (x_1), and the flow of the heat transfer fluid (x_2) is expressed mathematically in the form of a polynomial model, which gave the following two responses: the outlet fluid temperature Y_1 and the bottom water temperature Y_2 according to these variables. A second-order polynomial equation is presented in the following general form:

$$Y_k = a_0 + \sum_{i=1}^{2} a_i x_i + \sum_{i=1}^{2} a_i x_i^2 + \sum_{i=1}^{2} \sum_{j=1}^{2} a_{ij} x_i x_j \tag{1}$$

Table 1. The levels of the variables utilized in this study for the user-specified design

variables	**Levels of the user-specified design**				
x_1 (w/m^2)	250	400	550	700	850
x_2 (l/min)	0.6	1.2	1.8	2.4	3

Table 2. Conditions and experimental design results based on the plan of the user-specified design at five levels

N	**Factors values**		**Responses values**			
			Y_1 (°C)		**Y_2 (°C)**	
	x_1 *(w/m^2)*	**x_2 *(l/min)***	***Observed values***	***Predicted values***	***Observed values***	***Predicted values***
1	250	0,6	46,5	47,6914	38,8	38,8257
2	400	0,6	57,2	56,2931	46,4	45,4051
3	550	0,6	65,5	63,8777	52,0	51,6503
4	700	0,6	70,8	70,4451	57,8	57,5611
5	850	0,6	75,7	75,9954	62,7	63,1377
6	250	1,2	46,0	46,5766	41,3	42,3217
7	400	1,2	53,9	54,5183	47,1	48,5051
8	550	1,2	60,7	61,4429	52,9	54,3543
9	700	1,2	66,4	67,3503	58,4	59,8691
10	850	1,2	70,9	72,2406	63,5	65,0497
11	250	1,8	46,6	45,4103	44,9	43,3577
12	400	1,8	53,4	52,692	51,5	49,1451
13	550	1,8	59,9	58,9566	57,8	54,5983
14	700	1,8	64,9	64,204	63,3	59,7171
15	850	1,8	69,2	68,4343	67,8	64,5017
16	250	2,4	44,2	44,1926	40,4	41,9337
17	400	2,4	49,0	50,8143	43,8	47,3251
18	550	2,4	56,4	56,4189	49,8	52,3823
19	700	2,4	61,1	61,0063	55,3	57,1051
20	850	2,4	64,8	64,5766	59,2	61,4937
21	250	3	44,3	42,9234	40,0	38,0497
22	400	3	47,6	48,8851	42,7	43,0451
23	550	3	53,5	53,8297	48,5	47,7063
24	700	3	57,7	57,7571	53,0	52,0331
25	850	3	61,0	60,6674	56,2	56,0257

3. RESULTS AND DISCUSSIONS

3.1 Responses surface analysis and interpretation

The experimental data were employed to calculate the coefficients of the quadratic equation. Table 3 summarizes the results concerning the analysis of the variance (ANOVA) for the responses and the coefficients of the mathematical models.

The coefficient of determination R_2 represents the proportion of variation of the response attributed to the model rather than the random error. It has been suggested that a good fit of models should have R_2 not less than 90%. When R_2 is close to unity, the empirical models are adapted to fit the experimental data.

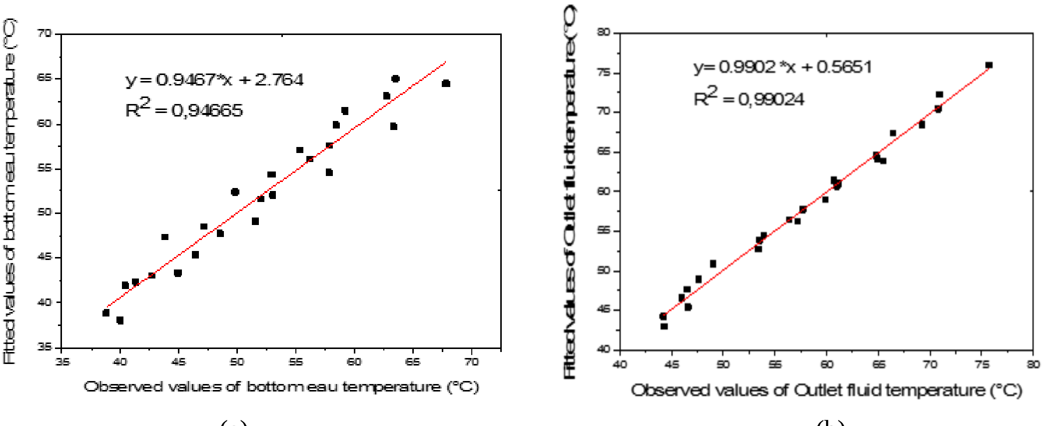
Based on these results, an empirical relationship between system responses and independent variables has been established for domestic hot water and then expressed by second-order polynomial equations as follows:

$$\begin{aligned} Y_1 = 31.06 + 0.08x_1 + 0.1x_2 - 0.071x_1^2 \\ - 0.0073x_1x_2 \end{aligned} \tag{2}$$

$$\begin{aligned} Y_2 = 20.5 + 0.05x_1 + 13.08x_2 - 0.0000074x_1^2 \\ - 3.42x_2^2 - 0.0044x_1x_2 \end{aligned} \tag{3}$$

The response surface analysis (RSA) of the data in Table 3 shows that the relationship between the responses and the independent variables (solar radiation and fluid flow) is quadratic, with a good regression coefficient (99.0237% for (Y_1, R_2) and 94.6654% for (Y_2, R_2). This indicates that there was good agreement between the experimental data and the two predicted responses.

The results show that the models used in this study were able to identify the optimal operating condition of this solar system dedicated to heating sanitary water. Figure 2 describes the correlation between the value of the observed response and that of the predicted response by the mathematical model; it shows a good correlation between the responses of the system obtained experimentally and those predicted by the mathematical models proposed from equations 2 and 3.

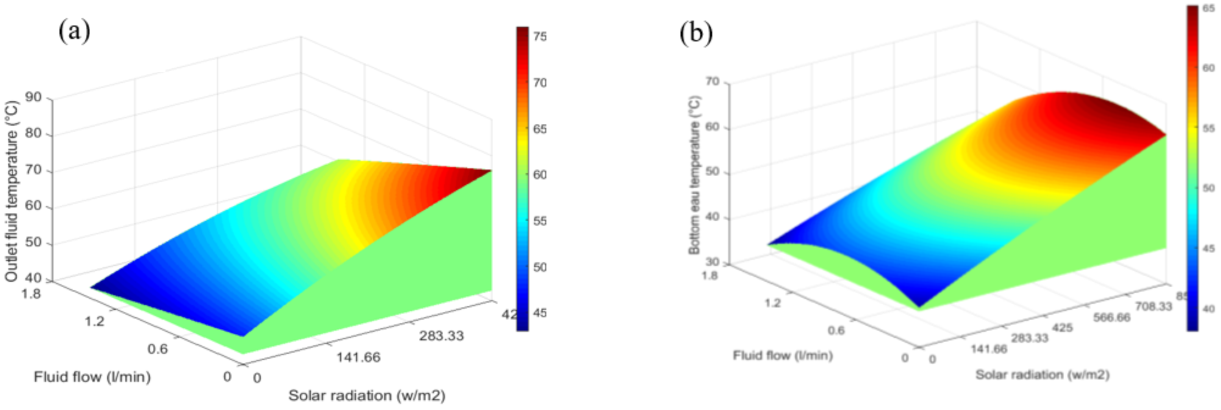


(a) (b)

Figure 2. Linear correlation between calculated and measured system responses

Table 3. Analysis of variance (ANOVA), linear, interaction and quadratic terms for each response variable and the prediction model coefficients

	Source	Coefficients	Sum of Squares	DDL	Mean of squares	F-value	p-Value prob>F
Outlet fluid temperature	x_1	0,0764368	1656,6	1	1656,6	1569,75	0,0000
	x_2	0,10381	315,5	1	315,5	298,97	0,0000
	x_1^2	-0,0000226032	18,105	1	18,105	17,16	0,0006
	x_2^2	-0,0714286	0,0463	1	0,0463	0,04	0,8363
	x_1 x_2	-0,00733333	43,56	1	43,56	41,28	0,0000
	Residual		20,051	19	1,05531	-	-
	R_2(%)	99,0237					
	Adj-R_2(adjusted for d.f.)	98,7668 %					
	the standard deviation of the residue	1,02728					
	Mean Sequare Error	0,737646					
	Durbin-Watson test	1,53068					
	x_1	0,0513314	1397,1	1	1397,1	300,18	0,0000
	x_2	13,0767	48,6	1	48,6	10,44	0,0044
	x_1^2	-0,00000742857	1,9556	1	1,9556	0,42	0,5246
	x_2^2	-3,41667	105,90	1	105,90	22,75	0,0001
	x_1 x_2	-0,0044	15,681	1	15,681	3,37	0,0821
	Residual		88,430	19	4,6542	-	-
	R_2(%)	94,6654					
	Adj-R_2(adjusted for d.f.) (%)	93,2616					
	The standard deviation of the residue	2,15736					
	Mean Sequare Error	1,55589					
	Durbin-Watson test	0,767507					



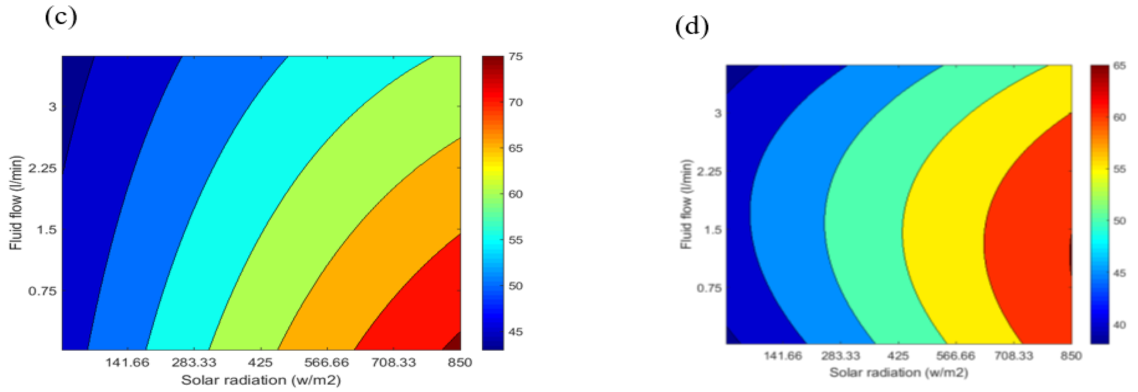


Figure 3. Response surfaces (a, b) and isopleth curves (c,d)

However, it is clear that the experimental results of the responses Y1 and Y2 and the predicted values obtained using equations 2 and 3 are not significantly different (Figure 2).

On the other hand, from equations 2 and 3, we can obtain the 3D response surfaces and the isopleth curves shown in Figures (3) (a-b) and (3) (c-d) respectively. These figures illustrate the effect of solar radiation (x1) and the fluid flow (x2) on the outlet fluid temperature in the solar collector and the bottom water temperature in the storage tank (Y1 and Y2).

We can see from Figure 3 that Y1 is proportional to x1 and inversely proportional to x2. However, Y2 is proportional to x1 and x2 around the mean level. As can be seen in figure 3 (a and c) that for lower or higher x2 values, both responses increase as solar radiation increases.

3.2 Optimization of parameters

According to the above analysis, solar radiation is the most important variable, so that the optimization of solar radiation always corresponds to the maximum value of the interval. Optimization of the variables is given in Table 4. So, it can be seen from this table that the optimal independent variables are as follows: the solar radiation is 850 w / m^2 and the fluid flow is 1.36641 l/min. Under these appropriate conditions, the temperature of the oulet fluid temperature can reach amaximum value of 75.9954 °C while the bottom water temperature in the vertical storage tank can reach the maximum value of 65.1443 °C.

Table 4. The levels of the variables used in this study for user-specified design in the response surface methodology

Levels	Optimal values of independent variables		Responses	
	Solar radiation (w/m^2) x_1	Fluid flow (l/min) x_2	Outlet fluid temperature (°C) Y_1	Bottom water temperature (°C) Y_1
Low	250	0.6	46,5	38,8
High	850	3	61	56,2
Optimum	850	1,36641	75,9954	65,1443

4. CONCLUSION

An experimental set-up was installed under optimal design conditions of the response surface methodology to investigate the influence of the above parameters on domestic solar hot water. From the quadratic models of the response surfaces, it was found that the outlet fluid temperature and the bottom water temperature in the storage tank were significantly affected by solar radiation. The optimized parameters are presented as follows: Solar radiation is 850 w / m^2, and fluid flow is 1.36641 l / min, under these optimal conditions, outlet fluid temperature is 75.9954 °C while the bottom water temperature is 65.1443 ° C.

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NOMENCLATURE

x_1	**Solar radiation (w/m^2)**
x_2	heat transfer fluid (l/min)
Y_1	Outlet fluid temperature (°C)
Y_2	Bottom water temperature (°C)