J. of Soil Sciences and Agricultural Engineering, Mansoura Univ., Vol 11 (8): 363-368, 2020

Journal of Soil Sciences and Agricultural Engineering

Journal homepage: www.jssae.mans.edu.eg
Available online at: www.jssae.journals.ekb.eg

Predicting Hot Water Production Using Parabolic Trough Solar Collector

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ABSTRACT

Recently, the problem of high electricity prices appeared in household uses, especially in water heating then the use of solar collectors was the best proposed solution to this problem. A computer program is written to predict domestic hot water production using a parabolic trough collector. The proposed system consists of a parabolic trough collector, a circulating system, a hot water storage tank, and a heat exchanger. The program was used to test the effect of three major design parameters. These parameters are mass flow rate of working fluid (0.50, 0.75 and 1.00 kg/m), collector aperture area (1.0, 1.5 and 2.0 m^2), and storage tank capacity (50, 75 and 100kg). The study also revealed that the hot water temperature depends on both storage tank capacity and the collector aperture area. It was concluded that a match between the collector aperture area and storage tank capacity must be taken into consideration when designing a solar hot water production system. The proposed system is capable of produce 60-80 °C, which is satisfactory for domestic hot water production with an average efficiency of 51.50% which is considerable higher compared to other solar collectors. It is recommended to be used system under aperture area of 1.00 m^2 and mass flow rate of 0.75 kg/min with 75 kg for storage tank capacity. Finally, a model validation was conducted by comparing the obtained results to those available through literature survey. A good match was found between the study results and published results.

Keywords: Solar energy, Parabolic trough collector, Hot water, System modeling.

INTRODUCTION

Solar energy applications became widespread nowadays. The escalating fossil fuels prices, scarcity, and greenhouse gas emissions are the pressing factors for looking for other reliable energy resources such as solar energy, wind energy, tidal energy, geothermal energy, etc.

Also, the ever-increasing world population and industrialization, are the main factors increasing energy demand worldwide. Solar energy is abundant, clean, and safe. It has numerous applications in the agricultural and industrial fields.

One of the promising solar energy applications is the domestic hot water (DHW) production using different types and configurations of solar collectors. The range of devices used for DHW is very wide. It can be as simple as a water-filled container exposed to direct solar radiation to very sophisticated sun-tracking collector arrays which are capable to elevate a fluid temperature to a few hundred degrees.

Parabolic trough solar collector (PTC) is a kind of concentrating solar collectors that can be used for DHW production. There are many types of PTC that differ in shape, size, tracking mode, and concentration ratio. Also, the receiver (heat collecting element HCE) of the PTC can be bare tube, glazed tube, or double-glazed tube depending on the desired fluid temperature and the intended application. It is estimated that 60 - 70% of DHW could be produced by solar water heaters. Arasu and Sornakumar (2007) stated that parabolic trough collectors are the most mature solar technology used to generate heat at temperatures up to 400 °C for solar thermal electricity generation or process heat applications. They conducted experiments to validate the results they obtained by theoretical analysis. They found a minor difference between the theoretical and the experimental results with respect to the test slope (5.92 %) and a moderate difference is for the test intercept (9.37 %). Rajamohan *et al.* (2016) tested a solar water heating system consists of a parabolic dish concentrator, conical heat absorber, water heater and water as a working fluid. They concluded that the potential and practicality of the solar collector is dominantly influenced by many factors such as; solar collector area, absorber tube arrangements, the solar heat flux, mass flow rate and overall heat loss coefficient. Nada *et al.* (2017) studied the thermal power generation using the parabolic trough collector at Alexandria, Egypt. They concluded that the number of sunny hours in the day ranges from 8 to 10 hours and the absorbed energy ranges from 0.0042 MW/m in winter to 0.005 MW/m in summer. Siqueira *et al.*, (2014) modeled heat transfer for a parabolic trough solar collector. They created a handy software tool that allows variation of parameters of the concentrator to evaluate the thermal performance. The program proved to be very useful as a design tool, being possible to determine the thermal and optical efficiency and thermal losses. Roy *et al.*, 2016 performed a parametric study of parabolic trough collector to examine the effect of working fluid mass flow rate and collector inlet temperature of collector thermal efficiency. They concluded that the effect of the mass flow rate is more significant than the absorber water inlet

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DOI: 10.21608/jssae.2020.114854

temperature as the collector thermal efficiency at the optimum mass flow rate is greater than that at the optimum water inlet temperature. And it happens for lower solar insolation levels around 552 W/m^2.

The key parameters for a PTC hot water system are aperture area, which defines the amount of energy intercepted; the working fluid flow rate, which defines the amount of energy transferred to the storage tank; and the storage tank capacity, which defines the amount of water to be heated. Designing a solar system involves a lot of complicated calculations. Simulation is used to carry out this task due to its capability to handle such complicated calculations. Using a simulation method speeds up the design process with high accuracy and saves effort, time, and material Kishta, (2004).

Arasu and Sornakumar (2006) investigated the performance of a parabolic trough collector hot water generation system with a well-mixed hot water storage tank. They stated that the storage tank water temperature is increased from 35 °C at 9:30 H to 73.84 °C at 16:00 H when no energy is withdrawn from the storage tank. The average beam radiation during the collection period is 699 W/m^2. The useful heat gain, the collector instantaneous efficiency, the energy gained by the storage tank water and the efficiency of the system as a whole are found to follow the variation of incident beam radiation as these parameters are strongly influenced by the incident beam radiation. The parabolic trough collector (PTC), is currently receiving considerable attention. Typical applications of PTC's vary from hot water production (typically 60 °C) to steam generation used for power and industrial process heat applications (up to 350 °C). The trough collector models can be serially connected with flexible ball joints to loops to form a solar field. Each loop can consist of six to eight trough collectors depending on the site conditions and solar field size. Geyer *et al.*, (2002).

Hrushikesh (2016) designed and developed a prototype cylindrical parabolic solar collector having aperture area of 1.89 m2 using low cost highly reflecting and absorbing material to reduce initial cost of project and improve thermal efficiency. He used ASHRAE Standard 93, 1986 to evaluate the thermal performance and it was observed that this system can generate hot water at an average temperature of 50 °C per day with an average efficiency of 49% which is considerable higher than flat plate solar collectors. Hot water produced by this system can be useful for domestic, agricultural, industrial process heat applications.

In recent years, environmental concerns and other geopolitical factors have focused attention on renewable energy resources, improving the prospects for PTC deployment. Further work is needed to improve system efficiencies and active areas of research including advanced heat collecting elements and working fluids, optimization of collector structure and thermal storage. Also, the integration of the system components such as the collector, the tracking mechanism, the circulation system and the storage tank, needs more detailed studies to improve efficiencies by decreasing heat losses throughout the system. The aims of this work are to optimize the system effective parameters such as aperture area, working fluid flow rate, and the capacity of hot water storage tank. The optimized system will be used to predict the hot water productivity year-round using a simulation program.

MATERIALS AND METHODS

Computer modeling of thermal systems presents many advantages. The basic one is that the modeling or simulation can be used to estimate the amount of energy delivered from a solar system. The simulation model can also indicate whether the temperature variations of a particular system design are reasonable i.e. the fluid temperature is not rising above the boiling point. The simulation models can produce information on effects of design variables changes on system performance by using the same weather conditions. The modeling used for this research includes components as shown in Fig. 1. For simplification no differential thermostat control of the pump is used (i.e. the pump is considered to work continuously). With the PTC simulation program, the yearly behavior will be investigated. The principle of program operation is that it uses the same routines as in the thermal analysis program presented by Kishta (2007). The program runs through the values of the solar radiation and ambient air temperature for Zagazig city (30.5765° N, 31.5041° E).

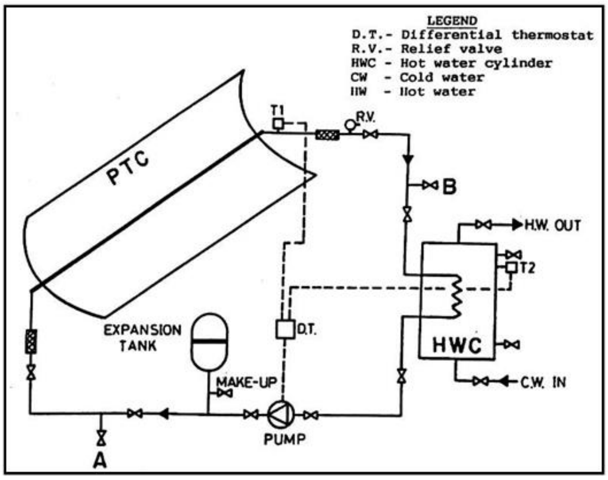

Fig. 1. System Configuration

In the program no use of stored hot water is assumed i.e. all the possible energy gain is stored in the cylinder. The values of solar beam radiation on horizontal surface in the data set used in the simulation were not used directly in the calculations. The mode of tracking assumed for this configuration is the polar mode i.e. the aperture opening is at angle of 35^0 from the horizontal following the sun. Therefore, a conversion factor is applied on the radiation values in order to obtain the beam radiation falling normal to aperture area. This conversion K, is given by Duffie and Beckman (2013) as:

$$K = cos(\theta)/sin(\alpha)$$

Where: θ is the angle of incidence and α is the solar altitude angle.

In the program only one day of each month is considered. The day of each month used is shown in Table (1). The reason for using that particular day is because the value of extraterrestrial solar radiation is closest to the month's average at that day.

Table 1. Average day of each month

Month	Day	Month	Day	Month	Day	Month	Day
Jan	17	Apr	15	Jul	17	Oct	15
Feb	16	May	15	Aug	16	Nov	14
Mar	16	Jun	11	Sep	15	Dec	10

Another condition of the program is that the initial storage temperature is considered equal to the ambient temperature at the first hour of the day.

Computer Simulation Program

The model in written in FORTRAN language. The basic algorithm of this program is the same as the algorithm of the thermal analysis (Kishta, 2007). The difference is that the collector is now part of a system comprising a storage tank, a heat exchanger and a circulating pump. The input of the program is the same as the thermal analysis program except that the characteristics of the system components are now required. These are storage capacity, kg; heat exchanger area, m^2; and heat exchanger pipe diameter, mm. The program requires a set of input parameters illustrated in Table (2). These values are the optimum values obtained from PTC optical and thermal analysis (Kishta 2004 and Kishta 2007).

The program is written in a modular form. The main program includes the input and data reading section, the calculation and data processing section, and the output section as illustrated in Fig (2).

Table 2. Simulation program input parameters.

Parameter name	Value	Unit	Parameter name	Value	Unit
Aperture area	varies	m^2	Receiver emittance	0.08	--
Aperture width	0.8	m	Glass emittance	0.9	--
Maximum optical efficiency	0.66	--	Glass thickness	1.0	mm
Geometric factor	0.32	--	Storage capacity	varies	kg
Receiver outside diameter	12.0	mm	Mass flow rate	varies	kg/min
Receiver inside diameter	10.8	mm	Air velocity	1.0	m/s
Glass outside diameter	26.0	mm	Heat exchanger area	1.0	m^2
Thermal conduct. of pipe	385	W/mK	Heat exchanger pipe diam.	22	mm
Thermal conduct. of glass	1.05	W/mK			

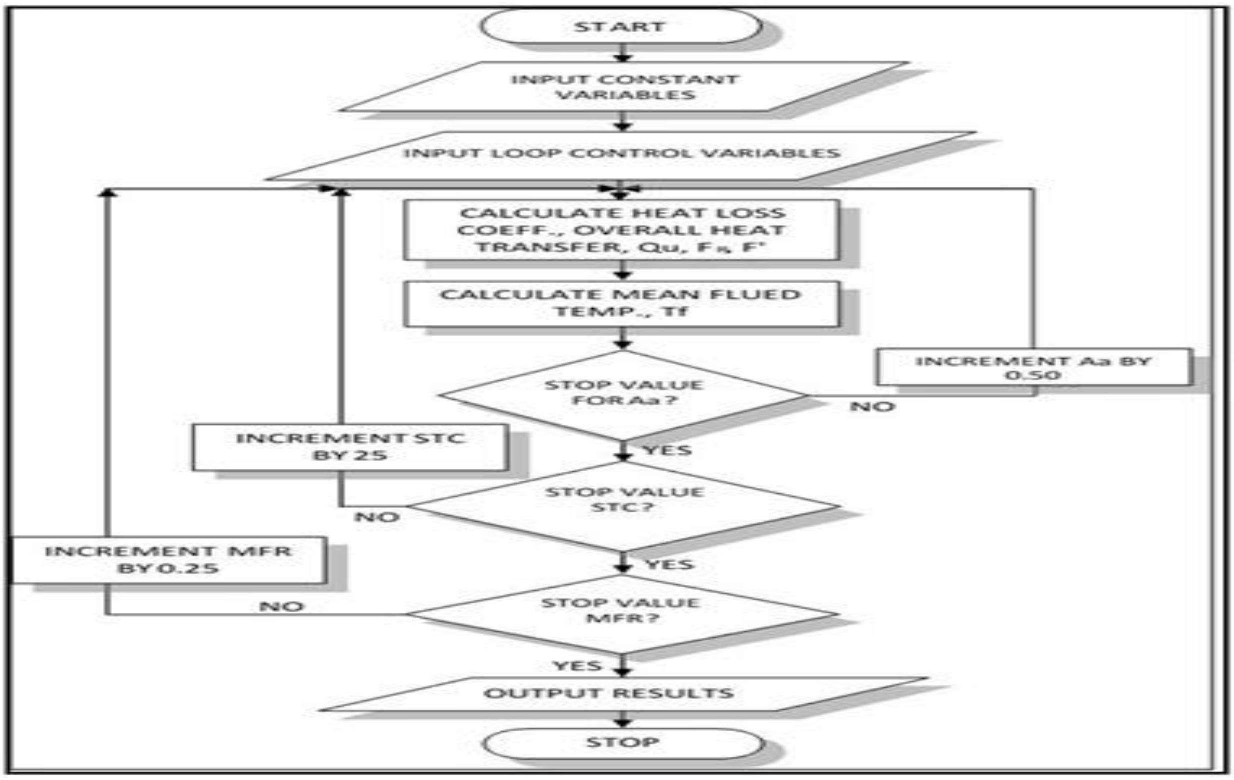

Fig. 2. Flow Chart of the Simulation Program

The calculation and processing section includes three loops to vary the values of key parameters. First loop varies the aperture area, Aa, from 1.0 to 2.0 m^2 in steps of 0.5 each. The second loop deals with variation of storage tank capacity, STC from 50 to 100 kg with 25 step value. The third loop is designed to test the effect of varying working fluid mass flow rate, MFR, from 0.5 to 1.0 kg/min in a step of 0.25. Fig (2) shows the flow chart of the program.

The calculation is performed hourly from 8 am to 4 pm which covers most of the sunshine hours. The values of solar radiation are corrected hourly to compensate the inclination angle of the collector and converted into beam radiation falling on the inclined surface of the collector. The program uses a step of one minute. The output is given every hour during which the weather conditions are considered constant. The relations used in the program for the interaction of the system components are as follows. The heat transfer coefficient between the heat exchanger and the stored water based on the outside area is given by (Duffie and Beckman 2013):

$$U = \left[\frac{D_o}{D_i} \cdot \frac{1}{h_f} + \frac{D_o \cdot \ln(D_o/D_i)}{2 \cdot K} + \frac{1}{h_o}\right]^{-1}$$

Where h_f **= heat transfer coefficient inside the heat exchanger tube** $[W/m^2K]$

K **= tube thermal conductivity** $[W/mK]$

h_o **= heat transfer coefficient outside the heat exchanger tube** $[W/m^2K]$

D_o **and** D_i **= outside and inside heat exchanger tube diameter [m].**

For submerged coils, which the case of the heat exchanger used, the heat transfer coefficient outside the heat exchanger tube is given by (Duffie and Beckman 2013):

$$Nu = (h_o \cdot D_o)/K_f = 0.53\ (Gr \cdot \Pr)^{0.25}$$

Where K_f **= fluid thermal conductivity** $[W/mK]$

Gr **= Grashof number,** Pr **= Prandtl number**

The Grashof number is given by (Duffie and Beckman 2013):

$$Gr = D_o^{\ 3} \cdot \rho^2 \cdot \beta \cdot g \cdot ((T_o + T_i)/2 - T_s)/\mu^2$$

Where ρ **= density of fluid** $[kg/m^3]$

β **= coefficient of thermal expansion [1/K]**

T_o **= collector outlet temperature (storage tank inlet) [K]**

T_i **= collector inlet temperature (storage tank outlet) [K]**

T_s **= storage water temperature [K]**

μ **= fluid viscosity [$Pa \cdot s$]**

Heat transfer coefficient inside the heat exchanger pipe

The heat transfer coefficient inside the heat exchanger pipe is obtained by using the equations presented by Kishta, 2007. The calculation of U-value in the way explained is approximate because the T_s is not the same on the top and bottom of the storage tank and the temperature of the flowing water is not fixed but it is changing from T_o at the inlet of the heat exchanger to T_i at the outlet.

The heat transfer to the storage water is (Duffie and Beckman 2013):

$$q_h = U \cdot A_h\ ((T_i + T_o)/\ 2 - T_s\ )$$

Where A_h **= heat exchanger area [m^2]**

The log mean temperature difference is not used here as in counter and parallel flow heat exchangers because there is no flow of the stored water. This is considered reasonable as the U-value estimated is approximate. During the running of the program, if the value of q_h is greater than q_u, the useful power extracted by the collector, then q_h is equal to q_u.

Now the new storage temperature, T_{sn}, is obtained by:

$$T_{sn} = T_s + (q_h \cdot 60)/(M \cdot C_p)$$

Where M **= mass of stored water [kg]**

The new inlet temperature in the collector is calculated by:

$$T_i = T_o - q_h/(m \cdot C_p)$$

The iteration process in continued until a satisfying T_s in reached. This happens when the difference between two successive estimations is less than one degree. The program runs for a whole year and outputs the calculated results in a tabulated form. A sample output of the program for the average day of January is show in Table (3).

Table 3. Sample output of the program for the average day of June(Aa = 1 m², STC = 75 Kg, and MFR = 0.75 Kg/min)

Time	Col. out Temp. °c	Therm. effic. %	Useful power w	Storage temp. °c	Heat rem. factor
8	42.36	52.21	379.41	35.24	0.99
9	45.89	52.17	390.46	38.57	0.99
10	49.57	52.08	403.90	42.01	0.99
11	52.79	51.99	395.70	45.39	0.99
12	56.00	51.93	389.68	48.71	0.99
13	59.15	51.71	383.72	51.98	0.99
14	61.64	51.48	356.25	55.02	0.99
15	63.93	51.18	328.80	57.82	0.99
16	65.18	50.75	269.40	60.12	0.99

RESULTS AND DISCUSSION

The obtained results were analyzed and plotted to visualize the differences between different scenarios.

1. Effect of Working Fluid Mass Flow Rate

The objective here is to have a high enough mass flow rate to ensure a good heat conduction between the pipe material and the working fluid. For such a case turbulent flow is required. The working fluid mass flow rate was optimized in a previous study Kishta (2007) and found to be 0.75 kg/min was rate was enough to ensure turbulent flow inside the collector receiver tube and heat exchanger tubes. It was concluded that at very high flow rates there is no increase in collector thermal efficiency.

2. Effect of Aperture Area

The collector aperture area loop was set to start at 1 m², stop at 2 m², and step equal to 0.5 m². The mass flow rate (MFR) and storage tank capacity (STC) were kept constant during the loop execution. Figures 3A, 3B, and 3C show the effect of aperture area change on the hot water temperature in the storage tank for the monthly average day of June.

It is clear that increasing aperture area increased the absorbed solar radiation. At smaller storage tank capacities, the water volume is small and heat flux is high, so the water temperature increased. Using aperture area of 1.0 m² and 50-liter storage tank capacity, from Fig. 3A, the maximum storage temperature attained at the end of operating period is about 83°C which is acceptable temperature for domestic hot water.

On the other hand, the other 2 capacities gave storage tank temperatures higher than 100°C which is not suitable for domestic hot water. In Fig. 3C, it is obvious that the 3 collector areas gave storage tank temperature in the 60-80°C which is satisfactory for domestic hot water production. It can be concluded using smaller collector area requires smaller storage tank capacity.

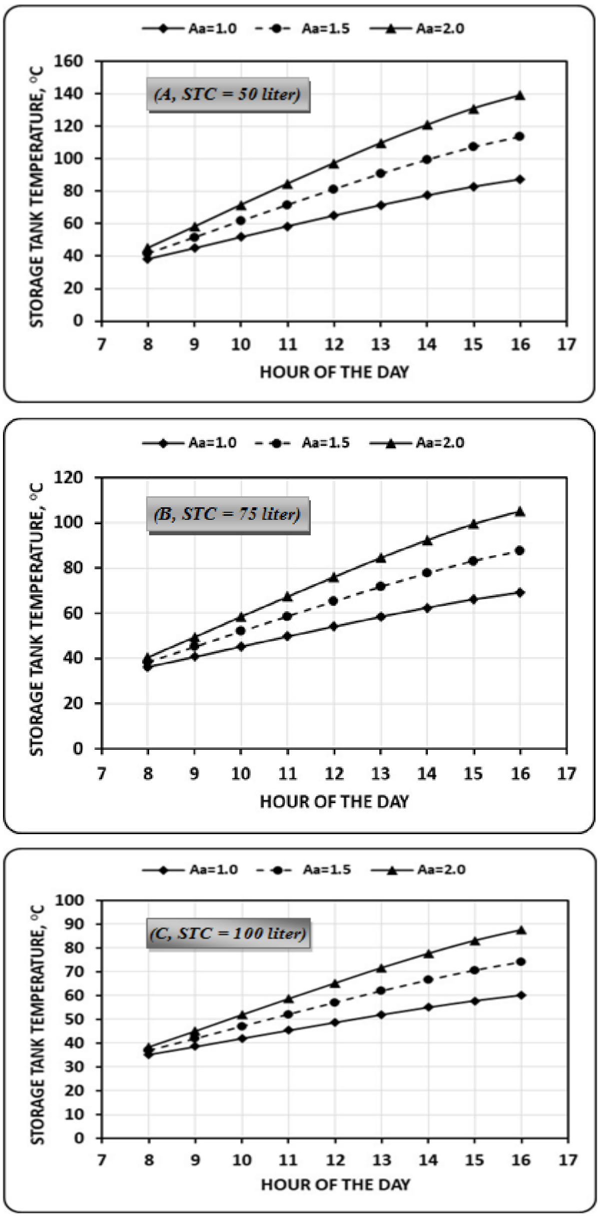

Fig. 3. Effect of hour of the day on storage tank temperature at different aperture areas

3. Effect of Storage Tank Capacity

The program tested the effect of storage tank capacities starting from 50 liter to 100 liter on the hot water temperature. Fig. 4 depicts the relation between storage tank capacity and water temperature at different collector areas.

It can be seen that using storage tank capacity of 100 liter under all collector areas gives hot water temperature in the range of 60 to 80°C which is desired for hot water production. On the other hand, smaller storage tank capacities give hot water temperature above 100°C.

Those relations can be interpreted in another way. If a smaller tank used, the water reaches the desired temperature by noon and we can withdraw water from the tank twice a day. By doing so, the system productivity can be doubled.

Validation of the proposed model

Due to insufficient funding resources and lack of accurate measuring devices, the model validation is done by comparing the obtained results to the available published results through the literature survey. The proposed program uses the same routines as in the thermal analysis program as well as runs through the values of the solar radiation and ambient air temperature. To validate the proposed system, the simulated results were compared with the experimental data of previous studies in this field. Comparisons between the proposed model predictions and experimental results of previous studies are presented in Table 4.

The predicted results of outlet temperature and thermal efficiency are compared with the corresponding test results of previous studies. It can be concluded that the proposed model predicts the outlet temperature with high accuracy. The estimation of thermal efficiency is also in good agreement with previous test results.

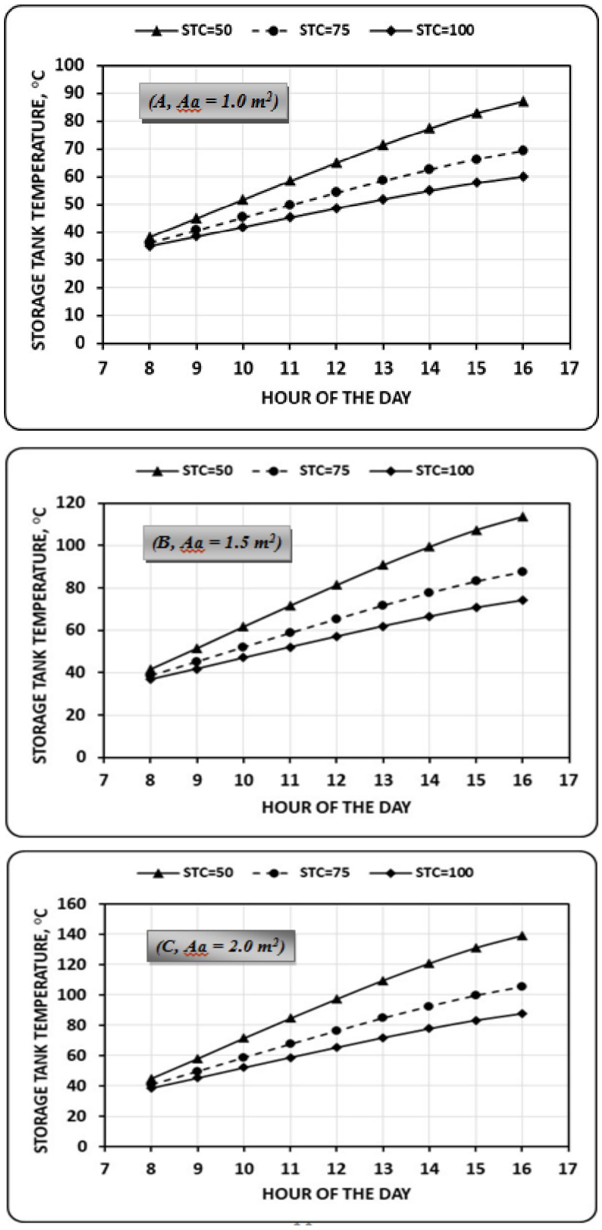

Fig. 4. Effect of hour of the day on storage tank temperature at different storage tank capacity.

Table 4. Comparison of model prediction with experimental results of previous studies.

Tests	Aperture Area, m^2	Process Temperature, °C	Flow rate, kg/min	Efficiency, %
Proposed model predictions	1	60-80	0. 5 – 1.0	50.75- 52.21
Selvakumar *et al*. (2014)	0.72	60	3 – 4.8	65.52
Xiao *et al*. (2014)	0.136	33– 80	0.26- 1.64	54.79
Mosleh *et al*., 2015	1.80	60	0.48 - 1.68	21.70- 65.20
Bouvier *et al*., 2016	46.5	60 – 80	0.5	50
Hrushikesh, 2016	1.89	50	0.07	49
Jaramillo *et al*., 2016	5.19	70 – 110	0.99- 5.95	41-61

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CONCLUSIONS

From the previous discussion, we can draw some generalized recommendations for domestic hot water production using parabolic trough collector. First, a match between collector aperture area and storage tank capacity must be taken into consideration when designing a solar hot water production system. Second, the system can be configured to produce 2 or 3 loads of hot water per day if the relation between storage tank capacity and collector area adjusted correctly.

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التنبؤ بإنتاج الماء الساخن باستخدام مجمعات القطع المكافئ للطاقة الشمسية

عبدالله مصطفى قشطة و أمانى عبدالمحسن متولى

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فى الآونة الاخيرة ظهرت مشكلة ارتفاع اسعار الكهرباء فى الاستخدامات المنزلية خاصةً فى تسخين المياه ومع استهلاك الكهرباء المتزايد .ومن ثم كان استخدام المجمعات الشمسية افضل الحلول المقترحة لهذة المشكلة .تناولت هذه الدراسة كتابة برنامج حاسوبى باستخدام لغة الفورتران للتنبؤ بإنتاج الماء الساخن للأغراض المنزلية باستخدام مجمع الطاقة الشمسية ذو القطع المكافئ. تم استخدام البرنامج لدراسة تأثير ثلاثة عوامل مهمة فى تصميم نظم تسخين المياه بالطاقة الشمسية. وقد تم تقييم النظام الشمسى وفقًا لثلاث مستويات مختلفة لمعدل التدفق الكتلى (0.5-0.7-1 كجم/د)، وثلاث مستويات مختلفة لمساحة المجمع الشمسى (1-1.5-2 م٢) و ثلاث احجام مختلفة لخزان الماء الساخن (50-75-100 كجم). تم كتابة البرنامج بلغة الفورتران واستخدمت خوارزمية التحليل الحرارى لتشغيل البرنامج باستخدام الأرصاد الجوية المتاحة لمدينة الزقازيق (30.58° شمالاً ، 31.50° شرقاً). يتكون النظام المقترح من مجمع شمسى حوضى مكافئ ، نظام تدوير السائل ، خزان ماء ساخن ، ومبادل حراري. تم كتابة البرنامج في شكل وحدات ويحتوي على ثلاث حلقات تكرارية لدراسة تأثير عوامل التصميم الثلاث المذكورة والتفاعل بينها. كشفت الدراسة عن التأثير القوي لمساحة تجميع الطاقة التي تنتقل إلى الماء ومن ثم تخزينها في خزان المياه. أيضاً، تم العثور على علاقة قوية بين سعة خزان التخزين ودرجة حرارة الماء الساخن. كما كشفت الدراسة أن درجة حرارة الماء الساخن تعتمد على التوافق بين سعة خزان الماء الساخن ومساحة المجمع. أوضحت النتائج التي تم الحصول عليها أنه يجب مراعاة المطابقة بين مساحة المجمع وسعة خزان المياه الساخنة تحت معدل التدفق المناسب عند تصميم نظام إنتاج الماء الساخن بالطاقة الشمسية. فقد تم الحصول على درجة حرارة للمياه الساخنة تتراوح من 60-80 درجة مئوية تحت 0.75 كجم/د كمعدل تدفق كلى، ومساحة للمجمع قدرها 1م٢ عند سعة قدرها 75 كجم لخزان الماء الساخن وهو أمر مرضٍ لإنتاج الماء الساخن المنزلي. وختاماً تم مقارنة النتائج المتحصل عليها بالنتائج المنشورة سلفاً حيث وجد توافق بين ما توصلت إليها الدراسة الحالية وبين الدراسات السابقة.