DESIGNING OF PARABOLIC SOLAR WATER HEATER TECHNICAL AND DIMENSIONAL SPECIFICATIONS USING GENETIC ALGORITHM

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Abstract

Calculating technical and dimensional specifications of a solar water heater through a simple model has always been a challenge. Nowadays such designs are being conducted by experiment more than calculations. Developing a capable model in order to simulate the thermal behavior of the collector and storage tank temperature with low computational load during its use in simulation and low error is required here. Recently such a thermal model for parabolic solar water heaters has been developed by adapting the fully mixed model of the storage tanks to consider the influence of storage tank inner box (Zahirnia at el., 2011); however, a process should still be presented to estimate appropriate technical and dimensional specifications of the solar water heater according to the customer needs and manufacturing and environmental conditions. In this paper, this process is presented. The designing idea is the same as the idea of identifying unknown parameters of a grey-box model. The only difference between these two ideas is that in identifying unknown parameters of a model experimental data are required, while in the presented designing method desired behavior of the device is expressed by a target diagram. Here as a simplifying assumption the target diagram is assumed to be a linear one depicted according to the customer needs. This linear target diagram is then modified along with the designing process. Applying an optimization method (genetic algorithm (G.A.) technique is used here), storage tank temperature in the simulated model is converged to the target diagram with minimum possible error. The set of numbers that G.A. has used in the simulated model to gain this minimum error are considered as the desired technical and dimensional specifications of the solar water heater. The results obtained demonstrate the viability of the proposed designing process.

Keywords: Parabolic solar water heater, Technical specifications, Dimensional specifications, Designing method, Genetic Algorithm method.

1. Introduction

In regard to solar water heaters, generally flat plate and evacuated tube collectors consist of a set of relatively more simple components. On the other side, parabolic trough collectors are more sophisticated collectors. This sophistication has led to lack of attention toward this type of solar water heaters. The advantages of the parabolic type have been demonstrated in other studies (Zahirnia, 2011). In this paper a thermal model of parabolic solar water heaters (Zahirnia at el. , 2011) is used to calculate collector dimensions and pump flow rate according to the customer needs. Like other thermal systems the model is a grey-box model which is involved with unknown parameters. After identifying the unknown parameters of the model, this designing method is applicable. Here the unknown parameters used in designing method, have been indentified for a specific manufacturer – K.N.Toosi University of technology, first prototype – (Zahirnia at el., 2011). Further detailed classification of the model parameters is described in section 3. Here pump flow rate and collector dimensions are assumed as designing specifications. To calculate these specifications, an optimization tool is used here. Through different optimization methods Genetic Algorithm (G.A.) method has been selected here due to its advantages over the conventional optimization methods (Fleming and Purshouse, 2002; Gray at el., 1998; Horst et al., 2000; Vazguez at el., 1997). G.A. optimization method adjusts storage tank temperature in the simulated model to the target diagram by changing the designing specifications.

This paper is organized as follows: Section 2 describes the first and the second prototypes of K.N.Toosi University parabolic solar water heaters in detail. Section 3 is dedicated to introducing the designing method. The thermal model and classification of the thermal model parameters is introduced in this section along with the storage tank temperature target diagram and G.A. settings. In this section a formula to modify the target diagram is also presented. This modification makes this designing method an iterative one. In Section 4 the calculated specifications of the parabolic solar water heater are tested by using them in the simulated model and the results are discussed. Conclusions come up at the end of the paper.

2. Parabolic solar water heater description

The first K.N.Toosi University parabolic solar water heaters shown in figure 1, was built in 2009 (Arebi, 2009). In 2011 the second prototype of this parabolic solar water heater shown in figure 2, was manufactured in Taban Industrial Group (Zahirnia, 2011). The second prototype has several advantages over the previous one (Zahirnia, 2011). In the various types of solar water heaters (Zahirnia at el. , 2011), these solar water heaters are split, open ones with parabolic collectors.

Fig. 1: First prototype of K.N.Toosi university parabolic solar water heater (Arebi, 2009)

Fig. 2: Second prototype of K.N.Toosi university parabolic solar water heater (Zahirnia, 2011)

In this paper the designing method has been conducted based on the identified unknown parameters of the first prototype (Zahirnia at el., 2011); thus, detailed specifications of the first prototype have been demonstrated in table 1.

Tab. 1: Specifications of the first prototype of K.N.Toosi University parabolic solar water heaters (Arebi, 2009)

Collector specifications			
Aperture width (meter)	1	Mirror thickness (mm)	4
Collector length (meter)	2	Concentration ratio	90
Parabola focal point distance (cm)	25	Acceptable angle (degree)	2.5
Receiver outer diameter (mm)	22	Edge angle (degree)	90
Receiver inner diameter (mm)	20	---	
Storage tank specifications			
Maximum capacity (lit)	60	Storage scale (cm)	$50 \times 50 \times 50$

Insulation type	2	---	
Equipments specifications			
Pump power (Watt)	40	Pump head (meter)	10
Pump flow (lit per min)	1-15	Stepper motor torque (Kg × cm)	40

3. Designing approach

3.1. Parabolic solar water heater thermal model

From control point of view, the manipulated variable is the fluid flow rate which can be adjusted by a control valve (see fig. 2). The most common controller in such apparatus is on-off controller (Haris, 2007), thus, the flow rate is constant during the operation but optimum constant value for the flow rate should be calculated. In this paper this optimum constant is considered as the only technical specification of the parabolic solar water heater. To design parabolic solar water heater pump flow rate and collector dimensions an appropriate thermal model is needed. The model used in this paper is indicated by (1) to (3) (Zahirnia at el. , 2011). Since this model contains physical parameters and low computational load during its use in simulation, it is suitable to be used in the designing.

$$\dot{T}_1 = \frac{\eta_{opt} G_b G - q\rho_f c_{pf}(T_1 - T_2) - \pi D_{out} L_c h_R \left(\frac{T_1 + T_2}{2} - T_a\right) - e}{\rho_f c_{pf} L_c A_R} \qquad \text{(eq. 1)}$$

$$\dot{T}_2 = \frac{q L_{st} \rho_f c_{Pf}(T_1 - T_2) - k A_{st_{in}}(T_2 - T_3)}{L_{st} \rho_f c_{Pf}(V + V_{eq})} \qquad \text{(eq. 2)}$$

$$\dot{T}_3 = \frac{k A_{st_{in}}(T_2 - T_3)}{L_{st} m_{st} c_{st}} - \frac{h_{st} A_{st_{out}}(T_3 - T_a)}{m_{st} c_{st}} \qquad \text{(eq. 3)}$$

Parameters and symbols used in the model are described in List of Symbols at the end of the paper; meanwhile, some of them are shown in figure 2. Collector aperture can also be easily calculated using (4).

$$G = W_c \times L_c \qquad \text{(eq. 4)}$$

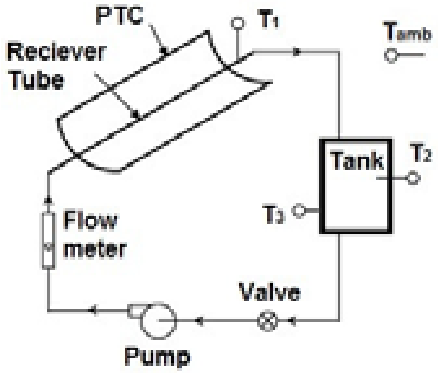

Fig. 2: Piping diagram of the solar water heater

3.2. Parameters classification

Since this designing method is a model base one, the model parameters must be classified first so that the designer knows how to treat them. Here four different classes are assumed for various parameters of the model.

3.2.1. Defined parameters

This category consists of the parameters which are considered to be constant and the parameters which vary according to a predetermined function (functions of time, temperature, number of users, etc.). Parameters which refer to physical properties, manufacturing and environmental conditions are listed here. All various defined parameters of the parabolic solar water heater model are indicated in table 2. In this paper the designing is dedicated to the K.N.Toosi University of Technology prototype installed in Iran-Tehran-K.N.Toosi University-mechanical department, thus, the related defined parameters (Zahirnia at el. , 2011) are used in the designing process. Here the average of 20 liters for one person per day is assumed to calculate the storage tank volume (Gleick and Iwra, 1996) and the solar water heater is designed for 4 users.

Tab. 2: defined parameters

Parameter	Unit	Quantity
h_R	$\mathrm{W\,m^{-2}\,K^{-1}}$	77.20
h_{st}	$\mathrm{W\,m^{-2}\,K^{-1}}$	58.66
T_a	$°C$ or K	293.15
G_b	$\mathrm{W\,m^{-2}}$	750
k	$\mathrm{W\,m^{-1}\,K^{-1}}$	0.666
e	Constant	4.23
η_{opt}	Constant	0.6875
L_{st}	m	0.025
ρ_f	$\mathrm{kg\,m^{-3}}$	A defined function of temperature
c_{pf}	$\mathrm{J\,kg^{-1}\,K^{-1}}$	A defined function of temperature
c_{st}	$\mathrm{J\,kg^{-1}\,K^{-1}}$	A defined function of temperature
V	lit	$4 \times 20 = 80$

3.2.2. Output parameters

These parameters are the model outputs. Here G.A. adjusts the target diagram to only one of the output parameters namely, storage tank temperature (T_2). Table 3 shows the model output parameters.

Tab. 3: Output parameters

Parameter	Unit	Category
T_2	$°C$ or K	active output
T_1	$°C$ or K	inactive output
T_3	$°C$ or K	inactive output

3.2.3. Calculating parameters

G.A. tries to adjust at least one of the model outputs to the related target diagram (section 3.3) by changing the calculating parameters. Table 4 indicates parameters that considered as calculating parameters here.

Tab. 4: calculating parameters

Parameter	Unit
L_c	m
W_c	m
q	m^3/s

3.2.4. Adapting parameters

The optimization tool uses different calculating parameters in various iterations. Due to the changes in calculating parameters, some parameters change consequently such as receiver inner diameter that changes according to the collector aperture magnitude. Table 5 shows the model parameters that are considered as adapting parameters.

Tab. 5: Adapting parameters

Parameter	Unit
D_{out}	m
A_R	m^2
$m_{st\,out}$	kg
$A_{st_{in}}$	m^2
$A_{st_{out}}$	m^2
V_{eq}	m^3

Appropriate formulas are required here to estimate changes in adapting parameters. These parameters are functions of collector dimensions. In this paper the concentration ratio is considered to be 50 (Kalogirou, 2009). Concentration ratio is presented by (5). Appropriate functions to describe two adapting parameters of the collector model are presented by (6) and (7).

$$C.R. = \frac{\mathrm{W_c}}{D_{in}} \qquad \text{(eq. 5)}$$

$$D_{out} = D_{in} + 2 \times Th_R \qquad \text{(eq. 6)}$$

$$A_R = \frac{\pi}{4} \times {D_{in}}^2 \qquad \text{(eq. 7)}$$

It should be noted that the formulas that present changes in adapting parameters are highly dependent to the manufacturing spatial specifications and can be both the same or different for various manufacturers. In this paper these formulas are presented based on the K.N.Toosi University first prototype spatial specifications (see fig.1). Since the storage tank is a square made out of sheets, (8) to (11) present storage tank adapting parameters.

$$A_{st_{in}} = A_{st_{in_{pr}}} \times \left(\frac{V}{V_{pr}}\right)^{2/3} \qquad \text{(eq. 8)}$$

$$A_{st_{out}} = A_{st_{out_{pr}}} \times \left(\frac{V}{V_{pr}}\right)^{2/3} \qquad \text{(eq. 9)}$$

$$m_{st} = m_{st_{pr}} \times \left(\frac{V}{V_{pr}}\right)^{2/3} \qquad \text{(eq. 10)}$$

$$V_{eq} = V_{eq_{pr}} \times \left(\frac{V}{V_{pr}}\right)^{2/3} \qquad \text{(eq. 11)}$$

3.3. Target diagram

In this designing method, appropriate target diagram(s) for at least one of the output parameters is required. These diagrams should present the desired properties of the device; thus, it is depicted according the customer needs. Here the following properties, described in table 6 are considered as the desired properties of the parabolic solar water heater.

Tab. 6: desired properties of the parabolic solar water heater

Properties	Parameter	Unit	Quantity
operating time	t_{op}	*min*	*150*
number of users	N	*Person*	*4*
initial temperature	T_s	$°C$	*20*
Customer desired temperature	T_f	$°C$	*50*

By considering these parameters the simplest assumable target diagram for the storage tank temperature is the linear line shown in figure 3. While storage tank temperature increases, the slop in a real diagram of storage tank temperature decreases slowly due to increment of the storage tank thermal waste. As a result the linear target diagram of the storage tank (fig. 3) should be modified. This modification is conducted along with the designing; thus, the designing method is an iterative one.

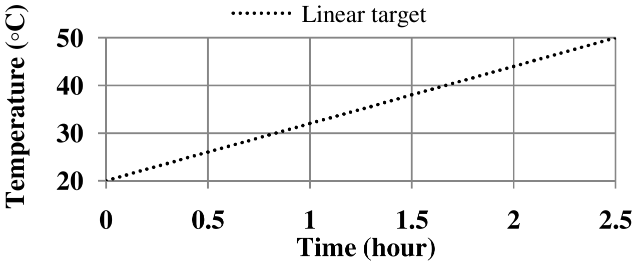

Fig. 3: Target diagram for the storage tank temperature in the first step of the designing

3.4. Optimization tool

To adjust three mentioned calculating parameters the G.A. optimization method is used here. The fitness function to be used in the G.A. in ith step of the designing is presented in (12) and G.A. settings are determined in Table 7.

$$Fitness\ Function_i = \sqrt{\left(T_{d_i} - T_{2_{Model}}\right)^2} \qquad \text{(eq. 12)}$$

Tab. 7: GA setting and parameters

Parameters	Value
Population size	20
Crossover rate	0.8
Mutation rate	0.2
Generations	20-30
Migration	Forward, fraction: 0.2, int.: 20
Selecting	Stochastic uniform
Reproduction	Elite count: 2

3.5. Target diagram modification

Due to the differences between real and linear target diagram for storage tank temperature, the target diagram should be modified as mentioned earlier. The target diagram correction factor for ith step of the designing is presented in (13).

$$\begin{cases} CF_{(i+1)} = T_f - T_{2fi} \\ \quad CF_1 = 0 \end{cases} \qquad \text{(eq. 13)}$$

Considering the mentioned formula, the target diagram for ith step of the designing is presented by (14).

$$T_{d_i} = T_s + \left(\frac{T_f - T_s}{t_{op}}\right) \times (t - t_s) + \sum_{n=1}^{i} CF_n \quad ; \; t_s \leq t \leq (t_s + t_{op}) \qquad \text{(eq. 14)}$$

4. Results and discussion

Table 8 indicates the three calculating parameters which are calculated in the first step of designing.

Tab. 8: Calculating parameters in the first step of the designing

Parameters	Value	Unit
L_c	2.82	m
W_c	1.53	m
q	1.00	lit/min

Based on the calculated parameters in table 8, storage tank temperature of the simulated model is compared with the first target diagram in figure 4.

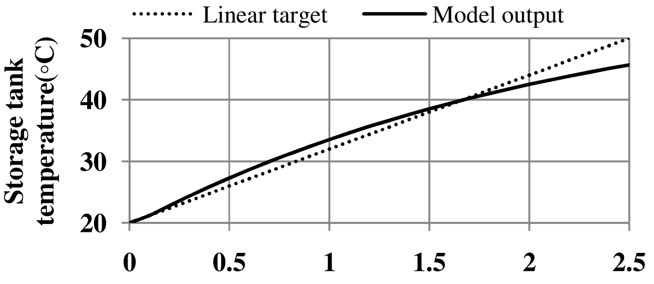

Fig. 4: Target diagram and the storage tank temperature of the simulated model in the first step of designing

As shown in figure 4, storage tank temperature in the simulated model has not reached to the desired temperature of 50 ˚C. In the second step, the target diagram is modified using (15) and (16).

$$CF_2 = T_f - T_{2f1} = 50 - 45.67 = 4.33 \qquad \text{(eq. 15)}$$

$$T_{d_2} = T_s + \left(\frac{T_f - T_s}{t_{op}}\right) \times (t - t_s) + 4.33 \quad ; \; t_s \leq t \leq (t_s + t_{op}) \qquad \text{(eq. 16)}$$

Considering (16) as the target diagram, three calculating parameters are calculated as shown in table 9.

Tab. 9: Calculating parameters in the second step

Parameters	Value	Unit
L_c	3.98	m
W_c	1.40	m
q	1.12	lit/min

Based on the calculated parameters in table 9, storage tank temperature of the simulated model is compared with the second target diagram in figure 5.

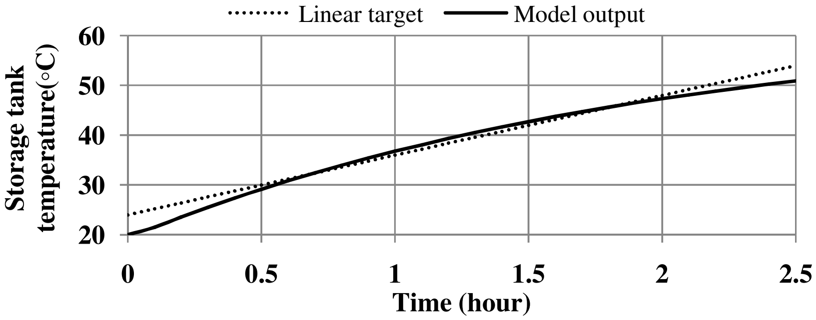

Fig. 5: Target diagram and the storage tank temperature of the simulated model in the second step of designing

As shown in figure 5 storage tank temperature in the simulated model has almost reached to the desired temperature of 50 ◦C. To check if the process would decrease the error step by step, the third step of designing is conducted. The third step target diagram presented in (17) and (18).

$$CF_3 = DFM - MFM_2 = 50 - 50.93 = -0.93 \qquad \text{(eq. 17)}$$

$$T_{d_3} = T_s + \left(\frac{T_f - T_s}{t_{op}}\right) \times (t - t_s) + 4.33 - 0.93 \quad ; \; t_s \le t \le (t_s + t_{op}) \qquad \text{(eq. 18)}$$

Considering (18), three calculating parameters are calculated as shown in table 10.

Tab. 10: model identified parameters in the third step

Parameters	Value	Unit
L_c	3.16	m
W_c	1.67	m
q	1.00	lit/min

Based on the calculated parameters of all three steps the storage tank temperatures of the simulated model are compared with each other in figure 6.

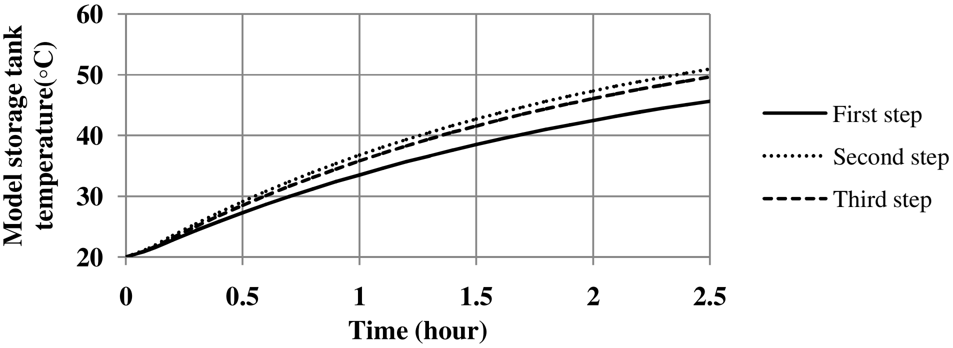

Fig. 6: Storage tank temperature of the simulated model in all three conducted steps

As shown in figure 6, final magnitude of the storage tank temperature diagram of the simulated model is becoming closer to the desired temperature. The designing error can be easily calculated by (19).

$$Error\ percentage_i = \left|\frac{T_f - T_{2fi}}{T_f}\right| \times 100 \qquad \text{(eq. 19)}$$

Continuing designing steps, the designing error is decreased as shown in table 11.

Tab. 11: Designing error

Designing step	Error
First step	8.66 %
Second step	1.85 %
Third step	0.74 %

5. Conclusion

In this paper a thermal model of parabolic solar water heaters is used to design a desirable solar water heater. This includes designing of both dimensional and technical specifications for the desired device. Due to the low computational load during its use in simulation and the accuracy of this model, it is suitable to be used in the presented designing method. In order to calculate the designing specification all the parameter of the model were classified first. This classification indicates how every single parameter of the model should be treated in the presented designing method. As it is shown in section 4, the designing method can present the desired specification in an acceptable manner. In this paper no limitation is considered for manufacturing various dimensions of collectors, however some standard size is assumable. Considering these standard dimensions can maturate this method.

List of Symbols

A_R	Receiver tube inner area
$A_{st_{in}}$	Storage tank inner surface in the simulated model
$A_{st_{in_{pr}}}$	Storage tank inner surface in the first prototype
$A_{st_{out}}$	Storage tank outer surface in the simulated model
$A_{st_{out_{pr}}}$	Storage tank outer surface in the first prototype
c_{pf}	Water specific heat
c_{st}	Specific heat of the storage tank outer walls
CF_i	Target diagram correction factor
$C.R.$	Concentration Ratio
D_{in}	Receiver tube inner diameter
D_{out}	Receiver tube outer diameter
T_{2fi}	Final magnitude for the storage tank temperature in the simulated model in ith step
e	Constant error in collector modeling
G	Collector aperture
G_b	Solar beam irradiance
h_R	Heat transfer coefficient of the receiver tube
h_{st}	Heat transfer coefficient of the storage tank
k	Thermal conductivity of the storage tank insulator
L_{st}	Width of the storage tank insulator
L_c	Collector length
m_{st}	Mass of storage outer walls in the simulated model
$m_{st_{prototype}}$	Mass of storage outer walls in the first prototype
T_f	Customer desired temperature
N	Number of users
q	Pump flow rate
t	Time
t_{op}	Water heater maximum acceptable operation time
t_s	Operation embarking time
T_a	Ambient temperature
T_1	Temperature of collector outlet and storage tank inlet

T_2	Temperature of collector inlet and storage tank outlet and temperature of storage tank (Temperature of the fluid inside the storage tank)
T_3	Temperature of storage tank outside walls
T_{d_i}	Target temperature
T_f	Desired final temperature
T_s	Average initial temperature of the storage tank
Th_R	Thickness of receiver tube
V	Water volume in the storage tank in the simulated model
V_{pr}	Water volume in the storage tank in first prototype
V_{eq}	Equivalent water volume to consider thermal effect of inner box of storage tank in the simulated model
$V_{eq_{pr}}$	Equivalent water volume to consider thermal effect of inner box of storage tank for the first prototype
W_c	Collector width

Greek Symbols

ρ_f	Water density
η_{opt}	Collector efficiency

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