Development of a Design Tool for Sizing and Optimizing Thermosyphon Solar Water Heater Systems: A Case Study for Tripoli-Libya

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Abstract: Thermosyphon solar water heaters can be considered the most popular solar technology for supplying households with the needed hot water for domestic purposes. However, sizing these systems is mainly based on experience and trial methods, these methods were established more on intuition instead of scientific approaches. This paper is aimed at studying the sizing of thermosyphon systems through the development of a dedicated generic design tool. The tool can be utilized by manufacturers and engineers to arrive at optimized systems designed according to the operating and weather conditions of certain geographical locations. The design tool is implemented in this study to find the optimum system design that fits households in Libya (as a case study in this work) and accounts for the weather conditions of Tripoli and a simple, but representative, hot water load pattern. Two different sizes of thermosyphon systems covers hot water load of 180 lit and 240 lit, and two different configurations with vertical and horizontal tanks are studied and the best fit designs are obtained. The design tool has shown a great potential, and with further development and validation would be capable of widespread commercial application.

تطوير أداة تصميم لتحجيم وتحسين آداء منظومات الطاقة الشمسية لتسخين المياه ذات الدوران الطبيعي: دراسة حالة ـ طرابلس ليبيا

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ملخص: سخانات المياه الشمسية ذات الدوران الطبيعي تعتبر من أكثر التقنيات الشمسية شيوعا لتزويد الأسر بمتطلبات المياه الساخنة للأغراض المنزلية. ولكن تحجيم هذه المنظومات مازال يعتمد على الخبرة وكذلك طرق المحاولة، وهذه الطرق تعتمد على

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الحس بدل من الأساليب العلميّة. هذه الورقة تهدف إلى دراسة تحجيم منظومات التدوير الطبيعي من خلال تطوير أداة عامّة لهذا الغرض. الأداة يمكن استعمالها من قبل المصنعين والمهندسين للحصول على تصميم المنظومة المثلى طبقا للظروف المناخيّة والتشغيليّة للموقع المحدد. أداة التصميم أستعملت في هذه الدراسة لإيجاد التصميم المثالي للمنظومات التي تتناسب مع الأسر الليبيّة (كحالة دراسيّة في هذه الورقة) وتأخذ في اعتبارها الظروف المناخيّة لمدينة طرابلس وكذلك حمل المياه الساخنة الافتراضي المعبر . حجمين مختلفين من منظومات الدوران الطبيعي تغطي أحمال مياه ساخنة 180 لتر و 240 لتر وكذلك شكلين مختلفين للمنظومات بخزان عمودي وافقي درست وافضل تصميم تم الحصول عليه. أداة التصميم أظهرت أمكانيات عاليّة وبمزيد من التطوير والتحقيق يمكن أن تكون ذات تطبيق تجاري موسع.

Keywords: *Thermosyphon solar water heaters; Genetic algorithm; Optimisation; Design tool.*

1. INTRODUCTION

Thermosyphon solar water heating systems are the most commonly used type of solar water heaters for providing households with their hot water requirements for domestic purposes worldwide. Well-designed thermosyphon systems have advantages over other types of systems that include lower investment cost, and reduced operating and maintenance costs. These sorts of systems are particularly suitable for moderate and hot climatic regions where risk of freezing is not an issue.

Designing and sizing of thermosyphon solar water heaters is not an easy task, yet it is very important to produce cost-effectiveness systems, as cost is the main issue that affects the spread of this technology. Literature review has revealed that there are no rigours easy-to-use methods for sizing and optimizing thermosyphon systems, and that most systems available in the market were designed based on trial and error methods which are more based on intuition rather than scientific methods [1]. This can be attributed to the fact that modeling the thermosyphon phenomenon in these systems is a very complicated task.

Most of the previous work regarding optimization of the design variables of domestic thermosyphon solar water heaters have applied the single variable optimization method (or parametric study) in their analyses [2-4]. This is conducted by fixing all variables, and then varying only one variable at a time to see its effect. Strictly, such a method cannot really represent accurately the problem under investigation since the number of variables is large and the problem inherently is multi-objective.

A great deal of work [5-9] has been published regarding sizing and optimizing of active solar water heaters, and of thermosyphon systems [10-16] based on classical optimization techniques. However, some work has been devoted to the use of evolutionary algorithms to optimize large scale solar water heaters utilized in industrial or service applications. Loomans and Visser [17] used a genetic algorithm to minimize the payback time of a large scale solar domestic hot water heating system.

Hin and Zmeureanu [18] utilised a Hybrid Particle Swarm and a Hooke-Jeeves generalized pattern search algorithm to optimize solar combisystem in a house in Montreal, Canada. The objective function used was to minimize the life cycle cost, energy use and exergy destroyed by the system. The optimization results show a reduction in life cycle cost of the combisystem of 19% and in the life cycle energy use of 34%. Rey and Zmeureanu [19] have used two different methods of optimisation: weighted sum method (WSM) using a hybrid particle swarm optimization/Hooke-Jeeves algorithm (PSO/HJ), and multi-objective particle swarm optimization for the optimisation of a solar combisystem (MOPSO). Also hybrid (MOPSO/HJ) is proposed to enhance the local search of MOPSO. Two conflicting objective functions, the life cycle cost and life cycle energy are used in the optimisation. The results have shown that the proposed MOPSO/HJ is six times faster than WSM in arriving at the solution, and the life cycle cost and life cycle energy were reduced by up to 88.6% and 63.9%, respectively.

An extensive review of implementing solar water heating systems in TRNSYS is given by Shrivastava et al

[20]. Nhut and Park [21] have developed a mathematical model to determine the optimal control variables of a collector pump to improve the overall solar water heater performance. The effect of various parameters were investigated under real weather condition of Jeju Island, South Korea. The results have shown that at optimal collector flow rate, the collector useful energy gain is improved by 1.54% and the electric consumption of the collector pump is decreased to 65.6%. Optimum sizing of solar water heating systems for Libyan households was studied using Generic Optimization Program (GENOPT) provided in TRNSYS by Abdunnabi [22]. The study has shown that the optimum tank volume to collector ratio is between 49 – 60 Litres/m² for the most common collector characteristics ratio ($F_RU_L/F_R(\tau\alpha) = 6$-$8$).

In this paper, a design tool for sizing and optimizing thermosyphon solar water heaters through the use of TRNSYS component Type45 with two new added components, employing an optimization routine based on the genetic algorithm technique. The design tool is used in this study to find the optimum design of thermosyphon solar water that best suits families in Libya.

1. THERMOSYPHON SYSTEM DESIGN TOOL (TSDT)

The design tool used in this study is based on a modified TRNSYS component Type 45 linked with other new components and modelled in TRNSYS to evaluate the thermal performance of thermosyphon systems, and uses the genetic algorithm routine for the optimization. Two new components were added to the TRNSYS component Type 45 to account theoretically for the information that would otherwise have to be determined experimentally (namely, $F_R\tau\alpha$, F_RU_L , b_o, U1, U2, UA_t, where all terms are defined in the Nomenclature). The new components and the combined model which is named "Modified TRNSYS Model" have been validated and satisfactory results have been obtained [23,24]. The optimization problem is defined as a multi-objective problem consisting of three objective functions: the cost of material contained in the system, the system performance (solar fraction in this case), and the average outlet temperature to the load. However, the problem can simply be treated as a constrained single optimization problem where the cost function is chosen as the objective, and the other two objectives are treated as constraints. Then the problem can be stated as:

Minimise $\quad \cos t(\vec{x})$ .... (1)

Subject to:

$SF(\vec{x}) \geq \varepsilon_1$ .... (1.a)

$T_{use}(\vec{x}) \geq \varepsilon_2$ .... (1.b)

Where $\vec{x} = [x_1, x_2, ..., x_n]^T$ is the vector of the n design variables of the system that are to be optimized and each variable x_i is bounded by lower and upper limits $[x_i^L, x_i^U]$, ε_1 and ε_2 are lower bounds of the constraints that can be varied to find multiple points on the Pareto-optimal front.

Due to the lower demand for hot water in summer and spring seasons in Libya, and to the clear sky as well as to the high solar irradiance, the yearly solar fraction might not be the best choice. Therefore, the calculation of solar fraction is considered only for the winter and autumn seasons (for exactly seven months, from October to April).

The system design parameters considered for optimization in this study are 13 parameters as listed in Table 1. The riser, header and connecting pipes diameters are not included amongst the optimized parameters. These parameters are instead considered to be fixed information inputs according to pipe standard sizes. The values of these parameters are considered in this study to be $D_r = 0.008m$ and $D_h = D_p = 0.081m$ respectively. The general configurations of thermosyphon solar water heaters found in practice are depicted in Figure 1. Both of these configurations have been considered in the optimisation process.
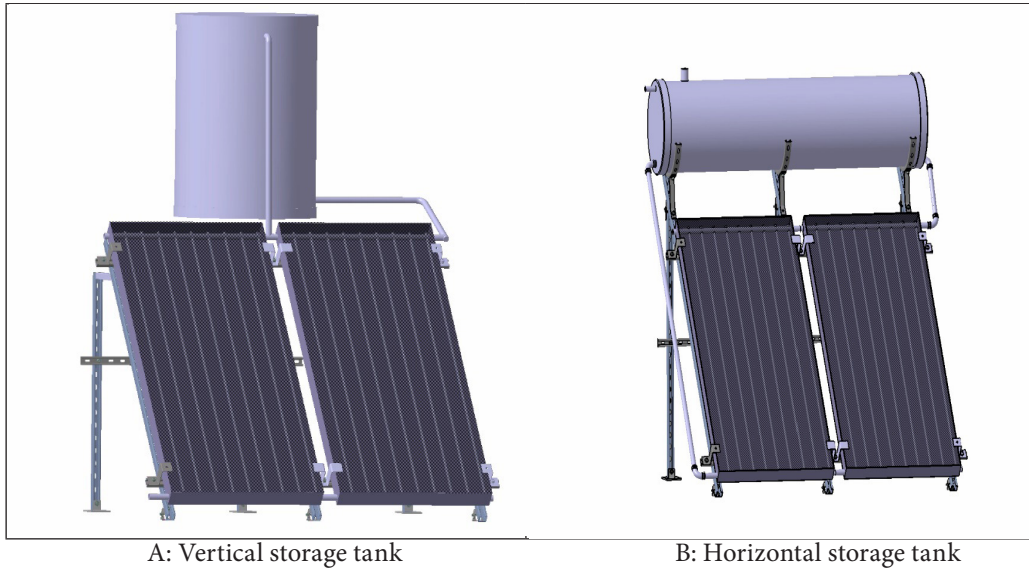
A: Vertical storage tank   B: Horizontal storage tank

Figure (1). The general view of thermosyphon solar water heaters

Table (1). Design variables of thermosyphon system

	Abbr	Stand for	Limits	increment
1	Ac	Collector Gross area (m²)	[1 , 2.2]	0.025
2	$\frac{L_C}{W_C}$	Collector aspect ratio	[0.5 , 2]	0.02
3	Nc	Number of collectors	[1 , 2]	1
4	W	Fin width (cm)	[9 , 20]	0.5
5	L_{gap}	Gap between cover and absorber plate (cm)	[1.5 ,10]	0.4
6	L_{inb}	Collector back insulation thickness (cm)	[2 , 5]	0.2
7	L_{ins}	Collector sides insulation thickness (m)	[1 , 4]	0.2
8	V_t	Tank volume (m³)	[0.4*Q_{Load} 1.5*Q_{Load}]	0.005
9	$\frac{H_t}{D_t}$	Tank aspect ratio	[1 , 3.2]	0.1
10	L_{tins}	Tank sides insulation thickness (cm)	[2 , 5]	0.2
11	L_{tint}	Tank top and bottom insulation thickness (cm)	[2 , 5]	0.2
12	P_{aux}	Auxiliary heater power (kJ/hr)	[8 , 16]	0.2
13	T_{set}	Auxiliary heater setting temperature (°C)	[T_{Load} -5, T_{Load}+5]	0.2

3. RUNNING THE DESIGN TOOL

The design tool consists of two main parts: The thermal performance model of thermosyphon solar water heater built in TRNSYS, and the optimisation routine using genetic algorithm built in Intel Visual Fortran 9. The two programs are connected together as illustrated graphically in Figure 2.
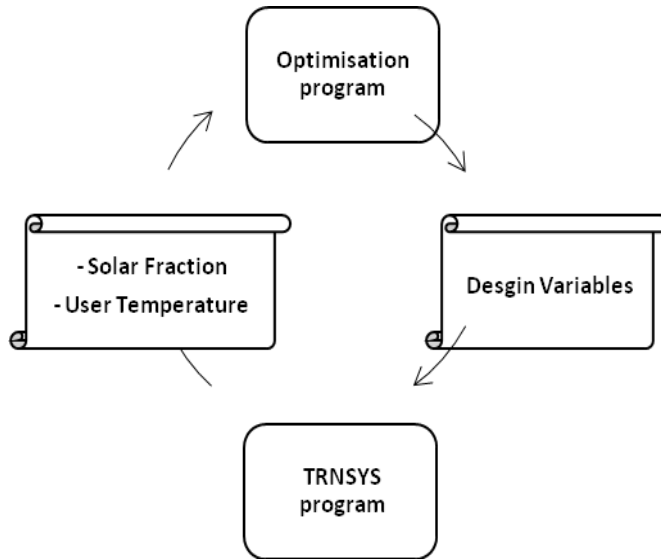
Figure (2). The flow chart of the thermosyphon system design tool

4. RESULTS AND DISCUSSION

The design tool can be implemented to obtain the optimum thermosyphon solar water heating system to suit a variety of households, conditions and geographic locations. As a case study, the design tool is applied according to the weather and operating conditions of Tripoli, Libya. A simple, but representative, hot water load pattern as depicted in Figure 3 is used. The thermosyphon system materials used and their optical and thermal properties as considered in this study are shown in Table 2 and Table 3.

Table (2). System materials and their thermal properties

Part	Material	Thermal conductivity W/m.K
Fin and tube	Copper	380
Collector insulation	Mineral wool	0.045
Connecting pipes	Copper	380
Pipe insulation	Armaflex	0.036
Tank material	Carbon steel	50
Tank insulation	Polyurethane	0.026

Table (3). The solar optical properties of the absorber and the cover plates

Part	Properties	Value
Absorber	Absorptivity	0.95
	Emissivity	0.05
Cover	Transmissivity	0.905
	Emissivity	0.8

The material prices required by the design tool are given in Table 4 which are based on Libyan free market values in the year 2008 (they are not taken from the manufacturer).

Table (4). Solar system material and prices

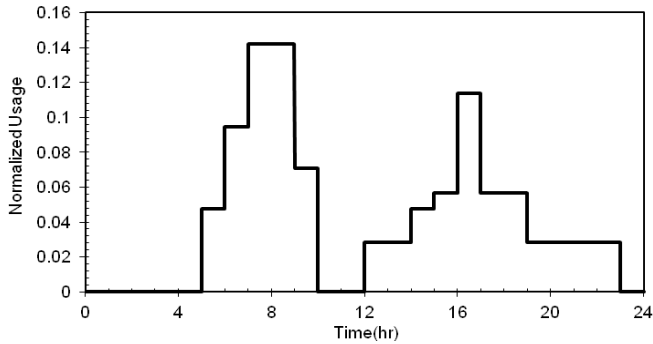| No	Material	Prices (£ /kg)
1	Copper	6.9
2	Carbon steel	1.41
3	Tempered Glass	1.2
4	Mineral wool	1.89 (40 kg/m3)
5	Polyurethane foam	3.27 (32 Kg/m3)

Figure (3). Hot water load pattern used for the study

Optimum Systems

The design tool is implemented to find the optimum system design that can provide the household with 180 litres of daily hot water at a temperature of 60 °C for different solar fraction values. This is depicted as 'System A'. The results of 64 simulation runs are shown in Figure 4 and corresponding design parameter values are given in Table 5. Figure 4 represents the trade-off curve between the material cost of the system and the solar fraction of the system in which the grey circular points represent feasible solutions set (dominated solution), and the solid line and white circular points represent the Pareto optimal set (non-dominated solution). The feasible solution set is the set of all solutions that do not violate the constraints, whereas the Pareto optimal set is the non-dominated subset of the feasible set.
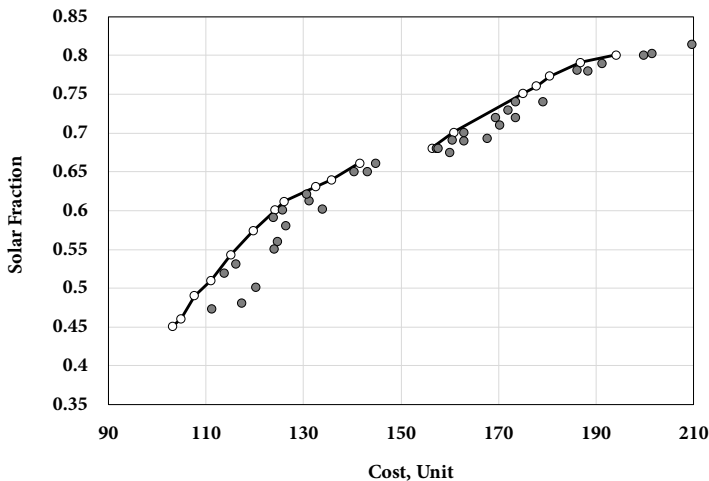

Figure (4). The trade-off between the cost and solar fraction (system A)

The optimum system design that can provide 240 litres of daily hot water at a load temperature of about 60 ºC is sought. This is depicted as 'System B'. The results obtained for the optimum design of the thermosyphon system for 240 litres is shown in Figure 5, where 48 resulting points were used to construct the graph.
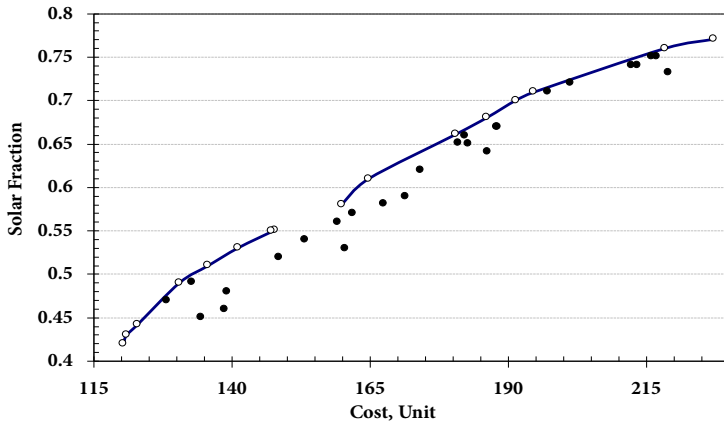

Figure (5). The trade-off between the cost and solar fraction of System B

Figure 6 shows that the shape of the Pareto optimal set of System A and System B have nearly the same trend. This is expected because of the weather condition, load pattern, and the fact that the temperature to the load is the same. The only difference is the amount of daily hot water withdrawn from the system which obviously requires a bigger system size.
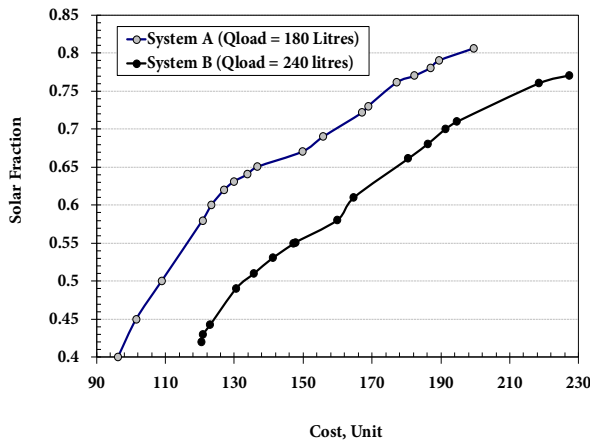

Figure (6). Pareto optimal fronts of System A and System B

Vertical and Horizontal Tanks

The previous results only examined the optimality of vertical tank systems (as depicted in Figure 1a) for providing 180 litres of hot water at 60 ºC. However, in this section, the optimum design of a thermosyphon system (System D) with a horizontal tank is sought (as depicted in Figure 1b). The trade-off curve between the

solar fraction and the system cost from 50 simulation runs is shown in Figure 7. Some of the design points on the Pareto optimal set are given in Table 6. Thermosyphon solar water heaters with horizontal tanks are very popular and have a better appearance than vertical tank systems and are relatively easier to be fitted to tilted roofs.

A comparison between vertical and horizontal tank systems is shown in Figure 8. It is clear from the comparison that vertical tank systems outperform horizontal tank systems for the same system prices, and therefore, wherever possible, it is advisable to use vertical tank systems rather than horizontal tank systems, despite aesthetic appearance.
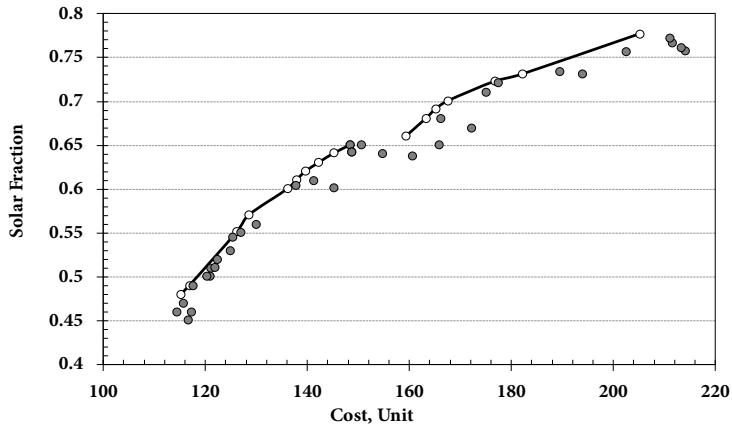

Figure (7). Trade-off curves for an optimum horizontal tank thermosyphon system D

Table (5) Some system design parameters at different solar fraction (System A)

Generation no	998	1000	1000	1000	1000	973
Cost	101.5	108.95	123.4	136.6	158.8	177.2
SF	0.450	0.500	0.600	0.650	0.700	0.761
T_{load} (°C)	59.71	59.71	59.71	59.70	59.71	59.70
Ac (m²)	1.610	2.010	2.162	2.200	1.457	1.700
Vt (m³)	0.133	0.133	0.133	0.154	0.186	0.215
Ht/Dt	1.071	1.071	1.000	1.284	1.284	1.568
W (m)	0.146	0.198	0.147	0.120	0.152	0.188
Nr	8	5	8	11	6	6
Lgap (m)	0.015	0.015	0.015	0.015	0.015	0.015
Paux (kJ/h)	11937	14476	9143	12317	13079	14984
L/W	1.067	1.823	1.409	1.161	1.551	1.209
Noc	1	1	1	1	2	2
Linb (m)	0.028	0.022	0.036	0.036	0.024	0.026
Lins (m)	0.010	0.010	0.012	0.018	0.010	0.010
Ltin (m)	0.037	0.0360	0.0400	0.040	0.044	0.048
Ltinb (m)	0.040	0.0380	0.0380	0.048	0.042	0.046
Tset (°C)	64	64	64	64	64	64

Table (6). Some system design parameters at different solar fraction (Horizontal System)

| Generation no	1000	1000	991	1000	1000	1000
Cost (£)	112.6	122.5	140.4	161.8	188.2	244.3
SF	0.450	0.500	0.601	0.650	0.700	0.850
Tload ($^\circ C$)	59.05	59.03	59.05	59.02	59.06	59.10
Ac (m²)	1.590	1.743	2.162	2.200	1.542	2.123
Vt (m³)	0.096	0.117	0.105	0.137	0.122	0.159
Ht/Dt	2.419	2.348	2.632	1.142	2.348	2.703
W (m)	0.117	0.119	0.124	0.090	0.125	0.125
Nr	12	13	15	20	13	16
Lgap (m)	0.022	0.022	0.022	0.030	0.022	0.022
Paux (kJ/hr)	12825	15492	8381	15619	8254	13714
L/W	0.736	0.677	0.583	0.642	0.547	0.500
Noc	1	1	1	1	2	2
Linb (m)	0.021	0.0200	0.0253	0.031	0.020	0.020
Lins (m)	0.010	0.0100	0.010	0.013	0.010	0.010
Ltin (m)	0.040	0.0400	0.040	0.040	0.040	0.040
Ltinb (m)	0.040	0.0360	0.039	0.040	0.036	0.040
Tset (ºC)	64	62	64	61	62	61
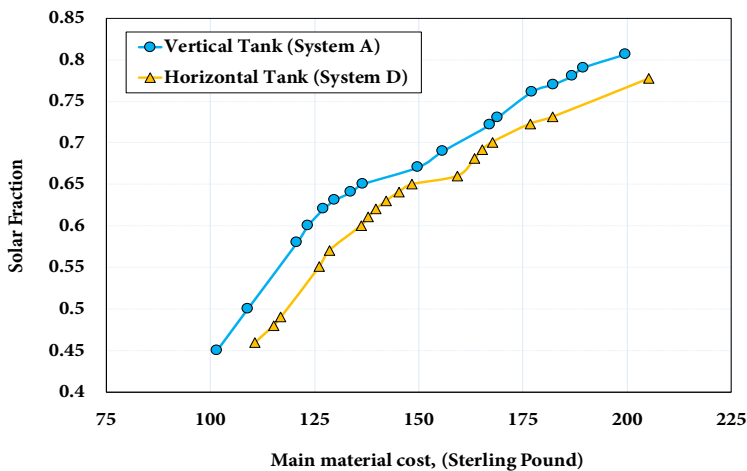
Figure (8). Pareto optimal fronts of vertical and horizontal tank systems

5. CONCLUSIONS

The purpose of the study was to develop an optimization routine (optimizer) to be used for finding the optimum design parameters of thermosyphon systems. The genetic algorithm optimization procedure was adopted in this study for this purpose because of its ability to optimize multiple parameters simultaneously.

This was then combined with the modified TRNSYS model to constitute the final design tool. Finally, the design tool was implemented to find the optimum thermosyphon system for the Libyan environment for different criteria. The conclusions are as follows.

i) The design tool produced is capable of delivering the optimum thermosyphon system design that fits a particular situation and purpose. This, in turn, eliminates the unnecessary cost resulting from the oversizing of systems.

ii) The design tool has shown the difference in cost and performance of vertical versus horizontal tank systems designed for the same purpose. For the case tested, it is better to have a vertical tank than a horizontal one.

iii) The study has extended the TRNSYS library by adding two new components: Type 210 (collector characteristic component), and Type 211 (pipe-tank heat loss coefficients component).

iv) The design tool developed offers a potentially very promising means for sizing thermosyphon solar water heating systems and has potential to be developed commercially for this purpose, subject to further successful validation.

NOMENCLATURE

Ac Collector area m^2	Nr Number of risers
Dp Inlet and outlet connecting pipes diameter (m)	P_{aux} Auxiliary energy input to tank (kJ/hr)
Dr Riser diameter (m)	Q_{load} Hot water demand (Lit)
Dt Tank diameter (m)	T_{set} Auxiliary heater setting temp (°C)
$F_R \tau\alpha$ Intercept of the collector efficiency curve	T_{load} User hot water temperature (°C)
$F_R U_L$Slope of the collector efficiency curve (kJ/hr m^2°C)	SF Solar fraction
L_{gap} The height between the absorber and the cover plates (m).	UA_t Overall UA value for tank (kJ/hr ° C)
L_{inb} Collector back insulation thickness (m)	U1, U2 Loss coefficients for inlet and outlet pipes (kJ/hr m^2 ° C)
L_{ins} Collector sides insulation thickness (m)	Vt Tank volume (Lit)
L_{tins} Tank insulation side thickness (m)	Wc Collector Width (m)
L_{tint} Top tank insulation thickness (m)	W Fin width (cm)
Ht Tank height (m)	
Noc Number of collectors	

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