Research, Society and Development, v. 9, n.8, e382985673, 2020
(CC BY 4.0) | ISSN 2525-3409 | DOI: http://dx.doi.org/10.33448/rsd-v9i8.5673

Uma nova abordagem para o dimensionamento de aquecedores solares operando por termossifão

A new model for sizing thermosiphon solar heating systems

Un nuevo enfoque para el dimensionamiento de calentadores solares que funcionan con termosifón

Recebido: 15/06/2020 | Revisado: 24/06/2020 | Aceito: 26/06/2020 | Publicado: 09/07/2020

Antônio Marcos de Oliveira Siqueira
ORCID: https://orcid.org/0000-0001-9334-0394
Federal University of Viçosa, Brazil
E-mail: antonio.siqueira@ufv.br
Alexandre Gurgel
ORCID: https://orcid.org/0000-0002-3120-8168
Federal University of Viçosa, Brazil
E-mail: agurgel@ufv.br
Zeji Ge
ORCID: https://orcid.org/0000-0003-4900-9690
University of Shanghai for Science and Technology, China
E-mail: pcx1928@gmail.com
Fernando Ariel Colque
ORCID: https://orcid.org/0000-0003-2599-4307
Universidad Nacional de Salta, Argentina
E-mail: fernandocolq@gmail.com
Gabriel Siqueira Silva
ORCID: https://orcid.org/0000-0002-2462-9263
Federal Center for Technological Education of Minas Gerais, Brazil
E-mail: gabrielsiqueira25@outlook.com

Resumo

O objetivo deste trabalho é apresentar uma metodologia simples para que seja possível dimensionar um sistema operando em termossifão, sem recorrer sempre a uma simulação computacional. Como resultado de muitas simulações de sistemas utilizando o programa *TRNSYS*, variando-se diversos parâmetros do projeto e dados operacionais do sistema, obteve-

se um conjunto de expressões que permitem a determinação da eficiência térmica diária (média mensal) do sistema. A correlação desenvolvida contempla os aspectos geométricos e térmicos relacionados ao coletor, ao tanque de armazenamento e às tubulações de conexão, bem como aspectos operacionais tais como carga térmica, radiação solar e temperatura ambiente. Este modelo é capaz de otimizar as variáveis do sistema de aquecimento solar de água por termossifão para os requisitos de uma aplicação específica. A correlação obtida mostra que a eficiência é uma função linear das condições meteorológicas, da qualidade do coletor e dos parâmetros que relacionam o volume do tanque de armazenamento, o volume de carga (perfil de consumo) e a área do coletor. A correlação é muito útil, uma vez que se trata de uma alternativa simples e rápida para o cálculo da eficiência do sistema, sem depender de determinação experimental ou resultados de simulação numérica. O dimensionamento, isto é, a determinação da área do coletor e do volume do tanque de armazenamento que satisfazem de maneira adequada a carga térmica necessária, pode ser realizado de maneira simples e rápida usando essa correlação.
Palavras-Chave: Aquecimento solar de água; Circulação Natural; Modelo matemático; *TRNSYS*.

Abstract

The purpose of this research is to present a simple methodology which enables to size a thermosyphon system without always having to resort to a computational simulation. As a result of many system simulations using the *TRNSYS* software, whereby several project and equipment parameters were varied, a group of expressions were obtained which allow the determination of the system thermal daily efficiency (monthly average). The developed correlation includes geometric and thermal aspects related to the collector, the storage tank and the connecting pipes, as well as operational data such as thermal load, solar radiation and room temperature. This model is able to optimize several variables that comprise thermosyphon solar water-heating systems for the requirements of particular applications. The resulting correlation shows that the efficiency is a linear function of meteorological conditions, collector quality and parameters related to storage tank volume, volume load (consumption profile) and collector area. The correlation is very useful since it is a simple, fast alternative for the calculation of system efficiency without depending on experimental determination or numerical simulation results. The determination and sizing of the collector area and the volume storage tank that satisfy the required thermal load can be appropriately performed in a simple and fast way by using the proposed correlation.

Keywords: Solar water heating; Natural circulation; Mathematical model; *TRNSYS*.

Resumen

El objetivo de este trabajo es presentar una metodología simple para que sea posible diseñar un sistema que funcione en un termosifón, sin recurrir siempre a una simulación por computadora. Como resultado de muchas simulaciones de sistemas que utilizan el programa *TRNSYS*, donde se variaron diferentes parámetros operacionales y de diseño del sistema, se obtuvo un conjunto de expresiones que permiten la determinación de la eficiencia térmica diaria (promedio mensual) del sistema. La correlación desarrollada contempla tanto los aspectos geométricos y térmicos relacionados con el colector, el tanque de almacenamiento y las tuberías de conexión, así como los aspectos operativos (carga térmica, radiación solar, temperatura ambiente). Este modelo puede optimizar las variables del sistema de calentamiento solar de agua mediante termosifón para los requisitos de una aplicación específica. La correlación obtenida muestra que la eficiencia es una función lineal de las condiciones climáticas, la calidad del colector y los parámetros que relacionan el volumen del tanque de almacenamiento, el volumen de carga (perfil de consumo) y el área del colector. La correlación es muy útil, ya que es una alternativa simple y rápida para calcular la eficiencia del sistema, sin depender de la determinación experimental o los resultados de la simulación numérica. El dimensionamiento, es decir, la determinación del área del colector y el volumen del tanque de almacenamiento que satisfacen adecuadamente la carga térmica requerida, se puede llevar a cabo de manera simple y rápida, utilizando esta correlación.

Palabras clave: Calentamiento solar de agua; Circulación natural; Modelo matemático; *TRNSYS*.

1. Introduction

Solar domestic hot water (SDHW) systems can be divided in active systems (fluid impelled by a pump) and passive systems (fluid flowing by natural convection in the circuit). In tropical countries, it is common to use thermosyphon solar water-heating systems, a term that applies to some passive systems. However, typical design and sizing methods generally contemplate active systems only, and are largely used in countries with colder weather. Due to the lack of specific methods, designers also estimate the area required for a given application based on criteria established for the case of forced-flow operations, often employing the F-Chart methodology (Duffie & Beckman, 1991), for a fixed operating flow rate.

Since the flow rate is an unknown variable, as occurs in natural circulation phenomena, and because of iteration of the constructive, environmental and operational conditions, it is necessary to evaluate the flow rate by means of a detailed simulation of the solar system thermal behavior. The execution of this operation is not simple and requires the use of sophisticated softwares like *TRNSYS*, *EnergyPlus*, *RETScreen International*, *SolDesigner* and *T*SOL* (Abdunnabi et al., 2019; Garwood et al., 2018; Villa-Arrieta & Sumper, 2018; Shrivastava et al., 2017; Gao et al., 2016). This model has been validated by a number of researchers and has been frequently used to investigate, evaluate and optimize the thermal performance and the design parameters of thermosyphon solar water heaters (Abdunnabi et al., 2019; Valdiserri, 2018; Collins et al., 2017; Shrivastava, et al., 2017).

This work aims to present a simple methodology which enables to size a thermosyphon system without always having to resort to computational simulation. As a result of many system simulations using the *TRNSYS* software, whereby several project and equipment parameters were changed, a group of mathematical expressions were obtained which allow to determine the system thermal daily efficiency as a monthly average. The developed correlation includes geometric and thermal aspects related to the collector, the storage tank and the connecting pipes, as well as operational aspects such as thermal load, solar radiation and room temperature. The purpose of the model is to optimize parameters of thermosyphon solar water-heating systems as required in particular applications.

An investigation system consists of an arrangement of solar flat collectors connected in parallel, a cylindrical thermal storage tank and hydraulic connecting pipes among the collectors and the tank. The system also comprises mixers for the interaction of hot water from the top of the tank with cold water from the main pipe, whenever the temperature of the water flowing from the tank is above the desired delivery temperature. An electric heater, here denominated as electric support, and a thermostat are integrated with the tank in order to maintain a determined temperature level in the tank upper position. The auxiliary power component must supply 100 % of the heated water without any assistance from the solar system, providing heat when the energy gain from the collector is not sufficient to meet the required energy delivery to the load.

There are two possible locations for the electric support: when an auxiliary heating element is inside the storage tank or when a separate auxiliary heating tank is connected in series or in parallel to the storage tank. Most manufacturers and professional installers of solar domestic hot-water systems use the first option, which has also be selected for the development of this work.

2. System Description

The primary module of the solar flat-plate collector, considered in the present simulation, has an approximated area of 0.75 m^2, with 8 pipes (diameter = 0.0079 m) and 1.2 m of distributor line (diameter = 0.0254 m). The simulation has been carried out for three collection areas: 3 m^2, 4.5 m^2 and 6 m^2, which correspond, respectively, to an arrangement of 4, 6 and 8 parallel modules.

Three different values of the intercept, $F_R(\tau\alpha)$, and the slope, F_RU_L, of the efficiency curve were adopted in this simulation (Table 1). These parameters represent the effects of the optical and thermal properties of the solar flat-plate collector, respectively (Duffie & Beckman, 1991). To specify each solar collector, these parameters were combined in order to obtain 9 pairs of $F_R(\tau\alpha)$ and F_RU_L values. Measurements of the thermal performance of the collector were obtained using a mass flow rate of 0.02 kg/(s.m^2).

Table 1. Parameters that characterize the solar collector performance (Duffie & Beckman, 1991, Almeida et al., 2014).

$F_R(\tau\alpha)$ -	F_RU_L [W/(m^2.K)]
0.85	5
0.75	7
0.60	9

Source: Authors.

When $F_R(\tau\alpha)$ = 0.85 and F_RU_L = 5 W/(m^2.K), a collector has high thermal efficiency, in agreement with Duffie & Beckman (1991); on the other hand, if $F_R(\tau\alpha)$ = 0.60 and F_RU_L = 9 W/(m^2.K), the thermal efficiency of the collector is low, as reported by Tiwari et al. (1991).

Due to the complexity of the simulation in thermosyphon solar water-heating systems, some variables were fixed. They are presented below:

Storage tank:

I. global heat transfer coefficient, UA = 1.39 W/(m^2.K).
II. collector hot water entrance position = 2/3 of the tank height (if the tank is horizontal, the height is the tank diameter; otherwise, the height is equal to the tank length).
III. vertical distance between the bottom of the tank and the collector entrance: 1.2

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m (usual).

Hydraulic pipes:

I. diameter = 0.0254 m.
II. collector output pipe length = 10 m.
III. collector input pipe length = 4 m.
IV. number of joints, tees, valves and other connections = 5 (at each pipe).
V. heat transfer coefficient = 2.78 W/(m^2.K).

Thermostat and electric support:

- ✓ (electric support and thermostat height)/(tank height) = ½.

Electric support:

- ✓ Maximum power = 2500 W, to keep the temperature in the top of the tank within (55 ± 0.5) °C.

The thermal storage capacity can be determined as the ratio between the tank volume (V_t) and the collecting area (A_c). For solar installations operating with water pumping, typical values for this relationship range between 50 and 75 L/m^2 (Duffie & Beckman, 1991; Shariah & Löf, 1997), and projects of Brazilian solar pumped systems, such as thermosyphon heaters, have complied with such limits.

The considered tanks are either vertical or horizontal cylinders with length/diameter (L/D) ratio equal to 2.5. Therefore, the demanded volume was specified as a function of the demanded volume/tank ratio, V_d/V_t. The considered values are: 1/3, 1/2 and 1, which can be applied in most major applications. The project temperature is 40 °C, which is common in domestic appliances, mainly destined to supply hot water for bathing.

The temperature control is achieved by the mixer, where cold water is added until the required level of temperature is reached. The residential and commercial hot water consumption profile is highly variable during a day depending on residents' consumption habits and duration of business hours. However, several studies have been reported on attempts to find a valid average consumption profile for residential applications. For example, Daghigh et al. (2015) and Abdunnabi et al. (2019) adopted a normalized profile of hourly hot water utilization for a domestic application in Malaysia, and Libya, respectively, where the usage of hot water is concentrated in morning and evening hours. Although being originally evaluated in American residences, this profile is commonly used in solar heating systems studies. However, the adopted consumption profile is more applicable to Brazilian conditions. Hence, the consumption of hot water in the morning (between 7 and 10 hours) corresponds to 30 %, and the remaining 70 % occurs at night (between 18 and 21 hours).

3. Simulation

The software *TRNSYS* models the thermosyphon solar water system by considering that:

i. the system operates at steady state conditions;
ii. the storage tank is stratified;
iii. the circuit is divided into a number of segments normal to the flow direction;
iv. Bernoulli's equation for incompressible flow is applied for each segment in the thermosyphon loop to calculate the pressure drop;
v. the mass flow is solved iteratively for each time interval, aiming to satisfy the balance between the pressure drop and the calculated buoyancy forces.

The required hourly meteorological data (humid bulb temperature, dry bulb temperature and global solar radiation in the horizontal surface) were obtained from the previous study, according to Siqueira (1996). In the present study, the Reduced Correlation by Reindl et al. (1990) was used to obtain the direct and diffuse radiation at horizontal surfaces from the total horizontal radiation. To convert the data for the sloping surface, the Perez's Model (Perez et al., 1988) was adopted. The simulations were performed for one year, using a temporal space of 3600 s.

4. Results and Discussions

More than 300 simulations were performed that resulted in about 4,000 monthly data of thermal efficiency for several combinations of V_t/A_c, V_d/V_t, $F_R(\tau\alpha)$, F_RU_L, H_T and T_a. The results show that the thermal efficiency:

I. is directly proportional to V_t/A_c. For the same collection area, the efficiency increases with increasing tank volume.

II. is directly proportional to V_d/V_t. It was observed that, if the other parameters are fixed, the efficiency also increases with increasing load volume.

III. is directly proportional to T_{sa}, which is a function of the incident radiation and the room temperature.

IV. depends strongly on the collector quality.

These results were statistically treated. The thermal efficiency (η) can be expressed by the correlation given by equation 1, as a function of several parameters, as follows:

$$\eta = a\eta_{ref} + b \tag{1}$$

$$\eta_{ref} = F_R(\tau\alpha) - \frac{F_R U_L (T_p - T_a)}{I_{T\,ref}} \tag{2}$$

$$a = a_1 T_{sa} + a_2 \tag{3}$$

$$b = b_1 T_{sa} + b_2 \tag{4}$$

$$a_1 = a_{11}\, {}^{V_t}/_{A_c} + a_{12} \tag{5}$$

$$a_2 = a_{21}\, {}^{V_t}/_{A_c} + a_{22} \tag{6}$$

$$b_1 = b_{11}\, {}^{V_t}/_{A_c} + b_{12} \tag{7}$$

$$b_2 = b_{21}\, {}^{V_t}/_{A_c} + b_{22} \tag{8}$$

$$a_{11} = 0{,}0003\, {}^{V_d}/_{V_t} - 0{,}0002 \tag{9}$$

$$a_{12} = -0{,}0159\, {}^{V_d}/_{V_t} - 0{,}0017 \tag{10}$$

$$a_{21} = -0{,}0086\, {}^{V_d}/_{V_t} + 0{,}0072 \tag{11}$$

$$a_{22} = -0{,}6690\, {}^{V_d}/_{V_t} + 0{,}2228 \tag{12}$$

$$b_{11} = -8.10^{-5}\, {}^{V_d}/_{V_t} + 2.10^{-5} \tag{13}$$

$$b_{12} = 0{,}0028\, {}^{V_d}/_{V_t} + 0{,}0014 \tag{14}$$

$$b_{21} = -0{,}0027\, {}^{V_d}/_{V_t} + 0{,}0009 \tag{15}$$

$$b_{22} = -0{,}0075\, {}^{V_d}/_{V_t} - 0{,}0935 \tag{16}$$

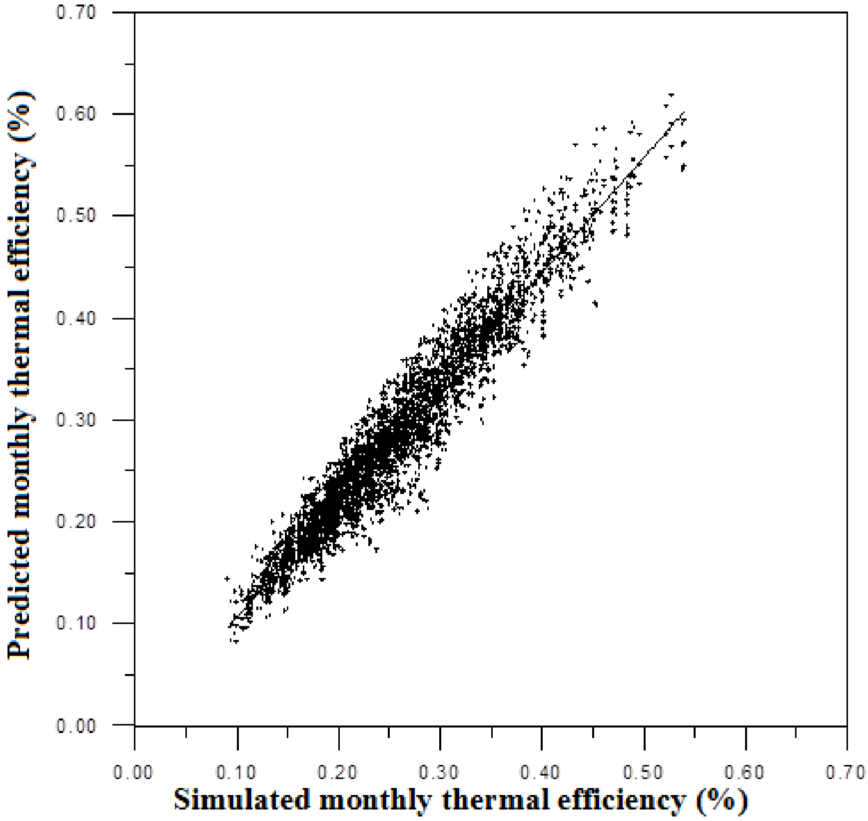
$$T_{sa} = T_a + \frac{F_R(\tau\alpha)_{ref}}{F_R U_{L\,ref}} \frac{H_T}{24} \tag{17}$$

Where:

- η_{ref} = reference thermal efficiency.
- $F_R(\tau\alpha)_{ref}$ and $F_RU_{Lref.}$ = reference parameters, 0.75 and 7 W/(m^2.K), respectively.
- T_P = project temperature (= 55 ºC).
- T_a = average monthly room temperature [ºC].
- H_T = average monthly daily global solar radiation at the collector surface [MJ/m^2].
- I_{Tref} = reference global solar irradiance at the collector surface (= 800 W/m^2).

The correlation given by equation 1 corresponds to a configuration that is usually weighted by considering a demanded profile for Brazilian conditions. It is necessary to highlight this finding, since it was observed that the demanded profile affects the thermosiphon performance. In Figure 1, the comparison between predicted (by correlation) and simulated results (obtained using *TRNSYS*) is graphically presented. The average relative deviation was 10 %, the absolute deviation was 3 %, and the maximum relative deviation was 14 %. It was observed that 81 % of the cases presented absolute deviation lower than 5 %, and 93 % of the studies presented absolute deviation lower than 7 %. Furthermore, 99 % of all the studied cases presented a deviation lower than 10 %, by comparing the values of the average thermal efficiency, calculated by correlation, and those obtained by simulation using the software *TRNSYS*.

Figure 1. Comparison of predicted and simulated monthly thermal efficiency.



Source: Authors.

Besides the V_t/A_c, V_d/V_t, $F_R(\tau\alpha)$, F_RU_L, H_T and T_a variables and the demanded profile, the thermal efficiency is also affected by the tank configuration (either horizontal or vertical), by the tank position related to the collector and by the tank L/D ratio. Aiming to evaluated the effect of these variables, additional simulations were performed. Although it was not possible to obtain a simple mathematical expression that could be related to efficiency, the simulation results showed, in a general way, that: (1) the thermal efficiency increased with the growth of the vertical distance between the tank bottom and the collector entrance, H_o; and (2) as the L/D ratio increases, the thermal efficiency decreases for horizontal tanks and increases for vertical tanks.

The first observation is coherent with literature data that demonstrated the necessity to use a vertical spacing between the collector top and the tank bottom, aiming to reduce the losses by reversed flux. Nevertheless, since the simulation considers a retention value associated with the system, the increase in efficiency with H_o refers to the rise of the system energy potency, which, in other words, corresponds to the thermosiphon load induced in the circuit (Siqueira, 1996; Huang, 1980). Vaxman & Sokolov (1986) demonstrated that the thermosiphon efficiency depends on the unevenness between the collector top and the thermal reservoir bottom (Δh). They concluded that the system performance is optimized for $\Delta h > 0$, recommending that Δh lies between 0.30 and 0.80 m.

The second observation expresses that the thermosiphon system operates with a higher thermal income as it becomes more thermally stratified. Therefore, the vertical tanks present better efficiencies than the horizontal ones, which is in agreement with Morrison and Braun (1985).

Thus, even if the obtained correlation does not consider the tank position or its L/D ratio, the results demonstrate that this correlation can be used for any radiation, H_T, average room temperature, T_a, and project ratio, V_t/A_c and V_d/V_t, values, considering the flat collector as a quality indicator expressed by the efficiency curve parameters $F_R(\tau\alpha)$ and F_RU_L. The correlation given by Equation 1 is, therefore, a simple and fast alternative for the thermal efficiency calculation of thermosiphon solar water-heating systems. This equation avoids the necessity to implement experimental procedures or complex numeric computational simulations.

5. Sizing

In order to fulfill the objective of this investigation, the technique of polymer chain characterization through probability density functions was examined. The algorithm used can be directly applied by scientists to develop new materials. This is particularly important for the generation of straight-chain polymers with one or more monomers, in temperature-controlled batch reactors, being the latter condition very common with current technologies. This is an improvement when saving time and reagents.

The obtained correlation can be used to size a thermosyphon solar water-heating system. It must be understood that *sizing* involves the establishment of the collection area and the volume storage tank that would be necessary to satisfy the load. Hence, it was necessary to previously specify the appropriate parameters, as follows:

i. collector type to be used, defined by parameters that characterize the optical and thermal losses, $F_R(\tau\alpha)$ and F_RU_L, respectively.
ii. the project temperature, that is, the temperature level at which the water tank should be maintained to reach the temperature required for the load.
iii. local meteorological data where the solar water-heating system is installed.
iv. maximum daily required hot-water consumption.

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The meteorological data accounts for the average monthly values of the temperature settings and the incident solar radiation on the collectors' surface. In general, the radiation data is only available on the horizontal surface. However, the user can estimate the values for inclined surface using specific correlations (Reindl et al., 1990; Perez et al., 1988), with satisfactory results.

Once the collector type is defined, the user can calculate the daily thermal load using the average monthly temperature setting and the reference thermal efficiency given by Equation 2. For the establishment of the monthly daily thermal load, the user should specify the amount of water to be consumed (V_d) and the consumption temperature (T_p). Then, the thermal load (CT, in MJ) can be calculated with Equation 18, where C_P is the water specific heat [kJ/(kg.K)].

$$CT = V_d C_p (T_p - T_a) \tag{18}$$

After determining the thermal load and the reference efficiency, the minimal collectors' area to satisfy the load should be estimated. Therefore, the project values for $(V_t/A_c)_p$ and $(V_d/V_t)_p$ parameters should be defined within the following ranges: $50 < V_t/A_c < 100$ and $1/3 < V_d/V_t < 1$. In the subsequent stage, the monthly thermal efficiency values are calculated for the configuration using the correlation obtained in this work (Equation 1). The collectors' area is calculated by dividing CT by the average monthly thermal efficiency product, η, and the solar radiation, H_T.

Table 2 shows some data for the methodology suggested to estimate the required size of the system in order to supply a water load of 200 L at 55 ºC. In this example, $F_R(\tau\alpha) = 0.75$ and $F_RU_L = 7$ W/(m^2.K). The second and third columns of Table 2 present the meteorological data applicable to the local installation, namely H_T and T_a. The fourth column exhibits the reference efficiency values, η_{ref}, and the fifth column shows the monthly daily thermal load, CT. The sixth columns lists the monthly thermal efficiency values estimated by the correlation with $(V_t/A_c)_p$ = 100 L/m^2 and $(V_d/V_t)_p = 1$.

Table 2. Thermosyphon solar water-heating system size determination. *

Month	H_T / [MJ/m^2]	T_a / ºC	η_{ref}	*CT* / MJ	η	$[CT/(\eta H_T)]$ / m^2	Q_{aux} / MJ	$\Im$
January	18.83	24.61	0.49	25.47	0.20	3.77	0.00	1.00
February.	15.84	24.35	0.48	25.68	0.22	4.27	0.00	1.00
March	15.23	23.42	0.48	26.46	0.22	4.50	0.00	1.00
April	13.50	19.83	0.44	29.47	0.24	5.43	0.00	1.00
May	11.05	14.42	0.40	34.01	0.27	7.32	6.11	0.82
June	9.47	14.87	0.40	33.63	0.27	8.26	9.19	0.73
July	9.68	13.69	0.39	34.62	0.27	8.32	9.67	0.72
August	10.98	16.24	0.41	32.48	0.26	7.02	4.72	0.85
September	13.90	16.94	0.42	31.89	0.25	5.70	0.00	1.00
October	13.90	18.31	0.43	30.75	0.25	5.51	0.00	1.00
November	16.92	21.27	0.46	28.27	0.22	4.42	0.00	1.00
December	18.65	23.20	0.47	26.65	0.20	3.94	0.00	1.00

*$F_R(\tau\alpha)$ = 0.75; F_RU_L = 7 W/(m^2.K); V_t/A_c = 100 L/m^2; V_d/V_t = 1; V_d = 200 L; T_p = 55 ºC. Source: Authors.

Finally, the seventh column exhibits the values of $CT/(\eta.H_T)$ for every month. The average of the 12 results given in this column is the recommended area, aiming to satisfy the specified consumption. The thermal storage tank volume is calculated by the product between the collectors' area and $(V_t/A_c)_p$. Thus, in order to supply the 200 daily liters of water at 55 ºC, approximately 6 m^2 of collector area is required, operating with $F_R(\tau\alpha)$ = 0.75 and F_RU_L = 7 W/(m^2.K), and a tank capacity of 600 L. It is observed that this area is lower than the minimum required in the winter and higher than that required for other seasons of the year in the Southern hemisphere. The eighth column presents the difference between the energy required by *CT* and the solar energy converted into heat, ηH_TA_c. These values correspond to the amount of energy that should be supplied by the energy auxiliary support (Q_{aux}). The last column contains the monthly values of the solar fraction, $\Im$, which is defined as the ratio between the energy supplied exclusively by the solar collector and the total energy required to supply the load (Equation 19).

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$$\Im = \frac{CT - Q_{aux}}{CT} \tag{19}$$

If $\Im$ is equal to 1, all energy supplied to heat the water is completely provided by the solar collector at the required temperature level, without the need of extra energy. In this specific example, it can be observed that auxiliary power source is required only in the winter. In the months of May, June, July and August, about 82, 73, 72 and 85 %, respectively, of the necessary energy was supplied by the solar system. In the other months, there was no need of auxiliary energy.

The sizing results for different project parameters, $(V_t/A_c)_p$ and $(V_d/V_t)_p$, are presented in Table 3. The values of the thermal efficiency annual source are listed in the third column. The final selection of the collectors' area should be made in agreement with the user's needs, as a function of the *autonomy days* (last column of Table 3) and the cost-benefit relationship.

As indicated by Table 3, the tank volume has a significant effect in reducing the system performance. It is noticed that the optimum tank volume $[(V_t/A_c)_p]$ would be about 100 L/m^2 when the daily amount of processed hot water is 1 liter per tank volume liter $[(V_d/V_t)_p]$. The effect of increasing the amount of processed hot water in the system is also shown in Table 3.

Table 3. Thermosyphon solar heater sizing for different project parameters, $(V_t/A_c)_p$ and $(V_d/V_t)_p$.**

$(V_t/A_c)_p$ / [L/m^2]	$(V_d/V_t)_p$	η_{annual}	A_c / m^2	V_t / L	V_d/V_t	*Aut. day*
50	1.00	0.28	8	400	0.50	2.0
50	0.50	0.19	12	600	0.33	3.0
50	0.33	0.16	14	700	0.29	3.5
75	1.00	0.34	7	525	0.38	2.6
75	0.50	0.24	9	675	0.30	3.4
75	0.33	0.21	11	825	0.24	4.1
100	1.00	0.40	6	600	0.33	3.0
100	0.50	0.29	8	800	0.25	4.0
100	0.33	0.25	9	900	0.22	4.5

**$F_R(\tau\alpha)$ = 0.75; F_RU_L = 7 W/(m^2.K); V_d = 200 L; T_p = 55°C. Source: Authors.

In theory, the analytical model-tool discussed in this work should significantly reduce the engineering time by creating the ability to test different variables in a computer program, rather than in physical test models. Also, theoretically, the use of the developed tool could reduce costs by eliminating the need for physical prototypes to be constructed and tested in a laboratory.

6. Conclusion

In this study, a great number of simulations were carried out with the *TRNSYS* software for the thermal behavior of thermosiphon solar water-heating systems, which are the most common ones in Brazil. After executing the simulations, it was observed that the system performance is affected by the variation of parameters such as (thermal storage volume)/(collector's area) ratio, demanded volume, temperature of the consumption hot water and meteorological conditions, as well as the collector's quality parameters $F_R(\tau\alpha)$ and F_RU_L. The data were statistically treated, creating a mathematical correlation to determine the average monthly thermal efficiency.

Having in account the developed correlation, a new approach to design and sizing of thermosiphon solar heating systems was presented. This new methodology is also benefited by the used of the *F-Chart* commercial program, one of the most employed in the market, and by the fact that the sizing program was developed exclusively for thermosiphon systems, without heat exchangers in the tank.

Furthermore, its mathematical modeling considers thermal stratification, which is an important requirement in such applications. The presented methodology is simple to be implemented and requires only basic knowledge on the concepts of solar energy. Similar studies can be developed to find the optimum design system for forced circulation (active) systems.

Acknowledgments

This research was carried out with financial support granted by the Higher Education Personnel Improvement Coordination - Brazil (*CAPES*), Financing Code 001, and the Minas Gerais State Research Support Foundation (*FAPEMIG*).

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Percentage of contribution of each author in the manuscript

Antônio Marcos de Oliveira Siqueira – 60%

Alexandre Gurgel – 20%

Zeji Ge – 10%

Fernando Ariel Colque – 5%

Gabriel Siqueira Silva – 5%