A Software for Performance Simulation of Solar Water Heating Systems

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Abstract: This paper presents a software that simulates the thermal performance of a solar water heating system. The implemented model computes the mass and energy balances in the thermal tank in each time step along a simulation interval. Its input data are values from a typical meteorological year of a chosen location and the hot water load. The system components are the hot water storage tank and the solar collector. Firstly, it is presented the validation of the model, and then a solar water heating system is simulated in two different cities along one year. It was obtained the water temperature in the storage tank for each hour of the year and those values were compared with the values obtained by the widespread TRNSYS simulation software. The results obtained from this comparison were satisfactory.

Key–Words: solar energy, water heating, thermal simulation, software

1 Introduction

The Brazilian electrical network presents an electric energy consumption peak from 6 pm to 9 pm, with a great contribution of instant electric water heaters. The solar water heating is the most appropriate solution for shaving this peak, and consequently, to postpone the necessity of expanding the national electrical power system.

Although a great solar energy potential is available countrywide, its exploitation is mainly restricted by the major equipment installation costs and the lack of a minimum performance guarantee.

Developing computational tools that allows predicting the thermal performance of solar water heating systems is a potential way to proportionate conditions to the designers to precisely estimate the payback period, contributing for increasing the solar water heater penetration.

It is widely recognised that the most accurate and complete solar design tool currently available is the TRNSYS computer simulation model, developed by [3]. This tool has been very much enriched and refined and its validity and accuracy has been repeatedly confirmed since then. It is very appropriate as an analysis and research tool, however, its widespread use is ruled out by cost, the relatively long user experience and appreciable expertise required to exploit the full model capabilities and the relatively complex meteorological data required [4]. The f-Chart method was developed as a low cost and simplified design tool ([2], [6]) based on the mathematical correlation of extensive computer simulation results by TRNSYS, in which conditions were varied over an appropriate range of system parameters involved.

Results obtained by the f-chart method have been compared extremely well with the results from detailed simulations for a variety of geographical locations in both the USA and Europe. With the exception of a slight under prediction in cloudy climates, it was found by [5] that the method predicted solar system performance with better than 2.2% accuracy for domestic solar water heating systems [4].

The f-Chart method offers serious advantages for the designer and field engineer, but it has many limitations, such as the specific design configuration, system size and design parameter restrictions, as well as the lack of flexibility to cover any hourly load demand profile [4]. Furthermore, the amount of f-Chart validation studies available for geographical locations in the South Hemisphere is still low, and some cold climate design characteristics, as anti-frozen fluid requiring an intermediate heat exchanger, are not applicable in the Brazilian designs.

This paper presents a computational simulation tool for predicting the thermal performance of solar water heating systems, with less configuration constraints than the f-Chart method, encompassing the design of systems with hot water consumption profiles varied and allowing altering many geometric factors of the system components and other design parameters.

2 Materials and Methods

2.1 Software Description

The software was developed in the MATLAB environment. It approaches water heating systems with a storage tank and a solar collector operating under forced circulation. The energetic analysis do not include neither auxiliary heater nor pipeline. Figure 1 presents the system configuration. The model assumptions are:

- The thermal tank containing the stored hot water is treated by the fully-mixed model, i.e. there is no internal thermal stratification.
- No intermediate heat exchanger is regarded and the same water flowing through the collector is stored in the tank.
- There is a controller that turns the pump only if there is a minimum temperature difference and an useful energy output from the collector to justify it. The reverse flow from the tank to the collector in the case of negative temperature gradient is not allowed.
- The solar collector model uses a linear form of the collector efficiency and does not include incidence angle modifier for correction of the inclination angle.

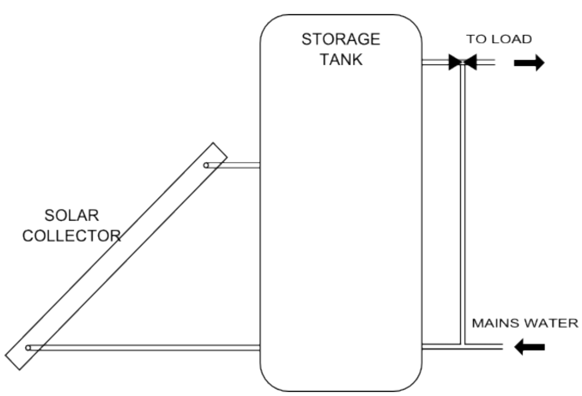

Figure 1: **Solar water system layout.**

The software principle is to apply the mass and energy balances on the storage tank at each time step. It considers the input heat from the solar collector, heat losses through the walls and output heat by the water consumed. At the end of each time step a new temperature of the water inside the container is calculated and the process restarts with new balances. The software then runs step by step till the number of increments desired is achieved.

The energy balance of the thermal tank leads to the differential equation with time as the independent variable according to [1]:

$$\frac{dE_{int}}{dt} = Q_u + E_{af} - E_{aq} - L_p \quad (1)$$

where Q_u is the useful heat flux from collector, E_{af} is the cold water enthalpy rate, E_{aq} is the hot water enthalpy rate, L_p is the thermal losses through the tank wall and t is time.

Maintaining constant the mass of water in the storage tank (m) and neglecting the variation of specific heat (C_p) with temperature (T), it follows:

$$\frac{(mC_p)dT}{dt} = Q_u + E_{af} - E_{aq} - L_p \quad (2)$$

For the solar collector, the useful output heat flux is the difference between the thermal power absorbed by the collector plate and heat losses to the environment. This difference can be expressed based on the Hottel-Williers equation as described in [1]:

$$Q_u = A_c F_R [G_T(\tau\alpha) - U_L(T_i - T_a)] \quad (3)$$

where F_R is the heat removal factor defined as the ratio between the actual useful energy gain of a collector and the useful gain if the whole collector surface were at the fluid inlet temperature. $(\tau\alpha)$ is the product of the coverage transmittance by the collector plate absorbtance, G_T is the incident irradiance on the collector. U_L is the overall heat loss coefficient, which includes all losses from the collector. T_i and T_a are the water temperature at collector inlet and the environment temperature, respectively. A_c is the total area of the collector.

The values of $F_R(\tau\alpha)$ and $F_R U_L$ express the collector efficiency linear behavior and are obtained from standardized tests (ABNT NBR 15747 [9], ASHRAE93 [7]), available in Brazil from the Brazilian Labeling Program (PBE) coordinated by INMETRO.

The balance of enthalpy related to hot water consumption can be written as follows, considering equal mass flow $\dot{m}_{af}$ of the hot water leaving and the cold mains water entering the tank:

$$E_{af} - E_{aq} = \dot{m}_{af} C_p (T_{aq} - T_{af}) \quad (4)$$

where T_{aq} and T_{af} are the consumed hot and restored cold water temperatures. The heat loss through the walls of the tank can be written by:

$$L_p = (UA)(T - T'_a) \tag{5}$$

where A is the corresponding area, T'_a is the environment temperature and U is the global coefficient, which includes all the thermal losses. This last parameter can be obtained from standardized tests prescribed by the ABNT NBR10185 [8], also within the PBE.

Replacing the equations of the components in equation (2) it is obtained:

$$\begin{aligned}(mC_p)\frac{dT}{dt} &= A_c F_R[G_T(\tau\alpha) - U_L(T_i - T_a)] - \\ &\dot{m}_{af} C_p (T - T_{af}) - (UA)(T - T'_a)\end{aligned} \tag{6}$$

Rearranging for the water temperature and using a simple Euler integration [1], it is achieved the equation for one time increment Δt:

$$\begin{aligned}T^+ - T = \frac{\Delta t}{(mC_p)} \{&A_c F_R[G_T(\tau\alpha) - U_L(T_i - T_a)] \\ &- \dot{m}_{af} C_p (T - T_{af}) - (UA)(T - T'_a)\}\end{aligned} \tag{7}$$

where T^+ represents the tank temperature at the end of a time step.

The software works with a hourly time step. In general, most weather data files available have average monthly or hourly radiation data.

2.2 Input Data

The incident radiation, ambient temperature, mains water temperature and the hot water load must be supplied at each time step. The radiation and the ambient air temperature are read from a file containing a typical meteorological year data. Those files have data generated from measurements made at each location for decades. The file used by the software has the EPW (Energy Plus Weather) format and is described by [10]. In this format, each file corresponds to a city, with information about the weather station and its geographical position.

This file has hourly radiation data that represents the average value integrated in one hour. The types of radiation are horizontal global, direct normal and horizontal diffuse. From these data the model calculates the total solar radiation incident on an inclined surface, I_T. In theory this is a sum of a set of radiation streams including the beam radiation, different types of diffuse radiation from the sky and the reflected diffusively by surrounding surfaces [1].

The software uses the *isotropic diffuse* method developed by Liu and Jordan (1963). The radiation on the tilted surface is considered to include the three components: the beam radiation, the isotropic diffuse, and solar radiation reflected from the ground. One tilted surface with inclination β to the horizontal has a view factor to the sky $F_{c-s} = (1 + \cos\beta)/2$ and a view factor to ground $F_{c-g} = (1 - \cos\beta)/2$. The total incident radiation can be written as[1]:

$$I_T = I_b R_b + I_d \left(\frac{1 + \cos\beta}{2}\right) + I\rho_g \left(\frac{1 - \cos\beta}{2}\right) \tag{8}$$

where ρ_g is the surrounding albedo, R_b is the ratio of beam radiation on tilted surface to that on a horizontal surface and is defined as:

$$R_b = \frac{\cos\theta}{\cos\theta_z} \tag{9}$$

where θ is the angle of incidence and θ_z is the zenith angle.

From the horizontal values of global (I) and diffuse (I_d) radiation it is calculated the value of beam radiation on a horizontal surface (I_b) making the simple subtraction:

$$I_b = I - I_d \tag{10}$$

The hot water load data must be specified through a file with 8760 lines, each one corresponding to one hour of the year. The entering values must be the mass of water consumed in kg.

2.3 Validation

The validation of the software was carried out in two parts. Firstly the calculated incident radiation on a tilted surface and the produced collector model were both compared with results generated by TRNSYS. Then the complete system was analysed in two cases and the tank temperature was compared with the values achieved by TRNSYS.

2.3.1 Radiation Processor

The TRNSYS TYPE 16 was used for validating the software calculation of the incident solar radiation on the collector. Table 1 presents the used values of the TRNSYS parameters.

PARAMETER	VALUE
1 (Horiz. Radiation Mode)	5 (I e I_d)
3 (Sky Method)	1 (isotropic diffuse)
5 (Latitude)	-23,3°

Table 1: Parameter configuration for TYPE 16 TRNSYS component.

The Radiation processor component also needs input values. The main input values used are shown in table 2.

INPUT	VALUE
1 - I	EPW file
2 - I_d	EPW file
5 - ρ (albedo)	0,2
6 -β (collector inclination)	23°
7 - γ (azimuth)	0 (to equator)

Table 2: Input values for configuring the TYPE 16 TRNSYS component.

The results obtained with the software and the TRNSYS results had negligible differences.

2.3.2 Collector

The TRNSYS TYPE 1 was used for validating the software collector model. The parameters and input values for configuration this TRNSYS component are shown in the table 3.

PARAMETER	VALUE
2	6.5
4	1
5	50
6	0.7
7	15
8	0
9	1

Table 3: Parameter configuration for TYPE 1 TRNSYS component.

The input values were adjusted constants except the incident radiation I_T read from a file. The values are shown as in table 4.

INPUT	Valor
1 - inlet temperature (T_i)	20°C
2 - inlet flow ($\dot{m}$)	325 kg/h
3 - ambient temperature (T_a)	25°C
4 - incident radiation (I_T)	read from file

Table 4: Input values configuring for TYPE 1 TRNSYS component.

The results obtained with the software and the TRNSYS results had negligible differences.

2.3.3 Complete System

For validating the complete system, the collector inclination was set equal to the local latitude for both two cases. The hot water load was configured to half volume tank per day at 19h. The mains water temperature was adjusted to 20°C. Table 5 presents the software input data.

Collector	
$F_R(\tau\alpha)$	0.7
$F_R U_L$ (W/m^2°C)	4.16
Area (m^2)	6.5
Inclination (°)	23(Rio), 41(Istanbul)
Azimuth	to equator
Mass flow (kg/h)	325
Thermal Tank	
Volume (m^3)	1
Height (m)	1.2
U (W/m^2°C)	1.3600

Table 5: Software input data.

3 Results and Discussion

The temperature in the thermal tank calculated by the current software and the TRNSYS has presented similar profiles throughout the year. Figures from 2 to 5 present the hourly values for the temperature in the tank in the beginning and in the middle of the year. In this comparison the average difference for the hourly temperature was 3.73% for Rio de Janeiro and 2.81% for Istanbul.

Additionally, for both locations the incident radiation on the collector surface have produced very closed values within a 0.05% of hourly average difference for Istanbul and 0.07% for Rio de Janeiro.

Figures 6 and 7 show a good approach between the present software and TRNSYS for the monthly and daily average tank temperatures for de Rio de

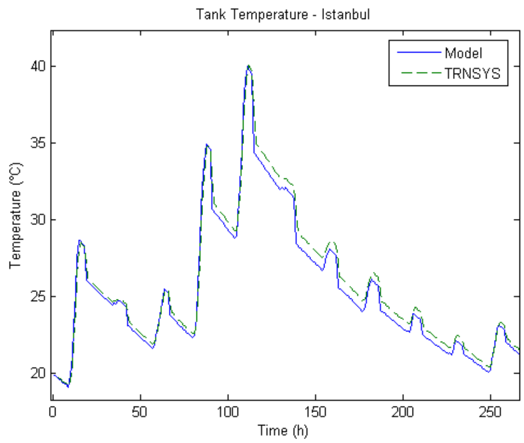

Figure 2: **Tank temperature for few days in January for Istanbul.**

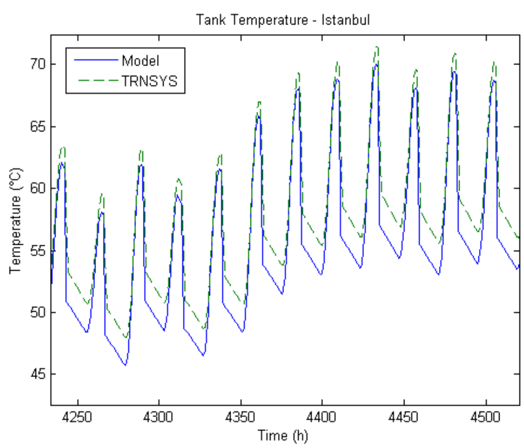

Figure 3: **Tank temperature for few days in June for Istanbul.**

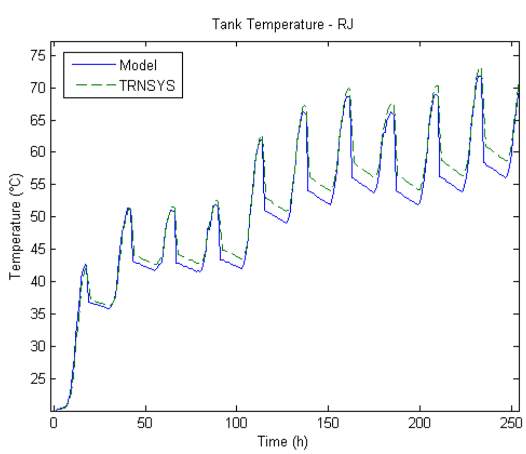

Figure 4: **Tank temperature for few days in January for Rio de Janeiro.**

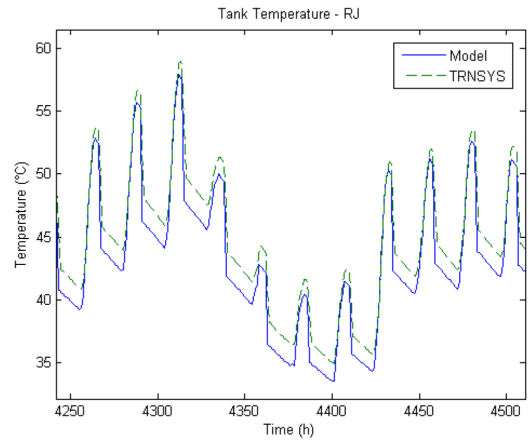

Figure 5: **Tank temperature for few days in June for Rio de Janeiro.**

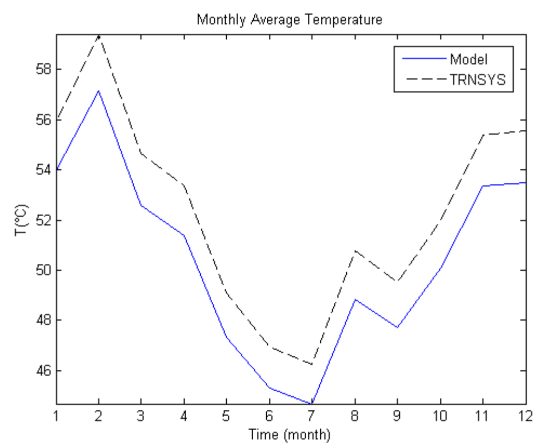

Figure 6: **The monthly average tank temperature for Rio de Janeiro.**

Janeiro. The same occurs for Istanbul and is shown in the figures 8 and 9.

4 Conclusion

The difference between the values obtained by the computer model presented in this paper and the widespread TRNSYS computer model was quite small and therefore acceptable. However the fact that the TRNSYS values for tank temperature are always greater than those for the present model deserves further investigation. In short, considering a conservative point of view it can be stated that the model herein presented achieved its objective.

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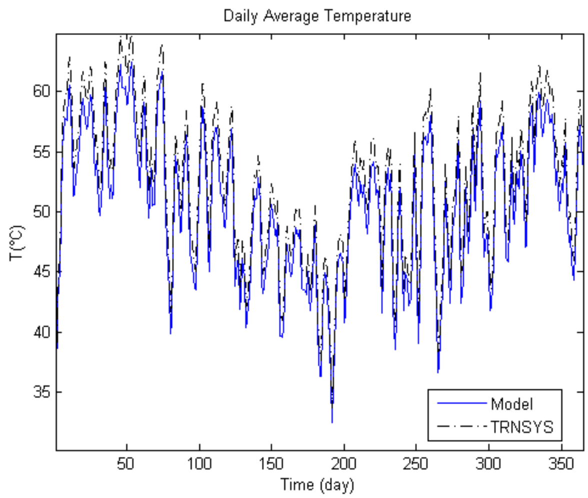

Figure 7: **The daily average tank temperature for Rio de Janeiro.**

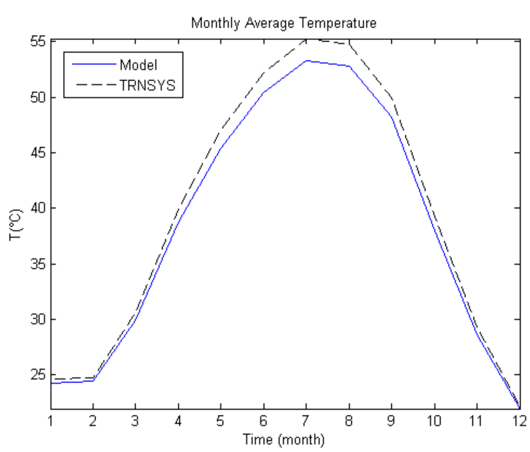

Figure 8: **The monthly average tank temperature for Istanbul.**

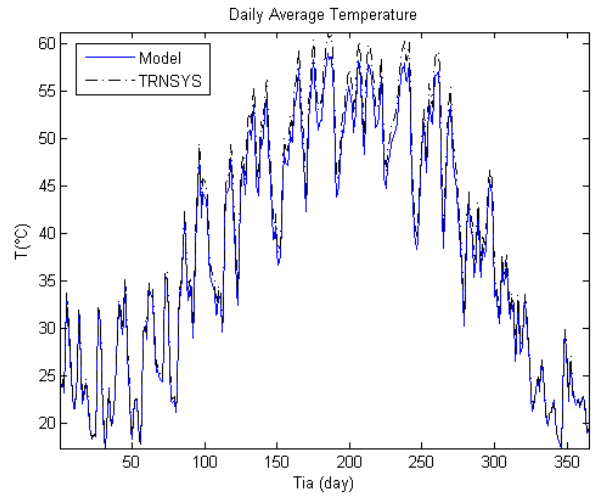

Figure 9: **The daily average tank temperature for Istanbul.**

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