A SIMULATION METHOD FOR THERMOSYPHON SOLAR WATER HEATER SYSTEM

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Abstract. *This paper presents an unsteady state theoretical analysis of a thermosyphon solar water heater system that have been widely used for a long time due lower installation cost and maintenance requirement comparing with forced systems. The energy and momentum governing equations of the solar collector, storage tank and connecting pipes are presented in dimensionless form. Calculations and measurements were performed on the mass flow rate, temperature rise fluid and storage tanks temperatures. The solar collectors are modeled according the classical quasi-steady approximation by Hottel-Bliss-Whillier theory. The storage tank is modeled as stratified liquid tank with internode convection and conduction, stored internal energy and different loss overall coefficients from tank exterior for the nodes. The collector mass flow rate is evaluated from a balance between the friction pressure drop and the pressure due to density differences around the thermosyphon circuit (thermosyphon head). A newly loop resistance relation is present in this work. Drawoff during the day, no ideal weather conditions, different load patterns and auxiliary heating are assumed. This simulation method developed can be useful in a rating method for the thermal performance of thermosyphon water heaters.*

Keywords*: Thermosyphon, solar systems, natural circulation, solar water heater.*

1. Introduction

The solar heater represents a technically and economically viable water heating system, which utilization has been increased in Brazil and in the world (Siqueira, 1996). The solar heater system is divided into flat-plate collectors, insulated storage tank, hydraulic pipes, auxiliary energy system and control device (optional). It employs natural or forced-circulation between the flat-plate-collector and the insulated storage tank (Fig. (1)). Based on the flow circulation, the system is classified as both open loop or closed loop (with heat exchanger between the solar loop fluid and the storage medium) and forced-circulation (by external pumping) or natural circulation (passive solar water heaters). In the natural circulation operational mode (typical for small systems), the fluid density reduction caused by the collector's warming up promotes a motion force (thermosiphon head). The warm fluid flows towards the storage tank and the cold fluid (tank bottom and tank-to- collector feed pipe) flows back to the collector. These systems are called for thermosyphons solar water heaters. The fluid flow is generated by an electric pump on larger systems. Electrical or gas auxiliary energy supply, thermostat controlled, is necessary for clouded days or for water overload.

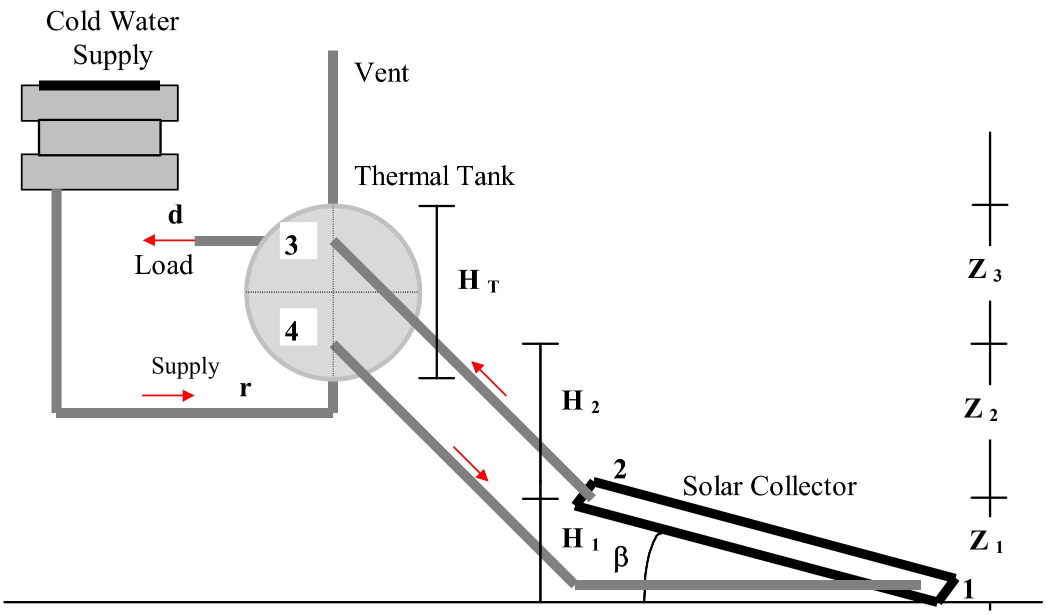

Figure 1. Schematic configuration of the natural circulation solar water heater.

Several theoretical works have been proposed (Norton, 1992 and Norton and Probert, 1986) on thermal performance evaluation and solar fraction estimation of solar water heaters. The models include many simplifications, which makes the analysis unrealistic, or are very complex, which makes the analysis inappropriate for long-term performance evaluation. Physical models are very expensive. They require time and cannot give accurate information under different operational solar radiation exposition and load conditions. However they are very important to compare different designs and experimental procedures. The accuracy of the analysis establishes the prediction error, which defines the appropriate dimensions, the correct design and cost for a solar water system. Solar water heating systems are usually designed, using empirical considerations (due to the lack of accurate information on appropriate geometric and operational characteristics) and comparative studies on system performance with both natural and forced-circulation fluid motion strategies. In countries like Brazil, most systems use natural circulation and there is a lack of user-friendly simulation softwares for these heaters (Salvadoretti and Krenzinger, 1995). To supply this necessity the software *TermoSim* is in conclusion at UFRGS (Siqueira, 2003).

This paper presents a performance analysis of natural circulation solar water heaters (see Fig. (1)). In this system, the heated water in the collector flows to the upper part of the storage tank and the colder water in the lower part of the tank returns to the collector. This fluid loop happens several times during the day. Outlet load water flows from the upper part of the storage tank and it can be warmed or cooled, if necessary. Cold water is supplied to the lower part of the storage tank simultaneously.

Thermal performance analyses of natural circulation solar heaters use dimensionless parameters. These parameters describe constructive aspects of main components, thermal and pressure losses in the pipes, water load profile and meteorological data. Their use allows the prediction of solar heaters working characteristics.

2. Mathematical Modelling

Close (1962) proposed a mathematical model for natural circulation, considering clear day, no water load, linear temperature distribution in collector and tank, laminar flow. Huang (1980) described a mathematical model in dimensionless form, making the following assumptions: steady state laminar flow, no water load, no tank and pipes thermal losses and adopting a sinusoidal approach for the solar radiation at constant ambient temperature. The present work improves Huang's method by including water load profile, thermal stratification in the storage tank and thermal losses in the hydraulic pipes.

Accurate thermal performance prediction of natural circulation solar system requires detailed analysis of the interdependent momentum and energy equations. The following assumptions are made on the mathematical model: sheet and parallel tube flat-plate collector configuration, quasi-steady state, uniform flow in the tubes, no absorption of solar energy by the cover, glass cover opaque to infrared radiation, one-dimensional heat flow, temperature drop through the cover neglected, small area of collector headers neglected, one-dimensional heat flow through the back insulation; sky treated as blackbody for long-wave radiation, temperatures gradient around the tubes neglected, heat losses through front and back of the collector to the same ambient temperature, no dust and dirt on the collector, no shading of the collector absorber plate, multipass operation, constant volume and thermal stratified tank with no disturbing effects of inlet and outlet water flow. The mathematical model for natural circulation system was evaluated by dividing the components in sections (multinode approach).

Figure 1 shows mathematical variables used for the analyzed system. The subscripts 1 and 2 denote collector inlet and outlet; 3 and 4 storage tank inlet and outlet and d and r load and supply, respectively. To prevent reverse circulation and consequent collector thermal losses at night or at very low radiation levels, a minimum height difference between the bottom of the tank and the top of the collector is necessary, depicted as H_2 in Fig. (1). H_T and H_1 denote the heights of tank and collector, respectively. Energy balances in the collector (in one fluid element at a position in the tube x and at an instant of time t - Hottel-Bliss-Whillier's theory), in the storage tank (with N thermal stratified sections – multinode approach) – (Hussein, 2002) and in hydraulic pipes (thermal losses) result:

Collector:

$$T^* = F'N_{r1} + (T_1^* - F'N_{r1})\exp(-x^*/NUT_c) \tag{1}$$

Storage-Tank:

$$\frac{d\theta^*_i}{dt^*} = -\left(\frac{1}{N_{T1}} + \frac{F_i^c\,NUT_c N}{N_{T2}} + \frac{F_i^d N}{N_{T3}}\right)\theta^*_i + \frac{F_i^c\,NUT_c N}{N_{T2}} T_3^* + \frac{F_i^d N}{N_{T3}} T_r^* + \begin{cases} \dot{m}^*_i(\theta^*_{i-1} - \theta^*_i)\,,\ se\ \dot{m}^*_i > 0 \\ \dot{m}^*_i(\theta^*_i - \theta^*_{i+1}),\ se\ \dot{m}^*_i < 0 \end{cases} \tag{2}$$

Piping:

$$T^*_{TUB2\text{-}3} = T_2^* \exp(-y^*_{TUB2\text{-}3} / NUT_c\, N_{TUB2\text{-}3}) \tag{3a}$$

$$T^*_{TUB4\text{-}1} = T_4^* \exp(-y^*_{TUB4\text{-}1} / NUT_c\, N_{TUB4\text{-}1}) \tag{3b}$$

Momentum Equation:

$$\int_0^{H_1^*}\left[SG(T^*_{TUB4-1})-SG(T^*)\right]dz_1^* + \int_0^{H_2^*}\left[SG(T^*_{TUB4-1})-SG(T^*_{TUB2-3})\right]dz_2^* +$$

$$\int_0^{H_T^*}\left[SG(\theta^*)-SG(T^*_{TUB2-3})\right]dz_3^* = NUT_c\left[\nu^*_c/N_{F1}SG(\overline{T}_c)+\nu^*_{TUB2-3}/N_{F2}SG(\overline{T}_{TUB2-3})+\right. \tag{4}$$

$$\left.\nu^*_{TUB4-1}/N_{F3}SG(\overline{T}_{TUB4-1})\right]+\left[NUT_c\right]^2\left[1/N_{F4}\left(SG(\overline{T}_{TUB2-3})\right)^2+1/N_{F5}\left(SG(\overline{T}_{TUB4-1})\right)^2\right]$$

where T^* and $\theta^* \equiv (T-T_a)/(G_{SC}/F'U_L)$ are dimensionless temperatures, $x^* \equiv x/L_c$ dimensionless position, $NUT_C \equiv m_c c_p/(A_c F'U_L)$, $N_{r1} \equiv S/G_{SC}$, T_a is the environmental temperature, G_{sc} is the solar constant, S is the absorbed solar radiation by the collector absorber plate, L_c is the collector length, SG(T) is a relative specific density, F_i^c and F_i^d are control functions for the flow from collector and the load return into the tank, m_i^* is dimensionless liquid flow in to the tank section (function of the mass flow from the collector and the mass flow returning from the load and their temperatures), $N_{T1} \equiv [(\rho c_p V_T/n)/(NUA)_i]$ number of transfer units for the tank, $N_{T2} \equiv [(\rho c_p V_T/n)/A_c F'U_L]$ tank number, $N_{T3} \equiv [(\rho V_T/n)/m_d)]$ liquid mass in the tank to the load number, $N_{TUB}|_k \equiv [A_c F'.U_L/(U.P.L)_{tub}|_k$, with k=2-3≡ pipe 2-3 or k=4-1≡ pipe 4-1] pipes thermal losses number, $H^* \equiv (H/H_T)$ relative positioning of the tank/collector to the total height, $N_F|_k \equiv [(\rho c_p)/(A_c F'U_L gHn\pi/(128\nu^o)(D^4/L)|_k$, with k=1≡collector piping, or k≡2≡ pipe 2-3, or k≡3≡ pipe 4-1] and $N_F|_k \equiv [(\rho c_p/(A_c F'U_L))^2 gH\pi^2/8(D^4/E)|_k$, with k≡4≡ pipe 2-3 fittings or k≡5≡ pipe 4-1 fittings] piping hydraulic resistance numbers, $\nu^* \equiv \nu/\nu^o$ with ν^o the cinematic viscosity at a reference temperature (Siqueira, 1996).

3. Methodology

Solar water heater analysis requires meteorological knowledge of the local characteristics. The present analysis was developed for the city of Belo Horizonte (latitude: 19.93°S). Available meteorological data used were: monthly maximal, minimal and average ambient temperatures, monthly number of sunshine hours (Normais Climatológicas, 1992). Radiation data – hourly beam and diffuse components of monthly radiation - were estimated using measured number of daylight hours. December was defined as the standard-month, due to the lower number of sunshine hours. Concerning ambient temperature, it was assumed a sinusoidal function of the hour angle and the daily maximal and minimal temperatures. Since domestic hot water service is very variable, depending on social position and number of users, two different load profiles were adopted in this work: 1. *Distributed Demand* - DD – average residential hot-water usage proposed by Mutch (Kreith and Kreider, 1978) and 2. *Concentrated Demand* - DC - average residential hot-water usage proposed by Companhia Energética de Minas Gerais – CEMIG (1995), for higher class residences, with 30% of daily usage in the morning (uniformly distributed between 7 and 10 a.m.) and 70% in the afternoon (uniformly distributed between 6 and 9 p.m.). To evaluate thermal stratification in the storage tank it was adopted a time increment of 60 seconds and 5 nodes (volume sections); the collector and piping were divided into 3 nodes.

In case of natural circulation, a initial mass flow was assumed, at a given instant of time, and then energy balances were written for each section, resulting in a model for the fluid temperature time distribution around the heater loop. Simultaneously, the pressure drop in the loop was estimated considering laminar flow and local pressure drops in the connections and valves. Once the loop temperature distribution is predicted, the fluid motion force can be calculated and compared to the pressure drop. The mass flow is then adjusted for each time increment satisfying the momentum equation, that is, after fluid velocity estimation through the collector the total pressure drop is equalized to the thermosiphon head.

4. Results

The natural circulation system performance is strongly influenced by the hydraulic resistance (N_F), which becomes one the most significative design variables with respect to the thermal efficiency and storage tank positioning (H_2^*). The thermal efficiency increases with H_2^*. Lower hydraulic resistances assure higher efficiency (Fig. (2), (5) and (6)) and allow smaller distances between the bottom of the storage tank and the top of the collector (Fig. (2)). Lower ratios between tank volume and collector area (N_{T2}) cause lower efficiencies (Fig. (2) and (4)) and storage temperatures (Fig. (3)), resulting in a optimum design factor of 78 liters/m^2. Piping thermal losses (N_{TUB}) have more influence on the thermal performance (Fig. (7)) than the tank thermal losses (N_{T1}, Fig. (3)). Concerning the collector slope, a 10° increment on the local latitude was verified, according literature suggestion, also 30° for Belo Horizonte. According to Fig. (8), December seems to be the design standard-month for our city due to the higher cloudiness and intense rain. The results shown that the hot water load profile (distributed and concentrated demand) did not show appreciable effect on the thermal performance.

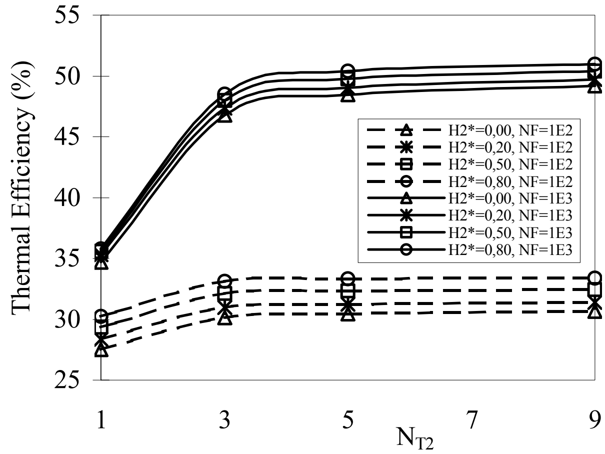

Figure 2. Effects of H_2*, N_{T2} and N_F on the thermal efficiency. (15≤ N_{T1} ≤ 1000; N_{TUB} = 10; F′ = 0.85)

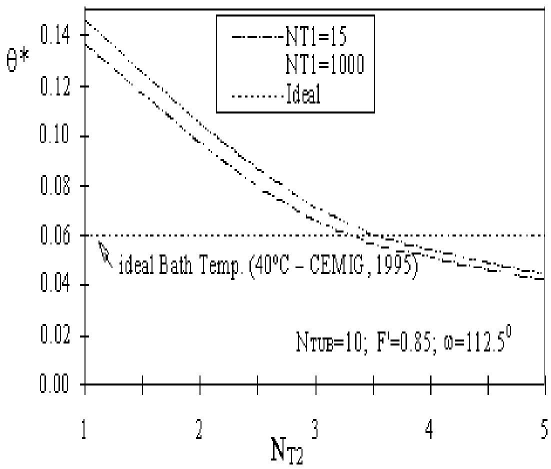

Figure 3. Effects of N_{T1} and N_{T2} on the temperature at the top of the storage tank.

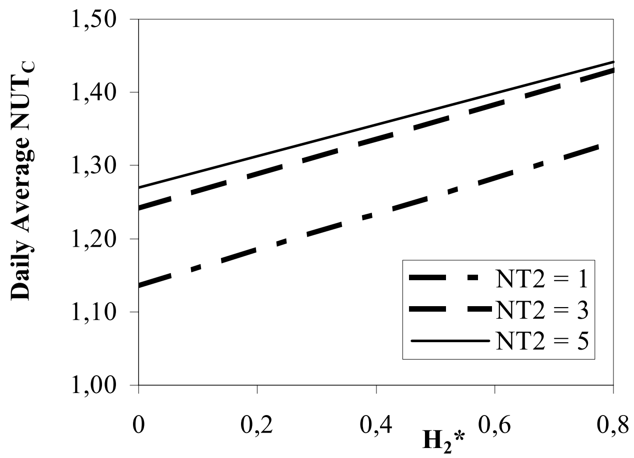

Figure 4. Effects of H_2* and N_{T2} on the daily average NUT_C.(15≤N_{T1}≤1000; N_{TUB}=10; F′=0.85)

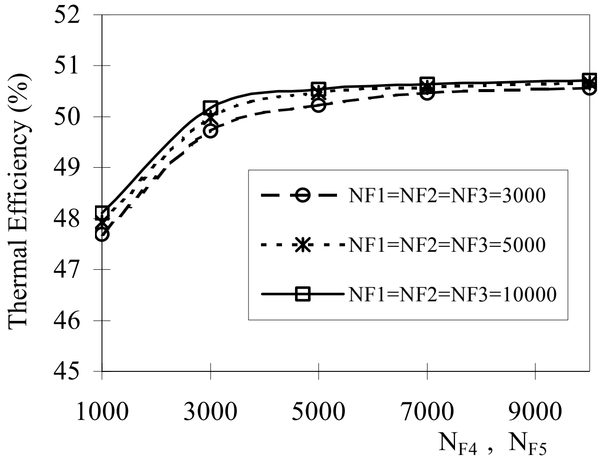

Figure 5. Effects of the hydraulic resistance numbers N_F on the thermal efficiency. (N_{T1} = 100; N_{T2} = 3; N_{TUB} = 50; F′ = 0.85; H_2^* = 0.20)

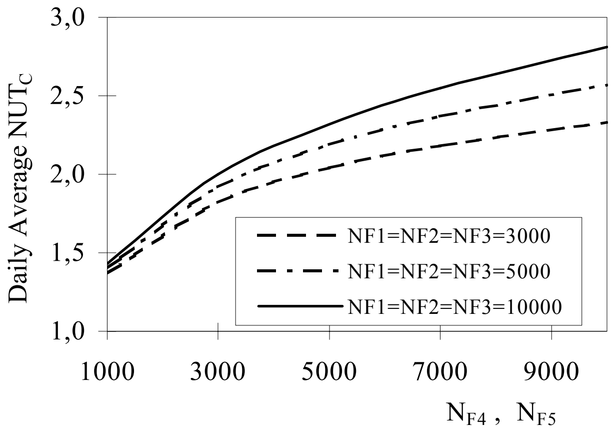

Figure 6. Effects of the hydraulic resistance numbers N_F on the daily average NUT_C. (N_{T1} = 100; N_{T2} = 3; N_{TUB} = 50; F′ = 0.85; H_2^* = 0.20)

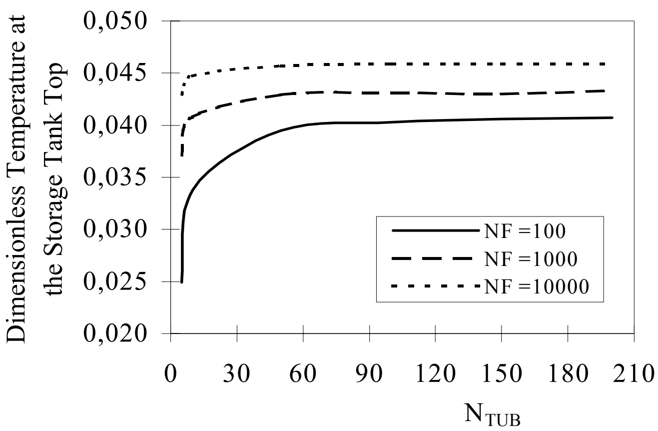

Figure 7. Effects of N_{TUB} on the dimensionless temperature at the storage top. (N_{T1} = 15; N_{T2} = 5; $N_F = 10^3$; F′ = 0.85; H_2^* = 0.20; ω =112.5°)

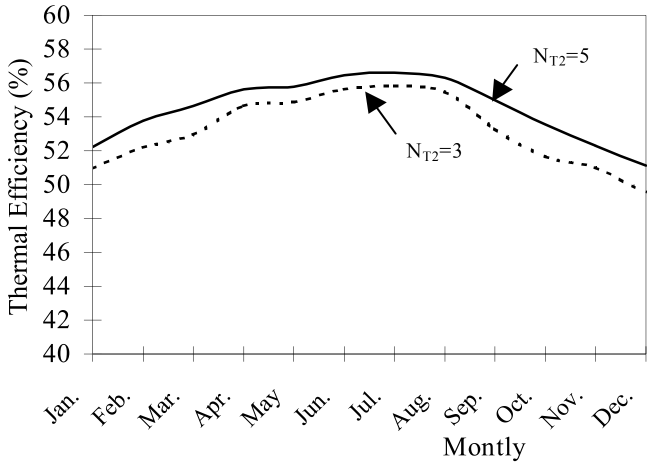

Figure 8. Thermal efficiency around the year ($N_{T1} = 15$; $N_{F1} = N_{F2} = N_{F3} = 10^3$; $N_{F4} = N_{F5} = 2.10^3$; $F' = 0.85$; $H_2^* = 0.20$; $N_{TUB} = 10$)

5. Conclusion

This work presents a thermal performance analysis of solar water heaters, using a mathematical model based on Huang's formulation, including water load profile, pipes thermal losses, etc.

The heater thermal performance was represented by a system of dimensionless differential equations, derived from the energy and momentum equations for the elements of the system. The effects of dimensionless relationships between geometrical and operational variables on the thermal behavior of the solar heaters are analyses, for typical domestic heat water load profile and meteorological data defined at the city of Belo Horizonte – Brazil, with the goal of searching for adequate dimensionless parameters values range maximizing the thermal efficiency.

6. Acknowledgement

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7. Reference list

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