COST OPTIMIZATION OF LOW-COST SOLAR DOMESTIC HOT WATER SYSTEMS ASSISTED BY ELECTRIC ENERGY

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Abstract – In the present paper the optimization of the insulation thickness of the storage tank of a low cost solar domestic water heating system (SDWHS) is carried out. The system is equipped with an auxiliary heater in the tank. The model assumes that the auxiliary energy needed to face the energy requirement for a shower in the evening, is supplied to the storage tank in the early hours of the morning. The modelling is intended to reproduce the current situation in Brazil, of low-income users who work during the day and usually take showers after 6:00 PM. As a result of the widespread use of electric showers between 6:00 PM and 8:00 PM the electricity peak demand is usually extremely high, for major cities in southern Brazil. Therefore, the optimization of the insulation thickness of the reservoir becomes economically relevant, in order to minimize the total (operational + capital) cost of the SDWHS. The optimization is performed by using TRNSYS for simulation of the solar system. The results presented here are compared with those obtained using a simple analytical model reported in ISES 2001.

1. INTRODUCTION

The most recent Brazilian energy crisis in 2000-2001 was mainly due to the drought season impact on the hydroelectric generation. Around 95% of the electricity generated in Brazil comes from hydraulic sources. On the demand side, the most useful equipment for domestic water heating for taking showers is the electric shower heater. Electric showers are the main responsible for the electricity peak demand, in the critical time period between 6 PM to 8 PM, mainly in the cities of the south and southeast of Brazil. Solar energy is very effective in respect to the electricity demand, mainly during the drought season, therefore it seems that its use in solar domestic hot water system connected to electric showers is an effective solution to reduce the peak of demand of showers in the critical time mentioned. In order to accomplish for the desired peak reduction, the solar domestic water heating system should be capable of supplying energy, even during periods with no available solar radiation, or radiation levels below the utilizability of the system. Since electric energy becomes expensive during day periods, the electric auxiliary storage tank heater should operate at the time period of minimum energy cost. On the other hand, the storage tank should have a good thermal insulation in order to maintain the temperature, at least at the specified temperature of a standard shower.

Most of the electric shower users have no economical conditions to acquire even a small solar system integrated to the shower. This system usually has a capacity of 100 liters for a collector area of 1.3 m^2. There are electric shower devices which are provided with electronic control regulation, so that the costumer can fix the water temperature during the shower.

Numerical simulation of a small-sized domestic heating water system is carried out in (Colle, 1999) and (Abreu, 2000), where it is shown that around 18% of the days in the southern region of Brazil require auxiliary heating shower power no less than 1.2kW. In spite of the fact the peak of demand is shown to be almost totally reduced during high solar radiation periods, it is likely to be reproduced whenever similar meteorological unfavourable conditions prevail. The reduction of the peak of demand during periods of incoming radiation below the utilizability level of the system can be accomplished by controlling the auxiliary heater in the storage tank. This control could be connected to a weather forecast meteorological information system, and therefore, hot water can ever be storaged for use at the evening critical time period mentioned above.

The works of (Abreu, 2000) and (Abreu and Colle, 2000) report the impact of the cost of the auxiliary heating on the payback time of investments, as well as the lifetime cost savings for this type of system. Payback time around five to six years is found. It is also shown in (Colle *et al.*, 2001a) that the uncertainty of the monthly means of the solar global radiation on the lifetime cost savings of many standard domestic solar heating water systems is not significant. However, since the payback time of the type of system focused here is usually high, not only the mentioned uncertainty can be significant, but also the capital cost of the system. Thermal insulation may be significant in the cost of the storage tank itself.

Low insulation means high heat loss and therefore, high auxiliary energy cost, particularly during the period of low solar radiation and low ambient temperature.

An analytical approach was reported in (Colle *et al.*, 2001b) to estimate the insulation thickness of the tank. In the mentioned work 65 climatically representative days were used in order to characterize the most unfavourable situation of days for which the auxiliary energy demand is high.

In the present paper the simulation of the SDWHS is carried out with TRNSYS and the estimation of the optimal insulation thickness is obtained by using the same total cost function of the previous work.

2. GOVERNING EQUATIONS AND SIMULATION

The following assumptions were made in the analysis reported in (Colle *et al.*, 2001b).

(i) The liquid in the storage tank is unstratified.
(ii) The heat loss of the pipes is neglected.
(iii) The pressure drop of the collector and the pipes is neglected.
(iv) The thermal capacity of both the collector and the storage tank wall is neglected.

With the above assumptions, the unstratified model described in (Duffie and Beckman, 1991) can be used, and therefore the energy balance of the systems is governed by the following differential equation,

$$\begin{aligned}(mc)_s\frac{dT_s}{dt} &= -(UA)_s(T_s - T_{ai}) \\ &+ A_c\left[G_T(t)F_R(\tau\alpha) - F_R U_L(T_s - T_{ae})\right] \\ &+ P_a\alpha_a - \frac{\Delta m_c}{\Delta t_c}c(T_c - T_f)\alpha_c\end{aligned} \tag{1}$$

where P_a is the heating power (kW), $(mc)_s$ is the thermal capacity of the storage tank, c is the specific heat of the water, U_s is the heat loss coefficient of the storage tank (W/m^2 K), A_c is the effective collector area, $F_R(\tau\alpha)$, and $F_R U_L$ are the collector efficiency factors, T_{ai} and T_{ae} are the indoor and outdoor ambient temperature, respectively, T_c is the hot water supply temperature and T_f is the cold water inlet temperature. G_T is the solar radiation incident on the tilted plate (W/m^2). Here α_a and α_c are flags, where α_a=1 if the auxiliary heater is on and α_a=0 if the auxiliary heater is off, and α_c=1 if shower is taken and α_c=0 otherwise. Δm_c is the amount of hot water supply, while Δt_c is the total time duration of the shower.

The initial condition assumed in the simplified model mentioned is given by,

$$T(t_c + \Delta t_c) = T_b \tag{2}$$

where T_b is the temperature at the end of the shower period Δt_c.

In the simplified model reported in previous work, it was assumed that a single analytical solution of equation (1) can play the role of a general solution for a meteorologically representative sample chosen from the TMY. This solution enables one to determine the time interval for which the auxiliary heater is on, in order to meet the hot water energy demand. The energy input is calculated for each value of the insulation thickness and then used to evaluate the total cost. In the present analysis the full TMY based on ten years of continuous measurements of global, beam and diffuse solar radiation is used in the system simulation. The following two simulation steps are carried out.

Step 1: The simulation of the system is carried out with no auxiliary heater, by assuming the same hot water energy demand as in the previous work. The complementary energy needed to meet the hot water energy demand is then calculated for each day of the TMY.

Step 2: The energy obtained in step 1, for each day of the year, is supplied to the storage tank at the same time very day early in the morning (4:00PM). The time interval, during which the energy is supplied to the system, is calculated from step 1, by assuming the electrical heater has a nominal power of 4kW.

The simulation is carried out for 30% and 50% of excess of the auxiliary energy estimated in the first step. The total cost function is then computed, for insulation thicknesses ranging from 0.025m to 0.275m.

The capital cost of the insulation thickness of the storage tank is expressed by

$$C_s = c_s V_s \tag{3}$$

where c_s is the specific cost of the insulation material (\$/m³), and V_s is the insulation volume which is given by

$$V_s = V_0\left[\left(1+\frac{2e}{D_0}\right)^2\left(1+\frac{2e}{L_0}\right)-1\right] \tag{4}$$

where $V_0 = \dfrac{\pi D_0{}^2}{4}L_0$ and e is the insulation thickness.

The global heat loss coefficient of the storage tank can be expressed by the following equation, where the external thermal resistance due to convection has been neglected,

$$(UA)_S = k_s \pi \left[2L_0 \Big/ \ln\left(\frac{D_0 + 2e}{D_0}\right) + \frac{D_0^{\,2}}{2e} \right] \quad (5)$$

where k_s is the thermal conductivity of the insulation layer (W/mK).

The cost of the auxiliary heating with fixed heater power P_a, for a period of N_e years of the economical analysis, and N_{sa} days of active heating is expressed by,

$$C_a = P_1 c_{E1} P_a \sum_{hours} \Delta t_a \qquad (6)$$

where $P_1 = PWF(i_E, d, N_e)$ is the present worth factor of the auxiliary energy annual expenses, i_E is the electric energy inflation, d is the discount rate, and c_{E1} is the electric energy specific cost ($/kWh) in the first year of the economical analysis. The total cost of both, capital and operating cost is thus given by

$$C = C_a + C_s \qquad (7)$$

3. DISCUSSION OF RESULTS

The SDWHS optmized in (Colle *et al.*, 2001b) is simulated, for which $F_R(\tau\alpha) = 0.8$, $F_R U_L$ = 3W/(m² K), P_a = 4.0kW, Δt_c = 60 min, V_o = 100 liters, k_s = 0.035 W/mK, i_E = 10%, d = 8%, and N_e = 20 years. The hot water supply temperature is 38°C.

In the previous work, a rather simplified optimization was carried out, by assuming the set of days of the winter season to be a representative sample of the most unfavorable days for both, the heat loss and solar radiation. A sample of 65 days was chosen, which is around 18% of the days of the year that correspond to the highest auxiliary energy demand, as determined in (Colle and Abreu, 2000a). The typical winter days sample was taken from the database of LABSOLAR (Abreu et al., 2000), for the site of Florianópolis-Brazil (27.6°S, 48.5°W). Ten years time series of temperature and solar global radiation data, (1 min total records), are available in the database.

The plots of the total cost C as a function of the insulation thickness is given in Figure 1, for a constant value of the energy cost c_{E1}. The curves of the simplified model were taken from the previous work. The total cost obtained in the present work is plotted for each excess energy level input.

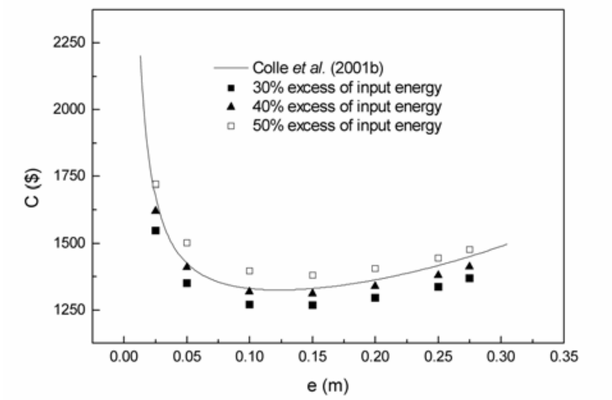

Figure 1 - Total Cost

From Figure 1 it can be seen that the total cost obtained from TRNSYS is lower than the cost obtained in the previous work, for every insulation thickness considered, for the case the energy input is equal to the complementary energy estimated from TRNSYS in the first step. The cost is higher for the case of excess energy input equal to 50% and lower for the case of excess energy equal to 30%. For an excess energy input of 40% the cost obtained from the present work is fairly equal to the cost obtained by the analytical method. In this case, about 69 days of the year correspond to cases for which the temperature of the hot water supply is below 37°C. In the remaining days of the year, the temperature of the hot water supply is equal or above 38°C. This number of days is comparable to the 18% of days (65 days) of the TMY series that were considered representative for the optimization carried out with the simplified model proposed in (Colle *et al*., 2001b).

The cost function obtained in this work leads to an optimum insulation thickness around the same value as obtained in the previous work.

Excess energy in relation to the estimated auxiliary energy obtained by simulation in step 1 is shown to be necessary, in order to assure that the hot water supply temperature after 6:00PM is above 38°C. It is expected from simulation, that if no excess energy is supplied to the system, it may result in a great number of days, for which the hot water supply temperature may not reach 38°C, due to heat losses and collector efficiency drops.

4. CONCLUSIONS

The economical optimization of the insulation thickness of a SDWHS is carried out by the TRNSYS simulation, for the hot water supply temperature of 38°C. The numerical results lead to an optimum insulation thickness of the storage tank around the same value obtained by the analytical approach given in (Colle *et al.*, 2001b). The total cost, as well as the optimum insulation thickness of the storage tank obtained by simulation with TRNSYS, is fairly equal to the values of the previous work, for an excess energy input to the system around 40%. It should be taken into account that high values of auxiliary energy input in the early hours of the morning, can impair the efficiency of the solar collector, since higher water temperatures in the morning result in lower efficiency (or lower utilizability) of the solar collector. On the other hand, higher temperatures in the storage tank result in greater heat losses to the ambient.

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