OPTIMIZATION OF SOLAR DOMESTIC HOT WATER SYSTEMS

T. Prud'homme and D. Gillet

Institut d'automatique, École Polytechnique Fédérale de Lausanne,
CH - 1015 Lausanne, Switzerland
e-mail: Thierry.Prudhomme@epfl.ch
Tel: (+41) 21 693-5925, Fax: (+41) 21 693-2574

ABSTRACT. The plant under consideration in this paper is a Solar Domestic Hot Water System (SDHWS). The heat exchanger is a mantle, which surrounds the entire storage tank.

Optimization of both the components and the operation of this system have been carried out. As a result, the overall performances have been improved simultaneously from an energy and a reliability perspective.

On the components side, a magnetic-driven pump with a PV-cells supply and a segmented auxiliary heater have been introduced. On the operation side, a combined optimal control of the collector mass flow rate and of the auxiliary heater has been implemented. The control strategy is designed with two objectives. The first aims at maximizing the difference between the energy drained by the collector and the energy required to pump the fluid. The second aims at providing users with hot water at the right time and at the right temperature, without reducing the solar energy transfer capability.

1 INTRODUCTION

The rate at which solar energy is collected in a SDHWS depends on the flow rate in the collector loop; however, increasing the flow rate also increases the power required to drive the pump. Kovarick and Less [3] have applied an optimal control strategy to a very simple model of a system without a heat exchanger so as to maximize the difference between solar power and fluid motion power. Unfortunately, it leads to an open-loop solution that could not be implemented in a practical controller. Indeed, this approach cannot cope with unanticipated changes in the process or the environment. Winn and Hull [6] were able to find a solution depending on the measurable states of the system. However, the model considered had no heat exchanger and some approximations were made. If the pumping costs are low, Dorato and Jamshidi [2] found that the performance of a simple on-off strategy could be very close to the performance of an optimal strategy.

To overcome the limitations previously mentioned, a consistent dynamic model of our particular system has been taken into account (Section 2) to solve the optimal control problem. Weather forecasts and the predicted user behavior in terms of draw-off have also been considered for that purpose.

Section 3 describes the reasons for introducing PV cells as the power supply for the circulation pump and the means to optimize the collector flow rate. Section 4 suggests the segmentation of the auxiliary heater and proposes a strategy to control the power supplied. Concluding remarks and perspectives are given finally in Section 5.

2 THE SYSTEM

For this optimization, a SDHWS manufactured in Switzerland by Agena[1] is considered. This system is schematized in Fig. 1. The storage, the mantle and the collector are modeled using seven, four and one nodes respectively. In reality the temperature of the water inside the storage tank and inside the heat exchanger vary gradually. This simple model, although detailed enough, is in fact well suited to develop and analyze the control strategies without cumbersome computational limitations. For detailed simulations, a higher order model should be considered [5].

Using the conditional factor ξ_i (which enables or disables the corresponding term according to the node location), the energy balance is represented by equation 1 for each node (s,i) of the store, by equation 2 for each node (h,j) of the heat exchanger and by equation 3 for the node (c) of the collector:

$$M_{s,i} C_{pf} \frac{dT_{s,i}}{dt} = \xi_i \kappa_{h,s} (T_{h,i-2} - T_{s,i}) + \dot{m}_L C_{pf} (T_{s,i+1} - T_{s,i}) + (1 - \xi_i) \kappa_{s,a} (T_{amb,in} - T_{s,i}) + \dot{Q}_i \qquad (1)$$

$$i = \{1, \ldots, 7\}, \quad T_{s,8} = T_{in}$$

$$M_{h,j} C_{pc} \frac{dT_{h,j}}{dt} = \kappa_{h,s} (T_{s,j+2} - T_{h,j}) + \dot{m}_C C_{pc} (T_{h,j-1} - T_{h,j}) + \kappa_{h,a} (T_{amb,ex} - T_{h,j}) \qquad (2)$$

$$j = \{1, \ldots, 4\}, \quad T_{h,-1} = T_c$$

$$C_{col} \frac{dT_c}{dt} = c_0 A I_T - c_1 A (T_c - T_{amb,ex}) + \dot{m}_C C_{pc} (T_{h,4} - T_c) \qquad (3)$$

$$\xi_i = 1 \quad \text{if} \quad i \quad \{3, \ldots, 6\}, \quad \text{else} \quad \xi_i = 0$$

where A is the collector area, C_{pc}, $\dot{m}_C$ the specific thermal capacity and the mass flow rate of the collecting fluid, C_{pf}, $\dot{m}_L$ the specific thermal capacity and the mass flow rate of the fluid in the store, C_{col} the thermal capacity of the collector, $\kappa_{s,a}$ the heat loss capacity rate from the store to ambient, $\kappa_{h,a}$ the heat loss capacity rate from the heat exchanger to ambient, $\kappa_{h,s}$ the heat transfer capacity rate from the heat exchanger to the store, M the mass of fluid of the corresponding node, c_0 the collector optical efficiency, c_1 the collector heat loss coefficient, $\dot{Q}$ the auxiliary heater input of the corresponding node and T the temperatures of the corresponding node. Note that the heat capacities κ are sometime referred as *(UA)*.

Simulations have been carried out with standard profiles for the weather conditions and the user's behavior in terms of draw-off. As for the meteorological conditions, data for the solar radiation and the ambient temperature of a winter sunny day in winter have been taken. With respect to the user's behavior, it was considered that eighty liters of water are tapped four times evenly spaced throughout the day.

1. Agena SA, av. Grand-Pré, CH-1510 Moudon, Switzerland

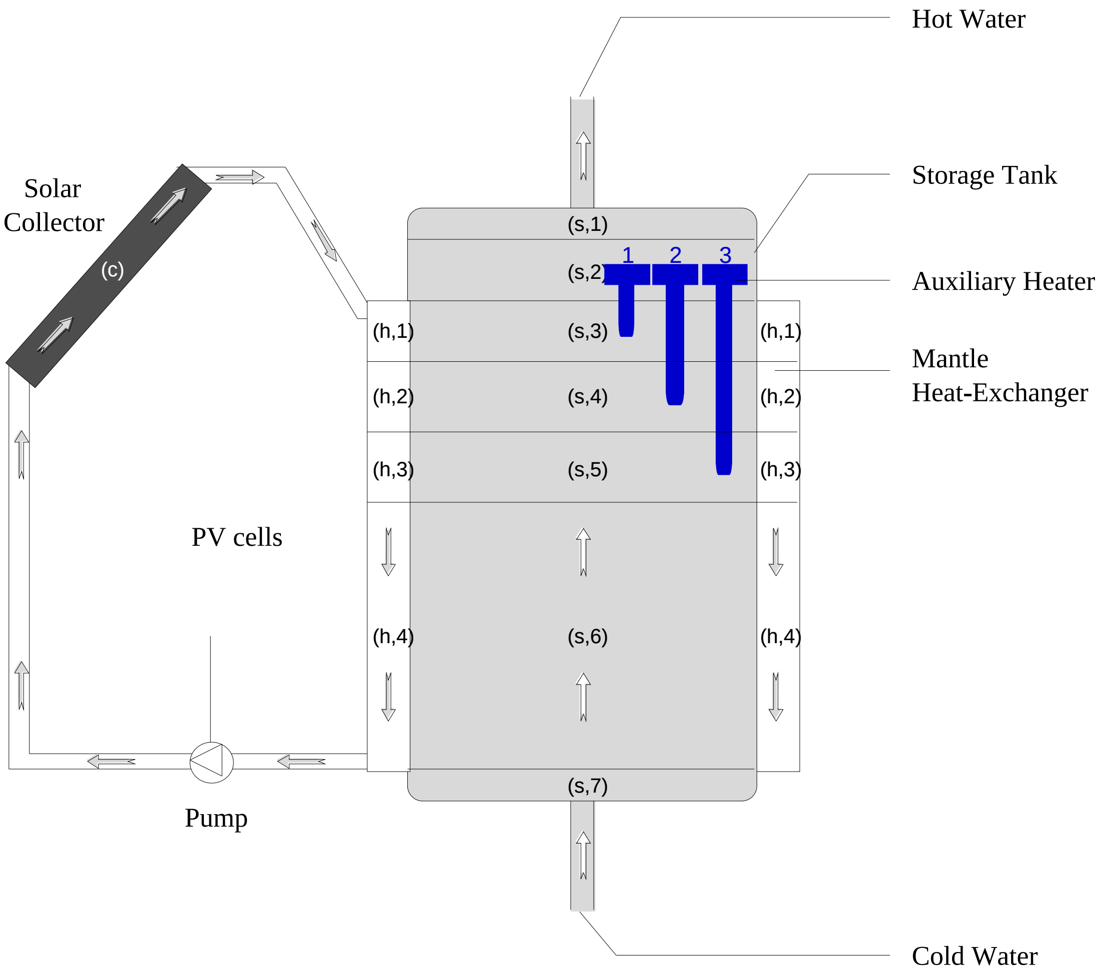

Figure 1: Model of the SDHWS

3 OPTIMIZATION OF THE COLLECTOR FLOW RATE

The optimization aims at maximizing the net energy delivered to the storage tank during a daily horizon interval. Therefore, the chosen cost function J_1 is:

$$J_1 = \int_0^{24h} \{Q_c - P(\dot{m}_C)\} dt \tag{4}$$

$$Q_c = \dot{m}_C C_{pc} (T_c - T_{h,4}) \tag{5}$$

$$P(\dot{m}_C) = K \dot{m}_C^3 \tag{6}$$

where Q_c is the energy collected and P the energy required to pump the fluid through the collector.

To maximize this cost function, the two-point boundary-value problem induced by the application of Pontryagin's minimum principle [4] can be numerically solved. A gradient algorithm is used to solve this problem [1] with the introduction of a clipping-off technique to make this algorithm cope with the inequality constraints on the flow rate, typically:

$$\dot{m}_C > 0$$

$$\dot{m}_C < \dot{m}_{C,Max}$$

The input $\dot{m}_C$ must be parameterized to transform the originally infinite-dimensional problem into a finite dimensional one. Therefore, it is taken as a piecewise-constant function that can vary every five minutes.

The solution is a sequence of optimal flow rate values. Owing to the pump, this input signal is applied in an open-loop fashion when the computation is completed. This means that no actual measurements are taken into account for an entire day. This limitation can be overcome since, in our special case, it takes less than a minute to run the optimization on a 200 MHz personal computer. Consequently, an optimal flow rate can be computed online easily with updates of the forecasts at each sample, following in a similar close-loop behavior. In this case, only the first computed value of the flow rate is applied before starting again the subsequent optimization.

Figure 2 exhibits another simpler solution to find the optimal flow rate. It is a consequence of the obvious similarity existing between the profile of the solar radiation and the optimal solution, the latter is obtained when Pontryagin's minimum principle is applied.

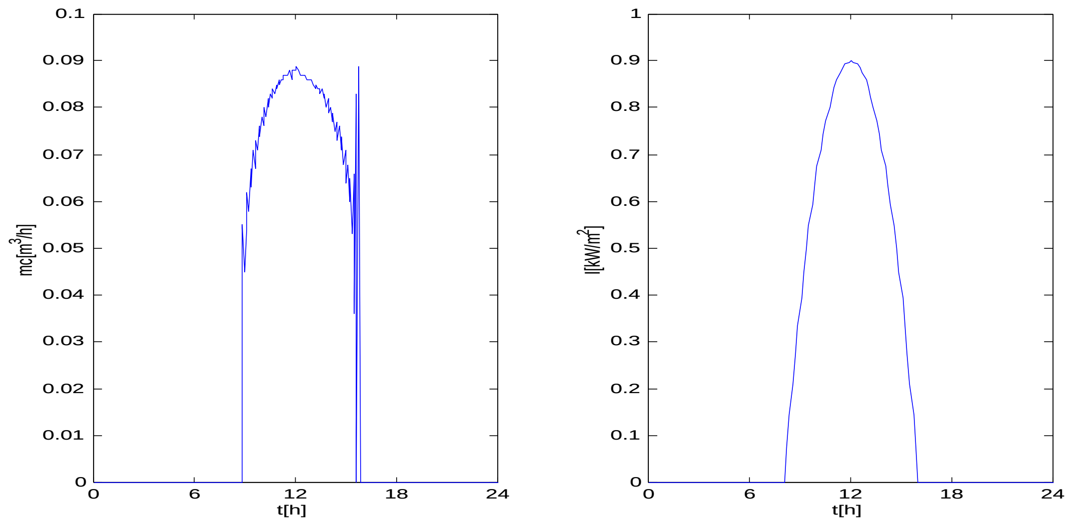

Figure 2: Optimal flow rate and solar radiation

Because of this similarity, it would be worth using PV cells to supply a good-sized pump. However, that implies the solution of a different optimization problem. Indeed, the pumping costs are equal to zero in that case. A family of explicit nonlinear relationships between the optimal flow rate and the solar radiation must to be found. These relationships depend of the temperatures within the storage tank.

4 OPTIMIZATION OF THE AUXILIARY HEATERS

In SDHWSs, an auxiliary heater is essential to meet the requirements of the user in terms of draw-off. However, a bad control strategy of this auxiliary heater may reduce the overall energetic benefit. This is particularly true with the system considered, since its mantle heat exchanger surrounds almost the entire surface of the storage tank, including the part in which the auxiliary heater stands. To overcome the drawbacks of that structure, a hardware enhancement has been designed. It consists of the replacement of the traditional single electrical element by three smaller ones with different lengths. These new elements have to supply together the same power as the previous one, but may be activated independently according with the expected load and solar radiation. A combined auxiliary heater like this allows a better control of the amount of heated water in the upper part of the store and helps to preserve the stratification.

The strategy applied for the control of the auxiliary heater is a trade-off which should be carefully defined. On the one hand, the temperature of the tapped water must be hot enough to ensure a given degree of comfort to the user. On the other hand, the temperature inside the store must be as low as possible so as to maximize the heat transfer from the heat exchanger.

The main drawback of this configuration is the fact that three constrained inputs must be optimized, corresponding to the power supplied for the three electrical elements. This requires more computational capabilities. The choice of the cost function J_2 is an essential decision. It must reflect how the SDHWS has to behave. In this special case, it is given in (7) and will be discussed below.

$$J_2 = \int_0^{24h} \{C_1(\dot{Q}_{aux,1} + \dot{Q}_{aux,2} + \dot{Q}_{aux,3}) + (T_{s,2} - T_{set})^4\} dt \tag{7}$$

where $\dot{Q}_{aux,i}$ is the input power of the ith electrical element, C_1 is a weighting factor, $T_{s,2}$ the temperature of the second fluid node in the store and T_{set} the desired temperature for the tapped water.

Obviously, the first term represents the electrical energy consumption and the second term a temperature discomfort factor. The constant C_1 is used to select a trade-off between these two terms. The term of discomfort is set to the power four in order to penalize only the significant differences between $T_{s,2}$ and T_{set}. It acts in almost the same manner as inequality constraints on $T_{s,2}$.

The approach described in Section 3 has also been applied to carry out this optimization. The problem has been solved first for the classical configuration, with only the largest electrical element, then with the three electrical elements. The power availability is the same for both configurations, 2.5 kW. For the second configuration, this available power is divided into three parts, each being proportional to the length of the corresponding electrical element.

With the initial configuration (one electrical element and on-off strategy), the solar fraction is approximately 15 percent. When using an optimal control strategy, this fraction increases to 46 percent. Finally, with the introduction of the two more electrical elements, an additional improvement of 4 percent is achieved.

5 CONCLUDING REMARKS AND PERSPECTIVES

The aim of improving the SDHWS performance has been achieved by the implementation of an optimal control approach to manipulate the flow rate in the collector loop and the power input of the auxiliary heater.

An efficient solution based on Pontryagin's minimum principle has been implemented to compute online the optimal control signals. The shape of the optimal flow rate has indicated an alternative means to generate that input directly using PV cells. The choice between an online digital implementation of the controller and the direct supply of the pump is a trade-off between versatility and cost. The digital solution enables better adjustment for a given site and has a greater potential for further extensions, such as the integration of failure detection capabilities.

Simulations have shown that additional hardware modifications can significantly improve the energy performance of the system. For example, promising results have been obtained when the traditional single element of the auxiliary heater is replaced by three parts having different lengths. The new inputs resulting from that modification must be handled by the optimal controller, according to the weather forecast and the predicted user load.

Finally, in the near future, the use of alternative optimization techniques should facilitate implementation of the optimal controller on low-cost micro-controllers.

6 REFERENCES

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