DEVELOPMENT OF AN ENERGETICALLY-BASED CONTROL FOR SOLAR THERMAL HEATING SYSTEMS

Richárd Kicsiny
Department of Physics and Process Control, Faculty of Mechanical Engineering,
Szent István University, H-2103, Gödöllő, Páter K. u. 1, Hungary
e-mail: Kicsiny.Richard@gek.szie.hu

ABSTRACT

This paper introduces the realization and application of a physically-based mathematical model of solar heating systems. The model was realized in TRNSYS 16 simulation environment which is well recognized and frequently-used in scientific researches of transient thermal processes. The model is flexible that is it can be easily adapted to a wide range of particular solar heating systems and is a good tool for analyzing and developing them. As an application the model was adopted to the particular solar heating system at the campus of Szent István University, Gödöllő and a new, energetically-based control was evolved and compared with the generally used on/off control method which operates with fixed temperature differences. Based on the relevant simulations it is shown that compared to the ordinary control the energetically-based control provides remarkable savings in auxiliary heating energy. This result should be valid for any systems similar to the particular one in Gödöllő.

1. INTRODUCTION

In view of the possibility of harnessing solar energy in solar thermal applications and the increasing amount of such installations, it is important to develop the efficiency of solar heated systems. In order to improve any simple or combined solar heating system, physically-based modelling is an exact, theoretically overseen tool.

The aim of this work is to realize a mathematical model corresponding to solar heating systems that takes into account all the substantial energy components as well as the physically-based specifications of them. Physical bases are well described in details by Duffie and Beckman (1991). The model should be flexible for easy adapting to a wide range of solar heating systems.

A new, energetically-based control method is shown and compared with the generally used ordinary control which operates with fixed on/off temperature differences.

2. INTRODUCTION OF THE INVESTIGATED HEATING SYSTEM AND THE PHYSICALLY-BASED MODEL

2.1. Main characteristics of the solar heating system at the campus of Gödöllő

A monitored combined solar heating system which has been installed at the campus of Szent István University (SIU), Gödöllő, Hungary is sketched in Figure 1. (Let it be called SIU-system.)

The term combined means actually that the installation has more than one consumers. It preheats water for an outdoor swimming pool and, in the idle period of this operation, domestic hot water for a kindergarten nearby. Auxiliary gas heated boilers are also included which operate in the same time with the solar heating if necessary.

The main system components are the flat plate solar collector field, with a total area of 33,3 m2, oriented to the south with an inclination angle of 45°, the plate heat exchangers, a 700 m^3 outdoor swimming pool with a surface of 350 m^2 and a 2000 litres solar storage tank. According to the notations above the following parameters are monitored on the system: temperatures (T, °C), specific solar irradiance (I, W/m^2), volumetric flows ($\dot{v}$, m^3/s). Measured data are available from the year 2001, apart from minor interruptions.

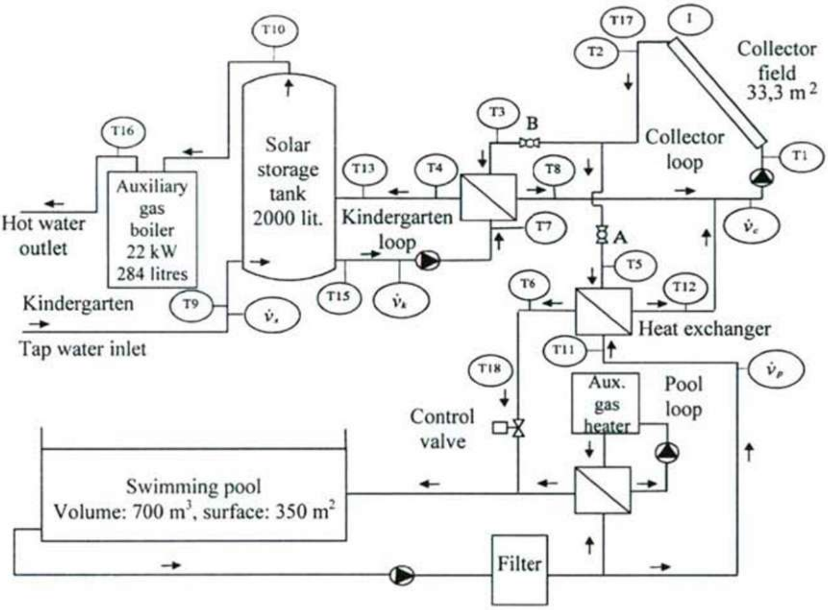

Figure 1. Simplified scheme of the combined solar heating system at the campus of SIU.

2.2. Modeling of the system

On the basis of the time-separated working, a distinct model has been elaborated for kindergarten operation (Figures 2-3), which is shown next in details.

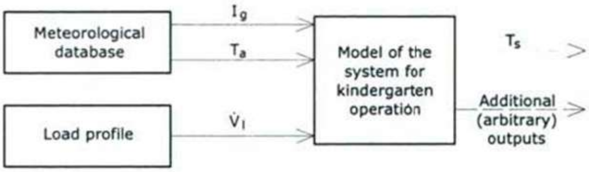

Figure 2. Flowchart of the model for kindergarten operation.

Notations: I_g: global solar irradiance on collectors' plane, W/m^2, T_a: outside, ambience temperature, °C, $\dot{V}_l$: domestic hot water load, l/h, T_s: calculated solar storage temperature, °C.

The problem was carried out by the TRNSYS 16 (Klein et al., 2005) and, for some particular calculations, by the MAPLE 8 software packages.

The main system units have been located in distinct sub-models, that are ready available in TRNSYS and can be used independently too. Such parts are the collector sub-model (Type 832 in TRNSYS (Heimrath and Haller, 2007)), the heat exchanger sub model (Type 5b), the stratified solar storage sub-model (Type 60c), the sub-model of the pumps (Type 114), the sub-model of the pipes (Type 31), the sub-model for the ordinary control (Type 2b) and the model part for the energetically-based control (Type 2b blocks with the related "Equations" blocks). It is possible to change either of them. (Actually the energetically-based control operates in Figure 3.)

(One could imagine auxiliary heating after the solar storage serially to afterheat the water till the all-time needed temperature level. It is not contained in the model now.)

The model can be run with inputs from special components. One of them is the "Meteorological database" component (Type 109) which calls a selected weather data file available in the program, the other is for the domestic hot water load ("Load profile" (Type 9c)) that also calls an external data file. (See Figure 2.)

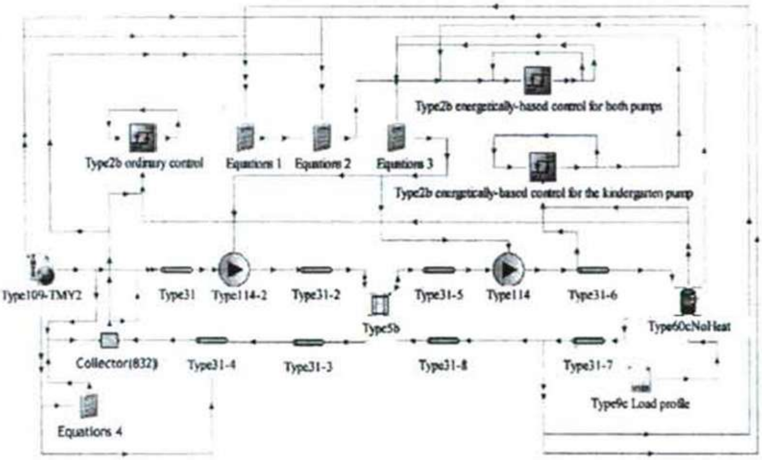

Figure 3. Flowchart scheme of the model in TRNSYS worksheet

The model determines and takes into account all energy components influencing the performance and the efficiency of the solar heating system, as like the irradiated energy on the collectors' plane, the utilized energy by the collectors, the transferred energy in the heat exchanger as well as the solar energy that finally used up by the consumers. Because of the limits in volume the specification of the other describing equations, which can be found along with their origins in the relevant TRNSYS documentation (Klein et al., 2005), is omitted now.

3. DEVELOPMENT OF THE ENERGETICALLY-BASED CONTROL

During the investigations the following one dimensional partial differential equation (Farkas and Vajk, 2002) relating to energy conservation law is needed. This equation models the cooling and delaying effects in pipelines of hydraulic systems.

$$\rho c A \frac{\partial T}{\partial t} = -\rho c \dot{V} \frac{\partial T}{\partial x} - k(T - T_{a,p}) \qquad (1)$$

Notations: A: area of pipe cross section, m^2, c: specific heat of pipe fluid, J/(kg°C), k: overall heat loss coefficient of the pipe, W/m/K, T: temperature of pipe fluid, °C, $T_{a,p}$: temperature of pipe ambience, °C, x: coordinate along the pipe, m, $\dot{V}$: volumetric flow in the pipe, m^3/s, ρ: mass density of pipe fluid, kg/m^3, t: time, s.

Here is the used energy balance equation and the equation of the Bosnjakovic-coefficient for a counter flow heat exchanger. (See Figure 4.)

$$\Phi(T_{c,h,in} - T_{k,h,in}) = T_{k,h,out} - T_{k,h,in} \qquad (2)$$

$$\Phi = \frac{1 - \exp\left(-\frac{k_h \varepsilon A_h}{\dot{W}_1}\left(1 - \frac{\dot{W}_1}{\dot{W}_2}\right)\right)}{1 - \frac{\dot{W}_1}{\dot{W}_2}\exp\left(-\frac{k_h \varepsilon A_h}{\dot{W}_1}\left(1 - \frac{\dot{W}_1}{\dot{W}_2}\right)\right)} \qquad (3)$$

Notations: Φ: Bosnjakovic-coefficient for a counter flow heat exchanger, $T_{c,h,in}$: inlet temperature to the heat exchanger from the direction of the collector field, °C, $T_{k,h,in}$: inlet temperature to the heat exchanger from the direction of the solar storage, °C, $T_{k,h,out}$: outlet temperature from the heat exchanger to the solar storage, °C, $k_h \varepsilon$: overall heat transfer coefficient of the heat exchanger between the working fluids, W/(m^{2}K), A_h: area of heat exchanger surface between the working fluids, m^2, $\dot{W}_1$: the smaller heat capacity flow rate of the two working fluids (in our particular SIU-system it belongs to the water in the kindergarten loop), W/K, $\dot{W}_2$: the greater heat capacity flow rate of the two working fluids (of the collector fluid in the SIU-system), W/K.

So that the pumping is economical in view of energy and costs, the following criterions must be always satisfied.

At first when the pumps are on, the medium which is to be heated must feed more heat energy per time unit than the amount of electric consumption by the pumping:

$$\Delta T > \frac{P_p}{c_w \dot{V}_k \rho_w} \qquad (4)$$

Notations: ΔT: warming temperature difference of the medium which is to be heated if the pumping is on °C, P_p: actual electric consumption of the pumping in the collector- and in the kindergarten loops, W, c_w: specific heat of water, J/(kg°C), ρ_w: mass density of water, kg/m^3.

Secondly the cost of the saved auxiliary (gas) energy per time unit by heating with solar energy the medium which is to be heated, also must be more than the cost of the consumed electric energy of the pumping:

$$\Delta T > \frac{P_p C_e}{c_w \dot{V}_k \rho_w C_g} \qquad (5)$$

Notations: C_g: specific cost of gas energy, e.g. in HUF/MJ, C_e: specific cost of electric pumping energy, e.g. in HUF/MJ.

3.1. Description of the energetically-based control

In the face of the ordinary control method which is commonly used in solar heating systems, a new energetically-based control has been elaborated for kindergarten operation though the principles are the very same in swimming pool operation too.

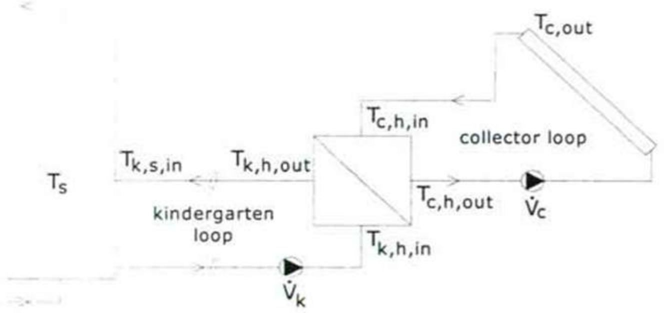

Figure 4. Simplified scheme of the solar heating system in kindergarten operation

Notations: $T_{c,out}$: outlet temperature of the collector field, °C, $T_{c,h,in}$: inlet temperature to the heat exchanger from the collector field, °C, $T_{k,s,in}$: inlet temperature to the solar storage from the direction of the heat exchanger, °C, $T_{k,s,out}$: outlet temperature from the solar storage to the heat exchanger, °C, $\dot{V}_c$: volumetric flow in the collector loop, m^3/s, $\dot{V}_k$: volumetric flow in the kindergarten loop, m^3/s.

Inside the storage there is no heat exchanger, it is not separated hydraulically from the kindergarten loop.

The pursuit of the elaborated control is the following according to Figure 4:

Case a, $T_{c,out}$, $T_{k,h,in}$, $T_{k,s,in}$ and T_s are monitored continually. Assuming switched on pumps $T_{c,h,in}$ is calculated from $T_{c,out}$ based on equation (1). Then $T_{k,h,out}$ is determined by equation (2). $T_{k,h,out}$ minus $T_{k,h,in}$ is the controlling temperature difference of the energetically-based control for both pumps. This is the one that is compared continuously with the switching off temperature difference - ΔT_{off} - that is the stricter economical criteria

according to (4) and (5) with $\Delta T = T_{k,h,out} - T_{k,h,in}$ and with the switching on temperature difference - ΔT_{on} - that is equal to ΔT_{off} plus the chosen hysteresis value - ΔT_{hyst} = 2 °C.
Case b, $T_{k,s,in}$ and T_s are monitored continually. Now the controlling temperature difference is $\Delta T = T_{k,s,in} - T_s$. It is compared continuously with the switching off temperature difference - ΔT_{off} - that is the stricter economical criteria according to (4) and (5) and with the switching on temperature difference - ΔT_{on} - that is equal to $\Delta T_{off} + 0{,}2$ °C. The collector pump works by Case a. The kindergarten pump works by the OR relation between Case a, and b,. So P_p is not the same in these cases.

3.2. Description of the ordinary control used for comparison

Generally the ordinary control switches off the pumps if T_c is less with a chosen value (e.g.: 2 °C) than T_s and switches on for another prescribed difference (e.g.: 5 °C).
The ordinary control does not deal with heat loss, only simply uses a prescribed switching off temperature difference, greater than 0 °C to ensure that the pumps work only if they take positive thermo energy into the kindergarten loop. Furthermore this value should be as small as possible to gain the most solar potential. So the efficiency of the ordinary control must be maximized to be fair to this control later, while comparing it to the new, energetically-based one.
So as to consider the biggest but still real losses in the system, let us calculate with 55 °C temperature in the kindergarten loop, 10 °C in its environment and -5 °C in the environment of the collector loop. Considering the parameters of the SIU-system and assuming switched on pumps, the minimal value of $T_{k,h,out}$ can be determined by equation (1) and the stricter condition of (4) and (5). (Here $\Delta T = T_{k,s,in} - T_s$.) $T_{k,h,in}$ can be also determined from T_s by (1). The minimal value of $T_{c,h,in}$ from (2) and $T_{c,out}$ from $T_{c,h,in}$ and (1) can be also calculated. The such resulted $T_{c,out} - T_s$ is the switching off temperature difference of the ordinary control. The hysteresis value is the same as in the energetically-based control (2 °C).

4. COMPARATIVE RESULTS OF THE ORDINARY- AND THE ENERGETICALLY-BASED CONTROL

According to the aforementioned the model has been run with the ordinary as well as with the energetically-based control then the results have been compared.
Simulation setups are according to the parameters of the SIU-system: investigated modelled day numbers: 1-5 April. Meteonorm data for Prague was used, since in TRNSYS database this place is the closest to our Hungarian system. The relevant TRNSYS weather file is: CZ-Praha-115180.tm2.
The consumption load is based on the realistic profile of Jordan and Vajen (2003) for five days without bathtub or shower with 1990 liters/day.
η_0 = 0,74, catalog data of the optical efficiency of the collectors, U_L = 7 W/m^2/K, recommendation from Bourges (1991) to the overall heat loss coefficient of the collectors, $k_h \varepsilon A_h$ = 5000 W/K, determined from data given by manufacturer. $\dot{V}_c$ = 0 or 1,08 m^3/h, $\dot{V}_k$ =

0 or 0,65 m^3/h, $P_p = 0$ or 300 W for both pumps / 0 or 150 W for only kindergarten pump. Initial temperatures: collector field: 5 °C (initial ambience temperature of the day 1st April), both sides of the heat exchanger: 20 °C (assumed temperature of the maintenance house), solar storage: 20 °C (discharged solar storage), pipelines between the heat exchanger and the solar storage: 16 °C, which is the initial solar storage temperature minus 4 °C, because the pipe water has come from the solar storage before and its insulation is good: $k = 0{,}025$ W/m/K by catalogue data. $c_c = 3623$ J/(kg°C), specific heat of collector fluid, $\rho_c = 1034$ kg/m^3 collector fluid mass density.

Volume of the collector field: 27 litres, volume of collector side of the heat exchanger: 2,5 liters. For kindergarten side: 2,6 liters. $C_g = 3{,}3$ HUF/MJ, $C_e = 11{,}1$ HUF/MJ.

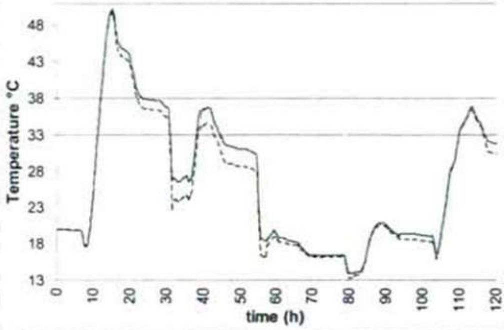

Figure 5. Average solar storage temperature by both controls

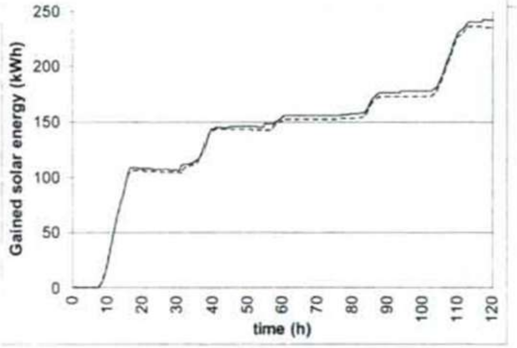

Figure 6. Gained solar energy for the kindergarten by both controls

Table 1. Results of the simulations for both controls at the end of the simulations (end of 5th April)

	Average storage temperature, °C	Gained solar energy for the kindergarten, kWh	Saved auxiliary (gas) energy, kWh
Ordinary control	30,3	235,0	-
Energetically-based control	31,8	241,8	6,8

Figure 5 and 6 show the results of the simulations comparing the two control methods. The dashed blue lines in the figures note the ordinary-, the smooth red ones note the energetically-based control. For both controls Figure 5 shows the average solar storage temperature, Figure 6 shows the sum of the consumed solar energy from the storage and the internal energy change inside the storage (compared to the initial internal energy).

5. CONCLUSIONS

Based on the simulation results it can be stated that under the same weather conditions the new, energetically-based control saved **6,8 kWh** solar energy for the consumer compared to the ordinary control which is used generally in practice. It means significant, **2,9 %** extra gained solar energy.

It should be said that the electric energy of the pumping also increases to some extent, so it is important to ponder the electric consumption surplus together with the extra gained solar energy.

6. ACKNOWLEDGEMENTS

The author says special thanks to them who contributed to a great extent to this work: To Professor István Farkas from the Department of Physics and Process Control, Szent István University, Gödöllő, Hungary for the help in making appropriate research conditions. To Professor Klaus Vajen from the Department of Solar and Systems Engineering, University of Kassel, Germany for the help in making appropriate research conditions and specially for the supply with the TRNSYS simulation environment. To János Buzás from the Department of Physics and Process Control, Szent István University for his help in many technical details. To the staff of the Department of Solar and Systems Engineering, University of Kassel for their help in many details.

REFERENCES

1. Duffie, J. A., Beckman, W. A., (1991): Solar Engineering of Thermal Processes. John Wiley and Sons, New York.
2. Klein, S. A. et al., (2005): A Transient System Simulation Program. Solar Energy Laboratory, University of Madison, USA.
3. Heimrath, R., Haller, M., (2003): Project Report A2 of Subtask A: The Reference Building, the Reference Heating System, A report of IEA SHC – Task 32. Graz University of Technology, Institute of Thermal Engineering.
4. Farkas, I., Vajk, I., (2002): Modelling and Control of a Distributed Collector Field. Energy and the Environment, I /ed. by B.Frankovic/, Croatian Solar Energy Association, Opatija, October 23-25, 2002., 91-99 p.
5. Jordan, U., Vajen, K., (2003): DHWcalc, version 1.10 - Tool for the Generation of Domestic Hot Water (DHW) Profiles on a Statistical Basis. University of Kassel, Institute of Thermal Engineering, Solar and Systems Engineering.
6. Bourges, B., (1991): European Simplified Methods for Active Solar System Design. Kluwer Academic Publishers for CEC.

This work has been supported by the Hungarian State Eötvös Scholarship.

Ez a munka a Magyar Állami Eötvös Ösztöndíj támogatásával készült.