SZENT ISTVÁN UNIVERSITY

Energetically-based control of a solar heating system

Thesis of PhD work

Richárd Kicsiny

Gödöllő, Hungary
2012

Doctoral school
Denomination: Mechanical Engineering PhD School

Science: Agricultural Engineering

Leader: Prof. Dr. István Farkas
Dr. of Technical Sciences
Faculty of Mechanical Engineering
Szent István University, Gödöllő, Hungary

Supervisor: Prof. Dr. István Farkas
Dr. of Technical Sciences
Institute for Environmental Engineering Systems
Faculty of Mechanical Engineering
Szent István University, Gödöllő, Hungary

……………………………………… ………………………………………
Affirmation of head of school Affirmation of supervisor

CONTENTS

NOTATION……….………..………………………………………..…….…………….4
1. INTRODUCTION, GOALS…….….…..…….....……………………………….…….…....6
2. MATERIAL AND METHOD…..……………………………………….……...…..7
2.1. The optimized ordinary and the energetically-based controls..…....7
The optimized ordinary control…….….…......………………………................8
The energetically-based control......……………………………….................8
Completion of the controls with a switching valve......……………..........9
2.2. Applied tools for the investigations……...……………...…………....9
The physically-based model...……………………………….…………....9
The augmented solar heating system……………….…………......10
2.3. Identification of the controls and the model....………...…...….......10
3. RESULTS…………...……….………………………………………………...…12
3.1. Investigations performed with the model........................……… …12
Settings of the simulations…..................…………………………...….12
Results of the simulations….…...............…………………………...…..12
3.2. Measurements…......…..........................…………………………... ..…15
3.3. Evaluation…..………….....…16
4. NEW SCIENTIFIC RESULTS……......….……………………………………....…20
5. CONCLUSIONS AND SUGGESTIONS...…...…...……………………….....…23
6. SUMMARY………...….....………………...…………………………….…....…24
7. MOST IMPORTANT PUBLICATIONS RELATED TO THE THESIS…........25

NOTATION

$A_{pipe,coll}$: inner cross-sectional area of the pipes in the collector loop (m^2),

$A_{pipe,s}$: inner cross-sectional area of the pipes in the storage loop (m^2),

c_{coll} : specific heat of the collector fluid (J/(kgK)),

c_w : specific heat of water (J/(kgK)),

I_g : global solar irradiance on the surface of the solar collectors (W/m^2),

$k_{pipe,coll}$: heat loss coefficient of the pipes in the collector loop (W/(mK)),

$k_{pipe,s}$: heat loss coefficient of the pipes in the storage loop (W/(mK)),

C_e : cost of electric energy (HUF/MJ),

C_g : cost of gas energy (HUF/MJ),

P_p : aggregated electric consumption of the collector and the storage pumps (W),

$P_{p,coll}$: electric consumption of the collector pump (W),

$P_{p,s}$: electric consumption of the storage pump (W),

$t_{pipe,coll}$: time of flowing between the collector and the heat exchanger (in single direction) (s),

$t_{pipe,s}$: time of flowing between the heat exchanger and the solar storage (in single direction) (s),

$T_{coll,env}$: environment temperature of the solar collector field (°C),

$T_{coll,env,m}$: measured environment temperature of the solar collector field (°C),

$T_{coll,env,su}$: supposed environment temperature of the solar collector field (°C),

$T_{coll,out}$: outlet temperature of the solar collector field (°C),

$T_{coll,out,m}$: measured outlet temperature of the solar collector field (°C),

T_s : solar storage temperature (at an appropriate level) (°C),

$T_{s,av}$: geometrical average temperature of the solar storage (°C),

$T_{s,env}$: environment temperature of the solar storage (°C),

$T_{s,m}$: measured temperature of the solar storage (°C),

$T_{s,su}$: supposed solar storage temperature (°C),

$T_{soil,su}$: supposed soil temperature (°C),

$T_{s,s,in}$: inlet temperature of the solar storage in the storage loop (°C),

$T_{s,s,in,m}$: measured inlet temperature of the solar storage in the storage loop (°C),

$\dot{V}_{coll}$: flow rate in the collector loop (m^3/s),

$\dot{V}_{load}$: flow rate of the consumption load (m^3/s),

$\dot{V}_{s}$: flow rate in the storage loop (m^3/s),

$\Delta T_{en,a}$: switching on temperature difference in process a/ of the energetically-based control, pipe consumptions are neglected (°C),

ΔT_{hyst} : hysteresis in the optimized ordinary control and in process a/ of the energetically-based control (°C),

$\Delta T_{hyst,en,b}$: hysteresis in process b/ of the energetically-based control (°C),

$\Delta T_{off,en,a}$: switching off temperature difference, process a/ of energetically-based control (°C),

$\Delta T_{off,en,b}$: switching off temperature difference, process b/ of energetically-based control (°C),

$\Delta T_{off,ord}$: switching off temperature difference, optimized ordinary control (°C),

$\Delta T_{on,en,a}$: switching on temperature difference, process a/ of energetically-based control (°C),

$\Delta T_{on,en,b}$: switching on temperature difference, process b/ of energetically-based control (°C),

$\Delta T_{on,ord}$: switching on temperature difference, optimized ordinary control (°C),

ΔT_{ord} : switching on temperature difference in the optimized ordinary control, pipe consumptions are neglected (°C),

Φ : Bošnjakovič coefficient (-),

ρ_{coll} : mass density of the collector fluid (kg/m^3),

ρ_{w} : mass density of water (kg/m^3).

1. INTRODUCTION, GOALS

It is fundamental to utilize renewable energy sources more and more effectively in the solution of energy problems of our society, because of the decrease in fossil sources and the environment pollution caused by them.

Control efficiency enhancement of active solar water heating systems (in short: solar heating systems) is a part of this endeavour.

The goals of my work are the followings:

1. Elaboration of the physically-based mathematical model of the investigated solar heating system type in a software environment accepted and applied generally in the corresponding scientific domain.
2. Fitting the mathematical model to the available SIU system. Validation of the model with measured data.
3. Development of a new, energetically-based control which contributes to the utilizability enhancement of solar heating systems.
4. Utilizability maximization of the ordinary control which works with fixed switching on and off temperature differences and is used generally in the practice, by minimizing the switching on and off temperature differences.
5. Augmenting the existing measuring and controlling system of the SIU installation such that the aid of which the developed energetically-based control and the ordinary control, optimized in the way above, can be applied and their efficiencies can be measured.
6. Comparing the efficiencies of the energetically-based and the ordinary controls. The comparison should be based on both model simulations and measurements.
7. Examining the efficiencies of the controls with the model of solar heating system supplied with a switching valve before the solar storage. Comparing the results of the investigations with the already gained ones in case of no valve.

The utilizability (of solar heating systems) is the following fraction: utilized solar energy for the consumer/overall solar irradiation on the surface of the collectors.

2. MATERIAL AND METHOD

In this section the ordinary control optimized to solar heating systems and the new energetically-based control are introduced. The software and hardware tools applied in the examination of the controls are also introduced.

2.1. The optimized ordinary and the energetically-based controls

My investigations correspond to systems of the type of Fig. 2.1., nevertheless the results can be easily adapted to other cases too. This work corresponds to on/off (or differential or bang-bang) controls.

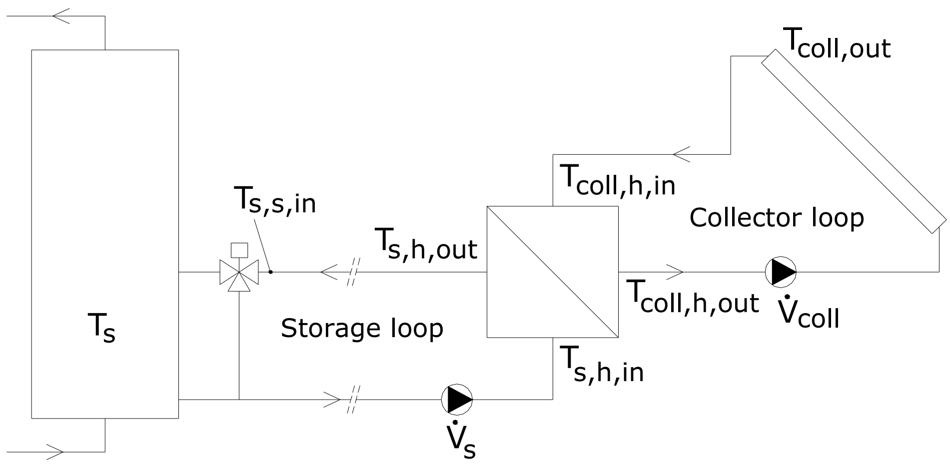

Fig. 2.1. Simplified flowchart of the solar heating system

It should be noted that the pipes of the storage loop of the investigated system are in the soil.

The collector and storage temperatures are measured and one work with fixed (switching) on and off temperature differences in the ordinary control. The difference of the mentioned temperatures determines when the pumps are switched on or off.

The energetically-based control works with variable on and off temperature differences in order to exploit as much available solar energy as possible, more than in the case of the ordinary control.

The optimization of the ordinary control has been carried out, that is the fixed on and off temperature differences have been determined such that this control also exploit as much solar energy as it is possible with this control.

In the comparison of the efficiencies of the controls, results corresponding to the optimized ordinary control are taken into account.

If the electric consumption of the pumps is considered, the following requirements should be fulfilled on the system for economic operation both in energetical and cost aspects.

If the pumps are on, more heat should be fed into the medium to be heated (the water in the storage) than the power consumption of the pumps in a time unit.
Furthermore the cost of the auxiliary (gas) energy, saved by the warming of the medium to be heated with solar energy, should be more than the cost of the used electric consumption of the pumps in a time unit.

Cases with and without a switching valve (three-way valve) have been examined in my work with computer simulations in the comparison of efficiencies of the controls.

In the development of the controls I supposed that the temperature change of the storage is neglected whilst the fluid leaving the collectors or the storage reaches the heat exchanger in case of switched on pumps.

The optimized ordinary control

The ordinary control does not calculate on the heat loss of the system, only uses a fixed positive switching off temperature difference to ensure that the pumps are on only if positive heat is transferred into the solar storage. Nevertheless this value should be as small as possible in order that the most solar potential is harnessed.
For considering the biggest but still real losses in the system let us assume that the temperature of the whole storage loop is 55 °C, $T_{soil,su}$ =10 °C and $T_{coll,env,su}$ = -5 °C. (Besides the relatively high system temperatures and low environment temperatures, the biggest heat losses are characteristical.)
Assuming these temperature values and switched on pumps, based on the law of conservation of energy corresponding to the flowing fluids in the pipes and the heat exchanger, the minimal value of $T_{coll,out}$, with which $T_{s,s,in} \geq T_{s,su}$ is still fulfilled, can be determined. Let the temperature difference of this minimal value of $T_{coll,out}$ and $T_{s,su}$ be denoted with ΔT_{ord}.
The goal of the control can be expressed as a dynamic optimization problem:

$$\int_{one\ day} \dot{T}_{s,av}\, dt \rightarrow \max . \qquad (2.1)$$

The problem can be solved with a prefixed hysteresis value (ΔT_{hyst}) to avoid oscillations of the control, supposing that in real operation conditions the difference of the current values of $T_{coll,out}$ and $T_{s,s,in}$ is always less or equal than in the detailed case above of highest heat losses.

The energetically-based control

Process a/

The switching off temperature difference is not constant here, it is continually recalculated according to the time step of the measurements. Based on $T_{coll,env,m}$,

$T_{s,m}$ and $T_{soil,su}$, assuming switched on pumps, from the law of conservation of energy corresponding to the flowing fluids in the pipes and the heat exchanger, the minimal value of $T_{coll,out}$, with which $T_{s,s,in} \geq T_{s,su}$ is still fulfilled, can be determined. Let the temperature difference of this minimal value of $T_{coll,out}$ and $T_{s,m}$ be denoted with $\Delta T_{en,a}$ which thus varies in time.

The goal of the control is (2.1) again. The problem can be solved with a prefixed hysteresis value (ΔT_{hyst}) to avoid oscillations of the control.

Process b/

The inlet temperature before the solar storage is directly measured here. $T_{s,s,in,m} - T_{s,m}$ determines if the storage pump is on or off at any moment.

The goal of the control is (2.1) again. A hysteresis value ($\Delta T_{hyst,en,b}$) is needed again, furthermore a (small) positive switching off temperature difference is needed to surely avoid cooling down the storage.

The collector pump operates according to process a/. The storage pump operates according to the logical OR relation between processes a/ and b/ that is if either of the processes orders the pump to be switched on then the storage pump is on.

The pumps always operate simultaneously in the ordinary control. In case of the energetically-based control the storage pump may operate alone.

Completion of the controls with a switching valve

The modelling of a switching valve to avoid the cooling down of the solar storage has been also carried out in my work. According to the difference of $T_{s,s,in,m}$ (temperature before the valve) and $T_{s,m}$ the valve switched on or off the storage from the hydraulic flowing. The switching off/on temperature differences can be set even 0/0 °C in the model (energetic optimum) but a positive off temperature difference, in view of measuring inaccuracies, and a positive hysteresis are needed in the practice.

2.2. Applied tools for the investigations

The physically-based model

The model of the system in Fig. 2.1. has been elaborated in the TRNSYS software package according to Fig. 2.2. (T_s means measured value in the figure.)

The main system units have been located in distinct sub-models. Such parts are the sub-models of the collector, the heat exchanger, the solar storage, the pumps, the pipes, the ordinary control and the energetically-based control.

The model can be run with measured data or with meteorological and consumption load models as inputs. The latter case is discussed henceforward.

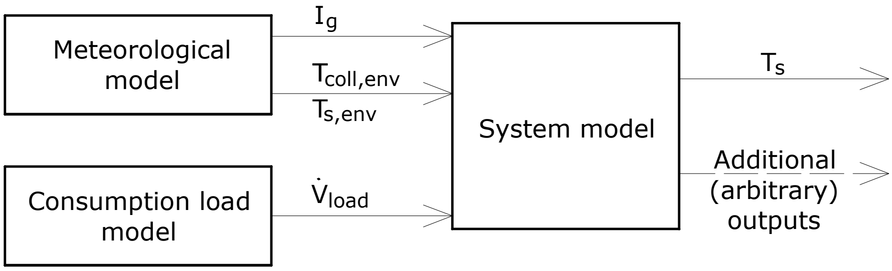

Fig. 2.2. Scheme of the solar heating system model

The extended solar heating system

The monitored solar heating system used in my measurements is installed at the campus of the Szent István University, Gödöllő, Hungary (let it be called SIU system). The system preheats water for an outdoor swimming pool in summer and domestic hot water in the solar storage of a kindergarten nearby in other time periods of the year. My investigations correspond to the latter case.
The volume of the storage is 2 m^3, the collectors are connected partly parallel and serial. The collector field oriented to the south and with an inclination angle of 45° is taken into account as an equivalent solar collector with 33,3 m^2 in the model. The length of the pipes is 80 m between the collectors and the heat exchanger (in both directions) and 115 m between the storage and the heat exchanger. The diameter of the pipes is 6/4".
Solar irradiance, temperature and flow rate values are measured in the system. A significant part of the monitoring system had been already available in the beginning of my work. As a part of my PhD work I have equipped the system with further measuring and control accessories according to the new tasks.
The controlling of the system is ensured by a new, highly reliable industrial computer in case of both controls. The measured physical data are recorded once in every minute.
My measurements were made with a switching valve always open to the storage.

2.3. Identification of the controls and the model

In absence of accurate enough preceding information the soil temperature has been estimated, the values of $k_{pipe,coll}$, $k_{pipe,s}$ and Φ have been determined with measured data.
The $k_{pipe,coll}$, $k_{pipe,s}$ and the Φ parameters have been determined by half-empirical identification, based on different measured data in the set of the switching on and off temperature differences of the controls and in the identification of the physically-based model.

In case of the set of the controls the parameters have been determined not as an overall average of measured values but from measurements of still real but

disadvantageous values in the matter of heat losses. Thus it is ensured that the cooling down of the storage is always avoided in case of continuously switched on pumps. This safety process affects both controls similarly so their authoritative comparison remains possible.
The results of the identification are $k_{pipe,coll}$ =0,45 W/(mK), $k_{pipe,s}$ =0,25 W/(mK), Φ =0,56.

In the identification of the physically-based model the purpose is not some security but to make the model as adequate as possible considering real system processes. Thus in the determination of the parameter values I have taken overall averages.
The results of the identification are $k_{pipe,coll}$ =0,22 W/(mK), $k_{pipe,s}$ =0,16 W/(mK), Φ =0,89.

The values of other parameters needed for the model identification are available in system documentations or are known physical parameters.
The validation of the model has been done based on the data of 13 May, 2011. The inputs of the model are the measured data of the global solar irradiance, the pump flow rates, the flow rate of the consumption load, the tap water temperature and the environment temperatures. The soil temperature has been assumed to be constant.
14 layers has been set in the solar storage sub-model, since the storage is a relatively high, 2,5 m tall cylindrical object.
Fig. 2.3. shows the measured and simulated temperatures in the upper third of the solar storage.

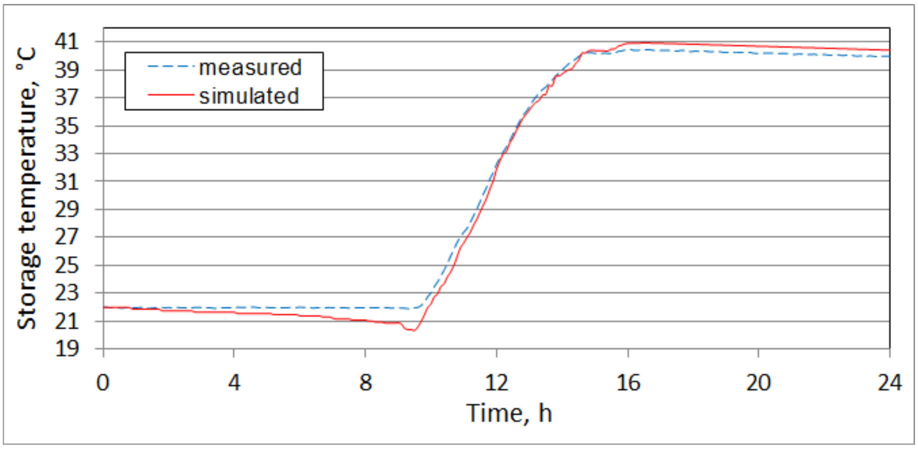

Fig. 2.3. Measured and simulated storage temperatures on the investigated day

The average absolute difference of the simulated and measured values is 0,5 °C that is 2,7% correlating to the daily maximal absolute temperature change.

3. RESULTS

The optimized ordinary and the energetically-based controls are compared in this section based on both TRNSYS simulations and measured data of the SIU system.
The main aspects of the comparison are the gained solar energy transferred into the solar storage, the electric consumption of the pumps and the number of their switches on (or off).

3.1. Investigations performed with the model

Settings of the simulations

Modelled days: 1-5 April. The METEONORM data of the closest geographical place to the investigated SIU system has been applied from the TRNSYS database.
The corresponding TRNSYS datafile is CZ-Praha-115180.tm2.
The load profile has been fed into the model from a realistic load model concerning five days with a consumption of 1,99 m^3/day, without shower and bathtub consumers. The supposed required water temperature is 55 °C. These data are in accordance with the particular kindergarten consumer. $T_{soil,su}$ =15 °C.

$\dot{V}_{coll}$ =0 or 0,98 m^3/h; $\dot{V}_s$ =0 or 0,63 m^3/h (based on measured average values).

$P_{p,coll}$ =60 W; $P_{p.s}$ =60 W. This can be easily achieved in the system with modern pumps with low consumption. The heating effect of the pumps is neglected.
Initial temperatures: collector field: 5 °C, heat exchanger: 20 °C, solar storage: 20 °C, pipe temperatures: 15 °C.

C_g =4,1 HUF/MJ(=14,8 HUF/kWh), C_e =13,8 HUF/MJ(=49,7 HUF/kWh).

The hysteresis in the ordinary control and in process a/ of the energetically-based control has been chosen 2 °C, and 0,5 °C in process b/ of the energetically-based control. The switching off temperature difference of process b/ of the energetically-based control has been set 0,3 °C.

Results of the simulations

Fig. 3.1., 3.2., 3.3. and Table 3.1. contain the comparison of the simulation results of the controls in the investigated time period. The consumption of the pumps was not considered in the setup of the controls.
Fig. 3.1. 3.2. and 3.3 shows the solar energy transferred into the storage, the number of switches on of the collector pump and the number of switches on of the storage pump accordingly. Table 3.1. summarizes the most important results of the simulations.

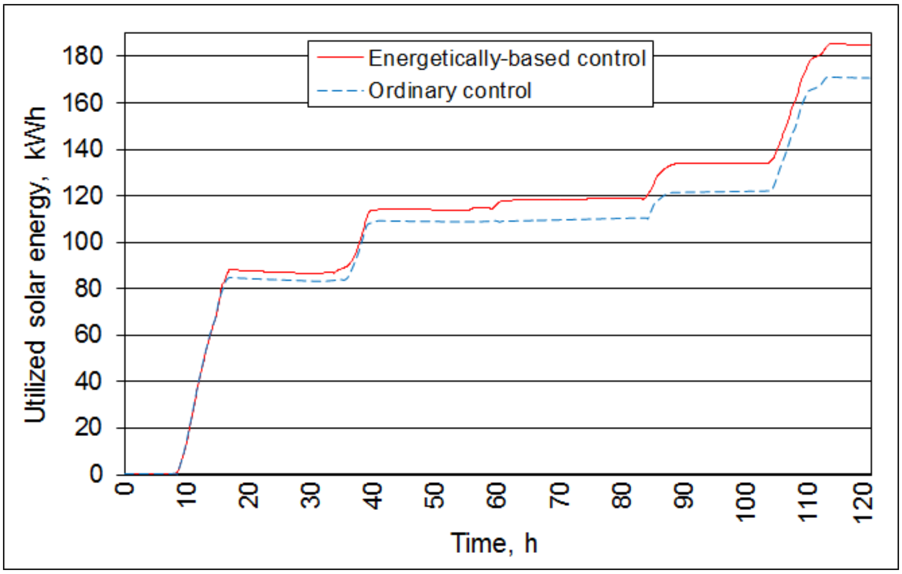

Fig. 3.1. Solar energy transferred into the solar storage, 1-5 April

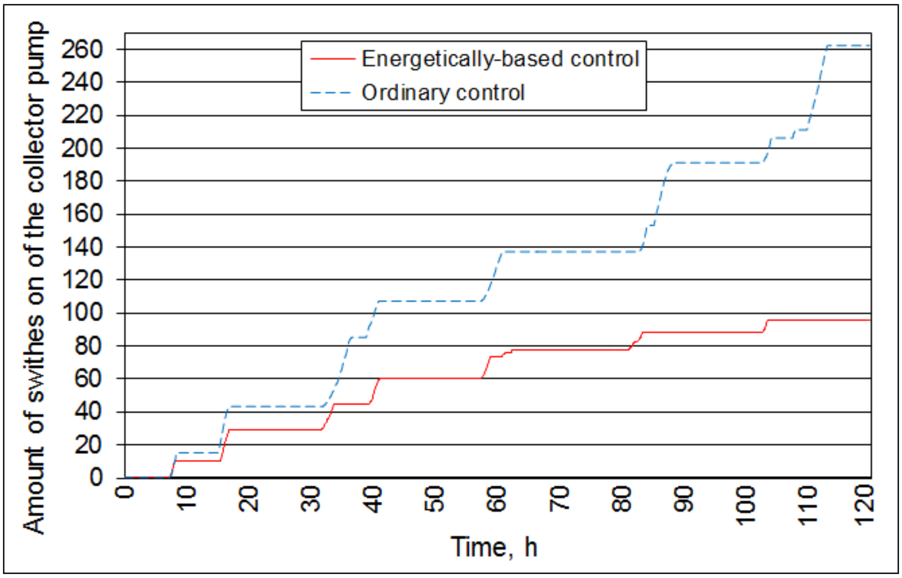

Fig. 3.2. Number of switches on of the collector pump, 1-5 April

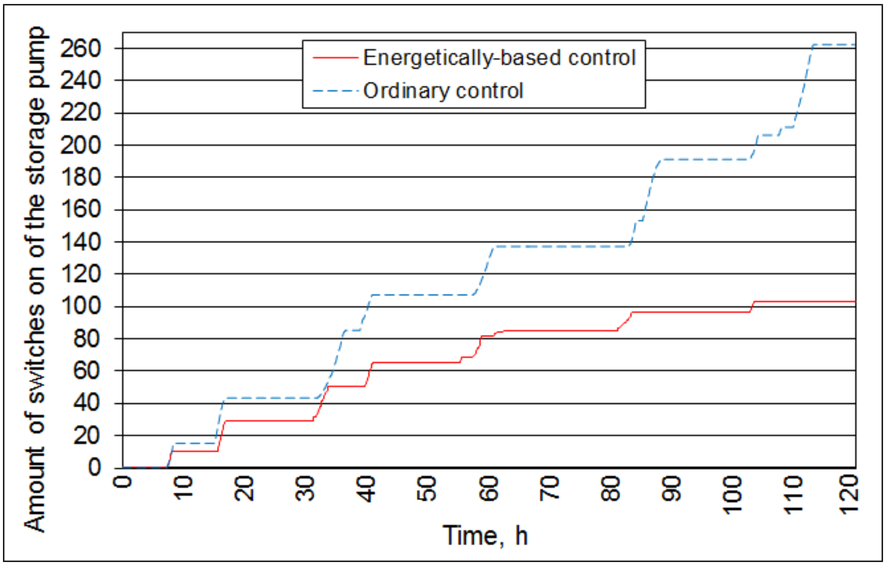

Fig. 3.3. Number of switches on of the storage pump, 1-5 April

Table 3.1. Simulation results without valve, pump consumption is neglected, 1-5 April

	Ordinary control	Energetically-based control
Solar irradiation on the collector field, kWh	548,8	548,8
Consumption load, kWh	499,2	499,2
Solar energy transferred into the storage, kWh	171,7	187,2
Utilized solar energy surplus	-	15,5 kWh=9%
Utilizability, %	31,3	34,1
Consumption of the pumps, kWh	2,5	4,0
Consumption excess of the pumps	-	1,5 kWh=60%
Specific electric consumption, Wh/kWh	14,8	21,2
Number of switches on of the collector pump	262	95
Decrease in the number of switches on of the collector pump	-	167=64%
Number of switches on of the storage pump	262	103
Decrease in the number of switches on of the storage pump	-	159=61%

As it can be seen in the table I have defined the specific electric consumption (of the current control) which is the fraction of the consumed electric energy by the pumps and the solar energy transferred to the consumer (into the solar storage).

Similar simulation investigations have been done for both controls in case of valve taking pump consumption into account and in case of no valve with and without taking pump consumption into account. The switching off/on temperature differences of the valve in the investigated cases are 0/0 °C and 0/0,3 °C.

3.2. Measurements

The controls have been applied in the real, measured SIU system too according to the same setup as in the simulations in the time period of 24 November 2010 – 18 December 2011.
The switching valve did not operate and the pump consumption was not taken into account in the setup of the controls.
The controls changed each other day by day. The random and incidental pauses concerned them alike. After all we have 119 measured days in the case of each control.
In view of the alternating operation, the nearly same irradiation (first row in Table 3.2.) and consumption load (second row in Table 3.2.) values, we can consider that the environment and consumption conditions were the very same in case of both controls, thus their comparison is relevant.
It should be mentioned that the irradiation and consumption data are not absolutely the same. It is evident since the measurements have not been carried out in laboratory but under real circumstances, so the same conditions could not be guaranteed in the days of the two controls. For instance the solar irradiation was 7601,0 kWh in case of the ordinary and 7744,4 kWh in case of the energetically-based control.
Obviously the difference can be said little nevertheless these values are not the same. So the results cannot be compared as directly as in the simulations.
We still have directly comparable, specific type indicators as the utilizability and the specific electric consumption.
The most important measured results are contained in Table 3.2.

Table 3.2. Measured results (24 November 2010 – 18 December 2011)

	Ordinary control	Energetically-based control
Solar irradiation on the collector field, kWh	7601,0	7744,4
Consumption load, kWh	5892,7	6340,0
Solar energy transferred into the storage, kWh	1147,7	1482,9
Utilized solar energy surplus, kWh	-	335,2
Utilizability, %	15,0	19,1
Consumption of the pumps, kWh	27,6	37,3
Consumption excess of the pumps, kWh	-	9,7
Specific electric consumption, Wh/kWh	24,1	25,2
Number of switches on of the collector pump	1011	741
Decrease in the number of switches on of the collector pump	-	270
Number of switches on of the storage pump	1011	749
Decrease in the number of switches on of the storage pump	-	262

3.3. Evaluations

Based on all simulation and measured results it can be stated that the energetically-based control results in higher utilizability and less switches of the pumps, but involves higher parasitic consumption of the pumps both in case of valve and in case of no valve. The main comparing results of the energetically-based control correlating to the optimized ordinary control are the followings:

Table 3.3. Summarized results

Increase in utilizability	2,5-4,1%
Increase in specific electric consumption	5-44%
Decrease in the number of the switches on of the pumps	41-64%

Simulation results showed that the valve is advantageous for the amount of the utilized solar energy in case of the ordinary control and has essentially no effect on the pump consumption and the number of their switches. There was 0,6 kWh=0,3% surplus in the amount of the utilized solar energy for the storage in both cases of 0/0 °C and 0/0,3 °C. The result corresponds to five modelled days in spring which means, 43,8 kWh auxiliary energy gain surplus, extrapolating to 365 days of a year.

Calculating with the former cost value of the gas energy, 14,8 HUF/kWh, this means 648 HUF cost savings surplus in a year. If we can completely install the valve even from 10000 HUF (in the beginning of 2012), 15 years would be needed for the cost payback.
Considering the abovementioned, it is only accidentally worth using a valve in the aspect of environment protection and it is practically not worth using it in the aspect of cost saving in case of the ordinary control.

It has been showed in simulations, that the valve is disadvantageous for the amount of the utilized solar energy and for the number of the switches of the pumps in case of the energetically-based control. The valve is advantageous to a small extent considering the parasitic consumption of the pumps.
Thus it is even more disadvantageous using a valve in case of the energetically-based control than in case of the ordinary control.

In the following the practically worthwile cases of the ordinary and the energetically-based control are compared in view of different indicators based on simulation results. These are cases with no valve.
The indicators are intended to show which control is rather worth using.

If the parasitic pump consumption is not considered, the convenient indicator is the amount of the utilized solar energy for the consumer (for the solar storage).
According to Table 3.1. 171,7 kWh solar energy has been utilized with the ordinary control and 187,2 kWh with the energetically-based control. This is 15,5 kWh=9% surplus in the saving of the auxiliary energy with the energetically-based control.

In the simulations when the parasitic consumption of the pumps was taken into account, 169,0 kWh solar energy has been utilized with the ordinary control and 184,0 kWh with the energetically-based control. The parasitic consumption of the pumps was 2,4 kWh with the ordinary control and 3,4 kWh with the energetically-based control.
If the auxiliary heating is from electric energy, the controls can be compared by the following indicator.

$$\frac{utilized\ \ solar\ \ energy}{direct\ \ efficiency\ \ of\ \ gas\ \ consumption} - parasitic\ \ pump\ \ consumption \qquad (3.1)$$

Assuming 95% for the direct efficiency of gas consumption, the indicator is 169,0/0,95-2,4=175,5 (kWh) with the ordinary control and 184,0/0,95-3,4=190,3 (kWh) with the energetically-based control. This means 14,8 kWh=8% surplus in the energy saving with the energetically-based control.

If the auxiliary energy is directly and the pump consumption is indirectly, through a power plant, from gas source then the overall efficiencies of both utilizations should be considered in view of environment protection. Here the controls can be compared by the following indicator.

$$\frac{\textit{utilized solar energy}}{\textit{direct efficiency of gas consumption}} - \frac{\textit{parasitic pump consumption}}{\textit{efficiency of parasitic consumption}} \qquad (3.2)$$

Assuming 95% for the direct efficiency of gas consumption and 30% for the efficiency of parasitic consumption (from the power plant to the final consumer), the indicator is 169,0/0,95-2,4/0,3=169,9 (kWh) with the ordinary control and 184,0/0,95-3,4/0,3=182,4 (kWh) with the energetically-based control. This means 12,5 kWh=7% surplus in the energy saving with the energetically-based control.

In view of costs the controls can be compared with the following indicator.

$$\textit{cost of utilized solar energy} - \textit{cost of parasitic consumption} \qquad (3.3)$$

With C_g=14,8 HUF/kWh and C_e=49,7 HUF/kWh, 169,0x14,8-2,4x49,7=2382 (HUF) has been saved with the ordinary control and 184,0x14,8-3,4x49,7=2554 (HUF) with the energetically-based control. This means 172 HUF=7% surplus in the cost saving with the energetically-based control.

Based on the four indicators above the energetically-based control is more advantageous than the ordinary control. Fig. 3.4. summarizes the results.

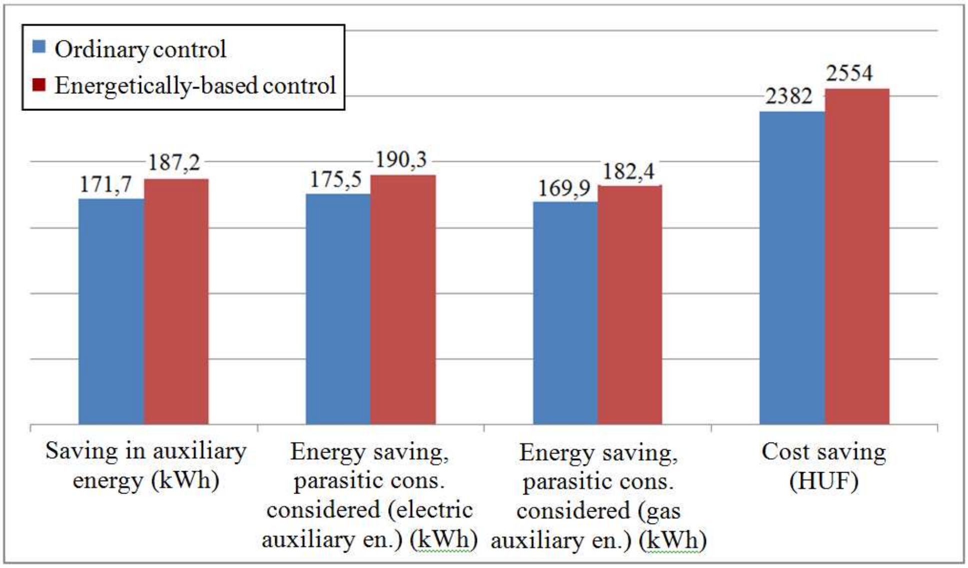

Fig. 3.4. Comparison of the controls by means of four indicators

The investment cost of the energetically-based control is a bit higher than that of the ordinary control. The payback time of this excess can be estimated by (3.3).
The ordinary control needs a simple controller with two temperature sensors. The energetically-based control needs a programmable controller which can handle four sensors. Besides the outlet temperature of the collector field and the temperature of the lower third of the solar storage, two more temperatures must be measured: the temperature of the collector environment and the inlet water just before the storage.

Extrapolating the value of (3.3) to a whole year, considering the costs of the controllers, the payback time of the extra investment is less than 2,5 years.

Based on the results, the energetically-based control results in surplus in all aspects of savings. The surplus is 7-9% by means of the different indicators.

It should be noted that the results above are for a system with relatively long pipes which favours the energetically-based control, since this control aims at transferring the all-time utilizable heat in the pipes for the consumer.
Accordingly the energetically-based control is in principle more effective in harvesting solar irradiation than the ordinary control for many sorts of solar heating systems (not only for systems with external heat exchangers).
If the pipes are shorter, the utilized solar energy surplus is less in favour of the energetically-based control, nevertheless the parasitic consumption excess is also less. So it can be still worth applying the energetically-based control according to the four indicators above, however this case is worse in view of the payback time of the extra investment of the energetically-based control.

4. NEW SCIENTIFIC RESULTS

The new scientific results of my PhD work corresponding to solar heating systems, more specifically to systems with external heat exchanger, are the followings:

1. I elaborated a method for the optimization of the ordinary control which is used generally in the practice and operates with fixed switching on and off temperature differences by the minimization of the switching on and off temperature differences. In this way I have maximized the utilizability of the ordinary control.
   I have established the algorithm of the optimized ordinary control as follows:

$$\text{the pumps should be on, if} \begin{cases} T_{coll,out,m} - T_{s,m} > \Delta T_{on,ord}\text{, or} \\ T_{coll,out,m} - T_{s,m} > \Delta T_{off,ord} \text{ and the pumps are on,} \end{cases}$$

$$\text{the pumps should be off, if} \begin{cases} T_{coll,out,m} - T_{s,m} \le \Delta T_{on,ord} \text{ and the pumps are off, or} \\ T_{coll,out,m} - T_{s,m} \le \Delta T_{off,ord}. \end{cases}$$

$\Delta T_{off,ord} = \Delta T_{ord} + \max\left(\frac{P_p}{c_w \dot{V}_s \rho_w}, \frac{P_p C_e}{c_w \dot{V}_s \rho_w C_g} \right)$, if the parasitic consumption of the pumps are considered and $\Delta T_{off,ord} = \Delta T_{ord}$, if the parasitic consumption is not considered. $\Delta T_{on,ord} = \Delta T_{off,ord} + \Delta T_{hyst}$.

$$\Delta T_{ord} = \left(T_{s,su} + \left(T_{s,su} - T_{soil,su} \right) \left(1 - \exp\left(\frac{-k_{pipe,t}\, t_{pipe,t}}{\rho_w\, c_w\, A_{pipe,t}} \right) \right) \left(\frac{1}{\Phi} - 1 \right) + \frac{1}{\Phi} \left(T_{s,su} - T_{soil,su} \right) \cdot \right.$$

$$\left. \cdot \left(\exp\left(\frac{k_{pipe,s}\, t_{pipe,s}}{\rho_w\, c_w\, A_{pipe,s}} \right) - 1 \right) - T_{coll,env,su} \right) \exp\left(\frac{k_{pipe,coll}\, t_{pipe,coll}}{\rho_{coll}\, c_{coll}\, A_{pipe,coll}} \right) - T_{s,su} + T_{coll,env,su}\,.$$

2. I have developed a new model- and energetically-based control which transfers the heat that can be utilized by or extracted from the solar heating system at all times. This control has higher utilizability than the ordinary control including the optimized version of the latter one.
   I have defined the energetically-based control with two processes, a/ and b/.
   I have established the algorithm of the energetically-based control as follows:

   Process a/

$$\text{the pumps should be on, if} \begin{cases} T_{coll,out,m} - T_{s,m} > \Delta T_{on,en,a}\text{, or} \\ T_{coll,out,m} - T_{s,m} > \Delta T_{off,en,a} \text{ and the pumps are on,} \end{cases}$$

$$\text{the pumps should be off, if} \begin{cases} T_{coll,out,m} - T_{s,m} \le \Delta T_{on,en,a} \text{ and the pumps are off, or} \\ T_{coll,out,m} - T_{s,m} \le \Delta T_{off,en,a}. \end{cases}$$

$\Delta T_{off,en,a} = \Delta T_{en,a} + \max\left(\frac{P_p}{c_w \dot{V}_s \rho_w}, \frac{P_p C_e}{c_w \dot{V}_s \rho_w C_g} \right)$, if the parasitic consumption of the pumps are considered and $\Delta T_{off,en,a} = \Delta T_{en,a}$, if the parasitic consumption is not considered. $\Delta T_{on,en,a} = \Delta T_{off,en,a} + \Delta T_{hyst}$.

$$\Delta T_{en,a} = \left(T_{s,m} + \left(T_{s,m} - T_{soil,su} \right) \left(1 - \exp\left(\frac{-k_{pipe,s}\, t_{pipe,s}}{\rho_w\, c_w\, A_{pipe,s}} \right) \right) \left(\frac{1}{\Phi} - 1 \right) + \frac{1}{\Phi} \left(T_{s,m} - T_{soil,su} \right) \cdot \right.$$

$$\left. \cdot \left(\exp\left(\frac{k_{pipe,s}\, t_{pipe,s}}{\rho_w\, c_w\, A_{pipe,s}} \right) - 1 \right) - T_{coll,env,m} \right) \exp\left(\frac{k_{pipe,coll}\, t_{pipe,coll}}{\rho_{coll}\, c_{coll}\, A_{pipe,coll}} \right) - T_{s,m} + T_{coll,env,m}.$$

Process b/

$$\text{the pumps should be on, if} \begin{cases} T_{s,s,in,m} - T_{s,m} > \Delta T_{on,en,b}, \text{ or} \\ T_{s,s,in,m} - T_{s,m} > \Delta T_{off,en,b} \text{ and the pumps are on,} \end{cases}$$

$$\text{the pumps should be off, if} \begin{cases} T_{s,s,in,m} - T_{s,m} \le \Delta T_{on,en,b} \text{ and the pumps are off, or} \\ T_{s,s,in,m} - T_{s,m} \le \Delta T_{off,en,b}. \end{cases}$$

$\Delta T_{on,en,b} = \Delta T_{off,en,b} + \Delta T_{hyst,en,b}$.

The collector pump operates according to process a/. The storage pump operates according to the logical OR relation between processes a/ and b/.

3. I have developed a physically-based mathematical model which can be directly applied for modelling thermal processes of solar heating systems with external heat exchanger. I have established the model by connecting the differential equations for the heat and mass transport processes of the parts of the solar heating system. I have validated the model with a real, measured solar heating system. I have appointed that the average absolute difference of the simulated and measured solar storage temperatures is 0,5 °C that is 2,7% correlating to the maximal absolute temperature change of the storage. So the model is accurate enough for research, development and practical engineering purposes.

4. I have elaborated a half-empirical method for the identification of the parameters $k_{pipe,coll}$, $k_{pipe,s}$ and Φ based on measured data. I have applied the method for the identification of the established control methods as well as for the identification of the physically-based model. I have defined the specific electric consumption (of the current control) which is the fraction of the

consumed electric energy by the pumps and the solar energy transferred to the consumer (into the solar storage). This indicator shows how much parasitic pump consumption is needed on the average to transfer 1 kWh solar irradiation to the consumer.

5. Based on simulation and measured results, I have justified that the energetically-based control results in higher utilizability and less switches of the pumps, but involves higher parasitic consumption and higher specific electric consumption under the same solar irradiation and consumption load conditions correlating to the generally used ordinary control.
   In case of the investigated solar heating system with external heat exchanger, under different operation conditions, the main comparing results of the energetically-based control correlating to the optimized ordinary control are the followings:

Increase in utilizability	2,5-4,1%
Increase in specific electric consumption	5-44%
Decrease in the number of the switches on of the pumps	41-64%

6. I have justified that it is worth using a valve neither in the aspect of environment protection nor in the aspect of cost saving even in the case of long pipes. This is true both for the ordinary and for the energetically-based control. Namely I have shown, based on the validated model, that the valve increases the utilizability to a so small extent that it takes too much time (15 years besides the current costs) for the investment to be paid back in case of the ordinary control. Specifically the valve decreases the utilizability in case of the energetically-based control.

5. CONCLUSIONS AND SUGGESTIONS

The energetically-based control enables the solar heating systems to operate more favourably since it results in higher utilizability and less switches of the pumps correlating to the case of the generally used ordinary control. Nevertheless it involves higher parasitic consumption.
The energetically-based control requires a programmable controller and four temperature sensors in face of the simpler controller of the ordinary control and its two sensors. This involves a bit increased investment cost.

It is evidently worth applying the energetically-based control in case of the investigated solar heating system, in spite of the increased parasitic consumption and investment cost. It hols according to the decision indicators in 3.3. as well as in the aspect of the payback time of the investment cost.

Accordingly in case of particular solar heating systems, I suggest executing the investigations (simulations) of 3.1. and the evaluation of the results by means of the indicators in 3.3. in view of the particular aims and costs of the system. Depending on the results I suggest applying the energetically-based control.

The investigations have been also shown that it is worth using a valve to avoid cooling down of the solar storage neither in the aspect of environment protection nor in the aspect of cost saving, even in the case of long pipes.

Accordingly I do not suggest applying a valve before the storage in case of any control algorithm.

Since the price of the gas energy will presumably increase in the future correlating to the electric energy price by reason of the decreasing fossil sources and the increasing global warming and because of the spread of harvesting renewable energy sources, the reason of the energetically-based control will presumably increase. Namely the parasitic consumption cost decreases with pumps powered by renewable energy sources (solar irradiation, wind energy) which decreases the electric consumption excess correlating to the ordinary control in case of the energetically-based control. The growth in the cost of gas energy in turn increases the cost saving in the auxiliary energy cost. This decreases also the payback time of the bit increased investment cost of the energetically-based control.

Another expectable reason for the decrease in the investment cost is the decreasing prices of the programmable controllers handling more temperature sensors and the decreasing sensor prices, since these items are more generally used in the future.

For the estimation of the unmeasured temperatures it is recommended to consider the applicability of so-called state observers which use the mathematical model of the solar heating system in the estimation process.

6. SUMMARY

In view of the global environment pollution problem, it is needed to possibly exploit renewable energy resources like solar energy. The efficiency enhancement of active solar water heating systems is a part of this endeavour.
The main contribution in this work is the development of a new, model- and energetically-based predictive control for maximizing the solar utilizability.
The optimization that is the utilizability maximization, corresponding to the ordinary control, used generally in practice and operating with fixed switching off and on temperature differences, has been also accomplished in this work, by minimizing the fixed switching temperature differences to such an extent that the cooling down of the solar storage is still avoided.
The energetically-based control which works with variable switching temperature differences results in a higher utilizability than the (optimized) ordinary control. This is a consequence of its operating principles.
A physically-based TRNSYS model, directly adaptable to solar heating systems with external heat exchanger, has been established. The model has been identified and validated based on a measured solar heating system at the campus of the Szent István University (SIU). The optimized ordinary and the energetically-based controls have been fed into the model both in case of a switching valve before the storage, to avoid its cool down, and without the valve. The controls have been also applied to the SIU system, without valve operation.
The followings have been arisen from the comparison of the controls based on model simulations and measurements on our real system. It is verified that the energetically-based control has a higher utilizability, that is, under the same solar irradiation this control utilizes more of the irradiation for the consumer (for the storage) than the ordinary control. It results in a softer operation of the pumps since they switch less in case of the energetically-based control, which is also an advantage. Nevertheless, it is disadvantageous that the pumps work for a longer time and consumes more electric energy. The excess in the operation costs coming from this, can be greatly moderated with the application of pumps using renewable energy resources. It means a bit higher investments since the energetically-based control needs a programmable controller unit and five temperature sensors instead of the simpler controller unit and two sensors of the ordinary control.
According to the results corresponding to the investigated system, it is worth to apply the energetically-based control instead of the ordinary one from all points of view concerning environment protection, operation costs and investments. On the contrary, it is not worth to apply a switching valve in case of any control type.
As a consequence, depending on the results of pondering, according to the mentioned points of view, the application of the energetically-based control is recommended in case of particular solar heating systems. However it is basically not recommended to use a switching valve for avoiding the cooling down of the solar storage in case of any control type.

7. MOST IMPORTANT PUBLICATIONS RELATED TO THE THESIS

Referred articles in foreign languages

1. **Kicsiny R.**, Farkas I. (2007): Combined solar swimming pool heating and hot water supply, Hungarian Agricultural Engineering, No. 20/2007, Gödöllő, pp. 30-31.
2. **Kicsiny R.** (2009): Development of an energetically-based control for solar thermal heating systems, Review of Faculty of Engineering, Analecta Technica Szegediensia, Szeged, pp. 50-57.
3. **Kicsiny R.** (2009): Energetically-based control for solar heating systems, Scientific Bulletin of the "Politechnica" University of Timişoara, Romania, Transactions on Mechanics, 54(68), 2, pp. 55-62.
4. **Kicsiny R.**, Farkas I. (2012): Energetically-based control for solar heating systems, Solar Energy (under review)
5. **Kicsiny R.**, Varga Z. (2012): Real-time state observer design for solar thermal heating systems, Applied Mathematics and Computation (accepted, in press, DOI: 10.1016/j.amc.2012.05.040)
6. **Kicsiny R.**, Varga Z. (2012): Real-time global state observer design for solar heating systems, Nonlinear Analysis: Real World Applications (under review)

Referred articles in Hungarian

7. **Kicsiny R.**, Farkas I. (2008): Kombinált napkollektoros rendszerek fizikai alapú modellezése, GÉP, LIX. évf., 12. sz., 21-24. o.
8. **Kicsiny R.**, Buzás J., Farkas I. (2009): Napkollektoros rendszer fizikai alapú modellje TRNSYS szimulációs környezetben, GÉP, LX. évf., 8. sz., 26-31. o.
9. **Kicsiny R.**, Farkas I. (2011): Napkollektoros rendszer energetikai alapú szabályozása, Magyar Energetika, XVIII. évf., 5. sz., 14-17. o.