SZENT ISTVÁN UNIVERSITY

BLOCK-ORIENTED MODELING OF SOLAR THERMAL SYSTEMS

Thesis of the doctoral (Ph.D.) dissertation

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Gödöllő
2009

Doctoral school

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CONTENTS

NOTATION

A_c - absorber surface of collector (m^2)
A_s - external boundary surface of storage tank (m^2)
c_c - specific heat capacity of fluid in the collector ($J\ kg^{-1}\ K^{-1}$)
c_s - specific heat capacity of fluid in the storage tank ($J\ kg^{-1}\ K^{-1}$)
C_c - heat capacity of fluid in the collector ($J\ K^{-1}$)
F' - heat transfer factor between the absorber and fluid (dimensionless)
k_s - heat loss coefficient of storage tank ($W\ m^{-2}\ K^{-1}$)
I_c - irradiance on collector plate ($W\ m^{-2}$)
$\dot{m}_c$ - mass flow rate of fluid in the collector ($kg\ s^{-1}$)
T_1 - outlet fluid temperature from heat exchanger coil (°C)
T_{abs} - collector absorber temperature (°C)
T_{cav} - average collector fluid temperature (°C)
T_{ca} - collector ambient temperature (°C)
T_{ci} - collector inlet fluid temperature (°C)
T_{co} - collector outlet fluid temperature (°C)
T_d - storage tank inlet supplied cold water temperature (°C)
T_{ha} - external heat exchanger ambient temperature (°C)
T_{hci} - storage outlet water temperature to external heat exchanger (°C)
T_{hco} - external heat exchanger outlet water temperature returns to storage (°C)
T_{hhi} - heat exchanger hot side inlet temperature returns from collector (°C)
T_{hho} - heat exchanger hot side outlet temperature returns to collector (°C)
T_s - water temperature in the storage tank (°C)
T_{sa} - storage tank ambient temperature (°C)
T_{si} - heat exchanger coil inlet heat transfer medium temperature (°C)
U_c - heat loss coefficient of collector ($W\ m^{-2}\ K^{-1}$)
U_L - overall heat loss coefficient of the collector ($W\ m^{-2}\ °C^{-1}$)
$\dot{v}_c$ - volumetric flow rate of collector and built in heat exchanger coil ($m^3\ s^{-1}$)
$\dot{v}_l$ - volumetric flow rate of extracted hot water from the storage tank ($m^3\ s^{-1}$)
$\dot{v}_s$ - flow rate of loop between storage and external heat exchanger ($m^3\ s^{-1}$)
V_c - het transfer fluid volume in the collector (m^3)
V_s - storage tank volume (m^3)

Greek symbols

η_0 - optical efficiency of the collector (dimensionless)
ρ_c - density of fluid in collector and the collector loop ($kg\ m^{-3}$)
ρ_s - density of fluid in storage and storage side of heat exchanger ($kg\ m^{-3}$)
τ_c - time constant of the collector (s)

1. INTRODUCTION AND AIMS

1.1. Significance of the research

Analyze the tendency of energy prices it could be determined that the rise in prices up to present and the expected increase in price forecasts the economic energy utilization. Similarly to the developed countries, the application of the decentralized energy production units will also increase in Hungary, which ensures partial autonomy for consumers. Beside this, another quite important aspect the spreading out of such environmental friendly energy production technological solutions, which reduce the environmentally damaging pollution emission, come from burning traditional fossil fuel. One possible solution is: growing application of renewable energy sources that fulfils the requirements with the above-mentioned aspects.

One form to use renewable energy is the active thermal utilization of solar energy. Today's solar thermal technologies are efficient and highly reliable, providing solar energy for a wide range of applications – from domestic hot water and space heating in residential and commercial buildings, to swimming pool heating, solar assisted cooling, solar assisted district heating, industrial process heat and desalination.

The total solar thermal capacity in operation at the end of 2007 reached 15,4 GW_{th} (22 million m^2 of collector area) in the member states of the European Union.

Hungary has advantages in the solar thermal utilization capability compare to many European countries. At present in Hungary several sources contain different data in reference to installed solar thermal in operation and the annually installed collector area. According to estimation in 2005 40 thousand m^2 total installed collector area was in Hungary, while in 2006 the market statistics published by the European Solar Thermal Industry Federation contains 6 250 m^2 collector area in operation and in one year later according to statistic 14 250 m^2 collector area was in Hungary. For comparison in Austria in 2007 the total collector area in operation was 2 892 627 m^2.

The solar thermal systems with fluid working medium is excepted to be used manly in domestic hot water heating, industrial process heat, swimming pool heating and in lesser proportion in heating in residential and commercial buildings in Hungary. An average family's approximately 55-60% of annual total hot water consumption could be produced a solar thermal system with 3-4 m^2 collector area and 150 l solar storage tank. Herewith energy could be substituted which produced from fossil or nuclear fuel, additionally the accompaniment harmful emission of energy production could also be reduced.

1.2. Aims of the research

The aims of the research were modeling and simulating of heat transfer processes of solar thermal systems for hot water heating and measurements and monitoring on the available solar thermal systems for validate the model results.

The heat production unit of the solar thermal system operating with fluid working medium is the solar collector. Apply the relevant literature the aim is to work out such a physical based model which able to describe the heat balance of flat plate collector with fluid working medium respect to irradiance, ambient temperature, inlet collector fluid temperature and mass flow rate.

The heat produced by the solar collector for later usage should be allocated in to the storage. In case of two loop system the heat transfer process between the collector loop and the storage implemented by a heat exchanger. There are two main constructions in solar thermal systems one is the internal heat exchanger when a heat exchanger coil is built into the storage tank and the other way is when no heat exchanger in the storage tank, but an external heat exchanger is installed. Hence it is important to develop such physical models, which describe the heat transferred by fluid stream from the collector through the heat exchanger coil get into the storage tank water or get into the fluid stream flowing on the cold side of external heat exchanger from the storage tank.

The energy production period of solar thermal systems and the energy demand of the consumer mostly different in time. Accordingly the function of storage tank is to store the heat accumulated by the collector and supply it by the needs of the consumers. Therefore physical based models are necessary to describe the inlet and outlet fluid and heat steams of the storage tank.

The heat flux between collector and storage unit in solar thermal systems regulates by the controller. In connection the modeling of controller models are necessary for the entire system simulations to regulate the heat transfer fluid streams in the system based on outlet collector temperature and the storage tank temperature. The aim is to develop controller models with the same operation as the installed controllers in the systems used model validation measurements during the research.

Based on the subsystem models describe the operation of the main components of solar thermal system such as solar collector, heat exchanger, storage tank and controller, the integrated model of the entire system can be developed. The aim is to develop such a simulation model which can be used to calculate the hot water temperature in the storage tank respectively estimate the heat production of the solar thermal system based on the input variables as irradiation, ambient temperature, supplied cold water temperature and the hot water consumption.

2. MATERIAL AND METHOD

The characteristic of the operation of solar domestic hot water systems are transient, time varying processes. For the description of the processes such a concentrated parameter ordinary differential equations were used which able to describe the time varying heat transfer processes with the required accuracy. For the solution of the equations block-oriented simulation software the MATLAB+Simulink was used. Beyond the modeling of the given physical processes the software able to model and examine the regulation and control functions of the system as well.

Most of the solar thermal systems in Europe installed with glass cowered flat plate collectors. This is also true for the Hungarian installations. Hence the dissertation deals with the modeling of flat plate collector.

For modeling physical based approach was applied. The physical based mathematical models can be used to parameter sensitivity analysis, simulation and control aims in addition to allow of the application of system analysis methods widely used in the control theory to determine the transfer features.

2.1. Physical based model of the flat plate collector

Assume the flat plate collector in Figure 1 the model describes the outlet fluid temperature of the collector $T_{co}(t)$ as a function of input variables and parameters.

In case of the steady state of the collector the inlet heat amount of the collector equal with the outlet heat amount of the collector. Thus the amount of heat carry from the collector by the heat transfer medium flowing through and warming up in the collector is equal with the difference of the heat gain of the collector from the solar radiation and the heat loss of the collector to the ambient.

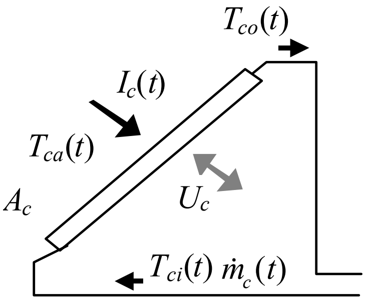


Fig. 1. Scheme of the collector

The state equation of the collector arranged to the first order differential of the outlet fluid temperature:

$$\frac{dT_{co}(t)}{dt} = \frac{A_c \eta_0}{C_c} I_c(t) - \frac{U_L A_c}{C_c}\left(T_{cav}(t) - T_{ca}(t)\right) + \frac{\dot{v}_c(t)}{V_c}\left(T_{ci}(t) - T_{co}(t)\right), \tag{1}$$

where $C_c = \rho_c c_c V_c$, $\dot{m}_c(t) = \dot{v}_c(t)\rho_c$ and $T_{cav}(t)$ is the average collector temperature:

$$T_{cav}(t) = \frac{T_{ci}(t) + T_{co}(t)}{2}. \tag{2}$$

2.2. Solar storage tank models

For modeling of hot water storage tanks numerous applicable methods can be found in the related literatures which are very differing from each other. The concentrated parameter model concerns to thermally completely mixed storage tank. The mathematical model is an ordinary differential equation describes the storage tank temperature varying in time. In this case the model valid only with a condition which assumes no temperature distribution in the storage tank so the temperature space considered homogeneous. In the course of research I applied this modeling method.

2.2.1. Storage tank model with built in heat exchanger coil

In the practice in small-scale solar thermal installations approximately up to 500 liters storage tank volume commonly apply storage tanks with built in heat exchanger coil.

In this case the heat transfer fluid returning from the collector going through the heat exchanger coil built in the lower part of the storage tank (Fig. 2.).

Assumptions: uniform temperature distribution or thermally completely mixed storage tank and $T_d(t)=T_d$ is constant. The model does not take into account the heat loss between the storage tank and ambient.

For the block-oriented simulation of the storage tank the differential equation describing the energy balance of the storage tank arranged to the first order differential of the storage tank temperature $T_s(t)$:

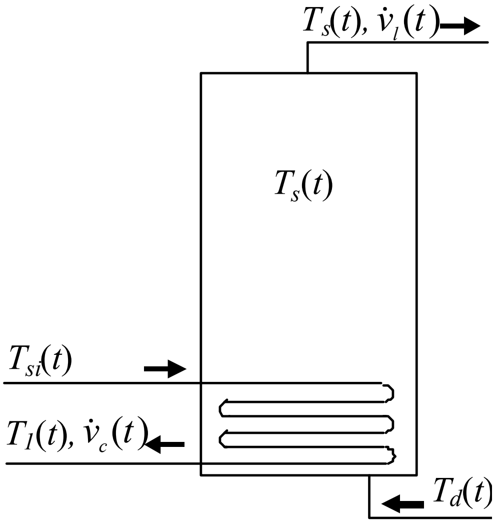


Fig. 2. Storage tank with built in heat exchanger coil

$$\frac{dT_s(t)}{dt} = \frac{\dot{v}_l(t)}{V_s}(T_d - T_s(t)) + \frac{\dot{v}_c(t)}{V_s}(T_{si}(t) - T_1(t)) \,. \tag{3}$$

The outlet heat transfer fluid temperature of the heat exchanger coil can be calculated as follows:

$$T_1(t) = \left(T_{si}(t) - T_s(t)\right) e^{-\frac{UA}{\dot{v}_c(t)\rho c}} + T_s(t) \,, \tag{4}$$

where ρ is the density of the fluid in the heat exchanger coil, c is the heat capacity of the fluid in the heat exchanger coil, U is the heat transfer coefficient of the heat exchanger, A is the surface of the heat exchanger coil.

2.2.2. Storage tank model without built in heat exchanger

Larger scale solar thermal systems frequently installed with external heat exchanger, so the storage tank does not contain built in heat exchanger. The scheme of the storage tank shown in Figure 3.

The developed model does not take into account the heat capacity derived from the storage tank construction.

Assumptions: the temperature space is homogeneous in the storage tank and the hot water temperature in the storage is the same as the outlet temperature towards to the external heat exchanger $T_{hci}(t)=T_s(t)$. Thus the state equation of the storage tank:

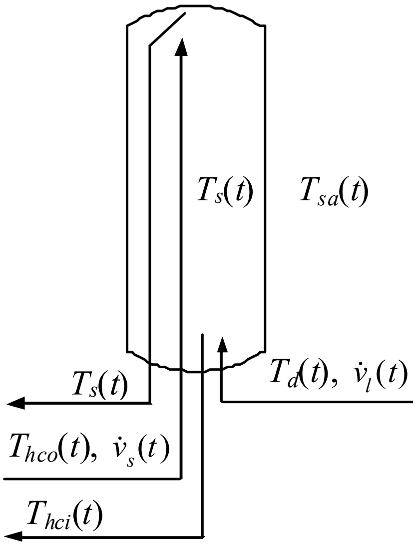


Fig. 3. Storage tank without heat exchanger

$$\frac{dT_s(t)}{dt}=\frac{\dot v_l(t)}{V_s}(T_d(t)-T_s(t))+\frac{\dot v_s(t)}{V_s}(T_{hco}(t)-T_s(t))-\frac{A_s k_s}{\rho_s c_s V_s}(T_s(t)-T_{sa}(t))\,. \quad (5)$$

2.3. External heat exchanger model

Larger scale solar thermal systems often designed with external heat exchanger. Among the solar thermal systems which were available for verification measurements also had this kind of construction. I have developed a model for external heat exchanger. The sketch of heat exchanger can be seen in Fig. 4. The variables and parameters on the hot side or collector loop side of heat exchanger are: fluid temperature in hot side of heat exchanger $T_l(t)$, hot side volume of heat exchanger V_l and the volumetric flow rate in the collector loop $\dot v_c(t)$ connected to the hot side of heat exchanger.

Variables and parameters on the cold side or storage loop side of heat exchanger are: fluid temperature in cold side of heat exchanger $T_2(t)$, cold side volume of heat exchanger V_2 and the volumetric flow rate in the storage loop $\dot v_s(t)$ connected to the cold side of heat exchanger.

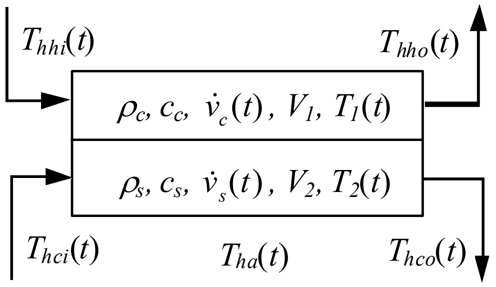


Fig. 4. External heat exchanger

Assuming homogeneous temperature distribution on both sides of the heat exchanger (assume thermally mixed fluid) and introducing the followings: $T_l(t)=T_{hho}(t)$, $T_2(t)=T_{hco}(t)$, $V_l=V_2=V$. The energy balance equation of the heat exchanger hot side:

$$\frac{dT_{hho}(t)}{dt}=\frac{\rho_c c_c \dot{v}_c(t)}{C_{h1}+\rho_c c_c V}(T_{hhi}(t)-T_{hho}(t))-\frac{A\,k}{C_{h1}+\rho_c c_c V}(T_{hho}(t)-T_{hco}(t))-$$
$$-\frac{A_a k_a/2}{C_{h1}+\rho_c c_c V}(T_{hav}(t)-T_{ha}(t)). \quad (6)$$

The energy balance equation of the heat exchanger cold side:

$$\frac{dT_{hco}(t)}{dt}=\frac{\rho_s c_s \dot{v}_s(t)}{C_{h2}+\rho_s c_s V}(T_{hci}(t)-T_{hco}(t))+\frac{A\,k}{C_{h2}+\rho_s c_s V}(T_{hho}(t)-T_{hco}(t))-$$
$$-\frac{A_a k_a/2}{C_{h2}+\rho_s c_s V}(T_{hav}(t)-T_{ha}(t)). \quad (7)$$

The average heat exchanger temperature:

$$T_{hav}(t)=\frac{T_{hho}(t)+T_{hco}(t)}{2}. \quad (8)$$

Further parameters of the heat exchanger model are: heat transfer surface between the hot and cold side A, heat transfer coefficient between the hot and cold side k, external boundary surface of the heat exchanger A_a, heat transfer coefficient between the heat exchanger and ambient k_a. The heat capacity of the hot and cold side of the heat exchanger concerning to the design $C_{h1}=C_{h2}=(c_h\, m_h)/2$, where c_h is the specific heat capacity of the heat exchanger material and m_h is the mass of the heat exchanger without fluid.

2.4. Solar thermal systems for verification measurements

In the course of research the experiments and measurements concerning to the modeling and simulation were carried out on two solar thermal systems.

One of the systems developed in the Department of Physics and Process Control, Szent István University (SZIU). The system installed with a 1,65 m^2 flat plate collector and a 150 l electric water-heater which was adopted for the solar thermal application. To connect the collector loop to the storage tank has two options, one is through a built in heat exchanger coil or the other is a compact brazed external heat exchanger. The monitoring of the ambient and system operation parameters and the pumps and valves regulation was carried out a computer controlled microcontroller based modular data logging system.

The other solar thermal system installed in the campus of SZIU Gödöllő. It contains 33,3 m^2 surface of collector field with 23,31 kW_{th} thermal capacity. The system includes two plate heat exchangers with 40-40 kW capacity. One is for swimming pool water heating with 1 m^2 heat transfer surface and the other is for heating kindergarten hot water with 2 m^2 heat transfer surface. The pool loop connects the pool heat exchanger and the 700 m^3 swimming pool, while the kindergarten loop operating between the kindergarten heat exchanger and the 2000 l solar storage. A data logging and monitoring system also installed.

3. RESULTS

3.1. Determination of the flat plate collector transfer function

Applying the method of Laplace transform I have determined the transfer function of flat plate collectors. The collector equation (1) can be considered as linear if the fluid flow rate in the collector is assumed $\dot{v}_c(t)=$ constant.

I have defined the time constant of the collector as follows:

$$\tau_c = \frac{1}{\dfrac{U_L A_c}{2C_c} + \dfrac{\dot{v}_c}{V_c}} \tag{9}$$

The transfer function for the certain input variables can be found. Considering linear collector equation because of the assumed constant flow rate the principle of the superposition can be used. According to this principle the response of the output variable caused by the input variables can be calculated as the sum of the individual responses caused by the individual inputs. At the determination of the transfer function of an individual input variable the reminder inputs and the initial value of the outlet collector temperature $T_{co}(0)=0$ are equal to zero.

Applying Laplace transform the time-domain variables signed by top line in *s*-domain. Denote the transfer function by W(s). The transfer function of the collector concerning to the solar irradiance:

$$W_1(s) = \frac{\overline{T}_{co}(s)}{\overline{I}_c(s)} = \frac{(\tau_c A_c \eta_0)/C_c}{\tau_c s + 1}. \tag{10}$$

The transfer function regarding to the collector inlet heat transfer medium temperature:

$$W_2(s) = \frac{\overline{T}_{co}(s)}{\overline{T}_{ci}(s)} = \frac{\tau_c}{\tau_c s + 1}\left(\frac{\dot{v}_c}{V_c} - \frac{U_L A_c}{2C_c}\right). \tag{11}$$

The transfer function referring to the collector ambient temperature:

$$W_3(s) = \frac{\overline{T}_{co}(s)}{\overline{T}_{ca}(s)} = \frac{(\tau_c U_L A_c)/C_c}{\tau_c s + 1}. \tag{12}$$

Finally the effect of the initial value of the collector outlet heat transfer medium temperature $T_{co}(0)$ can also be determined. The outlet medium temperature response caused by the initial value can be given as follows:

$$W_0(s) = \frac{\tau_c}{\tau_c s + 1}. \tag{13}$$

According to the superposition principle the aggregation of the transfer functions defined by equations (10-13) gave the overall transfer function concerning to the collector outlet heat transfer medium temperature. The individual inputs causing effects on the output thorough their transfer function.

The equation concerning to the outlet heat transfer medium temperature with transfer functions if the initial value of outlet collector temperature $T_{co}(0) \neq 0$:

$$\overline{T}_{co}(s) = W_0(s)T_{co}(0) + W_1(s)\overline{I}_c(s) + W_2(s)\overline{T}_{ci}(s) + W_3(s)\overline{T}_{ca}(s) \qquad (14)$$

3.2. Solving of collector model with block-oriented simulation

For the calculation of the collector outlet heat transfer medium temperature I applied the Simulink which is the simulation toolbox of MATLAB software and supports the model based dynamic system simulation. The block system has been constructed based on equations (1) and (2). Figure 5 shows the results of the simulation.

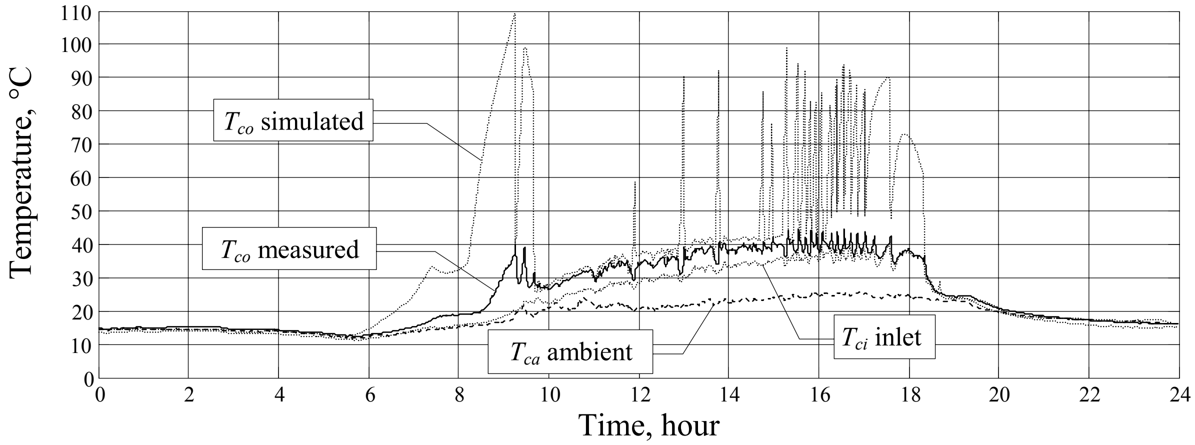


Figure 5. Measured and simulated collector outlet temperature

The average difference between the measured and simulated collector outlet temperature was 8,6 °C. The minimum of the difference -3,6 °C and the maximum was 72,1 °C, while the standard deviation was 16,4 °C. The error is influenced by more factors. The model takes into account only the heat capacity of the heat transfer fluid (C_c) in the collector, so the heat capacity of the absorber plates, the fluid carrier pipes and the additional structural parts of the collector are neglected. The applied optical efficiency value (η_0) and the heat loss coefficient of the collector (U_L) were chosen based on the relevant literature which is approximately could be typical based on the experience of practice but of curse it is not identical with the values of the tested collector.

3.3. Identification of the overall heat loss coefficient of the collector

The difference between the measured and simulated collector outlet temperatures can be reduced by parameter identification. Based on the measured collector outlet temperature the model parameter values can be refined. For instance this kind of parameter is the overall heat loss coefficient of the collector (U_L). For the identification more type of cost function can be constructed. One of the mostly used function is calculates the sum of the square difference between the measured and calculated collector outlet temperature. The cost function can be given by equation (15). Thus the identification means the minimization of the cost function.

$$J(U_L) = \sum_{i=1}^{n} (T_{co}(t_i) - \hat{T}_{co}(t_i))^2 \Rightarrow \min. \tag{15}$$

In equation (15) J denotes the sum of the square difference between the measured and calculated collector outlet temperature in the examined time interval. $T_{co}(t_i)$ is the measured value in the i-th sampling time point and $\hat{T}_{co}(t_i)$ is the calculated value for the i-th sampling time point and n is the number of measured values.

The results of the identification is the value of the overall heat loss coefficient of the collector arose to U_L=35,0 W m^{-2} °C^{-1}. The simulation carried out with the identified value the average difference between the measured and simulated collector outlet temperature was -0,3 °C. The minimum of the difference -15,8 °C and the maximum was 14,6 °C, while the standard deviation was 3,4 °C.

3.4. Solar thermal system simulation with internal heat exchanger

One of the most current version from the solar thermal system constructions applied in the practice is the design with heat exchanger built in the storage tank. The developed and previously introduced collector and storage tank model with internal heat exchanger can be used to compose the block-oriented model of the entire solar thermal system shown in Figure 6.

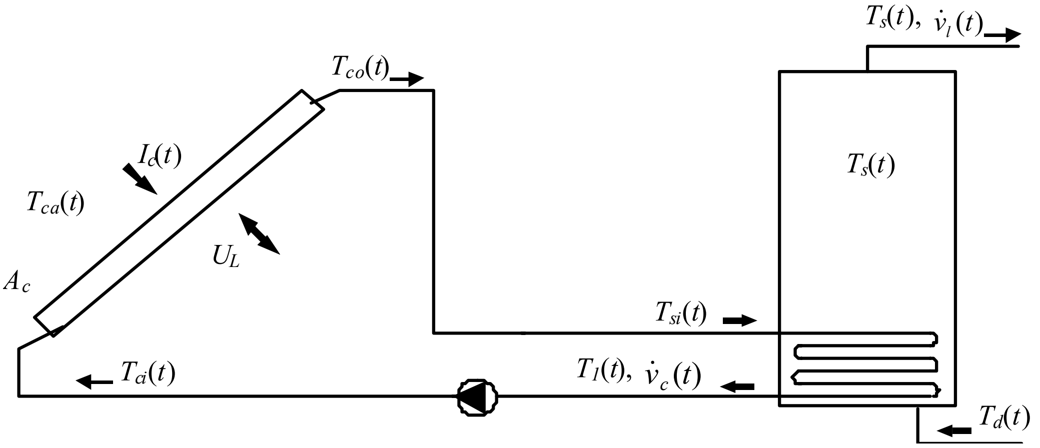


Fig. 6. Solar thermal hot water system with internal heat exchanger built in the storage tank

I have used block-oriented simulation technique for simulate the entire system containing collector and storage tank with built in heat exchanger by using the formerly detailed sub models. The measured input variables for the simulation were the collector loop flow rate $\dot{v}_c(t)$, the solar irradiance intensity $I_c(t)$, the ambient temperature $T_{ca}(t)$, the storage tank inlet cold water temperature $T_d(t)$

and the flow rate of the hot water extraction $\dot{v}_l(t)$ from the storage tank. In the course of simulation the calculated output variables are the collector outlet fluid temperature $T_{co}(t)$ and the storage tank temperature $T_s(t)$.

3.5. Simulation of solar thermal system with external heat exchanger

Beside the system construction introduced in the previous chapter the other most frequently applied solar thermal system construction is the use of external heat exchanger. This version mainly used such systems which has large collector field and large size storage or more storage tank are installed in the system.

I have used equation (1) and (2) for the calculation of the collector outlet fluid temperature. The measured input variables of the collector model are the solar irradiance intensity on collector plate $I_c(t)$, the collector ambient temperature $T_{ca}(t)$ and the heat transfer fluid flow rate $\dot{v}_c(t)$ through the collector. The output variable of the model is the outlet collector temperature $T_{co}(t)$.

The block-oriented solution of equations (6) and (7) relating to the hot and cold side of external heat exchanger is shown in Fig. 7. The model calculates the heat exchanger hot and cold side outlet temperatures ($T_{hho}(t)$, $T_{hco}(t)$).

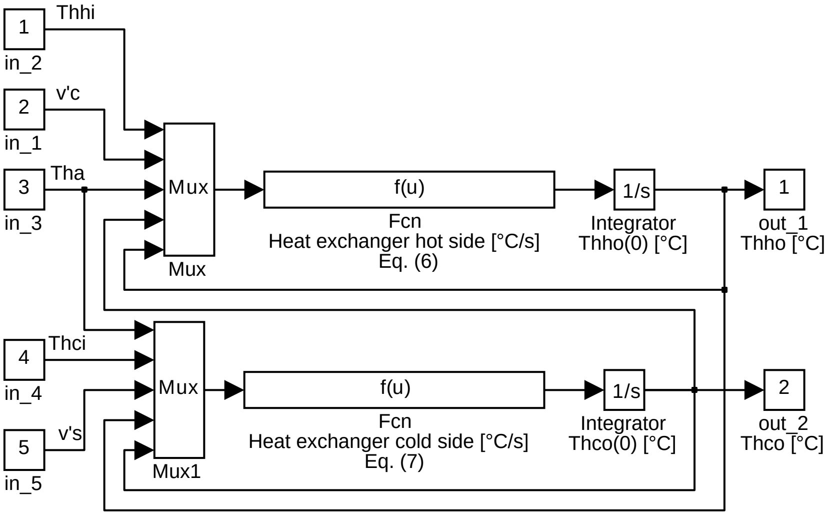


Fig. 7. Block-orientid external heat exchanger model

Since the storage tank and the connected external heat exchanger installed in the same room thus the heat exchanger ambient temperature $T_{ha}(t)$ and the storage tank ambient temperature $T_{sa}(t)$ was the same in the course of simulation.

The block-oriented solution of the storage tank energy balance equation (5) can be seen in Figure 8. The storage tank model calculates the stored water temperature $T_s(t)$.

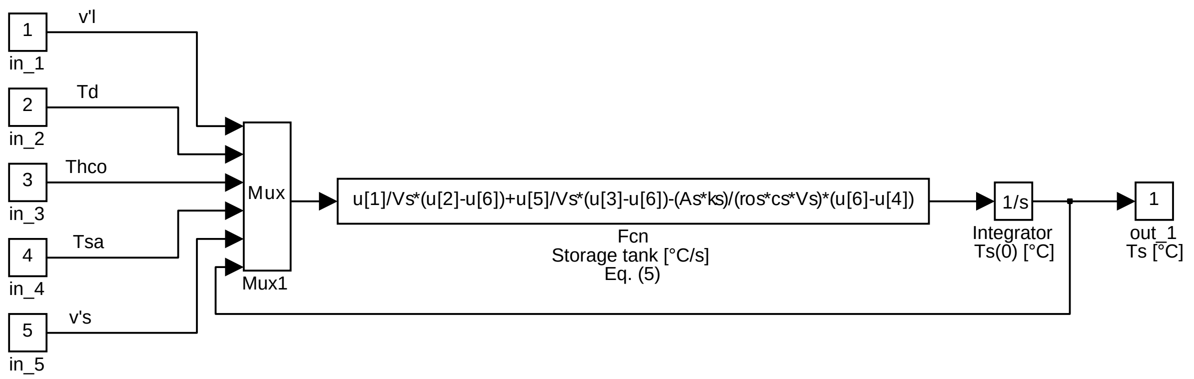


Figure 8. Block-oriented storage tank model based on equation (5)

Combined the developed subsystem models I have created the model of the entire solar thermal system installed with external heat exchanger.

Using the block-oriented simulation technique the model of the complete system built on different subsystem models shown in Figure 9.

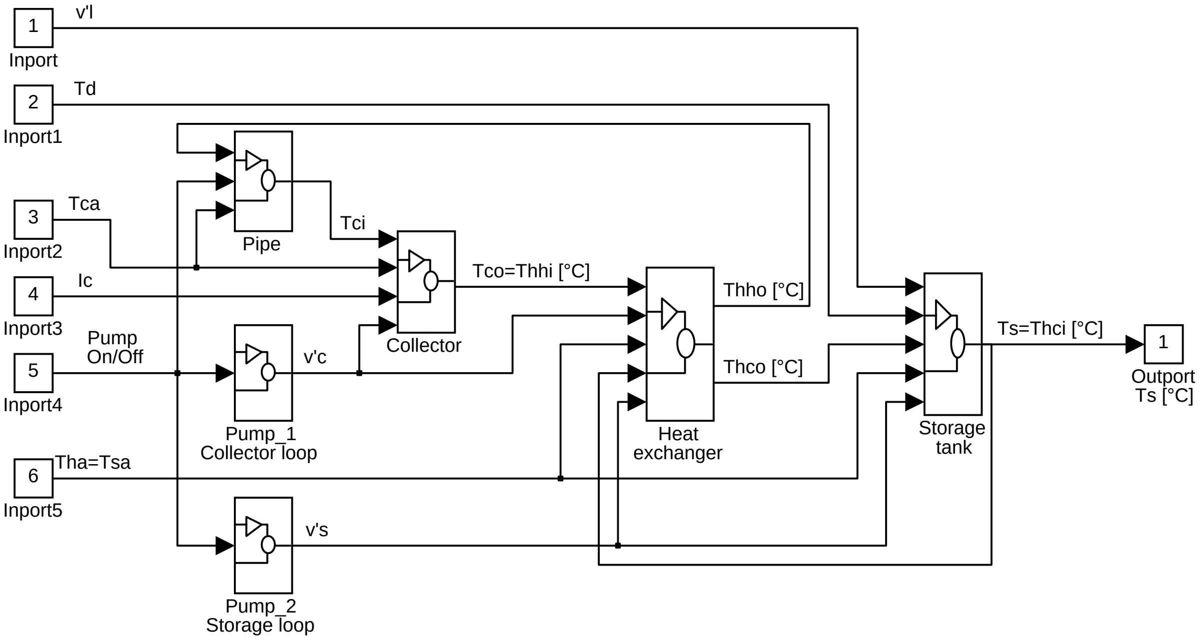


Fig.9. Block-oriented model of the solar thermal system with external heat exchanger

In the course of the simulation for modeling the circulation pump operation the measured "on" and "off" state of the pump was used in the collector loop and the storage loop. During the measurements the pumps in the collector and storage loop was controlled based on the temperature difference between the measured collector outlet temperature $T_{co}(t)$ and the storage tank temperature $T_s(t)$. The upper and lower dead band temperature difference was 3 °C.

The flow rate control in the collector loop operated as follows:

$$\dot{v}_c(t) = \begin{cases} 2{,}9\cdot 10^{-5}\,\mathrm{m^3 s^{-1}},\ \text{when } T_{co}(t) \geq T_s(t)+3 \\ 0\ \ \mathrm{m^3 s^{-1}},\ \text{when } T_{co}(t) \leq T_s(t)+3 \end{cases}$$

The flow rate control in the storage loop operated as follows:

$$\dot{v}_s(t) = \begin{cases} 5{,}9\cdot 10^{-5}\,\mathrm{m^3s^{-1}}, \text{ when } T_{co}(t) \geq T_s(t)+3 \\ 0\ \ \mathrm{m^3s^{-1}}, \text{ when } T_{co}(t) \leq T_s(t)+3 \end{cases}$$

3.6. Controller models of solar thermal systems

In this chapter three different controller models are introduced what I have developed. The block-oriented models of the controllers operated on the same way as it is used in the practice for circulation pump control in the collector loops of solar thermal systems.

I have developed the model of differential controller operating with the same upper and lower dead bend temperature difference. The controller model is shown in Figure 10.

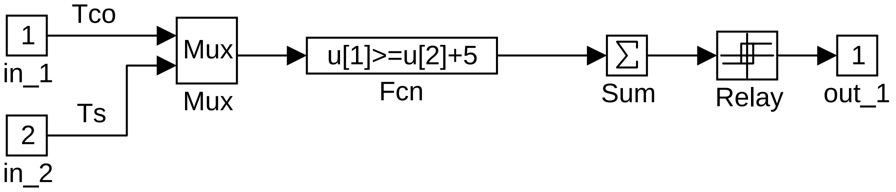


Figure 10. Simulink model of differential controller operating with same "on" and "off" dead band temperature

On the basis of the controller used in the solar thermal system for swimming pool water and domestic hot water heating I have developed the differential controller model operating with dissimilar "on" and "off" dead band temperature. In the controller model developed for entire solar thermal system simulation different upper and lower dead band temperature values can be set. The block-oriented model of the controller can be seen in Figure 11.

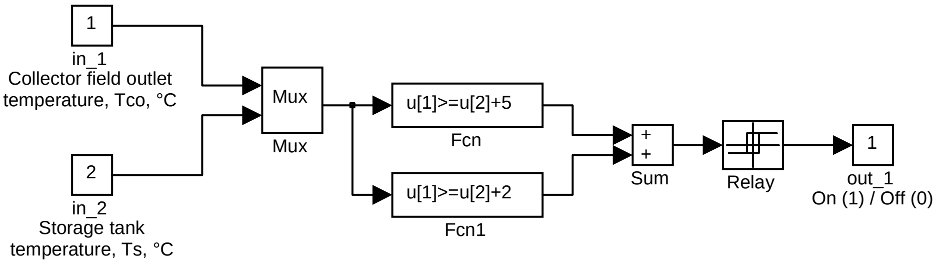


Figure 11. Block-oriented realization of the dissimilar upper and lower dead band differential controller

The third developed controller model type besides the on/off control of the pump is appropriate for flow rate control during the circulation pump operation. This controller model is includes the features of the previously discussed differing on and off dead bend differential controller. The controller switches on the pump if the collector outlet temperature $T_{co}(t)$ compared with the storage tank temperature is higher than the adjusted value for upper dead band temperature (dTE). During the circulation if the decreasing temperature difference reaches the set point value for lower dead band (dTA) the controller switches off the pump. Comparing this controller to the previously discussed two types this is able to control the flow rate of the circulation pump operating in collector loop. With that the outlet collector temperature could be kept on an optimal temperature. The controller calculates the optimal collector outlet temperature as it is shown below:

$$TKO=T_S+1/2(dTE+dTA),$$

where TKO is the optimal collector outlet temperature and T_s is the storage tank temperature. The block-oriented controller model shown in Figure 12.

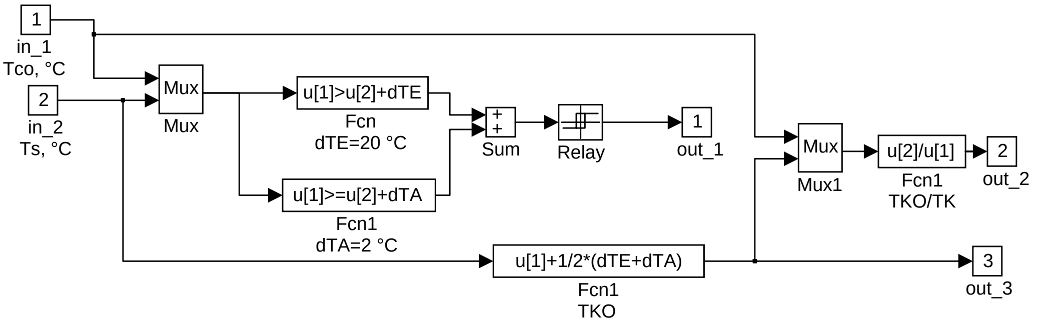


Fig. 12. Model of the collector loop circulation pump flow rate controller

The circulation pump speed correction factor calculated by the above control model appears in out port 2. This correction coefficient linked to the in port 2 in the model of the collector loop pump, illustrated by Figure 13. Finally the flow rate appears on the output of the circulation pump model. The introduced flow rate control model and the variable fluid transport rate circulation pump model can be used to control the heat transfer medium flow rate in the collector loop which assists the realization of stabilized operation of solar thermal systems.

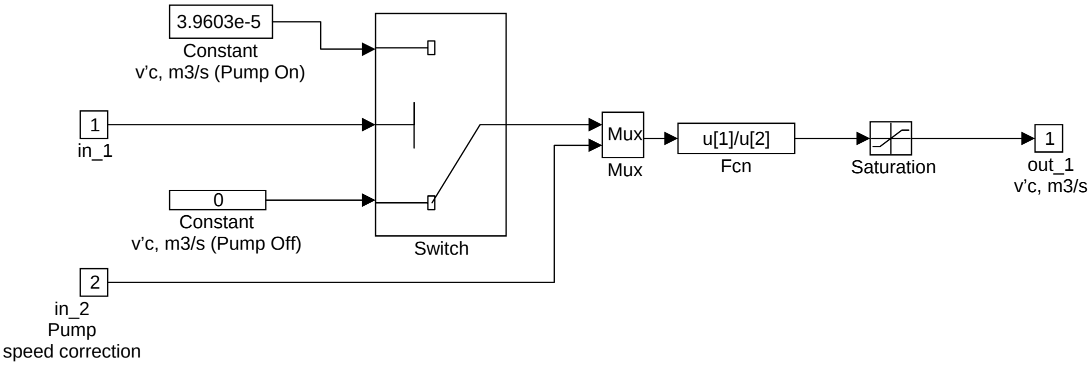


Figure 13. Model of the variable flow rate collector loop pump

3.7. Monitoring and simulation of swimming pool water heater solar thermal system

In the course of research I have carried out monitoring and simulation tasks on a swimming pool water and domestic hot water heater solar thermal system.

After the evaluation of measured data of the installed data logging system the monthly distribution of the solar insolation on collector field, the heat generated by the collector field and the utilized amount of heat is shown in Figure 14.

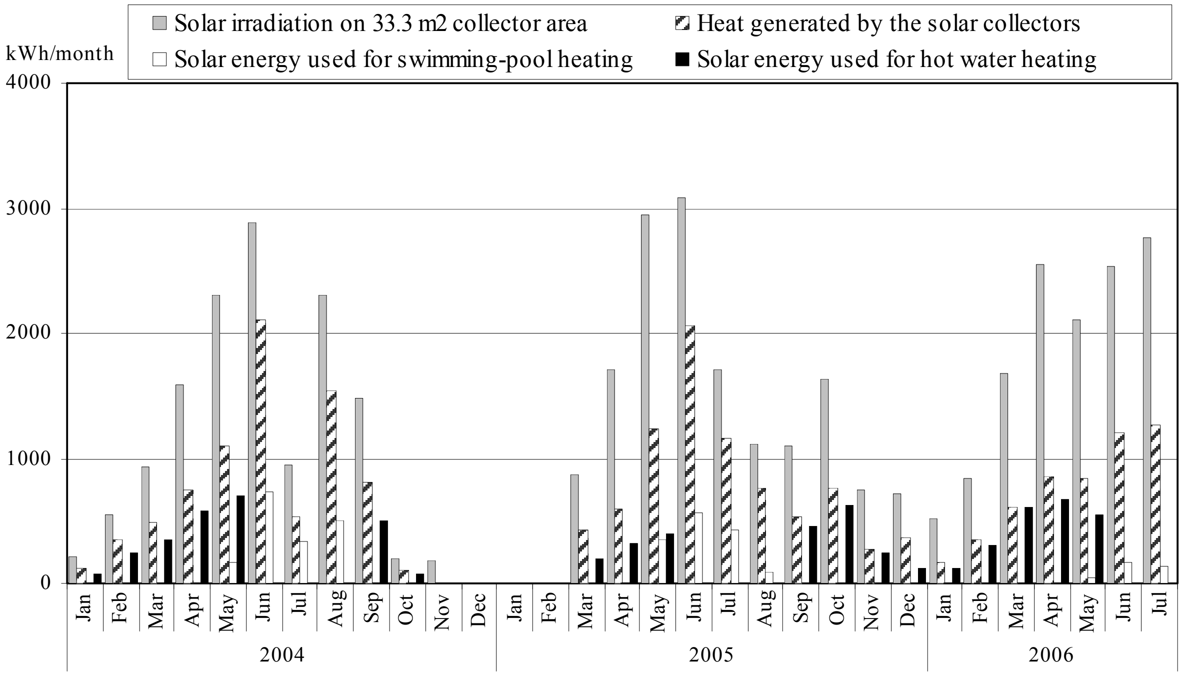
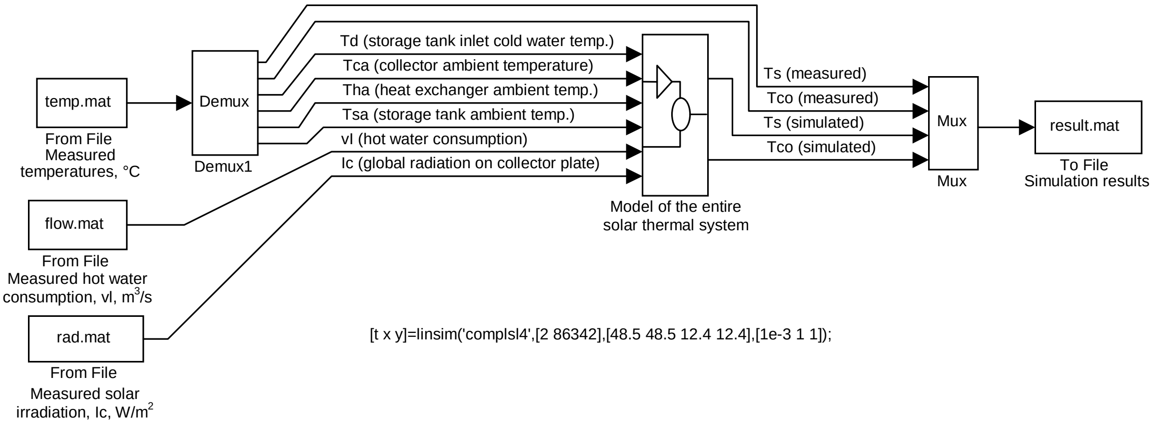


Figure 14. Monthly distribution of the solar irradiation on collector field and the utilized solar energy

During the monitored period of January 2004 and July 2006 the solar thermal system heated the swimming-pool water with 3,5 MWh thermal energy, while the solar energy utilized for kindergarten hot water heating was 7,2 MWh. In the evaluated period 0,34 kWh/m^2 day utilized thermal energy pertained for 1 m^2 collector field area.

Figure 15 shows the block-oriented model of the entire solar thermal system.

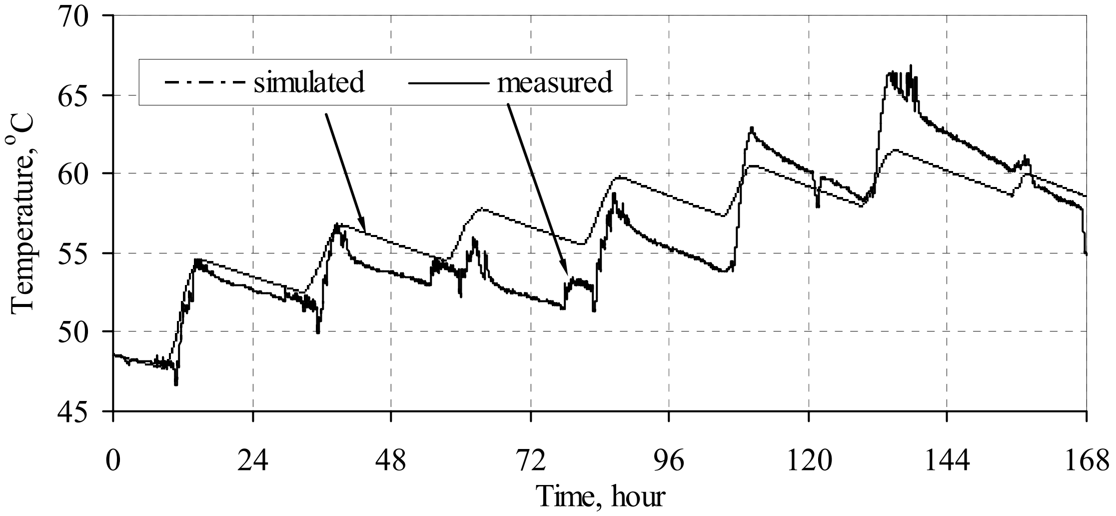


```
[t x y]=linsim('complsl4',[2 86342],[48.5 48.5 12.4 12.4],[1e-3 1 1]);
```

Figure 15. Block-oriented model of the solar thermal system

The simulation was carried out for the period of May 14-20, 2002. The measured and simulated outlet temperatures of the collector and the storage tank temperatures are shown in Figure 16.

a/ Storage tank temperatures, May 14-20, 2002



b/ Collector field outlet temperatures, May 14-20, 2002

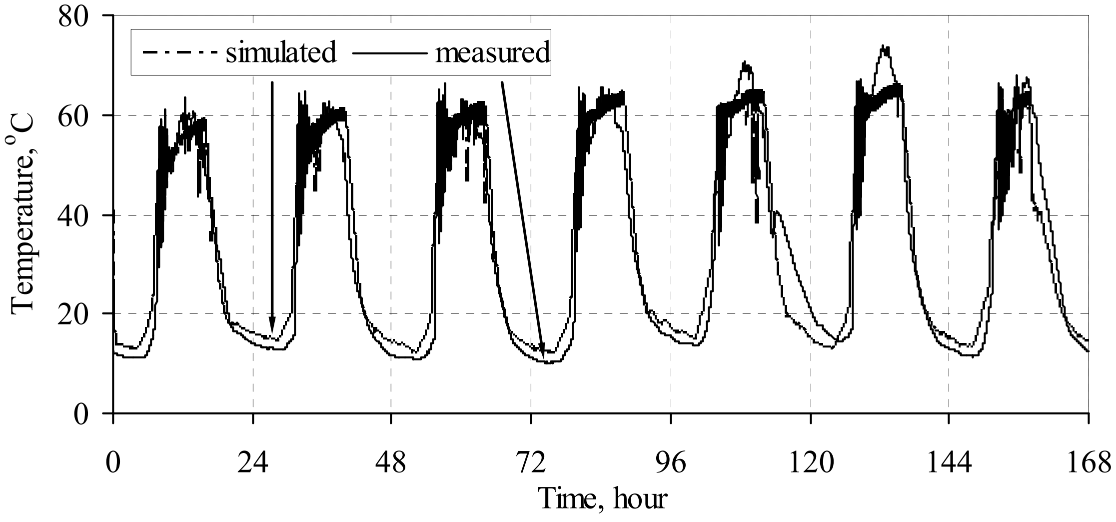


Figure 16. Comparison of the measured and simulated temperatures

The average difference between the measured and simulated collector outlet temperature was 4,26 °C, while the average solar storage tank temperature difference was 1,91 °C. To improve the model further measurements and investigation is needed. Based on the measured data the parameter values, the heat transfer coefficients of the components more precisely can be identified with this the accuracy of the simulation expectedly could be improved.

4. NEW SCIENTIFIC RESULTS

In reference to the research of solar thermal hot water systems the related new scientific results can be summarized as follows:

1. For the description of the main components of liquid working medium solar thermal systems as flat plate collector, heat exchanger and storage tank, applying the physical based modeling approach, I have developed concentrated parameter model with ordinary differential equations. I applied the block-oriented modeling technique to solve the energy balance equations describing the heat and mass transfer processes of the certain components. The elaborated dynamic models based on the input variables are appropriate for the thermal simulation and the computation of the time varying output variables of the individual subsystems.
2. I have determined the transfer functions of flat plate collectors concerning to the irradiance intensity, the inlet fluid temperature, the ambient temperature and the initial value of collector outlet temperature as input variables. Knowing the transfer functions of the inputs, allow a separation in the analysis of the input variables effects on outlet collector temperature. Thus, in the sense of input variables it can by analyzed the effect of construction parameters of flat plate collector basically determined the transfer properties. I have defined the overall transfer function of flat plate collectors as a linear superposition of the individual transfer functions concerning to different input variables.
3. I have elaborated an experimental identification method for the determination of the overall heat loss coefficient value for flat plate collectors. By means of this method utilizing measured data I have determined the overall heat loss coefficient value for flat plate collectors operating with liquid heat transfer medium.
4. In case of heat exchanger coil, built in the storage tank, applying analytical solution I have determined the function which describes the coil outlet temperature varying in time. In the developed model the storage tank water temperature is the state variable, the heat exchanger coil inlet temperature and the volumetric flow rate through the coil are the input variables.
5. Using the individual block-oriented models of the subsystems I have developed a linked model for the entire solar thermal system. I have elaborated the block-oriented realization of the entire solar thermal system for the case of internal and external heat exchangers of which have an importance in the construction practice.

6. I have developed different block-oriented control models in solar thermal systems for the differential controller based on the temperature differences and for the flow rate controller. One of the developed models is able to realize the same on/off temperature difference band control, while the other one is appropriate for differentiation in switching "on" and "off" statuses. The developed mass flow rate control model is able to maintain the process based on an algorithm, as it is designed along with a microprocessor control. Based on the control models I have elaborated a system model of a combined solar thermal system heating swimming pool water and domestic hot water.

5. CONCLUSIONS AND SUGGESTIONS

The comparison of the simulation results and the measured data proved that the developed concentrated parameter mathematical models appropriate for describing the time varying heat and mass transfer processes in components of solar thermal systems with liquid working medium. Based on the developed models the block-oriented realization is completed. The realized models are not only for system element simulation, but linking those ones is good for thermal simulation of the entire system.

Take advantage of the possibilities of block oriented simulation technique combine the developed component models of solar thermal systems, the entire system simulation can be executed. During the research the simulation of two different structure systems had been done. One of the systems had storage tank with built in heat exchanger coil, while the other one is constructed with external heat exchanger. In case of system with built in heat exchanger coil the calculated storage tank temperature fits fairly to the measured one. Only two lesser deviation was observed. These deviations were caused by two factors. One is when the storage tank heated up for night-time the calculated temperature remained on a constant value, while the measured one showed a smooth decreasing in time. This difference caused by the storage tank model which does not take into account of the heat loss between the storage and the ambient. The other deviation between the measured and calculated temperature occurred when the total water volume of storage tank had been discharged. This time, at the end of the discharging process the measured storage tank temperature was higher than the calculated. This is generated by that the storage tank model calculates only with the heat capacity of water in the storage tank, while the storage tank itself has heat capacity as well, which cause a so called "residual heat effect", when the remained heat is transferred to the inlet cold water in the storage tank.

In the course of the evaluation of measured and simulated results I have found that in the time periods of increasing and decreasing insolation intensity the controllers are switching frequently between on and off state. This phenomenon causes instability in the collector loop, which is disadvantageous in point of view of the system operation. To dissolve the described symptom and recover the collector loop stability I have suggested a minimal operation period for circulating pump which is needed to set. For minimal pump operation period I have recommend at least 3-5 minutes. Scaling this behavior of the system installations in the future, such controllers are needed to select which able to eliminate this problem.

Continuing the research it would be practical to examine the effect of control on the energy production of the system. In the future for development of control algorithms aspire to the optimization of energy production.

During the operation flat plate collector behave like a dynamic system. The heat and mass transfer in time domain can be described a one variable ordinary differential equation independently from the space coordinate. The equation from time-domain can be transformed to "*s*" domain with Laplace transformation. Using the time-domain equation parameters with physical meaning the transfer function can be determined in "*s*" domain. Thus finding the transfer function it gives possibility to use dynamic system test methods developed in control theory. In case of flat plate collectors the effect of the transient changes in the input variables as solar radiation, inlet heat transfer medium temperature, ambient temperature and the initial value of the outlet temperature can be evaluated as the response of the output variable, which is the outlet collector temperature. The time constant can also be determined which is depend on the heat and mass storage characteristics of the collector. Beyond the application possibility of dynamic system test methods the transfer function can be used for simulation, parameter sensitivity analysis and control tasks as well.

6. SUMMARY

In the course of the research a related literature survey was carried out concerning to the Hungarian solar radiation energy distribution and the subvention policy influencing the installation of solar thermal systems. The literature dealing with the main components of solar domestic hot water systems had been processed. A review was made on the standards connected with the tests procedures of solar thermal systems. Information was collected on different simulation software for modeling of solar thermal systems.

In the chapter of materials and methods – based on the literature – a detailed introduction was given on the physically based modeling of flat plate solar collectors operating with fluid working medium and most frequently used in solar thermal systems. A physically based model was developed which describes the heat transfer processes in the collector. The transfer functions concerning to the outlet heat transfer fluid temperature of the flat plate solar collector was determined for different input variables of the collector as solar radiation intensity, inlet working medium temperature, ambient temperature and the initial response of the outlet heat transfer fluid temperature.

Models were developed for the solar storage tank as another main component of the solar thermal systems. The different model versions can be used to describe divided storage tank, storage tank with built in heat exchanger coil and storage tank without heat exchanger.

For the one of the mostly used construction of the solar thermal systems a model with external heat exchanger was elaborated allowing to calculate the heat transfer between the collector loop and the storage loop.

To carry out of system simulations different block-oriented control models were developed. The control models can be parameterized on different ways and they are operated on the temperature difference between the collector outlet temperature and the storage tank temperature, as well.

A simulation was carried out using the block-oriented simulation technique with the integration of the developed subsystem models for different solar thermal constructions. In the course of the study the most frequently used two constructions were taken into account. One type of the system is installed a storage tank with built in heat exchanger coil, while the other one built with external heat exchanger. For the latter type, the simulation was carried out for two different size of solar thermal system.

Monitoring tasks of a solar thermal swimming pool heating system was carried out and the utilized energy ratio between swimming pool water heating and hot water heating was also determined.

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