Abstract - The paper deals with the block-oriented approach in modelling of a solar domestic hot water system. Due to the linking possibility to other technological processes (greenhouse, dryer, etc.) the Matlab+Simulink software was decided to use. The entire model consists of the sub-system models as collector, heat exchanger and storage tank. The governing heat and mass transfer equations are given along with the assumptions applied in the model. A measuring set-up was designed in order to validate the developed model. The simulation results with the identified model show reasonably good coincidence with the measured values. This implies also further activity in improving the model.

1. INTRODUCTION

For simulation of thermal energy applications several computer programs were developed. One of them is the TRNSYS, which is used throughout the world. The TRNSYS is a transient system simulation program with a modular structure including many of the components commonly found in thermal energy systems (Klein et. all, 1996). The program can be used, for example, for simulation of a solar hot water system, including the main components as solar collector, heat exchanger and storage tank.

There are several technological processes especially in the agriculture, which require hot water supply e.g. solar dryers, solar assisted greenhouses, etc. A solar hot water system could be used for such cases. In order to be able to link together all the sub-parts of an integrated solar energy/technology system the solar hot water system should be modelled with the same technique.

For solving the heat and mass transfer problem of the mentioned technological processes (greenhouse, drying, etc.) a block-oriented Matlab+Simulink software tool is frequently used. That implies to apply the same software package for simulation of the solar domestic hot water system, as well.

For the simulation of the entire system the following measured parameters are to be used, as global solar radiation on collector plate, collector ambient temperature, heat exchanger and storage tank ambient temperature, flow rate of the collector and storage loop, the cold tap water temperature and the hot water usage. For the validation of the model and for the identification of parameters as heat loss coefficients in situ measurements can be performed. Based on the developed models parameter sensitivity analysis and transient influences can be examining for the element and the entire system as well. The influence of the different control strategies can also be easily evaluated within the Matlab+Simulink software.

2. GENERAL SPECIFICATIONS OF THE SYSTEM

Concerning the thermal utilisation of the solar energy a solar hot water system was built as a part of the integrated renewable energy system. The hot water system has two separated flow loops. The primary or hot loop transports heat from the collector into the heat exchanger meanwhile the secondary or cold one is in operation between the heat exchanger and the storage tank. Because of the whole year operation in the collector loop, it is not offered to use ordinary water because of high pressure, danger of incrustation and frost. Therefore a special frost preventing fluid, as 50 % concentration of propylene glycol and distilled water is used. In the secondary or cold loop the ordinary tap water is used. In the primary loop the pipelines between the collector and heat exchanger are insulated in order to reduce the heat loss. The flat plate collector is installed in an adjustable slope frame. The aperture surface of the solar collector is 1.65 m². The orientation of the collector is south and the slope angle is 45 degrees. The flow rate of the collector loop can be adjusted by the pump in three gears. Between the hot (collector) and cold (storage) loop a compact brazed plate heat exchanger is used which is especially developed for low-pressure boiler applications (water to water) and at moderate temperatures. In the storage loop a 0.15 m³ storage tank is installed. The tank configuration is vertical cylinder of 1.082 m inside height and 0.446 m inside diameter. The fixed inlet and outlet positions of the storage tank are the followings: the height of supplied cold water inlet to tank above bottom of tank is 0.07 m; the height of the extracted hot water outlet from the tank above bottom of tank 1.07 m; the height of the heat exchanger return to tank above bottom of tank 0.97 m; the height of the tank return to heat exchanger above bottom of tank 0.07 m. For the circulation between the storage tank and the heat exchanger a constant flow rate pump is used in the storage loop. Apart from the storage
tank a heating unit for a laboratory greenhouse is abutted. The greenhouse can be heated directly by the collector or by the heat collected in the storage tank during the night or under unfavourable radiation conditions. The three switching valves provide the possibility to optionally involve or separate the collector, storage tank and greenhouse into the loop as it can be seen in Fig. 1.

For control the pumps in the primary and secondary loops an On/Off differential control algorithm was used. The upper and lower dead band temperature difference was equal. The host computer of the connected data acquisition and controlling system provides the automatic operation of the system. The data acquisition system is built up from ADAM modules along with the linked circuits performing measurements and control tasks.

3. MODELLING APPROACH

In this paragraph the block-oriented approach modelling of the solar domestic hot water system will be introduced. The entire model will be made up the sub-system (collector, heat exchanger and storage tank) models. For validation of the model an appropriate measuring arrangement was set-up.

The system was measured during April 2000. The measurements and control were carried out by a data acquisition and control system. The data were sampled and stored for every 60 seconds. The recorded data was used for checking the developed physically based model results.

3.1. Physically based models

Consider a flat plate solar collector shown in Fig. 2, where the temperature of fluid entering collector $T_{ci}$, temperature of fluid leaving collector $T_{co}$, temperature of the collector ambient air $T_{ca}$, aperture surface of the collector is $A_c$, irradiance on collector plate $I_c$, volumetric flow rate in the collector loop $\dot{v}_c$, overall heat loss coefficient of collector $U_L$. The model describes $T_{co}$ as function of $T_{ci}$, $\dot{v}_c$, $I_c$, $T_{ca}$ and $U_L$. 

Fig. 1 Configuration of the solar domestic hot water system
The state equation of the collector (Buzás et al., 1998)

\[
\frac{dT_{co}}{dt} = \frac{A \eta_0}{C} I_c - \frac{U_f A_c}{C} (T_{av} - T_{ca}) + \frac{\dot{v}_c}{V_c} (T_{ci} - T_{co})
\]

where \( \eta_0 \) is the optical efficiency of the collector, \( C = \rho_c c_c V_c \) is the overall heat capacity of fluid in the collector, \( \rho_c \) is the density of the fluid in the collector loop, \( c_c \) is the specific heat of the fluid in the collector loop, \( V_c \) is the volume of collector and \( T_{av} \) is the average fluid temperature in the collector.

The average fluid temperature in the collector is supported to be

\[
T_{av} = \frac{T_{ci} + T_{co}}{2}.
\]

The model assumes that the fluid in the collector completely mixed. The simplified block scheme of the solar collector can be seen in Fig. 3 where the variables in Eq. (1) are the followings:

- **State variable**: \( T_{co} \)
- **Output variable**: \( T_{co} \)
- **Input variables**:
  - Disturbances: \( I_c, T_{co}, T_{ci} \)
  - Manipulated variable: \( \dot{v}_c \)
- **Parameters**: \( A, c_c, \rho_c, U_f, V_c, \eta_0 \)

The scheme of the plate heat exchanger is shown in Fig. 4. The hot side parameters are the followings: \( T_{hhi} \) is the return fluid temperature from the collector to the heat exchanger hot side, \( T_{hho} \) is the return fluid temperature from the heat exchanger hot side to the storage tank, \( T_j \) is the fluid temperature in the heat exchanger hot side, \( V_f \) is the volume of the heat exchanger hot side.

The cold side parameters are the followings: \( T_{hci} \) is the return fluid temperature from the storage tank to the heat exchanger cold side, \( T_{hco} \) is the return fluid temperature from the heat exchanger cold side to the storage tank, \( T_2 \) is the fluid temperature in the heat exchanger cold side, \( V_2 \) is the volume of the heat exchanger cold side and \( \dot{v}_s \) is the volumetric flow rate in the storage loop and \( T_{ha} \) is the heat exchanger ambient temperature.

The energy balance equation of the hot (primary) side of the heat exchanger:

\[
\frac{dT_{hho}}{dt} = \frac{\rho_c c_c \dot{v}_c}{C_h + \rho_c c_c V} (T_{hhi} - T_{hho})
- \frac{A k}{C_h + \rho_c c_c V} (T_{hho} - T_{hco})
- \frac{A k_2}{2} \left( \frac{T_{hav} - T_{ha}}{C_h + \rho_c c_c V} \right).
\]

The energy balance equation of the cold (secondary) side of the heat exchanger:

\[
\frac{dT_{hco}}{dt} = \frac{\rho_s c_s \dot{v}_s}{C_h + \rho_s c_s V} (T_{hci} - T_{hco})
- \frac{A k}{C_h + \rho_s c_s V} (T_{hho} - T_{hco})
- \frac{A k_2}{2} \left( \frac{T_{hav} - T_{ha}}{C_h + \rho_s c_s V} \right).
\]
The average heat exchanger temperature can be assumed as:

\[ T_{hav} = \frac{T_{hho} + T_{hco}}{2}, \]  

(4)

Further parameters of the model are the heat transfer surface between the two parts of the heat exchanger \( A \), the heat transfer coefficient between the two parts of the heat exchanger \( k \), outside surface of the heat exchanger \( A_a \), the heat transfer coefficient between the heat exchanger and the ambient air \( k_a \). The heat capacity of the heat exchanger parts are \( C_{ch} = (c_h m_h)/2 \), where \( c_h \) is the specific heat of the heat exchanger material and \( m_h \) is the (empty) mass of the heat exchanger.

The simplified block scheme of the heat exchanger can be seen in Fig. 5, where the variables in Eq. (3a-3b) are the followings:

State variables: \( T_{hho}, T_{hco} \)
Output variables: \( T_{hho}, T_{hco} \)
Input variables:
Disturbances: \( T_{hhi}, T_{hci}, T_{ha} \)
Manipulated variables: \( \dot{V}_s, \dot{V}_l \)
Parameters: \( A, A_a, c_h, c_o, k, k_a, m_h, \rho, \rho_s, V_c \).

Fig. 5 Block scheme of the heat exchanger

The schematic diagram of the storage tank can be seen in Fig. 6. The model parameters are \( T_s \) is the water temperature of the storage tank, \( T_{sa} \) is the ambient air temperature of the storage tank, \( T_d \) is the supplied cold water temperature, \( \dot{V}_l \) is the volumetric flow rate of the extracted hot water, \( V_s \) is the volume of the storage tank, \( A_s \) is the boundary surface of the storage tank, \( k_s \) is the heat loss coefficient of the storage tank, \( \dot{V}_s \) as it was mentioned before, is the volumetric flow rate in the storage loop.

Before set-up the energy balance equation of the storage tank the following assumptions are introduced \( T_{hco} = T_s \) and full mixing in the storage rank.

The state equation of the storage tank is

\[ \frac{dT_s}{dt} = \frac{1}{V_s} \left( \dot{V}_l (T_d - T_s) + \dot{V}_s (T_{hco} - T_s) - \frac{A_s k_s}{\rho_s c_s} (T_s - T_{sa}) \right). \]  

(5)

The model does not take in to the account of the heat capacity of the storage tank material.

The simplified block scheme of the storage tank can be seen in Fig. 7 where the variables in Eq. (5) are the followings:

State variable: \( T_s \)
Output variable: \( T_s \)
Input variables:
Disturbances: \( T_d, T_{hco}, T_{sa}, \dot{V}_l \)
Manipulated variable: \( \dot{V}_s \)
Parameters: \( A_s, c_s, k_s, \rho_s, V_s \).

Fig. 7 Block scheme of the storage tank

3.2. Model realisation in block-oriented simulation

For solving of the differential equations block-oriented Matlab+Simulink software were used. In the following
figures show the separated models of the main elements of the solar domestic hot water system.

The Simulink model of the collector can be seen in Fig. 9, which was constructed based on Eq. (1-2). The output parameter of the model is the collector outlet temperature ($T_{co}$).

Fig. 10 shows the heat exchanger model, which calculates the hot and cold side outlet temperatures ($T_{hho}$, $T_{hco}$) using equations (3a-b and 4).

The storage tank model is shown in Fig. 11 where the model computes the storage tank temperature ($T_s$) by the Eq. (5).

All of the Simulink graphs on Figs 9-16 contain the input variables on the left-hand side and the output variables of the model on the right hand side.

The sub-system models can be used now for the construction of the entire system. Based on the individual models of each element the complete system simulation can be carried out by the connection of sub-systems. The complete system model is shown in Fig. 12.

The block scheme of the complete system can be seen in Fig. 8 where the variables are the followings:

**Output variable**: $T_s$

**Input variables**:
- Disturbances: $I_c$, $T_{ca}$, $T_d$, $T_{ha}=T_{sa}$, $\dot{v}_j$

**Manipulated variables**: $\dot{v}_{c}$, $\dot{v}_s$.

It is supposed that the ambient temperatures around the heat exchanger ($T_{ha}$) and the storage tank ($T_{sa}$) are identical.
The entire model does not take into account the heat loss of the pipelines so the collector outlet temperature $T_{co}$ is the same as the heat exchanger hot side inlet temperature $T_{hi}$ when $v_c \neq 0$. Obviously the heat exchanger hot side outlet temperature $T_{ho}$ is the same as the collector inlet temperature $T_{ci}$ if the pump is in operation in the collector loop otherwise $T_{co}=T_{so}$. This subsystem is named "Pipe" in Fig. 12, which is shown in details in Fig. 13. For the simulation the measured pump states (On/Off) were used. During the test period of the system for the pumps control in the primary and secondary loops the On/Off differential control method was used. The upper and lower dead band temperature difference was $3 \, ^\circ C$.

The flow rate in the collector loop

$$
\dot{v}_c = \begin{cases} 
2.9 \times 10^{-5} \, m^3 \, s^{-1} \quad & \text{when } T_{co} \geq T_s + 3 \\
0 \, m^3 \, s^{-1} \quad & \text{when } T_{co} \leq T_s + 3 
\end{cases}
$$

The flow rate in the storage loop

$$
\dot{v}_s = \begin{cases} 
5.9 \times 10^{-5} \, m^3 \, s^{-1} \quad & \text{when } T_{co} \geq T_s + 3 \\
0 \, m^3 \, s^{-1} \quad & \text{when } T_{co} \leq T_s + 3 
\end{cases}
$$
The Simulink models of the flow rate simulation in the collector and storage loop are shown in Fig. 14 and 15.

The measured data was taken from a file. The Simulink block scheme and the Matlab simulation starting parameters are shown in Fig. 19.

### 3.3. Measurements

The measured parameters can be divided in two parts. One is the meteorological or ambient parameters and the others are the operational parameters of the system. The detailed list of the measured parameters and description of the sensors used are given in Table 1.

**Table 1 Parameters monitored and description of the sensors used**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Sensor Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_{H}$</td>
<td>Pyranometer Eppley Model 8-48</td>
<td>Irradiance on horizontal surface</td>
</tr>
<tr>
<td>$I_{c}$</td>
<td>Pyranometer Kipp &amp; Zonen CM-11</td>
<td>Irradiance on collector plate</td>
</tr>
<tr>
<td>$T_{ca}$</td>
<td>LM335 Integrated circuit temperature sensor</td>
<td>Collector ambient temperature</td>
</tr>
<tr>
<td>$T_{ci}$</td>
<td>LM335 Integrated circuit temperature sensor</td>
<td>Collector inlet temperature</td>
</tr>
<tr>
<td>$T_{co}$</td>
<td>LM335 Integrated circuit temperature sensor</td>
<td>Collector outlet temperature</td>
</tr>
<tr>
<td>$v_{c}$</td>
<td>Flow meter Schlumberger Unimag DN Qn=1.5 m$^3$/h, EEC/ISO Class B</td>
<td>Flow rate of collector loop</td>
</tr>
<tr>
<td>$T_{hei}$</td>
<td>LM335 Integrated circuit temperature sensor</td>
<td>Heat exchanger hot side inlet temperature</td>
</tr>
<tr>
<td>$T_{heo}$</td>
<td>LM335 Integrated circuit temperature sensor</td>
<td>Heat exchanger hot side outlet temperature</td>
</tr>
<tr>
<td>$T_{hei}$</td>
<td>LM335 Integrated circuit temperature sensor</td>
<td>Heat exchanger cold side inlet temperature</td>
</tr>
<tr>
<td>$T_{heo}$</td>
<td>LM335 Integrated circuit temperature sensor</td>
<td>Heat exchanger cold side outlet temperature</td>
</tr>
<tr>
<td>$v_{s}$</td>
<td>Flow meter Schlumberger Unimag DN Qn=1.5 m$^3$/h, EEC/ISO Class B</td>
<td>Flow rate of storage loop</td>
</tr>
<tr>
<td>$T_{sa}$</td>
<td>LM335 Integrated circuit temperature sensor</td>
<td>Storage tank and heat exchanger ambient temperature</td>
</tr>
<tr>
<td>$T_{sa}$</td>
<td>LM335 Integrated circuit temperature sensor</td>
<td>Hot water storage tank temperature</td>
</tr>
<tr>
<td>$v_{i}$</td>
<td>Flow meter Schlumberger Unimag DN Qn=1.5 m$^3$/h, EEC/ISO Class B</td>
<td>Hot water flow rate</td>
</tr>
<tr>
<td>$T_{d}$</td>
<td>LM335 Integrated circuit temperature sensor</td>
<td>Storage tank inlet cold water temperature</td>
</tr>
</tbody>
</table>
4. SIMULATION RESULTS AND DISCUSSION

For starting the simulation the initial parameter values were taken from the literature. The value of collector optical efficiency $\eta_0=0.8$ and the overall heat loss coefficient of the collector $U_L=7 \text{ Wm}^{-2}\text{K}^{-1}$, which are normally used in case of single glazed collector in the temperature range of 10-60 °C (Burges, 1991). In case of the heat exchanger the heat transfer coefficient $k=1509 \text{ Wm}^{-2}\text{K}^{-1}$ between the two sections of the heat exchanger was provided by the manufacturer. The heat loss coefficient of the storage tank $k_s=1 \text{ Wm}^{-2}\text{K}^{-1}$ and the heat exchanger $k_a=2 \text{ Wm}^{-2}\text{K}^{-1}$ was estimated from the measured data.

A daily simulation result of the system is shown in Fig. 17. The measured and calculated collector output temperatures has two oscillating interval in the increasing and decreasing radiation intervals. The calculated collector outlet temperature has higher oscillation than the measured one as because in case of the collector only the fluid heat capacity was taken into account in the model. The oscillation can be reduced by the calculation of the heat capacity of the collector structure. Eliminate the oscillation another possibility is to construct a pipe model, which can calculate the heat capacity, the losses and conduction along the pipeline.

![Fig. 17 The measured collector ambient temperature and the measured and calculated collector outlet and storage tank temperatures](image_url)

Between the measured and computed storage tank temperatures at the maximum values has 3.3 °C difference. Further investigation is needed to improve the model in that direction.

5. CONCLUSIONS

For modelling of hot water system a block-oriented approach was applied. Physically based sub-models were developed first to describe the heat and mass transfer process in the main components of the solar hot water system as flat plate collector, plate heat exchanger and storage tank. The applied assumptions are given in the sub-models.

The sub-models were realised and link together in the by Matlab+Simulink block-oriented software package. For simulation purposes the heat loss coefficients of the main components were estimated by measured data.

In situ measurement of the entire solar hot water system was performed. The data were sampled and stored for
every 60 seconds. The recorded data was used then for the validation of the developed model.

The simulated collector outlet temperature shows higher oscillation than the measured one as because in case of the collector only the fluid heat capacity was taken into account in the model.

In case of the storage tank the dynamics of the simulated tank temperature shows some difference from the measured one. The maximum difference between the measured and simulated storage tank temperatures is 3 °C. To improve the model further investigation is needed in that direction.

Finally, it can be concluded that the block-oriented approach in modelling of a domestic hot water system is a reasonably good tool. One of the main benefit is to allow flexible linking the solar sub-models together and also to the relevant models of the technological processes for which the solar energy is supplied.

Acknowledgement - The authors wish to thank for the Hungarian Scientific Research Fund (OTKA, ID Number: T 032510) to support the project.

REFERENCES


