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DYNAMIC MODELING OF OPERATION OF CONTROLLED SOLAR HEATING SYSTEM IN ECOSIMPRO

DYNAMICZNE MODELOWANIE DZIAŁANIA STEROWANEGO GRZEWCZEGO UKŁADU SOLARNEGO W PROGRAMIE ECOSIMPRO

Abstract

The article describes the structure and operation of virtual one-dimensional dynamic model of the solar heating system using components from the libraries of the EcosimPro program. The model is based on a fragment of a real hybrid sorption-compressor refrigeration system, designed and built in the Laboratory of Thermodynamics and Thermal Machines Measurements at the Faculty of Mechanical Engineering of the Cracow University of Technology. In the second part of the paper, the results of the dynamic simulation are shown along with their comparison to the actual measurement data recorded during one day (and night).

Keywords: dynamic modelling, solar heating system, EcosimPro

Streszczenie

Prezentowany artykuł zawiera opis struktury i działania wirtualnego jednowymiarowego dynamicznego modelu solarnego systemu grzewczego przy użyciu komponentów z bibliotek programu EcosimPro. Model oparty jest na fragmencie rzeczywistego hybrydowego sorpcyjno-sprężarkowego systemu ziębniczego, zaprojektowanego i zbudowanego w Laboratorium Termodynamiki i Pomiarów Maszyn Ciepłych na Wydziale Mechanicznym Politechniki Krakowskiej. W drugiej części artykułu pokazano wyniki dynamicznej symulacji i ich porównanie do rzeczywistych danych pomiarowych, zarejestrowanych w ciągu jednej doby.

Słowa kluczowe: modelowanie dynamiczne, system ogrzewania słonecznego, EcosimPro

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1. Introduction

In the laboratory of Institute of Thermal and Process Engineering seated at the Faculty of Mechanical Engineering of the Cracow University of Technology, there has been designed and assembled a prototype of a two stage hybrid adsorption-compression cooling system [1]. The high temperature stage component of the system is the adsorption chiller driven by the heat generated by the solar collectors. The adsorption chiller works during the summer period as a chiller rejecting the heat from the condenser of the low temperature compressor stage with CO₂ as the cooling agent. Generally, all heating systems driven by solar collectors are characterised by periodic operation and unstable availability of a heat source. This enforces the use of heat accumulators to store the surplus of the heat generated during day and use it during periods of low solar operation (e.g. at nights). The excessive solar heat load to the system may cause a rise of the temperature above limits, thus an additional safety protection system is necessary. There are two possible solutions: a heat rejection system (e.g. by using a cooling tower) or thermally controlled solar blinds blocking the solar radiation.

In the present paper, the structure and operation of a virtual one-dimensional dynamic model of the solar heating system is shown. The model built in the EcosimPro software is based on a fragment of the above-mentioned hybrid refrigeration system.

2. Hybrid sorption-compressor refrigeration system

In Figure 2.1, a general scheme of the hybrid cooling system is shown.

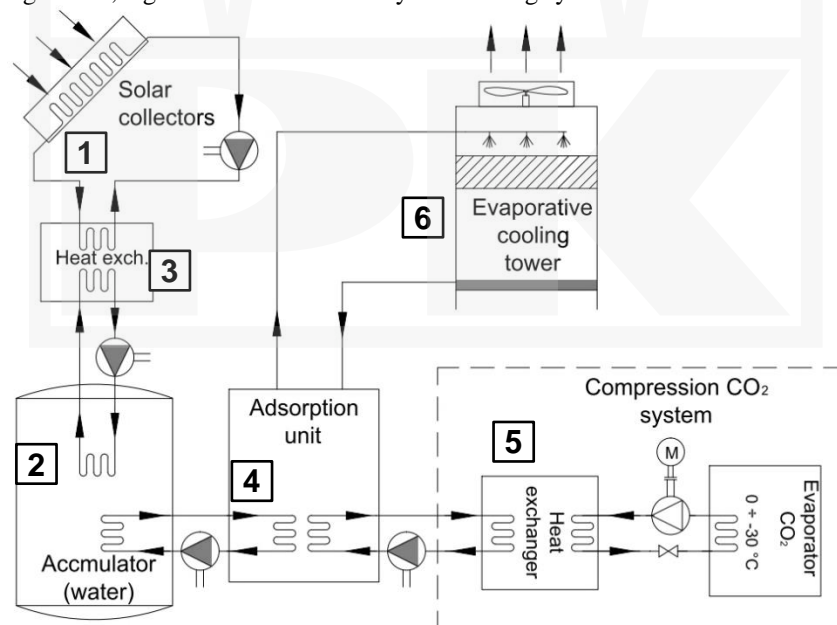


Fig. 2.1. General diagram of the system

The system consists of four main subsystems:

- solar collectors (1) with accumulator (2) coupled by the heat exchanger (3),
- adsorption chiller (4),
- compression CO₂ system (5),
- cooling tower (6).

The aim of the present paper is to build a virtual model of one complete subsystem comprising of a set of solar collectors (1), an accumulator (2) and the heat exchanger (3). The model allows to simulate a dynamic behaviour of the solar heating subsystem during a period of several days. A detailed diagram of the solar heating subsystem is shown in Figure 2.2.

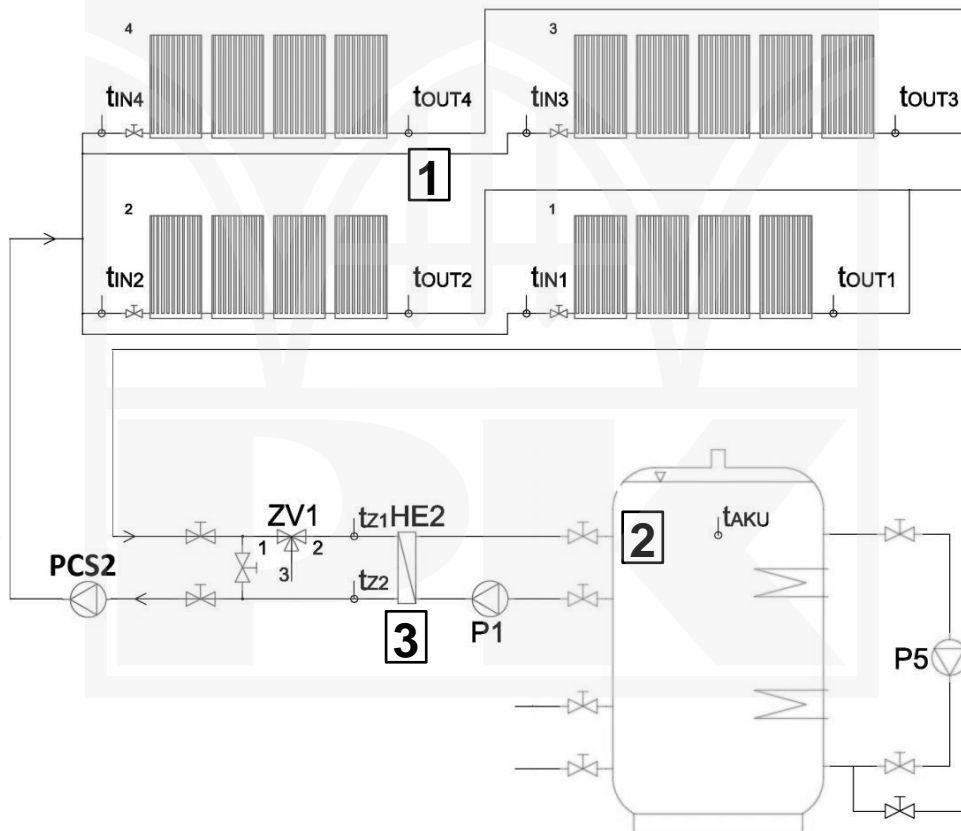


Fig. 2.2. General diagram of the system [2]

3. One-dimensional dynamic modelling in EcosimPro

EcosimPro is a modelling and simulation tool developed by Empresarios Agrupados and used, among others, by ESA¹ and CERN². It allows to build mathematical models of 0D or 1D multidisciplinary continuous-discrete systems and any kind of systems based on differential-algebraic equations (DAE) and discrete events [3].

Models can be created with predefined components from multiple libraries or custom objects written in EL (EcosimPro Language). In order to simulate a schematic model, a mathematical model called partition has to be created. For each partition, the user can define experiments, which contain information about simulation settings, such as time or file name, to save results, initial and boundary conditions.

The greatest advantage of EcosimPro is the possibility of reusing models outside of the software environment in several forms, e.g. standalone C++ application. This feature guarantees model reusability by others and further development possibilities like dedicated applications for operator's training, testing models with control programs from real PLC device etc.

The model described below has been created with EcosimPro 5.2.0 by using major components from embedded libraries: Fluidapro, Control, Thermal. The Control and Thermal libraries are standard and free to use, the Fluidapro is a separate library that requires an additional, extra paid, license.

3.1. Virtual model description

In Figure 3.1, a diagram of the created model of solar heating system with the heat storage is shown. The model presents one of the optional states of the system – the heat generated by solar collectors (1) is stored by the accumulator (2).

Fluidapro elements like pipes, tees, valves, volume, heat exchanger, tank and temperature sensors can be distinguished by their symbol shapes. The *Working Fluid* abstract elements (WF) define the working medium (e.g. water). The real pumps are virtually modelled by a simplified component (PCS2, P1).

Elements, which serve to model solar irradiance (G), temperature outside (T_OUT) and mass flow (QM), are imported from the Control library. There are also two Thermal components to simulate the impact of environmental temperature on heat storage.

SolarCollectors element represents a sub-model, which is separately defined in a different file, in order to clarify the scheme view. The *Psolar* element is used to calculate the power gained by solar collectors with given inputs, where the temperature sensor T_MIX registers the current working medium temperature.

In the current *Psolar* model, the measuring point of controlling (feedback) temperature is located after the solar collectors because all solar collectors are identical and thus all are characterised by the same parameters. This workaround simplifies the computational effort and also improves the scheme view. Further simplifications are discussed in the next chapter.

¹ European Space Agency

² European Organization for Nuclear Research

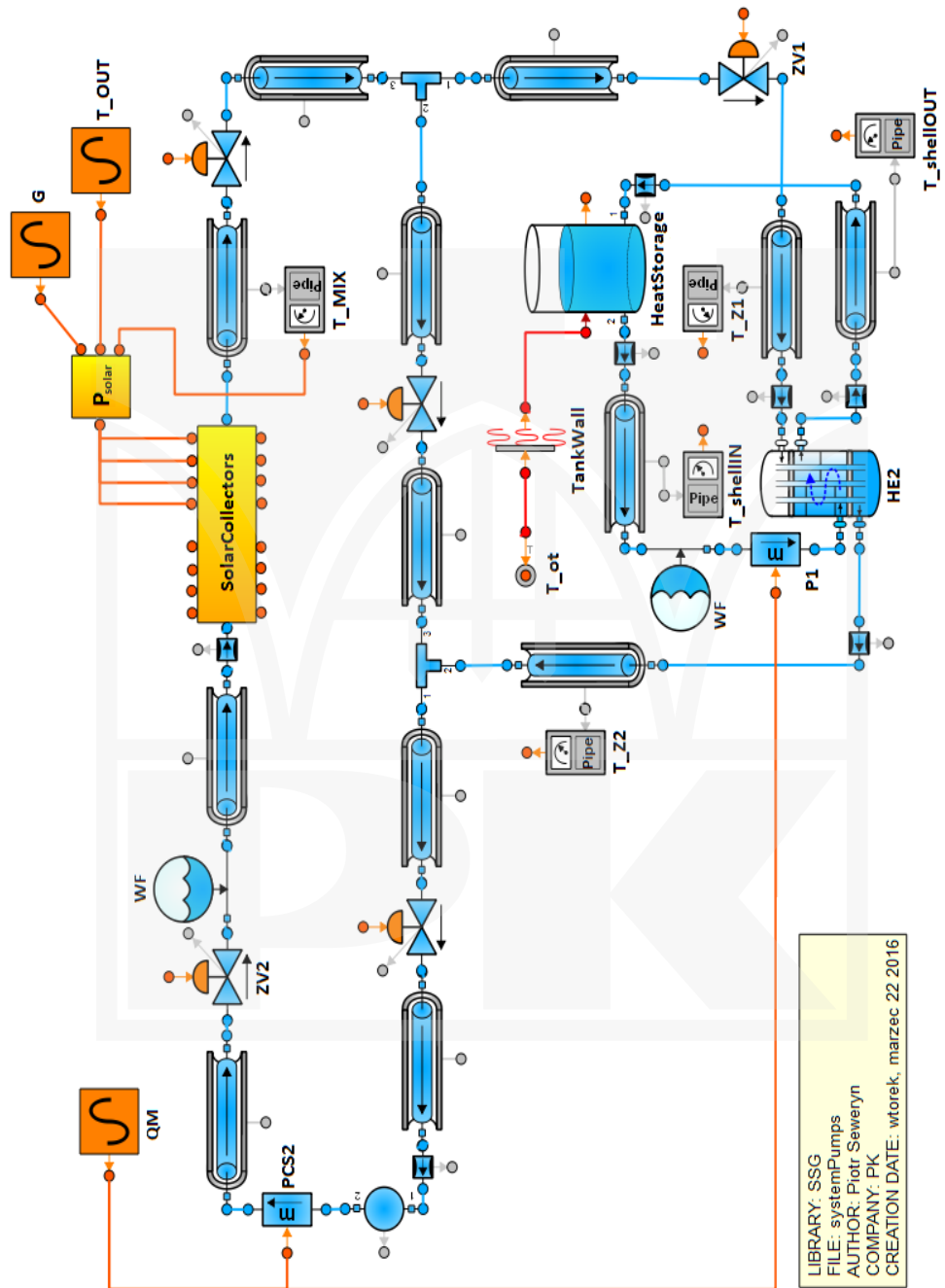


Figure 3.1. Schematic model of solar heating system created in EcosimPro

3.2. Major components of the model

Default parameters of each component have been modified according to the real objects in order to provide as accurate results as possible. The parameters are, e.g. geometrical dimensions, heat exchange coefficients, applied materials etc.

The model of solar heating system in EcosimPro includes some simplifications:

- In order to simplify calculation process, internal boundary conditions (PCS2, P1) are used instead of pumps.
- Working fluid is water instead of glycol mixture, which is not defined in a properties library. It is possible to add it manually in the future.
- In the real solar heating system the brazed plate heat exchangers are used. Due to lack of that element in the library and complexity in custom modelling, a shell-tube heat exchanger (HE2) with appropriately tuned parameters is used instead.

Solar collectors are wrapped in an additional custom component to clarify the scheme view. In Figure 3.2, the model of solar collectors with its distribution pipes, valves and temperature sensors is shown. Heat load from the solar radiation to tube elements is modelled by a heater element from the Thermal library.

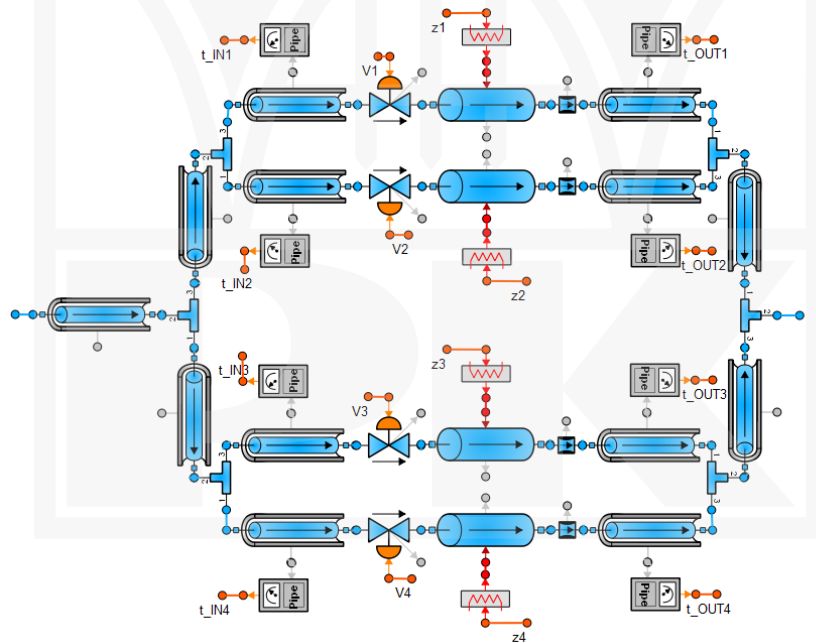


Fig. 3.2. Schematic model of solar collectors

The P_{solar} is a user defined and arranged component that calculates the solar power. It takes into account solar irradiance, ambient temperature and working fluid temperature. It uses the following formula [4]:

$$P = S \cdot (\eta_0 \cdot G - a_1 \cdot (T_m - T_a) - a_2 \cdot (T_m - T_a)^2)$$

where:

- S – total aperture area of the collector array, m^2 ,
- η_0 – collector optical efficiency, – ,
- G – solar irradiance, W/m^2 ,
- T_m – collector operating temperature (T_{MIX}), K,
- T_a – ambient temperature (T_{OUT}), K,
- a_1, a_2 – temperature difference loss coefficients, $W/m^2K, W/m^2K^2$ [4].

3.3. Simulation strategy and boundary conditions

In order to carry out the simulation, it is necessary to provide simulation settings, initial and boundary conditions. They are all defined in an experiment file, which is a script written in EL. Regarding initial and boundary conditions, which default values are suggested by the program in each new experiment file, the user may change them by modifying partition file.

All results, presented in the following chapter, have been acquired with the following conditions:

- Initial conditions for the temperature impact on the solar collector's tubes objects are 293.15 K.
- Boundary conditions regarding not fully constrained components are:
 - all valves, except for bypass, are in open state,
 - ambient temperature of heat storage room is 293 K.

Some boundary conditions remain in default values due to their constant character, e.g. gravity acceleration or lack of need to use them in this particular model.

3.4. Simulation results

EcosimPro allows to present and save the simulation results in two ways. The first option is to use an additional application called Monitor to display the results and then save them as images or data files. Another way is to use in the experiment file a function that defines the target file and variables to save in it and then use of acquired data to draw plots in a different application, e.g. Microsoft Excel.

In Figure 3.3, simulation results of the presented model with already defined initial and boundary conditions are shown. The first plot presents a simulated temperature of water in the accumulator (T_{AKU}) and in the piping located after the solar collectors (T_{MIX}) and also the ambient temperature T_{OUT} . The second plot shows the solar irradiance G , with assumption of a warm, sunny and cloudless day in Krakow. Results registered within temperature plots are consistent with preliminary calculations.

The temperature T_{AKU} of water inside of the heat accumulator (2) is rising consequently, but day by day less effectively. Moreover, during nights, the temperature drops are registered. To reduce this effect, a more complex model with a controlled pump shall be worked out. Switching off the pump during nights and speed control is highly recommended.

In the real system, the collected heat is used not only to charge the heat accumulator (2), but also to drive the adsorption unit (4). Moreover, for safety reason, the wet cooling tower (6) is used for rapid cool down of the overheated working fluid. The presented simplified

model does not include the mentioned safety solutions and in result the overheating (T_{MIX} above limit of 373 K) of the working fluid is registered during the time of maximal sun irradiation.

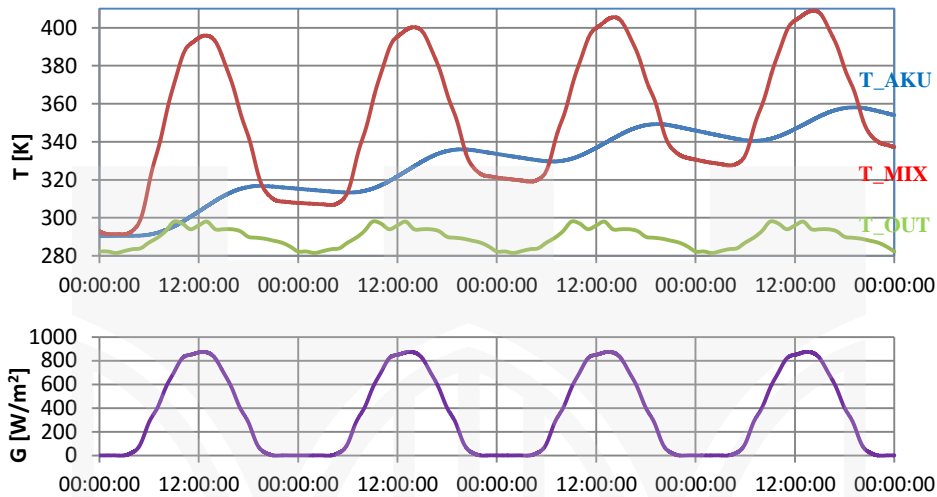


Fig. 3.3. Simulation results – temperature characteristics T_{AKU} , T_{MIX} , T_{OUT} and solar irradiance G

There are two possible solutions to keep the temperature of the working fluid below the limit. The first is a heat rejection system by using a cooling tower, applied in a real installation. The second is a thermally controlled solar blind system, blocking the solar irradiation. For the aim of the present paper, the solar blind system has been modelled. The blinds are being closed on temperature 368 K or above and remain closed until temperature drops to 335 K.

Registered results of the simulation (24 hours) are shown in Figure 3.4. The T_{MIX} temperature saw-shaped characteristics shows that this is a very efficient method of maximum temperature controlling. The temperature fluctuation span can be narrowed, but in result, this will increase the frequency of the open-close cycle of the solar blind system.

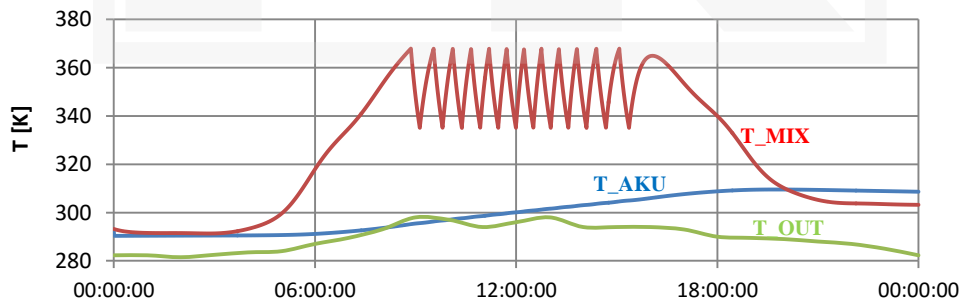


Fig. 3.4. Simulation results for a model with solar collectors covers

4. Experimental verification of the virtual model

The virtual model is based on the real system and there is a certain possibility to compare selected results of the simulation with measurements on the real object in real conditions. It allows to verify the model, performance and effectiveness in comparison to the real installation. However, it is a rare phenomenon characterised by several days of clear unclouded sky, during which one could register quasi-optimal system parameters and the theoretical solar irradiance (Figure 3.3).

4.1. Verification points and parameters

The selected temperatures, presented in Figure 4.1, were registered on 16.06.2015 in the existing system during operation. The temperatures were registered during a sunny day with small rare clouds. It is noticeable on the T_OUT plot that the weather deteriorates from 9 a.m. till 12 a.m. Moreover, during considered time of the year – June, heat accumulator (2) was already charged (T_AKU) and in a stand-by mode. The plot of temperature T_MIX clearly shows the heating process broken by cloudy sky periods. This effect is similar to the mechanical operation of blocking out the solar collectors by the solar blinds during the sunny period of the day.

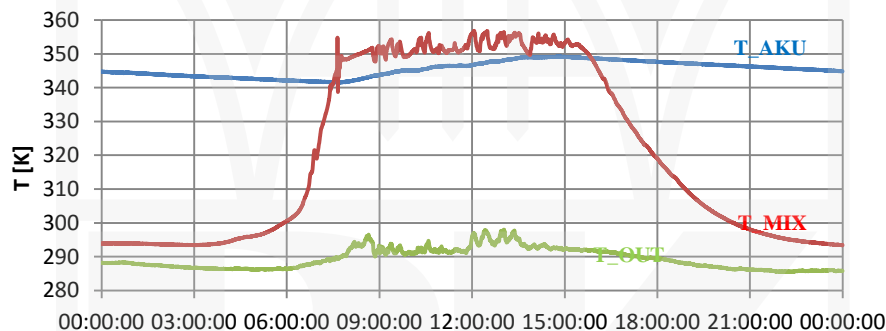


Fig. 4.1. Selected measurements in the real conditions – 16.06.2015 (by courtesy of Roman Duda, Institute of Thermal and Process Engineering)

4.2. Results discussion

In spite of the above-mentioned differences, it is a valuable comparison, showing the performance of the system with both solutions of the maximum temperature control. Although the currently used system is thermally effective, it requires a circulating pump to be frequently switched on during rapid cooling of the overheated working fluid. It is much more effective to use the controlled solar blind system together with the controlled heating medium flow rate (pump speed).

Results of measurements partially resemble those from the simulation. The visible oscillations are the result of cloudy weather. On the other hand, the working fluid temperature measured that day is from 10 to 20 K smaller than on the virtual model with solar blinds, which is mostly caused by ideal solar irradiance applied to the model.

Regarding the heat storage temperature, it is increasing and decreasing in a similar way in all 3 cases and measurements results confirm that during heating process each next day charging is less effective, which mainly is caused by a smaller temperature difference between liquids in the heat exchanger (3).

5. Conclusions

Simulation software, like EcosimPro, is widely used in a modern and innovative industry. It is mostly due to the possibilities of analysing and simulating conceptual solutions without incurring costs of physical implementation. Moreover, it also can be used with existing installations for the purpose of testing new modifications, e.g. the mentioned in this paper system with implemented solar collector blinds.

The virtual model of solar heating system presented in this paper is only a fragment of the much larger and more complex cooling system and any physical difference between the real and the virtual system can have an influence on the results.

The simulation effort allows to save money and time by simulating the virtual experiment. Although to obtain reliable results, it is often required to precisely define the whole system and all of its components.

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