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Auto-optimization control of hybrid ecological refrigeration system

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Auto-optimization control of hybrid ecological refrigeration system

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Abstract. The optimization problem of the two-stage hybrid compression-sorption refrigeration control system is presented. The idea is an eco-friendly energy conversion, powered by the waste heat or renewable energy. Eco-friendly means that using only natural energy carriers H_2O and CO_2 are used. The goal of the optimization is maximization of the renewable energy usage and increasing of the system COP, by minimization of the power consumption. The optimization problem is complex due to the large amount of control parameters. In the programmable logic controller (PLC) a set of functions is implemented. As a result the consumption of all kinds of energy supplied to the system in the different modes of operation may be calculated online. This can be applied as the control function for optimal usage of the available heat sources, while maintaining the temperature in the refrigerator compartment at desired level. Similar method of process optimization in the last years was introduced for the energy consumption and cost reduction in the operation of industrial and home appliances. In larger industrial scale more energy savings are possible using this approach. The work of entire refrigeration system can be based on this idea, reducing the consumption of electricity used to drive compressors, fans and pumps. Each step of the optimization has to consider process disturbances and external condition changes, therefore the system control becomes a complex issue. Number of optimization methods may be found in the literature. However in this case the application of the simple adjustment method based on the selected variables, control parameters, with dependence between them was proposed. This approach has been called auto or self-optimization. In this method the nominal value is set, but some possibility of losses are accepted. This type of optimization is used with single or several linear variables depending on the measured value in the system, which are usually controlled by PI or PID controllers.

1. Introduction

In the Laboratory of Thermodynamics and Thermal Machines Measurements at the Cracow University of Technology the refrigerating laboratory stand has been designed and constructed [1]. The system is hybrid and unique since it combines the approach of adsorption unit driven by low temperature heat source, with standard compression low temperature stage working in subcritical cycle using CO_2 as refrigerant. To achieve optimized results and assure safe plant operation the specially designed control system has been designed [2].

The control system is composed of several parts/levels for each thermodynamic subsystem, however a master level control system with programmed setups for different ambient conditions as well as refrigeration chamber requirements has been also worked up.

2. Composition of the control system

The schematic diagram of the double stage hybrid refrigeration system is presented in Figure 1. Control system information flow for the system presented in Figure 1 is depicted in Figure 2.

The main criterion for optimization is the minimization of the total electric power consumption of all systems during 24 hour operating period. Due to the energy balance this criterion requires maximization of the renewable energy usage since the renewable energy (solar in this case) is not available 24 hours. Therefore the criterion is more complex that simple minimization of actual power consumption. Measured parameters and model functions are averaged then the criterion is formulated for averaged values. The model equation for each subsystems are shown below. Constrains on decision variables are: the requirements for refrigerating chamber temperature, working parameters limits for subsystems. The optimisation is treated as quasi-steady state, this means that the model equations are time independent, assuming that system is considered as steady state and parameter changes between two states of the system are in thermodynamic equilibrium. The dynamic changes are secured by internal safety devices inside subsystems.
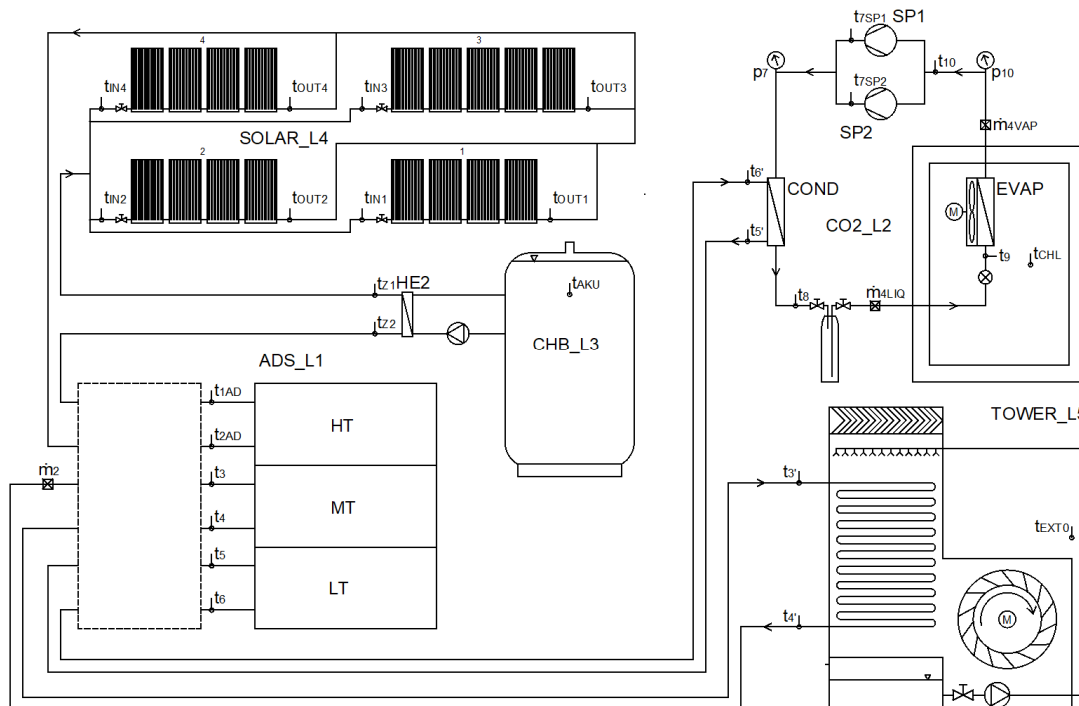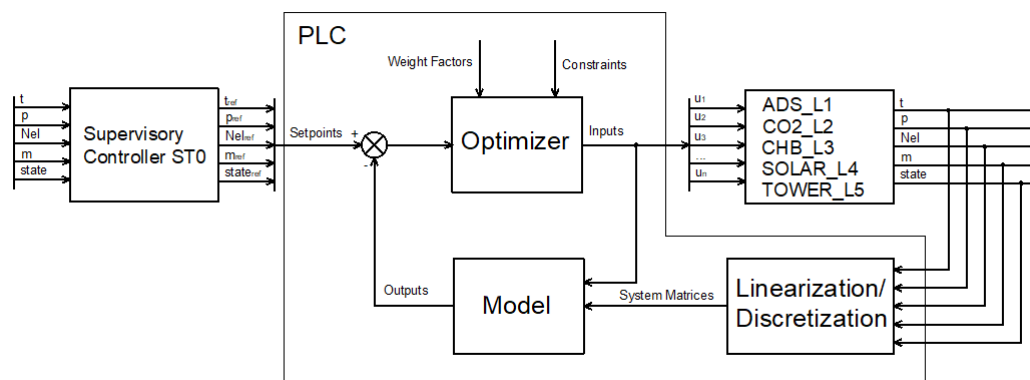

Figure 1. Block schematics of the system.

Figure 2. Information flow in the system.

Selection of the controlled variables as a first subtask in the control or control structure design problem [3,4] was addressed. Subsystem elements are as follows:

EQP subsystems of the refrigeration stand:
- SOLAR_L4 solar subsystem depicted in figure 2: temperature measurements, t_{IN1}, t_{IN2}, t_{IN3}, t_{IN4}, t_{OUT1}, t_{OUT2}, t_{OUT3}, t_{OUT4}, pressure measurements p_{IN}, p_{OUT}, mass flow measurement m1. Liquid pump - PCS2" with electric power measurement.
- ADS_L1 adsorption unit depicted in figure 3: temperature measurements, t_1, t_2, t_3, t_4, $t_{4'SP}$, $t_{5'SP}$, t_5, t_6, mass flow measurements, m_{1AD}, m_2, m_3. Circulating pumps: PCS1, PCS2, PCS2", PCS3, PCS4. All also with electric power measurements.
- CHB_L3 heat container depicted in figure 4: temperature measurements, t_{z1}, t_{z2}, t_{AKU} in liquid container. Circulating pumps, P1, P2. Electronic valves, ZV1, ZV6.
- TOWER_L5 water sprayed cooling tower depicted in figure 5: temperature measurements, $t_{3'}$, $t_{4'}$. Mass flow measurements. Fan supply and water spraying pump with electric power measurements.
- CMEQP common part depicted in figure 6 of the acting elements: servomotors for valves, circulating pumps.

3. Subsystems

The optimum solution is to minimize the use of electricity when making the best use of renewable or waste heat sources [5,6]. For this purpose, the control layer elements discussed below are implemented.

3.1. Solar collectors subsystem

Mass flow rate $\dot{m}_1$ through solar collector pipes depicted in Figure 3 in start of preheating is controlled by t_{IN} and t_{OUT} values and sets revolution speed of a pump to maintain required fluid flow and simultaneously check for solar irradiation. This prevents from stall operation. A PID controller during heat accumulation maintains t_{OUT_mean}-t_{in_mean} = 5 K. A PI controller maintains volumetric flow rate during operation of adsorption unit at set point 20 l/min. Heat balance is calculated from equations 1 – 5.
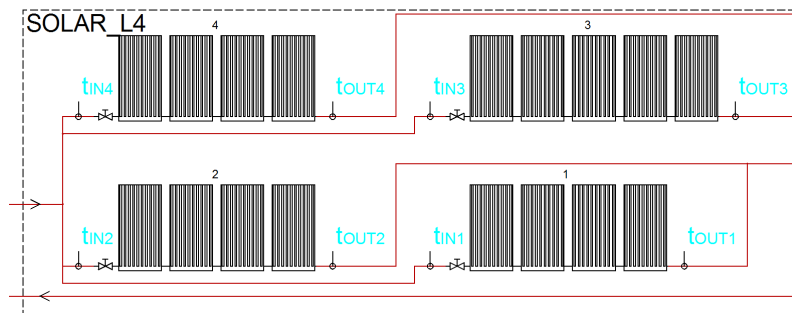

Figure 3. Schematic connections of solar collectors.

$$\dot{Q}_{solar1} = \dot{m} \cdot c_p \cdot \Delta t = \frac{\dot{m}_1}{4} \cdot c_p \cdot (t_{OUT1} - t_{IN1}) \qquad (1)$$

$$\dot{Q}_{solar2} = \dot{m} \cdot c_p \cdot \Delta t = \frac{\dot{m}_1}{4} \cdot c_p \cdot (t_{OUT2} - t_{IN2}) \qquad (2)$$

$$\dot{Q}_{solar3} = \dot{m} \cdot c_p \cdot \Delta t = \frac{\dot{m}_1}{4} \cdot c_p \cdot (t_{OUT3} - t_{IN3}) \qquad (3)$$

$$\dot{Q}_{solar4} = \dot{m} \cdot c_p \cdot \Delta t = \frac{\dot{m}_1}{4} \cdot c_p \cdot (t_{OUT4} - t_{IN4}) \qquad (4)$$

Assuming that solar irradiation per solar area is the same, then the sum of heat from solar collectors can be calculated as:

$$\dot{Q}_{solar} = \dot{Q}_{solar1} + \dot{Q}_{solar2} + \dot{Q}_{solar3} + \dot{Q}_{solar4} \qquad (5)$$

so coefficient of performance for solar collectors circuit can be defined as:

$$EES_{SOLAR} = \frac{\dot{Q}_{solar}}{N_{el}} \qquad (6)$$

3.2. Adsorption unit eCoo subsystem

Adsorption unit is composed of three circuits, high temperature HT, medium temperature MT, and low temperature LT (Figure 4).

$t_{LT} = t_6$ can be set by voltage control signal, taking into account conditions needed to properly operate of adsorption unit. If there is enough heat stored in heat storage tank and cooling demand is high then $t_{LT} = t_6$ is set/kept as low as possible, heat balance is calculated from equations 7 – 11.
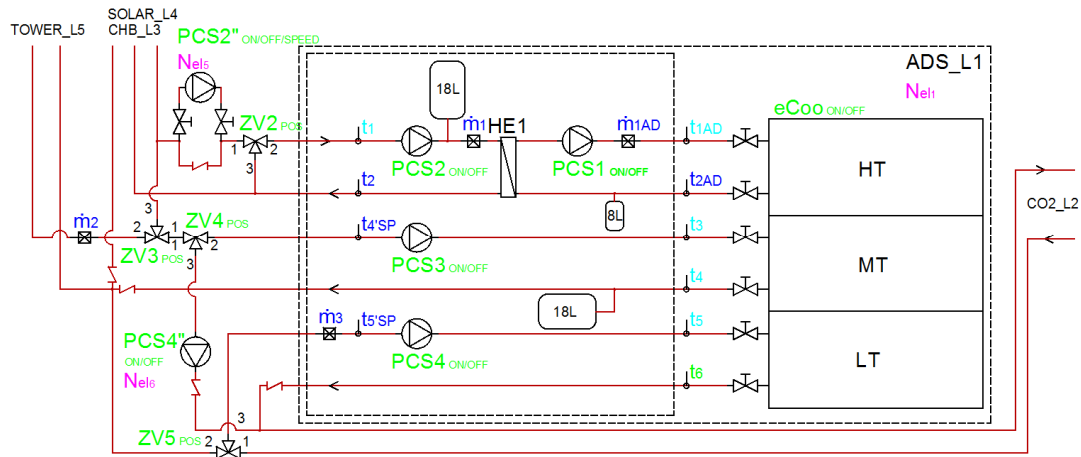

Figure 4. Schematic connections of adsorption unit eCoo with other subsystems.

$$\dot{Q}_{HT} = \dot{m} \cdot c_p \cdot \Delta t = \dot{m}_{1AD} \cdot c_p \cdot (t_{1AD} - t_{2AD}) \qquad (7)$$

$$\dot{Q}_{MT} = \dot{m} \cdot c_p \cdot \Delta t = \dot{m}_2 \cdot c_p \cdot (t_4 - t_3) \qquad (8)$$

$$\dot{Q}_{LT} = \dot{m} \cdot c_p \cdot \Delta t = \dot{m}_3 \cdot c_p \cdot (t_5 - t_6) \qquad (9)$$

Coefficient of performance of adsorption unit reads:

$$COP_{ADS} = \frac{\dot{Q}_{LT}}{\dot{Q}_{HT} - \dot{Q}_{LT}} \qquad (10)$$

Energy balance equation, while neglecting thermal loses is valid:

$$\dot{Q}_{MT} = \dot{Q}_{HT} + \dot{Q}_{LT} \qquad (11)$$
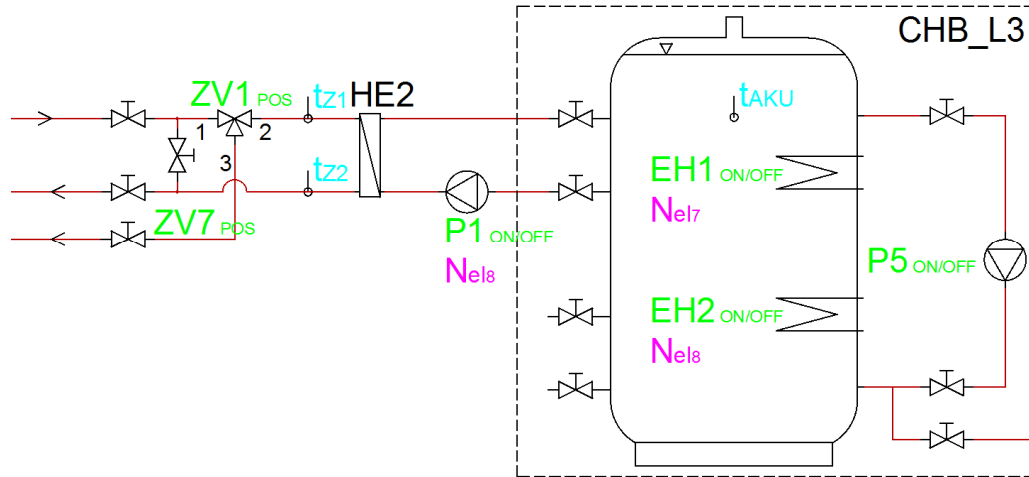
3.3. Heat storage chamber subsystem

Figure 5. Schematic connections of a heat storage tank with other subsystems.

During heat accumulation thermal energy collected by solar collectors is transferred to heat storage tank by heat exchanger HE2 (Figure 5). Thermal stratification in tank is compensated by pump P5, and heat balance is calculated from equations 12 – 13.

$$\dot{Q}_{HS} = \eta \cdot \dot{m} \cdot c_p \cdot \varDelta t = \eta_{HE1} \cdot \dot{m}_1 \cdot c_p \cdot (t_{Z2} - t_{Z1}) \tag{12}$$

$$\dot{Q}_{HS\_IN} = \frac{m \cdot c_p \cdot \varDelta t}{\tau} = \frac{m_{H2O} \cdot c_p \cdot (t_{AKU\tau_1} - t_{AKU\tau_0})}{\tau} \tag{13}$$

Where τ is time from beginning to end of accumulation process.

Based on measurements during different conditions heat loss dependence on temperature difference on heat storage and ambient air has been described using linear fit heat loss from heat storage tank can be presented as:

$$\dot{Q}_{HS\_loss} = 18.2253 \cdot (t_{AKU} - t_{B05})\text{-}82.45 [\text{J/s}]$$

Above equation shows that usage of heat accumulated in the storage tank is time limited due to heat loss. Taking into account need of desired temperature level for running adsorption unit eCoo and knowing parameters in system like actual solar irradiance or absence of solar energy and ambient temperature the time remaining for system operation with adsorption unit can be calculated. If ambient conditions are poor i.e. high humidity and high ambient temperature then the additional electric heaters inside heat storage tank may be used as a backup thermal energy source.

3.4. Water sprayed cooling tower subsystem

Coefficient of performance of wet cooling tower is calculated using temperature of coolant (glycol). The difference between wet bulb temperature t_{wb} and outlet coolant temperature is called "Approach". The liquid temperature decrease – "Cooling range".

Cooling range:

$$R_{cool} = t_{in} - t_{out} \tag{14}$$

Approach:

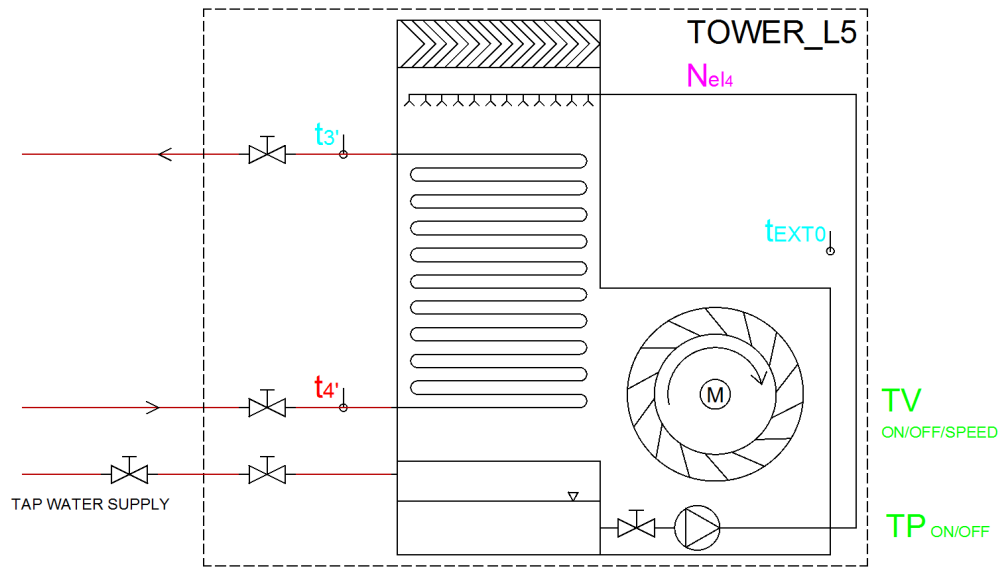$$A_{approach} = t_{out} - t_{wb} \tag{15}$$

Figure 6. Schematic connections of water sprayed tower.

Coefficient of performance of cooling tower can be calculated as:

$$\eta_{cool} = \frac{R_{cool}}{A_{approach}} = \frac{t_{in} - t_{out}}{t_{out} - t_{wb}} = \frac{t_{4'} - t_{3'}}{t_{3'} - t_{wb}} \tag{16}$$

Cooling capacity of the cooling tower can be calculated using the following equation:

$$\dot{Q}_{cool} = \dot{m} \cdot c_p \cdot R_{cool} = \dot{m}_2 \cdot c_p \cdot (t_{4'} - t_{3'}) \tag{17}$$

Where $\dot{m}$ is mass flow rate of the applied coolant, c_p is specific heat of the coolant.
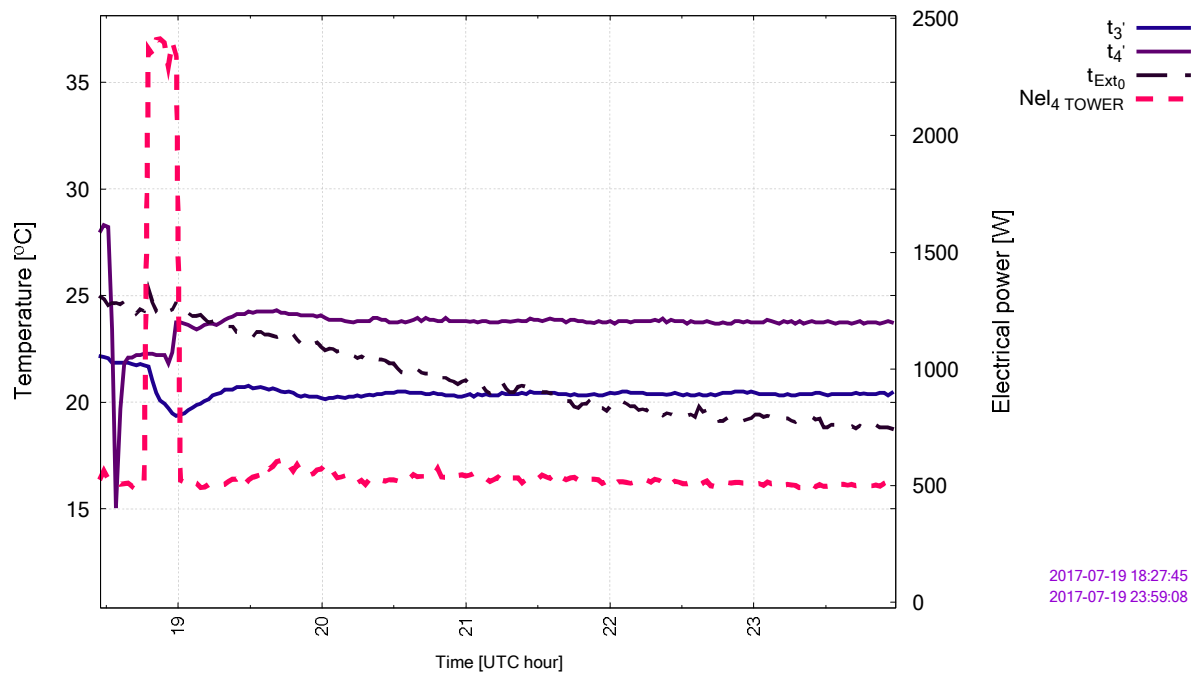

Figure 7. Temperature and electrical power distributions versus time in TOWER_L5 subsystem.

Electrical power needed for cooling tower operation it is a sum of electrical power of tower fan motor N_{TV} and water spraying pump motor N_{TP}:

$$N_{el4} = N_{TV} + N_{TP} \tag{18}$$

Tower fan motor revolution speed is controlled by simple PID controller, using inverter. Set point $t_{3'\_SET} = t_{3'\_MIN} + 1$ is set during the test of minimum temperature which can be achieved in current conditions, then $t_{3'} = t_{3'\_SET}$ is maintained by PID controller. This process is depicted in figure 7.

The goal for optimum operation in this subsystem is to keep cooling tower thermal performance as high as possible while maintaining as low as possible electric power consumption.
For situation described above:
Cooling capacity:

$$\dot{Q}_{cool} = \dot{m}_2 \cdot c_p \cdot (t_{4'} - t_{3'}) = 0.12[kg/s] \cdot 4[kJ/(kgK)] \cdot 3[K] = 1.44[kJ/s]$$

Coefficient of performance of cooling tower:

$$\eta_{cool} = \frac{R_{cool}}{A_{approach}} = \frac{3}{3,8} = 0.789$$

Average electrical power of tower fan and spraying pump:

$$N_{el4} = N_{TV} + N_{TP} = 650W$$

For data from tower manufacturer documentation, cooling capacity at nominal conditions:

$$\dot{Q}_{cool(m)} = \dot{m}_2 \cdot c_p \cdot (t_{4'} - t_{3'}) = 3.5 \cdot 4 \cdot 5 = 70kJ/s$$

Coefficient of performance of cooling tower according to manufacturer data:

$$\eta_{cool(m)} = \frac{R_{cool}}{A_{approach}} = \frac{5}{6} = 0.83$$

Average electric power consumption of cooling tower fan and spraying pump:

$$N_{el4} = N_{TV} + N_{TP} = 2000[W]$$
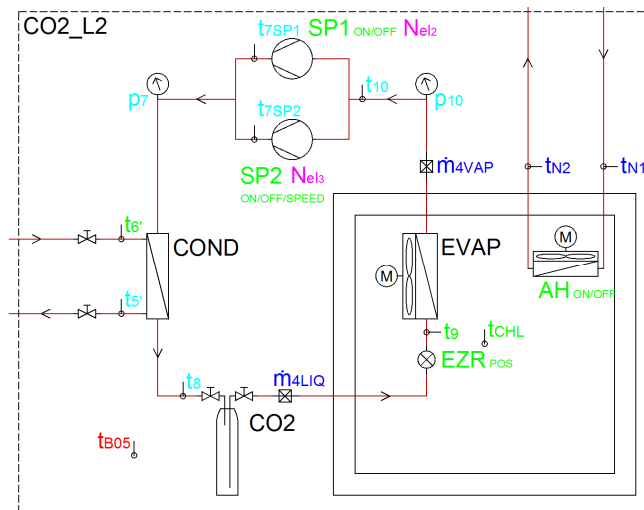
3.5. CO₂ refrigeration subsystem

Figure 8. Schematic connections of CO_2 subsystem with cooled chamber.

Heat flow rate transferred in the CO_2 condenser to water-glycol coolant can be calculated as:

$$\dot{Q}_{COND} = \dot{m}_x \cdot c_p \cdot \Delta t = \dot{m}_x \cdot c_p \cdot (t_{5'} - t_{6'}) \tag{19}$$

For TOWER-COND mode $\dot{m}_2$ mass flow meter is operating, for eCoo-COND $\dot{m}_3$ mass flow meter is operating.

For CO_2 circuit energy balance is as follows:

$$\dot{Q}_{COND} = \dot{m}_{4VAP} \cdot (h_7 - h_8) \tag{20}$$

$$\dot{Q}_{COND} = N_{el} + Q_{EVAP} \tag{21}$$

$$\dot{Q}_{EVAP} = \dot{m}_{4LIQ} \cdot (h_{10} - h_9) \tag{22}$$

$$COP = \frac{\dot{Q}_{EVAP}}{N_{el}} \tag{23}$$

4. One day system operation

Figures 9 and 10 show the system operation on July 19, 2017. The graphs are presented in UTC time zone.
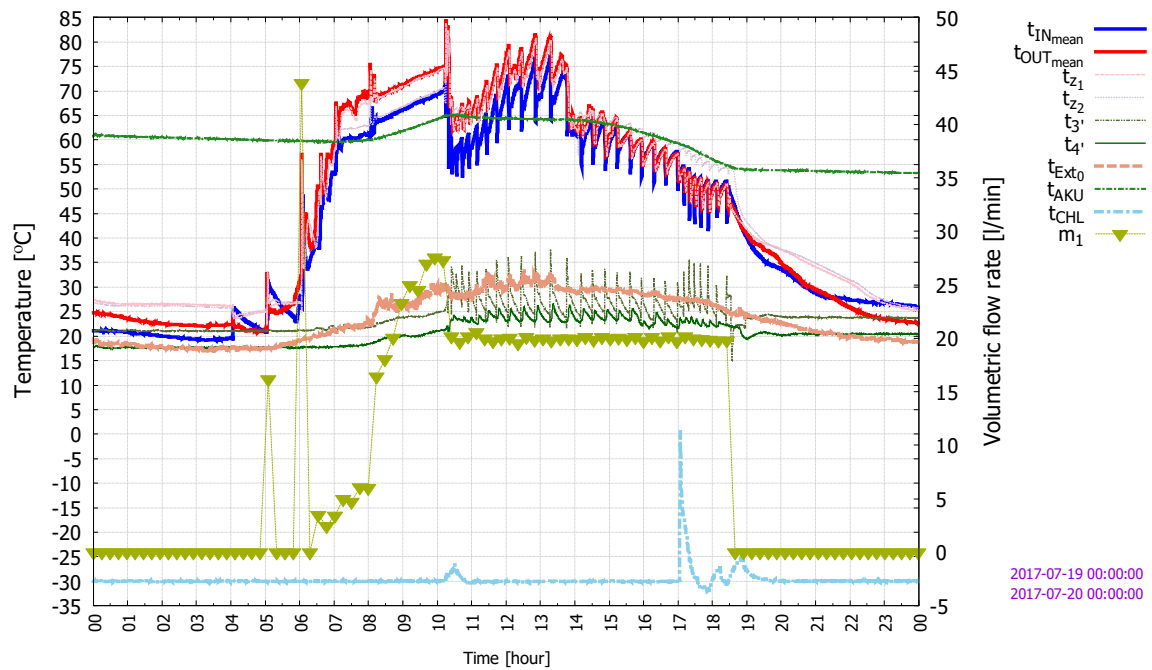

Figure 9. Temperature graph and volume flow rate in SOLAR subsystem.

During this time, the master system was set to maintain a constant temperature in the cooling chamber -30 °C. During the morning hours (4:00; 5:00; 6:00; 7:00) the part of the algorithm that detects the sun irradiation was on, forcing for 60 s flow at 2/3 of the maximum through the solar collectors. When the temperature increased at the inlets and outlets from individual solar collectors and HE1 solar heat exchanger, the volume flow rate in solar collectors was increased, controlled by the increase of the rotational speed of the solar pump PCS2". About 7 o'clock the outlet glycol temperature, from the solar collectors exceeded the temperature in the heat storage tank, then the solar energy accumulation begun. The control over the volume flow rate in the solar circuit was maintained by the PID controller of the PCS2" pump.

The safety control of compliance of the current volume flow rate with the permissible values ensures a control function implemented in master control. In case that the minimum conditions were not met, this function took control over the pump, with set points of minimum values schedule according to the time of day and the current system status.
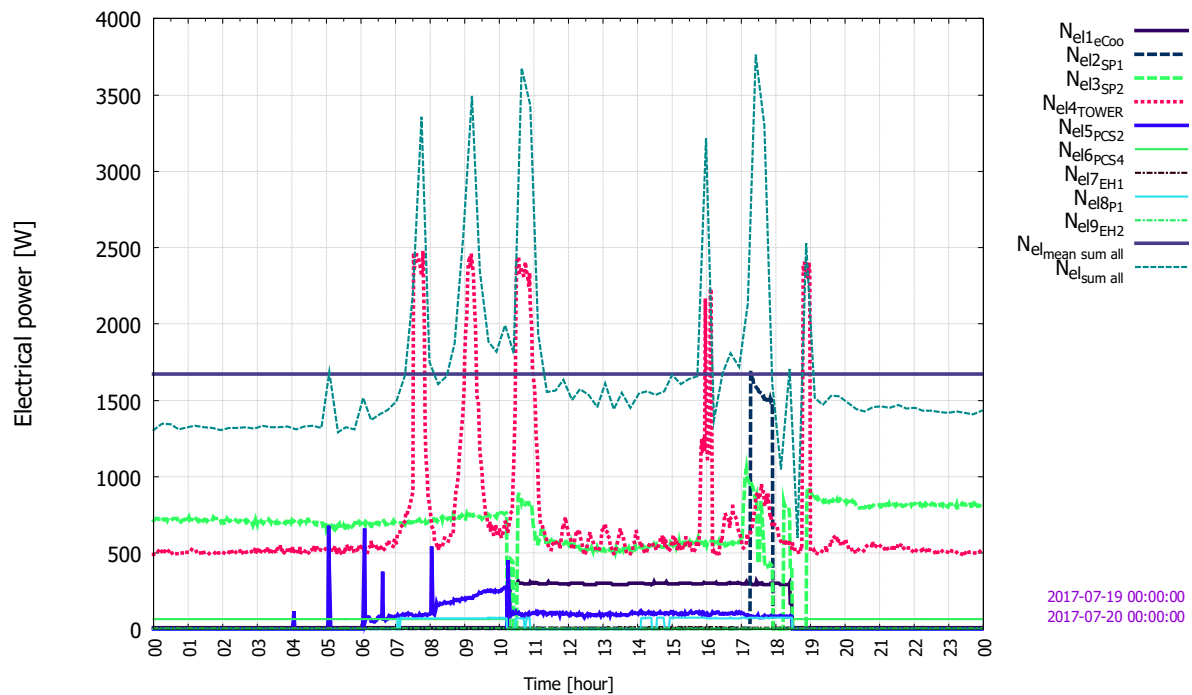
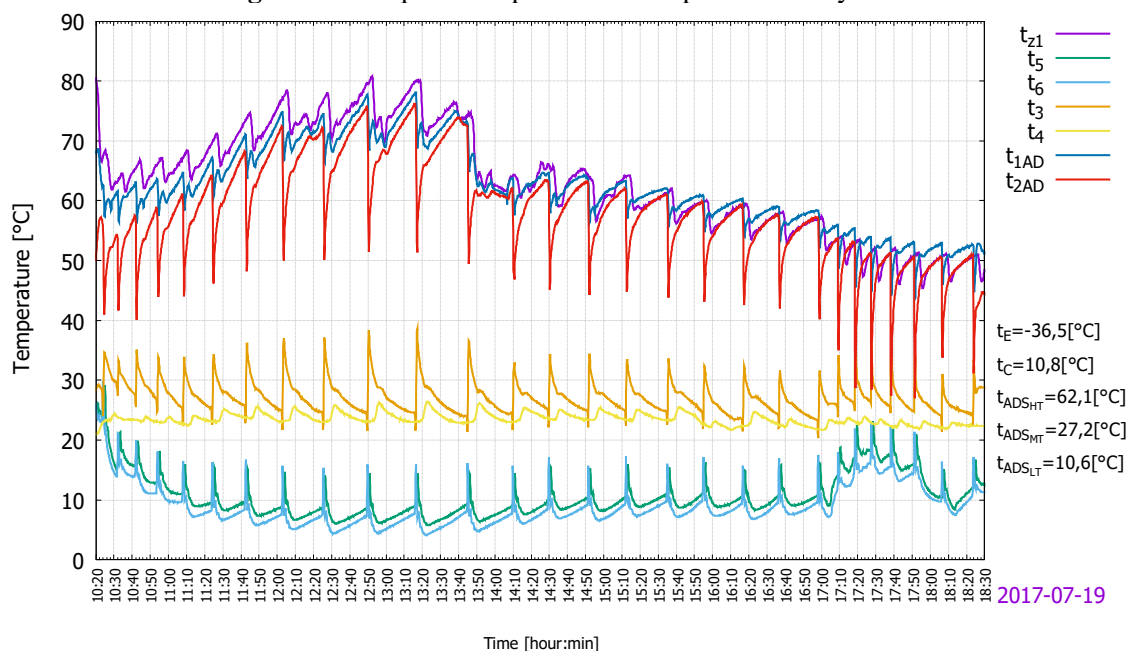**Figure 10.** Graph of the power consumption of the system.

Figure 11. Graph of the temperature distributions during operation of adsorption unit eCoo.

Until 10:20, the work of the compressor cycle was based on the cooling of the condenser by the cooling tower. After this hour, the temperature set point $t_{AKU} = 65°C$ was exceeded by the glycol in the accumulation tank. The ambient temperature exceeded $20°C$. Then the adsorption cycle started and the compressor cycle was set to pause and necessary changes in system valves configuration were introduced. And after the launch of the adsorption system eCoo, zoomed graph of temperatures since start of this mode were registered (Figure 11). From this time on the temperature in LT subsystem of the adsorber was set to $10°C$. The averaged CO_2 condensation temperature during work of adsorption device was $t_C = 10.8°C$ and evaporation temperature $t_e = -36.5°C$. The adsorption device operation

allowed to switch on the compressor SP2. The second compressor SP1 could be switched on only when the temperature in the chamber exceeded required value. During the operation the adsorption controlled its own pumps also the PCS2 solar pump. The system was scheduled to maintain a volume flow rate of 20 l/min by the PCS2" pump. This was required because during changes in internal valves settings in the device eCoo due to periodical operation, PCS2 pump was also stopped for short time. The volume flow rate in the solar circuit was kept in the required minimal level without interruption in the period of high irradiation to maintain reasonable solar temperatures. The adsorption device continued its work periodically by switching the adsorption/desorption chambers up to the 7 PM. At this time approximately, the temperature in the heat storage tank decreased to $55^{\circ}C$, the lowest possible temperature for adsorption cycle. Then the eCoo unit was switched off and the condenser was cooled again using the cooling tower. The averaged CO_2 condensation temperature during cooling was $t_C=15.4^{\circ}C$ and evaporation temperature $t_e=-37.0^{\circ}C$.

In the presented case, the average $\dot{Q}_{EVAP}$ = 683 W and $\dot{Q}_{COND}$ = 875 W and electric power required to maintain the system was $N_{el,mean}$= 1600 W, which was calculated by integrating the power under the curve and then dividing by the test time. To compare the average power consumption for an optimized system to an uncontrolled system, some assumptions should be made. For uncontrolled systems, all devices (fans, pumps and compressors) use nominal power, which results in an electrical power consumption of $N_{el,max}$= 4000 W.

5. Conclusions

The developed control system, based on the energy balance equations, operates in the shown range automatically. Further optimizing functions for other devices, in particular the connection of the compressor inverters to the other subsystems within the master layer, are implemented. As shown in the sample graphs, the experimental average power consumed by the system's actuators was 1600 W. Without the optimized control, the average electric power would be around 4000 W for the same conditions. This is because the electric power consumption of the PCS2 pump and cooling tower would not be controlled accordingly to the system needs. Also the operation of the compressor system would be based only on the on/off operation controlled by a simple regulator in the CC2 control cabinet. Proposed algorithms in the PLC and PID controllers provided constant temperature control in the cooling chamber and quick response to changing ambient conditions, including easy change of operating mode. Maintaining statistics in the controller's memory allows to limit the number of switching on and off of system components to the necessary minimum. All control and measurement data are accessible form the operator panel and stored during operation. So the PLC software maybe upgraded by the operator, if needed during system operation and system may recover from stored data. The power reduction resulting from the presented control system allows to conclude that the carried out optimization resulted in reducing the average power consumption of the system by 60%.

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