Design of module-based controller for solar micro combined heat and power technology

Wojciech Mazurek, Tymoteusz Świeboda, Marek Malinowski
Electrotechnical Institute
50-369 Wrocław, ul. M. Skłodowskiej-Curie 55/61, e-mail: m.mal@iel.wroc.pl

Control and Data Acquisition System for the micro-CHP unit has been designed as a new approach to the microgeneration system supplied by energy of the Sun. This paper describes only the part of the system which is intended for controlling and measurement data collecting. Owing to the Unit, in a households, radiation absorbed by collectors can be used for heating of water, generation of electricity or obtaining the cold for air-conditioning. This top-down engineering approach are implemented by three independent subsystems. In order to manage whole station Programmable Automation Controller has been mounted. The System equipped in a proper number of flow meters, pressure and temperature sensors and liquid pumps according to an algorithm is able to control the heat distribution, calculate thermal power display these data and actual state of the unit. In addition, using LabVIEW software special programs have been written. These programs make possible to display and control states of the Unit. The entire controlling system is supplied by the 1 kW using PV Panels Subsystem. In case of the sun's energy is not sufficient, the PV system has an ability of over-switching on supply from the power network.

1. Introduction

Currently, the main electricity suppliers, intended for the industries and households are commercial power plants, which utilize fossil fuels as energy sources. Due to limited resources, serious environmental impacts and rising energy consumption these fuels will have to be replaced by renewable and coal-free energy forms. There are different methods to obtain "green" energy. Wind, solar, hydrologic or biomass – all methods accomplish common feature i.e. they can be used both in large power plants and next to typical dwellings facilities for small-scale generators. That is why huge power electric market could be efficiently covered regardless of distance from the power plants, amount of customers or their requirements. Current model for production of the electricity is one of the significant reason why there are so many "black" areas for instance in "third world" countries. The response for this problems is cogeneration which provides to large distribution of small power stations. Furthermore, due to worldwide shortage of electrical capacity and because of the costs of power transmissions and inconvenience in constructions of the new electrical lines small-scale heat and power generation plants have been becoming technically and economically advantageous. A possible method for improving of availability of the electricity could become micro-CHP which is the kind of microgeneration technology. Micro

Combined Heat and Power (micro-CHP) technology is an alternative idea of cogeneration for the private houses, dwellings or small office buildings. Small, useful micro-CHP unit supplied by renewable energy sources can be assemble in location according to the needs of the customers. The energy is delivered on demand as a heat and an electricity. This solution has significant advantages in comparison to the conventional power plants therefore can be used as the method in areas where the costs of the electrifying exceed the profitability of the investment or in places where are the needs to implement the energy saving process.

The other form of energy which is utilized for domestic or industrial purposes is a heat. Similarly to electricity, the heat can be transferred from power plants or produced locally. As well-known, the efficiency of the energy conversion is limited by physical laws regardless of methods which involve these conversions. Traditional combustion, nuclear fission or direct transformation in fuel cells lead to excess of the heat generation which is treated as a waste in typical power plants. In many of large power stations this heat can not be spent due to different economic and technical reasons. An idea to produce useful heat with electricity generation directly for the customers, meaningfully rises conversion efficiency. The results are lower costs and fuel utilization at carbon mitigation. The brilliant advantage of micro-CHP in terms of principle of operation is possible intermittent generation. The unit of µ-CHP is capable to achieve certain amount of energy according to current consumption, avoiding, thereby, redundant losses.

Plenty of advantages of CHP units in comparison to commercial power plants have been scaling up their involvement. In spite of different economic problems, the CHP technology is being especially developed for small-scale applications. Furthermore, the climate changes and environmental problems increase the interests for renewable energy sources which have been successfully beginning to replace fossil fuels. The association of small-scale CHP with green energy sources creates excellent opportunity to propagate the cogeneration around the world.

Nomenclature

µ-CHP	micro Combined Heat and Power	ORC	Organic Rankine Cycle
C&DA	Control and Data Acquisition	CAU	Cooling Absorption Unit
PAC	Programmable Automation Controller	VCU	Vapor Compression Unit
WHS	Water Heating System	PV	Photovoltaic

However, to realize above conceptions different technical conditions have to be fulfilled. One of these is completely automatic and reliable operation of the installed units. This is the main term to implement micro-CHP for domestic and small-industrial facilities. Utilization of green energy as for example the energy from the sun or wind which magnitudes are quite unpredictable is the answer on question why microcontroller control systems have to be used to guarantee reliable operation. This paper first of all describes the adequate system which works in accordance with digital algorithm acquiring the data from measurement instruments. The control and data acquisition (C&DA) system has been constructed to efficiently manage μ-CHP unit supplied by solar energy.

2. Construction of the Micro-CHP system

For proper description of C&DA System, construction of the μ-CHP Unit should to be introduced. One of the significant issues to obtain the best method for energy conversions is suitable investigation. Simple calculations and/or simulations can not give sufficient answer when there are a lot of unknowns. Due to adequate reason multistage conversion structure of the Unit has been made to evaluate which form of energy is the most suitable when the main source are solar collectors. The sun's energy can by utilize as a coolness, heat and an electricity. According to Carnot cycle principles, the absorbed energy is converted for heat engine or refrigerating system. The structure scheme of the micro-CHP unit is illustrated in Fig. 1. For supplying the system upper and lower heat sources are utilized. As the upper heat source flat-plate solar collectors have been mounted. The collectors can provide up to 30 kW of total thermal power. This thermal energy is utilized for heating of water, generation of electricity and obtaining the cold for air-conditioning. For lower heat source surrounding is used where the heat from the condenser is dissipated for refrigeration purposes.

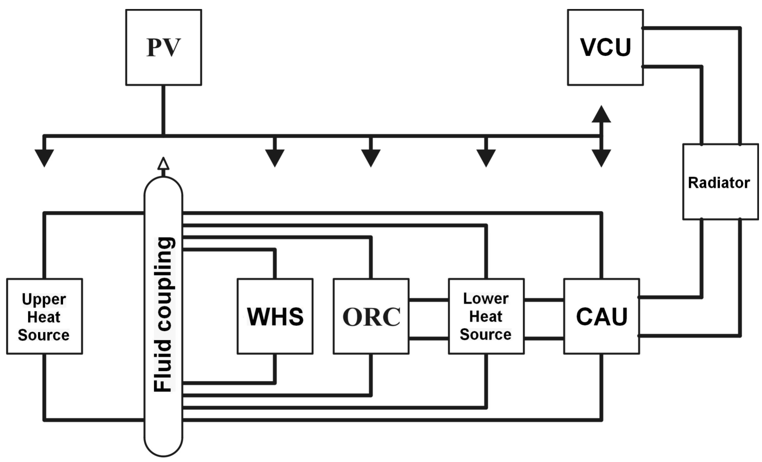

Fig. 1. Configuration of the μ-CHP system with subsystems: WHS – Water Heating System, ORC - Organic Rankine Cycle, CAU – Cooling Absorption Unit, VCU – Vapor Compression Unit; all additionally supplied by photovoltaic panels (PV)

The main subsystems which have been created to achieve various form of energy from solar collectors, are: ORC – Organic Rankine Cycle [1] for generation an electricity, CAU – Cooling Absorption Unit [4] and VCU – Vapor Compression

Unit for obtaining a cool [6] and WHS – Water Heating System. These subsystems can be used independently according to current requirements.

Apart from solar collectors and ORC, photovoltaic panels (PV) are mounted in order to deliver electricity for Control and Data Acquisition System and circulating pumps i.e. for all electric devices in the Station which require power supply. The PV system has an ability of providing up to 1 kW of power and over-switching on supply from the power network in case when the sun's energy is not sufficient.

Microgeneration Unit is supplied by vacuum flat solar collectors connected in serial-parallel way which work even up to 90 – 100°C. The active surface of single collector is app. 1,9 m^2 thus for whole solar station the surface is about 38 m^2. Placed inside the collectors working medium is made of aluminum nitrate which accomplishes high absorption coefficient of 0,95 and low emission factor of 0,05. Depending on the intensity of the radiation these values allow to achieve sufficient efficiency of the entire solar power station. Absorbed energy is transported from solar collectors to particulars subsystems of micro-CHP by a main fluid of the Unit which bases on 1,2-propylene glycol.

ORC subsystem have been created to prepare indirect generation of the electricity basing on thermodynamic conversions of heat into work. The organic fluid allows an energetic conversion at a low temperature of the resource, a better collecting efficiency and hence the possibility of reducing the size of the solar field. Furthermore, at low temperatures, organic working fluids lead to higher cycle efficiency than a water.

Two independent refrigerating subsystems (CAU and VCU) allow transfer the heat from a space into the surroundings. They can be successful used for air-conditioning aims, mainly due to great connection between them and a space being cooled: the bigger radiation from the Sun and temperature of the environment, the higher efficiency of the refrigeration.

The simplest method to utilize solar energy is a heating of water. By virtue of this Water Heating Subsystem has been built. The system makes possible of convenient raising the temperature of water to the useful value of 60°C.

2. 1. Control and Data Acquisition System

The proper managing of whole solar power station requires suitable devices intended for automation, reliable, and remote operation. This operation basing on input measurement data is depended on current state of the Unit and has to be correctly programmed with prediction of all possible regular and emergency events. To realize such a conception independent microcontroller system had to be consider. For the Solar Power Station Programmable Automation Controller (PAC) have been chosen as a main core of the Control and Data Acquisition System. PAC offers the flexibility and ease of a PC and the reliability of a programmable logic controller for each connected measuring/controlling instrument. The controller have 400 MHz real-time processor and 256 MB of SDRAM which is absolutely enough for these quite not exacting purposes. It uses TCP/IP protocol for communication interface. The real-time PAC connected to 8-slot solid backplane controls a wide variety of hot-swappable I/O modules. The modular I/O architecture with built-in signal conditioning and isolation provides direct connectivity to temperature, pressure and flow meters, DAC and ADC circuits. The I/O modules filter, calibrate and scale raw sensor signals to engineering and perform self-diagnostic to search for problems, such as open thermocouple or out-of-range events. Unsophisticated scheme in Fig. 2 depicts fundamental principles for PAC, modules and intended components.

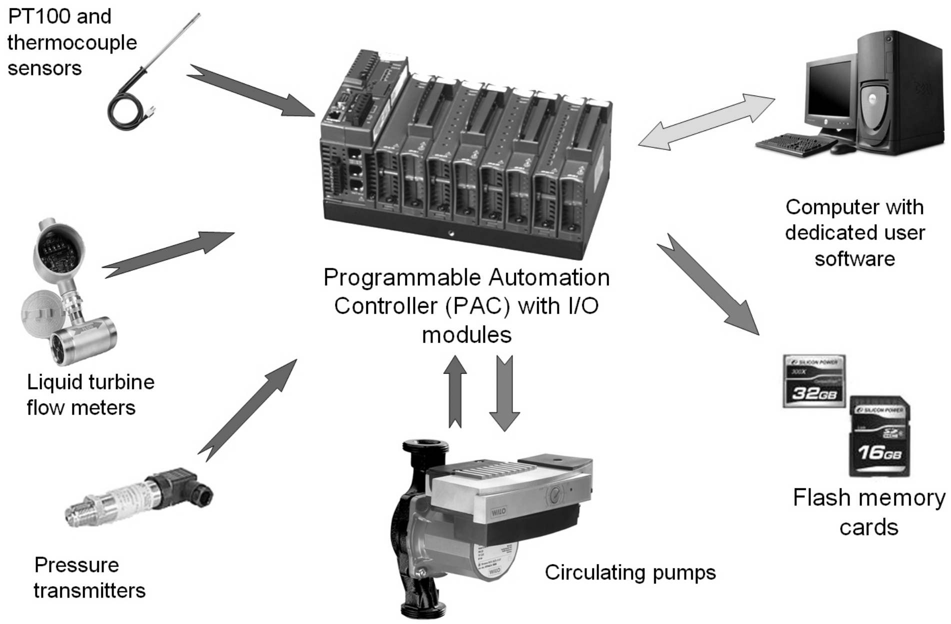

Fig. 2. Illustration of connections in C&DA system

Various modules are used to manage the station. 8-channel, 16-bit thermocouple and 4-wire RTD modules are mounted to record the temperature from thermocouples and resistive thermal devices. The only targets for above sensors and dedicated modules are the working fluid of solar station and a water that is heated by WHS subsystem. One of the most important parameter which is crucial to characterize the efficiency of μ-CHP unit is a stream of the heat-carrying agent. Pressure and flow of the fluids have been measuring to evaluate the stream. This is realized by implementation of 8-channel Analog Voltage Input Module and 12 to 24 V Sinking Counter Module dedicated for pressure transmitters and flow meters, respectively. Programmable Automation Controller converts the voltages in range from 0 to 12 V in order to process the pressure and counts voltage impulses to achieve the flow values. There is only one way which affords the control system to manage the power transmissions of the Unit. The widely-used circulating pumps are controlled, switched on and managed by the different I/O modules. 8-channel Analog Voltage Output Module controls the speed of the pumps by applying of appropriate potential difference in range from 0 to 10 V. Sending by circulating pumps emergency signals accomplishes 24 VDC Sinking Digital Input Module. When control algorithm changes current state of the Unit (e.g. from electricity production to air-conditioning or scaling up or down of power transmission) 16-channel Sourcing Digital Output Module switches chosen pumps to obtain suitable state.

2.2. Electric driver design

Both electronic control signals and measurement data are sent through the constructed electrical driver being part of C&DA system. The main driver with visible PAC device and different modules are shown in Fig. 3. In addition there is circuit diagram presented in Fig. 4. Two various electrical components of the µCHP unit are switched by particular relays built into the driver. According to circuit diagram the circulating pumps and cooling radiator intended for Lower Heat Source are indirectly switched on and off by the modules due to supply of ~230 V. The rest of C&DA system's equipments are directly managed with aid of dedicated modules.

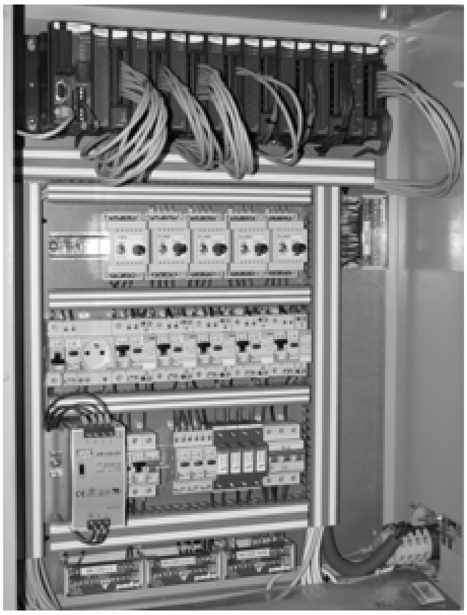

Fig. 3. C&DA system's driver

One of the sophisticated feature of C&DA system is a fully automatic and reliable operation. Due to necessary testing, improvement and maintenance manual control option has been also implemented. Two depicted figures illustrate this option – for instance as the knobs being visible in the Fig. 3 and as a part of the circuit diagram shown in Fig. 4. Manual controlling, basing on real or user program settings, have been enabled to improve an algorithm written into PAC. From this point of view manual control option is crucial during development of the solar station while it could be passed over in final commercial version of the μ-CHP Unit.

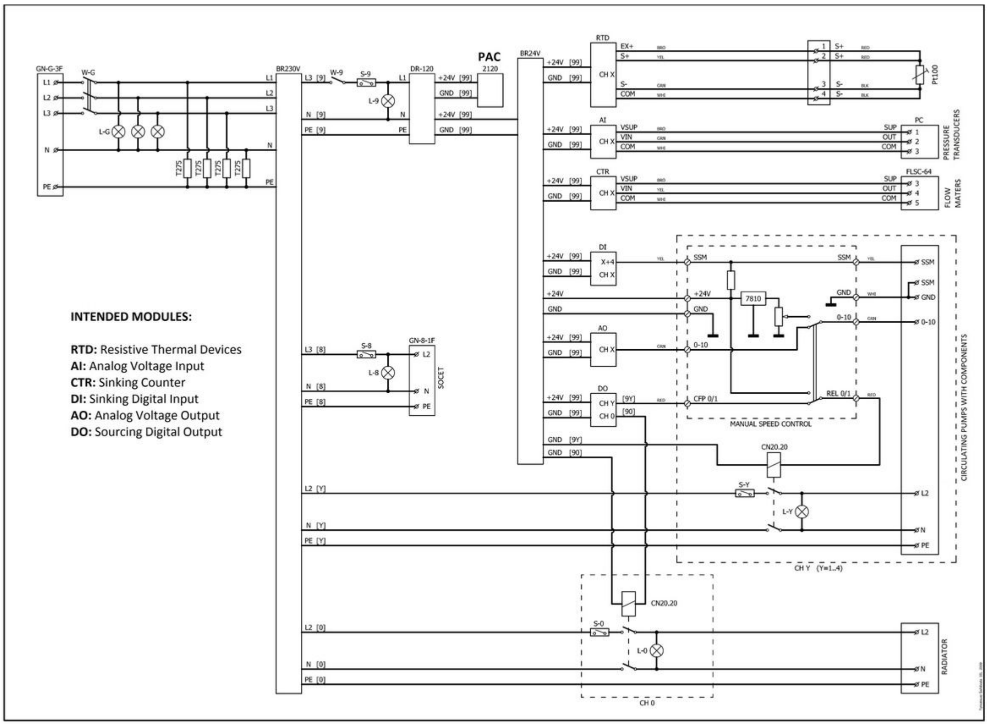

Fig. 4. Detail of the driver logic schematic

2.3. Control Algorithm Implementation

During power plant's operation various events can occur. Hence, software development was as important task as engineering design and construction. The development has been lead in graphical environment NI LabVIEW – created for programming of measurement test control systems. Schematic representation of the algorithm is shown in Fig. 5. The meaning of C&DA's algorithm is as follows.

Loop structure control program bases on priorities, i.e. there are built-in loops which are firstly executed in comparison to the others. An example is flow meters' reading function. This loop counts the voltage impulses sending in time by intended module. The loss of certain impulses caused due to non-hierarchy structure of the algorithm would has an influence on current magnitude of the flow. From this point of view a loop such as above is outside a main complex loop depicted in Fig. 5 and has the highest priority. The main loop clarifies the principles of operation of control algorithm. Firstly Read/Write I/O module function is executed. It means the reading of measurement data and/or writing configuration settings into circulating pumps or fun (radiator) using particular I/O modules. Basing on captured data proper rotational speed of chosen pumps is calculated. These velocities have to fulfill specific conditions in terms of power distribution for active subsystems. In other words to enable chosen energy conversion (from solar energy to heat, coolness or electricity) and/or keep conversion efficiency the PAC should switch on and set suitable speed of circulating pumps.

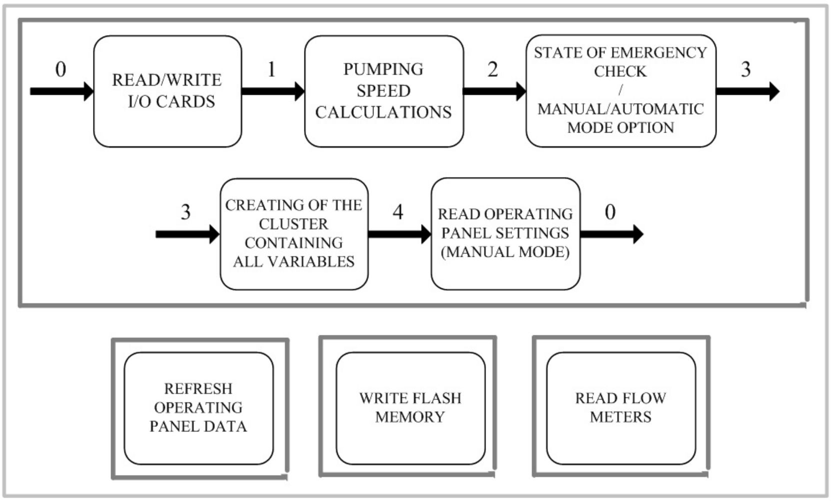

Fig. 5. Diagram of the control algorithm intended for Programmable Logic Controller

In the next stage of the algorithm State of Emergency Check function is executed. The aim of the function is a searching of emergency states which car appear during μ-CHP unit operation and start-up an alarm procedure in case of any emergency events. According to principles of operation following events may be found:

- collector temperature over range,
- organic working fluid over pressure,
- water pressure over pressure,
- circulating pumps failure.

Looking for above problems Emergency Check function aids to avoid serious crash of μ-CHP unit such as uncontrolled rise of pressure or temperature of various fluids. The same stage contains an option of Manual/Automatic mode. In the automatic mode The PAC with the algorithm manages the station while in manual the user has an ability to control the micro-CHP unit. Creating of Clusters Containing All Variables function is due to the LabVIEW structure. The cluster aids to put in order a huge amount of data which are sent in C&DA system. The last stage in the main loop is Read Operating Panel Settings option which is active in manual mode. In this mode the control algorithm is passed over.

2. 4. User program description

Regardless of control algorithm implementation, different user programs have been written to display the working of the Unit. Using these programs testing, improvement and illustration of states of the operation is possible. The main user program contains six bookmarks which depict the main heat source with WHS subsystem and necessary tools for the manual management. Fig. 6 shows Heat Source bookmark. There are four banks of solar panels (6a), plenty of points of temperature measurements (6b), data of flows (6c), values of pressure (6d) and circulating pumps settings (6e) in the figure. In addition the window depicts current value of thermal power achieved from solar collectors (6f).

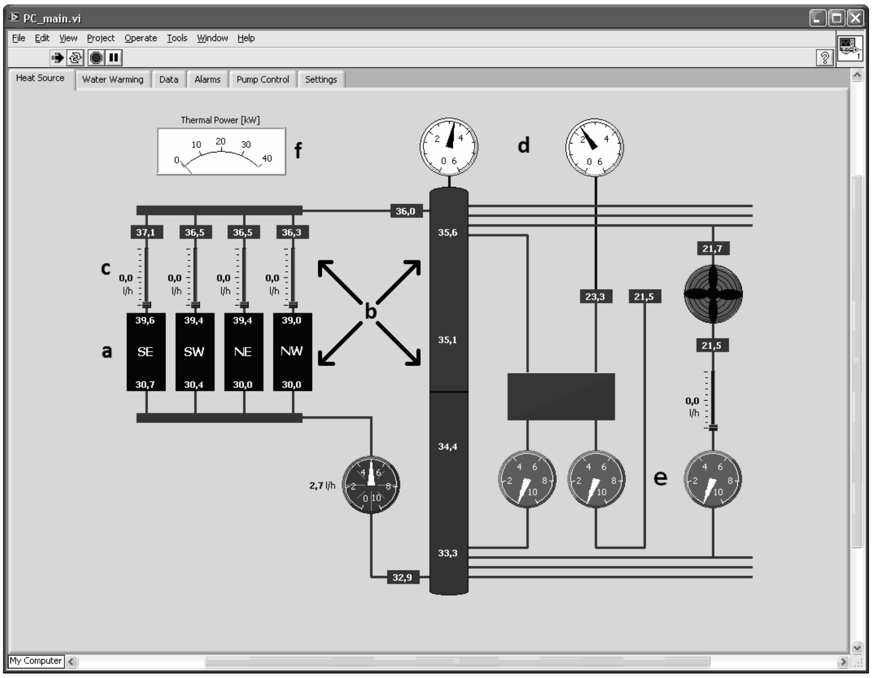

Fig. 6. The main user program with Heat Source bookmark: solar collectors (a), points of temperature measurements (b), data of flows (c), values of pressure (d), circulating pumps settings (e) and current value of thermal power (f)

The other functions of the program are as follows:

- water warming (fig. 7), which illustrates a connection between water heated by μ-CHP and the water received from commercial thermal power plant,
- displaying of measurement data of whole solar station,
- alarm window, that displays emergency states,
- circulating pumps settings function which allows to set the pumps in manual way,
- other settings which for instance allow to force certain temperature of heated water or the speed of the power transmission.

Similar to heat source with WHS windows the other subsystems found their graphical implementations in LabVIEW programs. Such a window of ORC subsystem is presented in Fig. 9. The window illustrates components of the subsystems i.e. shell-and-tube JAD-type heat exchanger (9a), expander with generator (9b), heat regenerator (9c), condenser (9d), condensate vessel (9e), electric boiler (9f) and circulating pumps (9g). In addition there are different measurement data such as temperature and pressure of working fluid in various parts of the subsystem. The user program aids to investigate ORC subsystem by tracing and displaying of particular stages of the operation.

Cooling Absorption Unit subsystem with its user program is shown in Fig 8. Likewise was written above the window reflects the structure of the subsystem, thus facilitates technical and scientific researches.

Both user program have a function to enable 9 kW 3-phase electric boiler with volume of 3 dm^3. Hence, in manual mode this external heat source is used when solar radiation is not sufficient.

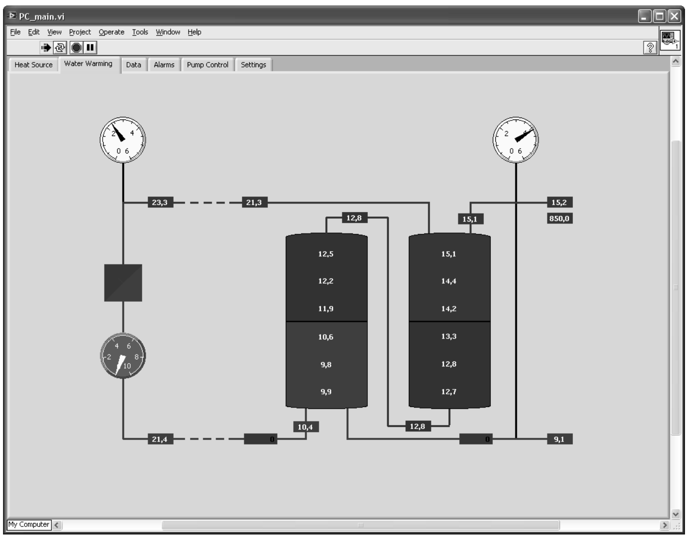

Fig. 7. Water warming bookmark

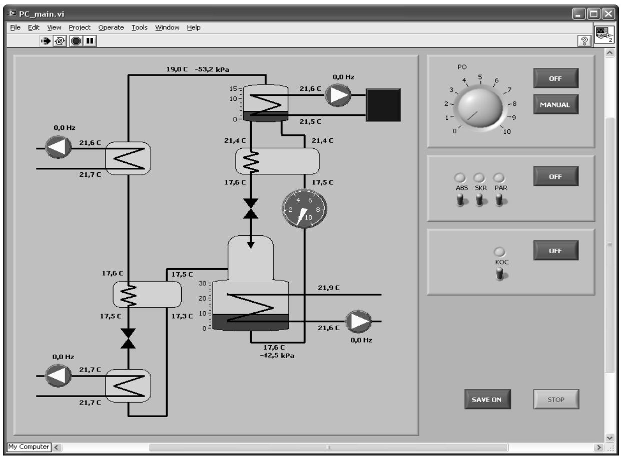

Fig. 8. Cooling Absorption Unit window

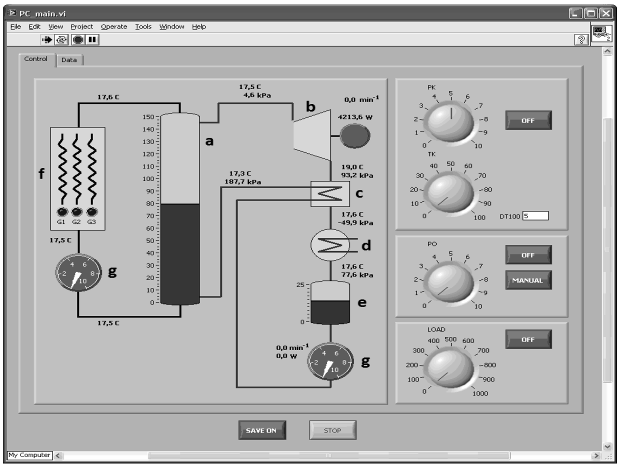

Fig. 9. ORC subsystem user program: shell-and-tube JAD-type heat exchanger (a), expander with generator (b), heat regenerator (c), condenser (d), condensate vessel (e), electric boiler (f) and circulating pumps (g)

3. Exemplary results from C&DA system

Various data are captured mainly due to controlling of the solar station. However, from a scientific point of view acquiring measurement data is also very important. Investigating micro-CHP unit through analyzing values of magnitudes such as temperatures, pressures and flows makes possible to confirm and prove that the idea of combined heat and power is quite successful and can be use in typical domestic or industrial applications. The graphs placed bellow show temperature values of working fluid that have been measured during operation of the micro-CHP unit.

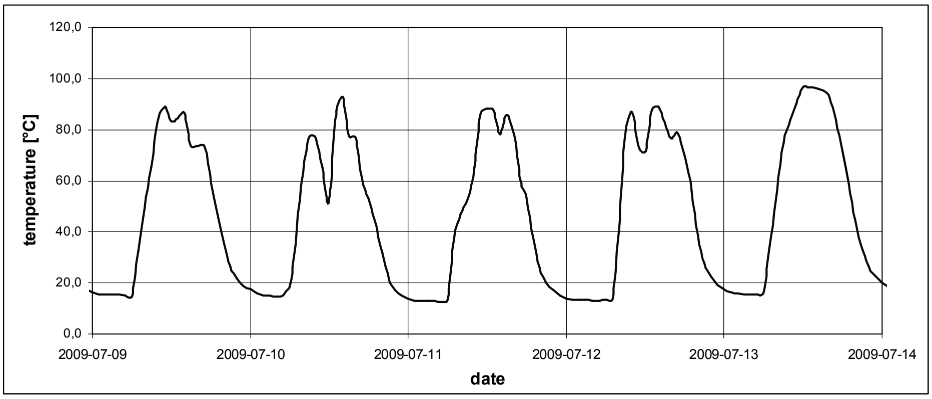

Fig. 10. Temperature of working fluid collected during a few sunny days of summer

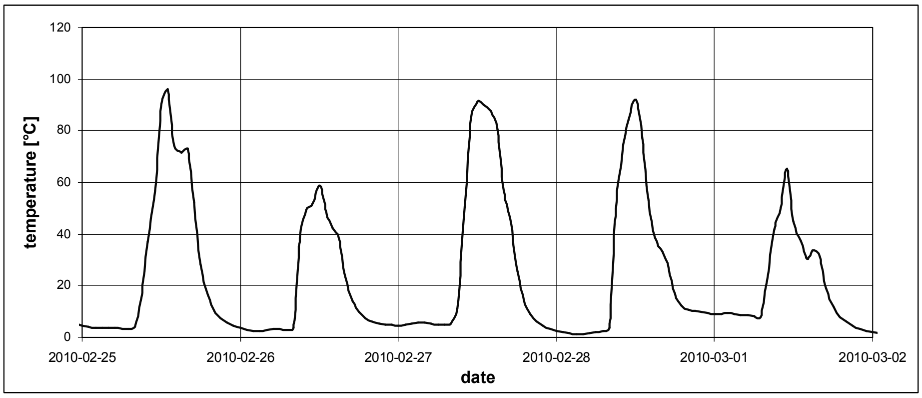

Fig. 11. Temperature of working fluid collected during a few sunny days of winter

Some conclusions can be considered when the above data are analyzed. During sunny days, regardless of a season of the year similar temperatures can be obtained. First of all a reason is the construction of vacuum solar collectors and the chemical composition of working fluid which lead to excellent absorption coefficient. In addition these collectors are mounted on the roof at an angle of 60° which is as acceptable in winter as in summer. The result is that μ-CHP unit is able to work whole year and support or replace classic methods of heating of water or even of obtaining an electricity or a coldness.

4. Conclusions

Control and Data Acquisition System has been made to provide automatic or manual regulation of the micro Combined Heat and Power unit supplied from solar collectors. The system makes possible to efficiently manage entire unit by controlling the stream of the heat with the aid of the Programmable Automation

Controller and LabVIEW programs. This control is being realized on the basis of primary data from pressure and temperature sensors and flow meters which are assembled in the different subsystems of the micro-CHP. The data which have been collected within a period of work are used to evaluate the most appropriate method for thermal energy conversion in typical habitable facilities.

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