Outdoor simulation model of photovoltaic thermal (PV/T) water based solar collector

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Abstract - Photovoltaic modules and solar collectors are used together in hybrid photovoltaic-thermal solar collectors (PV/T) for simultaneous provision of electrical and thermal energy. This paper proposes design of a simulation model for testing of efficiency of photovoltaic-thermal solar collectors. The model is used for testing of dependence of thermal and electrical efficiency of the systems on a series of factors; material of the photovoltaic module, type of cooling medium, flow of cooling medium, collector design, exposure to sunlight, speed of wind and environment temperature. Values measured within the system were recorded and the measuring equipment and methods for the measuring system were proposed.

Keywords: hybrid PV/T system, photovoltaic, solar collector, absorber collector, thermal efficiency, electrical efficiency.

I. Introduction

Over the last few years, problems related to shortage of energy, climactic changes and preservation of the environment brought the renewable sources of energy into the professional and scientific focus. The most significant renewable sources are the wind and the sun. The wind is mainly used for production of electrical energy, while the sun is used as a source of both thermal and electrical energy. In solar thermal collectors a fluid or a gas are heated and they are then used to heat water or spaces in households or industrial buildings [1-4]. Photovoltaic modules, which are made of solar cells, are used for direct conversion of the solar into the electrical energy. However, solar cells use only a smaller part of the radiated solar energy for production of electricity (between 4 and 17 % [2]), and the rest is irretrievably lost as heat that additionally heats the cells, Figure 1. [4].

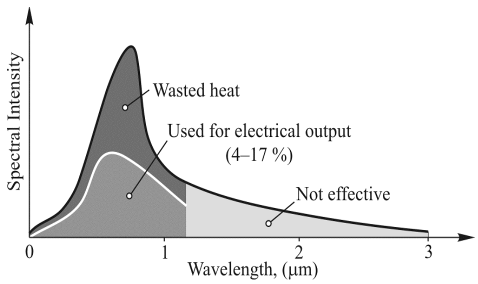

Figure 1. Diagram of the partition of the sunlight converted to electricity or to heat, as a function of the wavelength

Nowadays, solar cells are mainly made of silicon which is a good absorber and conductor of the heat. By heating in the sun, the temperature of the photovoltaic modules rises significantly, and with the temperature rise, electrical efficiency of the module is reduced [5, 6].

One of the methods to increase the electrical efficiency is forced or natural cooling of the module. The replacement method is use of hybrid photovoltaic-thermal collectors (so called PV/T collectors). These are systems where photovoltaic modules and solar collectors are connected together and where they simultaneously produce electrical and thermal energy. The solar collector has a double function in the PV/T systems. It cools the photovoltaic module, and simultaneously collects the thermal energy in the form of heated liquid or heated air. During this process electrical efficiency of the solar cells i.e. the photovoltaic modules is improved.

The PV/T system accumulates the thermal energy in the heat tank. The electrical energy produced by the PV/T systems can be transmitted into a local network or the system acts autonomously, powering own DC or AC loads. The connection to the network or own loads is achieved by an electronic power converter – DC/DC converter or inverter [7].

II. Efficiency of PV/T system

A. Efficiency of solar collector (thermal efficiency)

The thermal efficiency of PV/T system, η_{th} is determined based on thermal properties of the photovoltaic module and the solar collector. The thermal efficiency is mainly determined by design performance of the system and the properties of the cooling media, and is usually calculated by using the Hottel and Whillier equation [5]. One of the expressions for calculation of the thermal efficiency is:

$$\eta_{th} = \frac{\dot{m} C_p \Delta T}{A_p G_T} \cdot 100\% \qquad (1)$$

Where:

$\dot{m}$	mass flow rate (kg/sec)
C_p	specific heat of the collector cooling medium (J/kg °C)
ΔT	differences between fluid or air outlet temperature (T_o) and fluid or air inlet temperature (T_i)
A_p	area covered by absorber collector (m^2)
G_T	solar radiation at NOCT[1] (irradiation level 800 W/m^2, wind velocity 1 m/sec, ambient temperature at 20°C)

[1] NOCT - nominal operating temperature, determined on the basis of International Standard EN-61215 for modules without load.

The fluid mass flow rates can be calculated using the equation below:

$$\dot{m} = \rho A v_{av} \quad (2)$$

where:

A tube cross section area (m^2)
ρ density of the fluid or air drain input area (kg/m^3)
v_{av} fluid or air velocity (m/sec)

B. Efficiency of photovoltaic module (electrical efficiency)

When fill factor (*FF*) is introduced and defined for the characteristic of solar cell/module as:

$$FF = \frac{P_{max}}{I_{SC} \cdot U_{OC}} \quad (3)$$

electrical efficiency, η_{el} can be written as:

$$\eta_{el} = \frac{I_m U_m}{A_p G_T} \cdot 100\% = FF \cdot \frac{I_{SC} \cdot U_{OC}}{A_p G_T} \quad (4)$$

where:

P_{max} maximum generated power (W)
I_{sc} short circuit current (A)
U_{oc} open cell voltage (V)
I_m maximum current (A)
U_m maximum voltage (V)

The electrical efficiency of the photovoltaic module is reduced with the temperature rise due to the lower mobility of carriers, diffusion length, as well as lifetime of minority carriers and saturation current, Figure 2. [6].

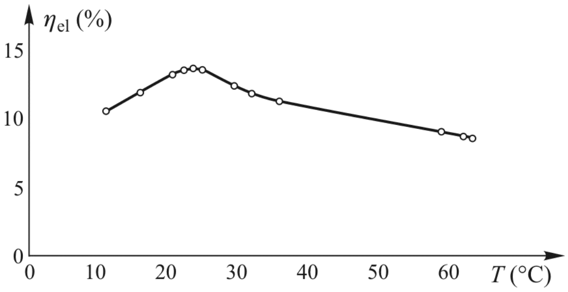

Figure 2. The photovoltaic efficiency of the silicon solar cells/module in the function of temperature.

The electrical efficiency μ_{el} of the crystalline silicon (c-Si) solar cells/modules is given as a function of temperature:

$$\eta_{el} = \eta_0[1 + \beta(T_{cell} - 298K)] \quad (5)$$

Where:

η_0 efficiency of the module at temperature 298 K
β silicon efficiency temperature coefficient, usually for c-Si: $\beta \approx -5 \cdot 10^{-3} K^{-1}$ [6],
a-Si: $\beta \approx -2{,}5 \cdot 10^{-3} K^{-1}$[8]
T_{cell} cell/module temperature

Often power loses are equal to 0.5 %/K.

C. Total efficiency of PV/T system

Performance of the hybrid PV/T collector can be best described by the combined efficiency of the collector. This consists of thermal efficiency η_{th} and electrical efficiency η_{el} and amounts to:

$$\eta_o = \eta_{th} + \eta_{el} \quad (6)$$

A total efficiency of about 60 % can be achieved in this manner, as shown in Figure 3.

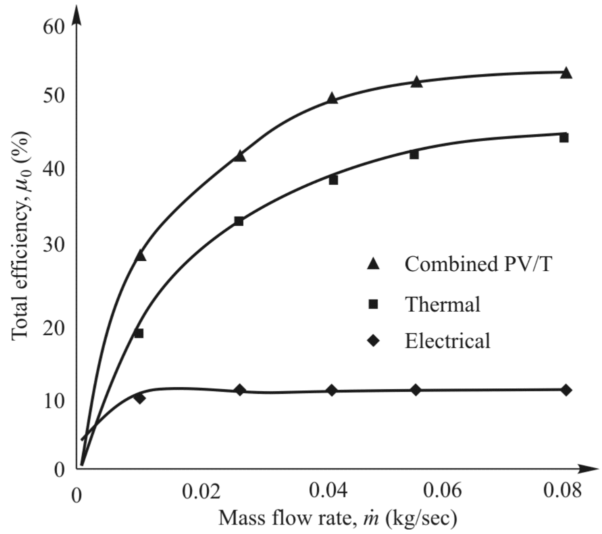

Figure 3. Combined PV/T efficiency versus mass flow rates

III. EXISTING SOLUTIONS

A. Flat plate PV/T collector classification

PV/T systems can be divided into the systems cooled by air, water or a combination of water and air, Figure 4. [7]. The systems cooled by water have channels of different shapes through which the water circulates cooling the photovoltaic module. For the systems that use combination of air and water as the cooling media, the absorbers are in the form of channels or the air is in direct contact with the photovoltaic module. The air type PV/T collectors can be distinguished according to the air flow configuration such as air above, below or on both sides of the absorber collector. They can be either single or double pass.

The collectors are normally designed with pump and can be either with forced or natural circulation. The Figure 5. shows examples of typical design solutions of the PV/T systems [1].

B. Different types of photovoltaic materials

For the type of cooling medium and the method of collection of the thermal energy, properties of the PV/T system are essentially determined by the type of material the solar cells are made of. More than 80 % of solar cells and modules manufactured all over the world are based on the mono-crystal (c-Si) and poly-crystal silicone (pc-Si). Only 13.23 % of manufactured solar cells are made of the amorphous silicon (a-Si), 0.39 % of cadmium-telluride

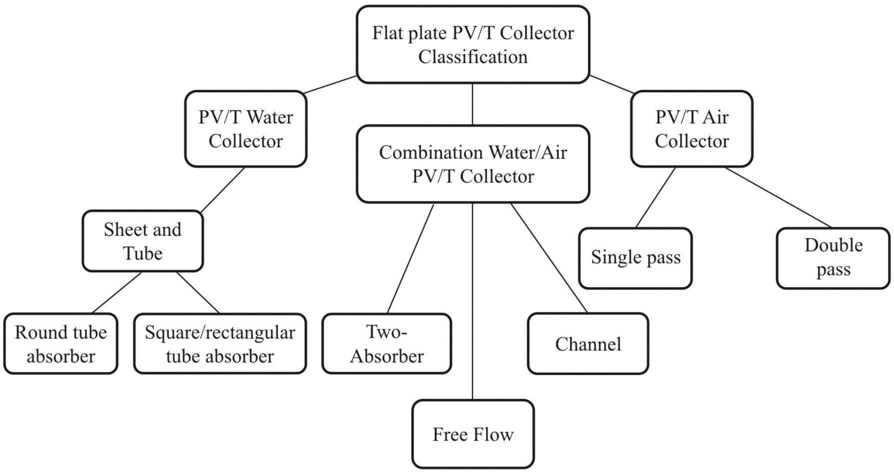

Figure 4. Flat plate PV/T collector classifications

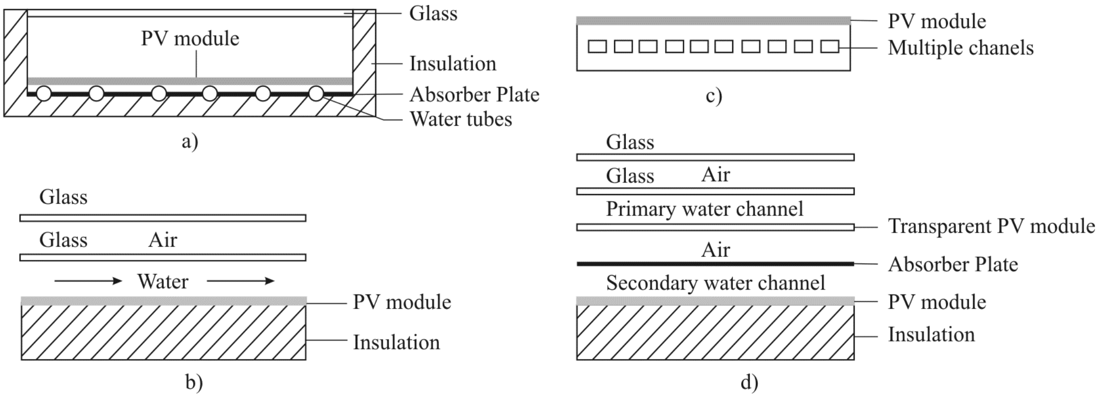

Figure 5 Cross-sectional view of PV/T system; a) basic PV/T collector, b) liquid flowing on top of the PV module, c) channel PV/T concept with liquid flow beneath the PV cells, d) two-absorber PV/T model

(CdTe) and 0.18 % of copper-indium diselenide (CIS). Solar cells made of crystalline silicon have better efficiency but are more expensive than the amorphous cells since the technological process of production is conducted under high temperatures (above 1000 ^{o}C).

The manufacturing technology for solar cells made of developed thin films a-Si uses less materials and offers a possibility to manufacture cells on larger surfaces of various substrates (silicon, glass), [1].

C. Shortcomings of the existing solutions

Between all types of PV/T systems, the best known lately are the systems that use air as the cooling medium; although this type of collector, in comparison to the collector that uses the water, is used more seldom.

The PV/T systems that use water as the cooling medium are more efficient than those that use air, due to high thermal conductivity, high specific temperature, and high density, thus permitting transfer of larger volumes of heat [2]. Use of water requires more complex design of the collector and primarily water-proofing and protection of the module against corrosion must be achieved.

In addition to that, researchers make great efforts to solve two large problems that appear when PV/T collectors are manufactured: (i) imperfect connection of the photovoltaic module and the absorber, and (ii) imperfect connection between the absorber and the metal pipes for flow of the cooling medium, i.e. the water [9].

IV. PROPOSED EXPERIMENTAL SETUP

A. The model structure

To test possible improvements of the observed shortcomings in the water-cooled PV/T systems, a simulation model is proposed to test the system under external conditions. The block scheme of the system is shown in Figure 6.

The basic parts of the model are: photovoltaic module and solar collector, connected together, cooling medium flow system, electronic power convertor (exchanger) and the measuring system.

On the back side of the photovoltaic module of the PV/T system, a system of water pipes is mounted as the cooling medium. The heated water circulates between the photovoltaic module and the heat tank to which it transfers the thermal energy. To research the impact of flow of the cooling medium on the efficiency of the PT/V system, it will be necessary to change the flow of the mass, using a pump and a regulating electric valve.

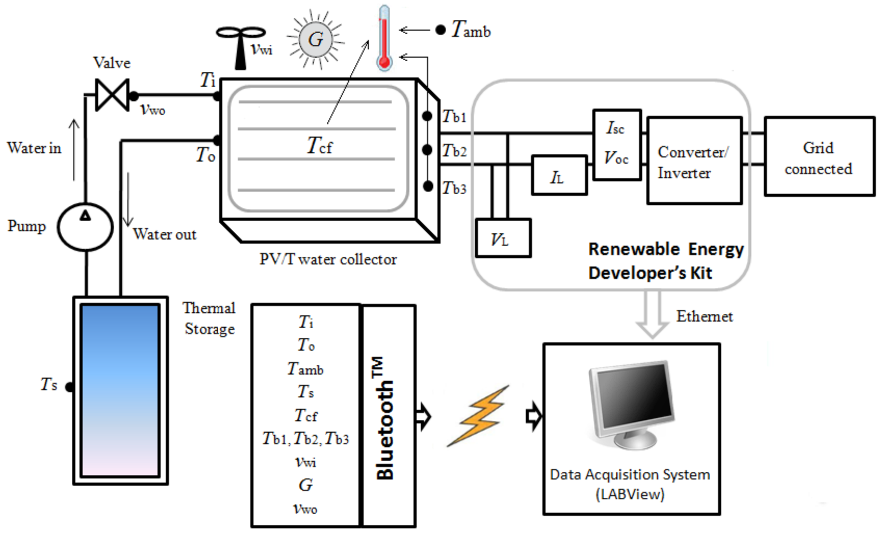

Figure 6. Schematic diagram of simulation model of PV/T water based system

Output voltage and current of the photovoltaic module are transmitted to the loads or to the local network via an electronic power converter.

Converter is a Renewable Energy Developer's Kit evaluation board designed to work with Texas Instruments C2000™ microcontrollers. This kit is a part of TI's digital power tools package designed to give customers an opportunity to quickly evaluate TI C2000 products for power conversion applications at a safe input voltage and power level.

Figure 7. gives a simplified block diagram of the system here. The system consists of an inverter section, a front-end DC-DC boost section, a line sensing/synchronizing section and a synchronous buck battery charging section. This board offers all the voltage and current measurement hooks so that one can create and test new topologies and techniques.

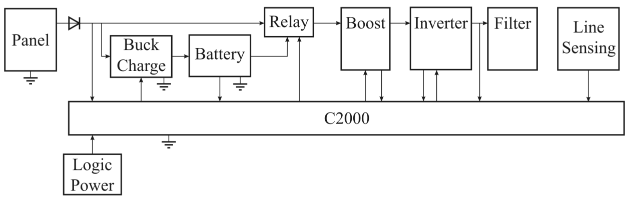

Figure 7. System block diagram

The control algorithm is implemented on a C2000 microcontroller (MCU). The MCU interacts with the hardware by way of the feedback signals and the PWM drive signals. Thus the key control peripherals on C2000 devices for this application are: the on-chip ADC to sense all feedback signals mentioned above, PWM modules to drive the MOSFET switches, different communication peripherals and different general purpose IOs, Figure 8. The duty cycle of the PWM output driving the MOSFET switch determines the amount of boost imparted by the boost converter. This is the controlled parameter for the boost stage. For the inverter stage, the duty cycles of the four/six PWM signals driving the two/three inverter legs are modulated in a sinusoidal fashion. This modulation is also synchronized in phase and frequency to the AC mains input voltage to provide an appropriate AC output for the load. Thus the controlled parameters here are the phase, frequency and amplitude of this sinusoidal modulation, which in effect control the duty cycle of the PWM signals. The duty cycle of the PWM output driving the two MOSFET switches determines the amount of charging energy imparted to the battery. This duty is the controlled parameter for the battery charging stage. All this control is made possible by the high frequency/high resolution PWM modules, an equally high control loop frequency and a 12-bit on chip ADC available on the high performance 32-bit C2000 controllers.

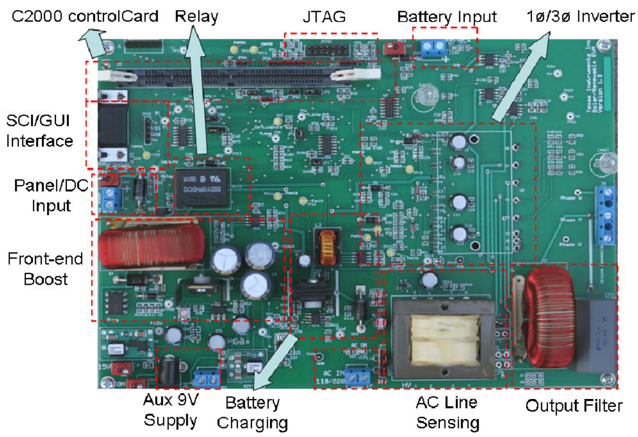

Figure 8. Renewable energy board

The measuring system measures the water temperature at the entry into the collector, exit from the collector, temperature in the cooling media tank, temperature on the front/back surface of the photovoltaic module, environment temperature, flow of the cooling medium, voltage and current on the exit from the photovoltaic module (on the load), insolation of the module, wind speed and air flow speed.

B. Goals of the experiment

The proposed simulation model of PV/T system tests dependence of the electrical and thermal efficiency of the system in relation to:

- material of the photovoltaic module (c-Si, pc-Si, a-Si)
- type of the cooling medium
- flow of the cooling medium
- design of the channels for the cooling medium
- wind strength and speed of the air flow
- thermal resistance between the photovoltaic module and the collector

The purpose of the experiment is to test the properties of PV/T system for insolation expected in the territory of the City of Zagreb to define optimal design of PV/T system according to the criteria of maximum electrical and thermal efficiency.

V. INSTRUMENTATION AND MEASURING METHODS

A. Measured values

To achieve the experiment goals with the proposed simulation model of PV/T system, it is necessary to measure the following values during the experiment (Figure 6.):

- inlet water temperature (T_i)
- outlet water temperature (T_o)
- ambient temperature (T_{amb})
- thermal storage temperature (T_s)
- solar cell temperature
  - front side (T_{cf})
  - back side (T_{b1}, T_{b2}, T_{b3})
- wind velocity (v_{wi})
- solar intensity (G)
- water velocity (v_{wo}) or water flow
- load current (I_L) and load voltage (V_L)
- short circuit current (I_{sc}) and open circuit voltage (V_{oc})

B. Measuring equipment

Several devices are going to be used to take measurements and characterize the performance of PV/T system, including seven digital thermo probes, anemometer, a pyranometer and a device for measuring the flow. For measuring of the voltage and current the facilities provided by the Renewable Energy Developer's Kit development circuit board are used. To measure the surface temperature of the photovoltaic panel a thermal camera will also be used.

In order to characterize the thermal performance of PV/T system, temperature measurements have to be taken at various locations throughout the assembly. For measuring the temperature digital thermo probes DS18B20 of accuracy ± 0.5 °C are selected.

One digital thermo probe will be mounted on the outside surface (away from PV/T module) to measure ambient temperature (T_{amb}). One thermo probe will be used to measure solar cell temperature (T_{cf}). Three thermo probes will be embedded between the PV panel and the solar absorber measured interior panel temperature or back side cell temperature (T_{b1}, T_{b2}, T_{b3}). With three digital thermo probes the temperatures of the cooling medium at entry into the solar collector (T_i), at exit from the collector (T_o) and temperature of the cooling medium in the heat tank (T_s) are measured.

For calculation of the thermal efficiency (1) and electrical efficiency (4) it is necessary, in addition to the temperature, to measure the mass flow of the cooling medium and irradiation. The coolant flow rate through the solar collector (0.01 – 0.03 kg/s per square meter of collector) will be measured with ultrasonic flow and heat meter. The insolation measurements will be taken by a pyranometer (Kipp&Zonnen - CM21) mounted in the same plane as the panel.

Forming the remainder of the data collection suite is anemometer. It is important to collect wind speed and direction measurements to determine how wind will influence the efficiency of the panel. An anemometer (P-670-M) with two mini probes will be mounted on the exterior of the assembly, to measure the wind speed.

Mass flow of the cooling medium, irradiation and wind speed change slowly. Neither the voltage nor the current have to be sampled very frequently, so a cheaper acquisition system can be used, that should have at least 16 bit A/D conversion, for accuracy.

For capture of digital data from the thermal probes and analogue values from the anemometer, piranometer and devices for measuring the flow, a special measuring system was developed, Figure 9., [10]. The temperature signals and signals of other physical values are converted into the digital ones, which are sent to the computer in packages, via wireless communication. The measuring system is intended as a universal dislocated platform for which the operational principle and the operating algorithm can be remotely changed.

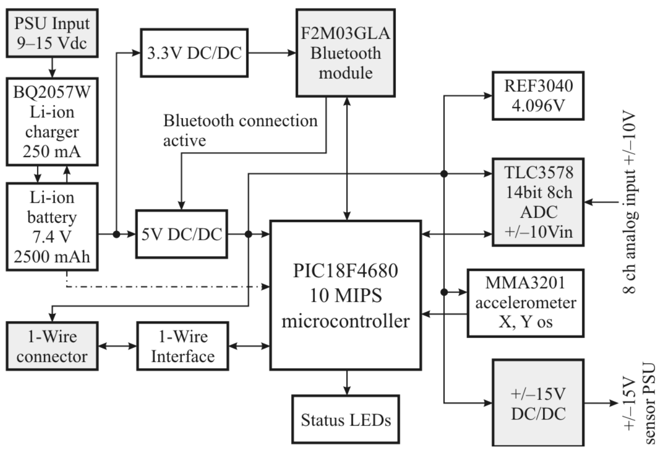

Figure 9. Measuring system block diagram

The measuring system consists of several parts:

- Bluetooth communication module
- microcontroller
- 14-bit ADC
- Li-ion battery

For wireless communications media Bluetooth^{TM} is selected for its simplicity of use, high data transfer speed, low power consumption, and for safety of the data flow (additional safeguards to protect the correctness of the packages are not required).

The heart of the measurement system is PIC18F460 microcontroller which routes data from the sensors to the Bluetooth interface. Each thermo sensor DS18B20 has a unique 64-bit serial code, which allows multiple DS18B20 to function on the same 1-wire bus. Routines for searching, addressing and reading 1-wire temperature sensors are integrated in the embedded code of the microcontroller.

The measuring system uses 14 bit 8-channel analogue-digital converter connected to the microcontroller via a synchronous serial SPI (Serial Peripheral Interface) interface. The analogue-digital converter has the input voltage range of +/-10 V and the maximal sampling rate of 200,000 samples per second. Anemometer, pyranometer and cooling medium flow meter are connected to the analogue-digital converter.

3 DC/DC convertors are built into the measuring system since several powering voltages are needed (3.3 V, 5V, 15V, -15V). The 3.3 V converter is permanently switched on and powers only the Bluetooth^{TM} module, while the other converters are switched on when the successful Bluetooth^{TM} connection is established. When other converters are switched on, the microcontroller is also switched on and the system is then ready for work.

Bluetooth module F2M03GLA is connected to the microcontroller via a USART interface, so the system acts as a virtual serial port on the host computer. A protocol for communication between the PC host and the measurement system was also developed.

The values of voltage and current of the photovoltaic collector, as well as the values of voltage and current on the exit of the inverter obtained by a *Texas Instruments* development circuit board are connected to the host computer via Ethernet.

The data from all of the sensors have to be monitored and logged on to the host computer. The application for the graphical user interface was developed in the National Instruments programming language *LABView*. The GUI application sends commands to the measurement system over the Bluetooth virtual serial port and waits for its response. The time base of the measurement is generated by the host system. The application searches for sensors and monitors the temperature and other measured values. Monitored values of each sensor together with time base are logged in a textual file which is used for further analysis. Minimum sampling period is limited with the resolution of sensors.

VI. Expected Results

The proposed simulation model of the hybrid photovoltaic-thermal solar collector tests the dependence of electrical and thermal efficiency of a PV/T system on a number of factors. The models that can be found in the literature are primarily models used within closed spaces, with artificial light source. The proposed model is for use under real conditions. A research is planned of the model behaviour on the area of the City Zagreb, over a longer timescale. Also, impact of properties of the model itself on its efficiency will be researched. The aim is to determine the electrical and thermal efficiency depending on the type of silicone, type of the cooling medium (air, water) and flow of the cooling medium and design of the solar collector. It is expected the research will provide evaluation of the behavioural efficiency of commercially available photovoltaic modules in the PV/T system and that it will propose solutions for some of the discovered shortcomings of the existing PV/T systems.

VII. Conclusion

This paper described the model for hybrid photovoltaic -thermal solar collector for testing efficiency of the system under real life operating conditions. A structure of the measuring system was proposed that will be used to collect the values required for controlling the flow of the cooling medium, and for assessment of electrical and thermal efficiency of the photovoltaic module and thermal collector.

References

[1] M. Arif Hasan, K. Sumathy, Photovoltaic thermal module concepts and their performance analysis: A review, Renewable and Sustainable Energy Reviews 14 (2010) 1845–1859.

[2] T.T. Chow, A review on photovoltaic/thermal hybrid solar technology, Applied Energy 87 (2010) 365–379.

[3] H.A. Zondag, Flat-plate PV-Thermal collectors and systems: A review, Renewable and Sustainable Energy Reviews 12 (2008) 891–959.

[4] Wim G. J. van Helden1, Ronald J. Ch. van Zolingen and Herbert A. Zondag, PV Thermal Systems: PV Panels Supplying Renewable Electricity and Heat, 2004.

[5] A. Ibrahim, G. Li Jin, R. Daghigh, M. Huzmin, M. Salleh, M. Y. Othman, M. H. Ruslan, S. Mat and K. Sopian, Hybrid Photovoltaic Thermal (PV/T) Air and Water Based Solar Collectors Suitable for Building Integrated Applications, American Journal of Environmental Sciences 5 (5): 618-624, 2009.

[6] Ewa Radziemska, Performance Analysis of a Photovoltaic-Thermal Integrated System, International Journal of Photoenergy, Volume 2009, Article ID 732093, doi:10.1155/2009/732093.

[7] A. Ibrahim, M. Y. Othman, M. H. Ruslan, S. Mat, K. Sopian, Recent advances in flat plate photovoltaic/thermal (PV/T) solar collectors, Renewable and Sustainable Energy Reviews 15 (2011) 352–365.

[8] S.A. Kalogirou, Y. Tripanagnostopoulos, Hybrid PV/T solar systems for domestic hot water and electricity production, Energy Conversion and Management 47 (2006) 3368–3382.

[9] Chow TT. Performance analysis of photovoltaic-thermal collector by explicit dynamic model. Solar Energy 2003;75:143–52.

[10] M. Kovačić, M. Vražić, I. Gašparac, Bluetooth wireless communication and 1-wire digital temperature sensors in synchronous machine rotor temperature measurement, Power Electronics and Motion Control Conference (EPE/PEMC), 2010 14th International , vol., no., pp.T7-25-T7-28, 6-8 Sept. 2010 doi: 10.1109/EPEPEMC.2010.5606582