DEVELOPMENT OF A SYSTEM OF SUPERVISION AND DATA ACQUISITION FOR TESTS OF PERFORMANCE OF SOLAR COLLECTORS

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Abstract. *A instrumentation and control system for test of performance of solar collector is presented. Units of refrigeration and auxiliary heating of liquid were developed and implemented to provide adjustments of values of temperature of the circulating liquid. The setpoint mass flow rate is achieved through a control system based a frequency converter and pulley acting on a pump. A graphical interface show on real time the values of the temperature of the circulating fluid, the set points (temperature and mass flow), the state of the actuators of solid state that set the units of heating and also monitorial cooling of liquid and the values of incident radiation in the solar collector. Electronics transducer circuits of signals and two modules of data acquisition of 12 bits with analog to digital converter (ADC) and digital to analog converter (DAC) were used. The results are registered electronically and used for determination of the performance of solar collectors, in accordance with the NBR-10184/1988.*

Keywords*: supervisory system, solar water heating, data acquisition*

1. INTRODUCTION

The use of electric heaters of passage, for water heating for residential use, represents a thermal comfort for the users and at the same time provokes an increase of the demand in the Brazilian electrical system. According to the PROCEL (2005), 6 % of all the Brazilian consumption is destined to the water heating for residential use.

Due factors as simplicity of installation and low cost of acquisition, the electric heaters represent the predominant way of residential water heating, as demonstrated in the Fig. 1 whereas the use of the solar energy for the water heating is 0.4%.

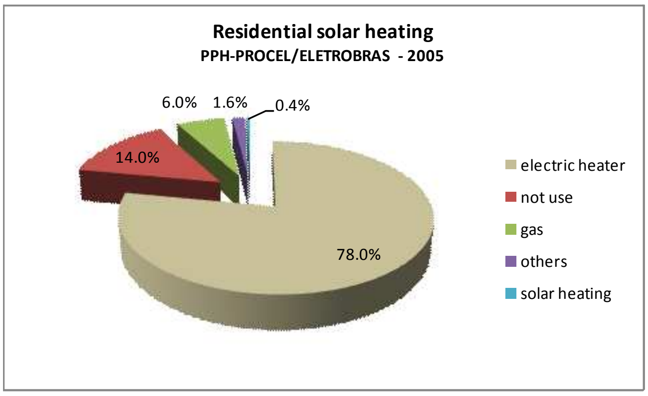

Figure 1. Residential water heating
PPH-Procel/Eletrobras 2005 – adapted

The technological advancement, the improvement of the life expectancy of the world-wide population and the increase of the industrial production, are factors that develop the demand for energy.

In this case, the developments of alternative sources of low ambient impact, and low financial cost have been the investigation focus for several investigators.

According to ALDABÓ (2002), the Brazil presents the best rate of solar radiation, principally in the Northeast region, where has yearly values between 1752 kWh/m^2 to 2190 kWh/m^2, which demonstrates the big potential for thermal use of the solar energy in substitution or reduction of the use of electric heaters, just like others countries as China, Israel, Greece, Austria, Australia, Turkey, United States, Japan, Denmark and Germany (ABRAVA, 2008). With the objective to add an alternative to the existing methods for analysis of performance of solar collectors, for the solar water heating, was developed in this work an apparatus of tests of solar collectors - ATECOL, composed by units of cooling and heating of liquid implemented through electronic circuits of interface, system of acquisition of data, supervision and control, in such way to provide control of temperature and mass flow rate of the system of control for tests of a solar collector.

This work presents the results of characteristics of the unit of liquid refrigeration, of the unit of liquid heating, the control of temperature and mass flow rate of the system of control for tests of a solar collector.

2. METHODOLOGY

The use of the solar energy as effective measure of energy conservation and reduction of operational costs requires studies on the profit of the solar collectors, in function of the individual efficiency of each equipment and of the uniformity of the mass flow rate in the respective batteries of solar collectors.

According to Duffie and Beckman (1991) the test of analysis of performance of a solar collector can be carried through in three parts:

I - Determination of the instantaneous efficiency, with incident radiation on the absorber surface;

II - Determination of the effect of the angles of incidence of the solar radiation;

III - Determination of the collector time constant, a measure of the capacity of effective heat.

The basic method of measurement of the performance of the solar collector consists of the exposition of the collector under solar radiation and measurement of the values of inlet and outlet temperature of the fluid. In this way, the useful energy of the solar collector can be obtained through the Eq. (1) Duffie and Beckman (1991).

$$Q_u = \dot{m} c_p (T_{out} - T_{in}) \tag{1}$$

The solar collector has his thermal efficiency described as the reason between the useful energy acquired by the solar collector and the radiation that reaches his plan (Aita, 2006). The Eq. (2) represents the efficiency of the collector.

$$\eta = \frac{Q_u}{A_c G_T} = \frac{\dot{m} C_p (T_{out} - T_{in})}{A_c G_T} \tag{2}$$

Where η is the efficiency, Q_u is the energy transferred to the water, G_T is the incident solar radiation in the plan of the collector, A_c is the area of the collector, $\dot{m}$ is the mass flow rate of the water, c_p is the specific heat of the water, T_{out} is the outlet temperature of the water and T_{in} is the inlet temperature of the water. The plain collectors theory makes possible to calculate the total energy of a collector by means of the difference between the absorbed energy and its thermal losses, as presented in the Eq. (3).

$$Q_u = A_c F_R \left[G_T (\tau\alpha) - U_L (T_{in} - T_a) \right] \tag{3}$$

Where F_R, is called factor of removal of heat, represents the capacity of the collector to heat transfer of the plate to the water; (τα) is the product of the transmittance-absortptivity; U_L is the global coefficient of losses, that congregates all the thermal losses of the collector and T_a is the ambient temperature. $F_R(\tau\alpha)$ and $F_R U_L$ are parameters that represent, respectively, the effect of the properties optics and the thermal properties of the solar collector (Duffie and Beckman, 1991; Shariah and Löf, 1997). The values of these parameters are gotten in the experimental assay for the determination of the thermal efficiency of the collectors, which can be effected in accordance with norms techniques as NBR 10184(1988) and ASHRAE STANDARD 93-1977 (1977). The combination of the values of F_R (τα) and $F_R U_L$ is used to define the quality of the collector, what express the behavior of the curve of efficiency of the same. With this, the efficiency of the system can be defined by the Eq. (4):

$$\eta = \frac{Q_u}{A_c G_T} = F_R \left[(\tau\alpha) - \frac{U_L (T_{in} - T_a)}{G_T} \right] \tag{4}$$

Then,

$$\eta = \frac{\dot{m} c_p (T_{out} - T_{in})}{A_c G_T} \tag{5}$$

The Eq. (4) represents a similar behavior to the linear equation of the type y = bx + a, where the "a" (constant term) represents linear coefficient, $F_R(\tau\alpha)$ and the inclination represented for "b", angular coefficient F_RU_L. The results presented graphically facilitate to the attainment of these two parameters, demonstrating in simplified way the behavior collecting. The graphs present in the vertical axis the efficiency η and in the abscissas axis, the result of division between the difference of temperature of the fluid in the input of the collector and the ambient temperature and the solar radiation in the plan of the collector.

Being U_L, F_R e (τα) constant, the graph η versus $\frac{(T_{in} - T_a)}{G_T}$ will be a line with interception in: $F_R(\tau\alpha)$ and the derivative in - F_RU_L.

Soon, the efficiency of the collector is related with the value of the inlet temperature of the water in the same, so the bigger value of the solar radiation incident, most vertical will be his curve, according to shown in the Fig. 2.

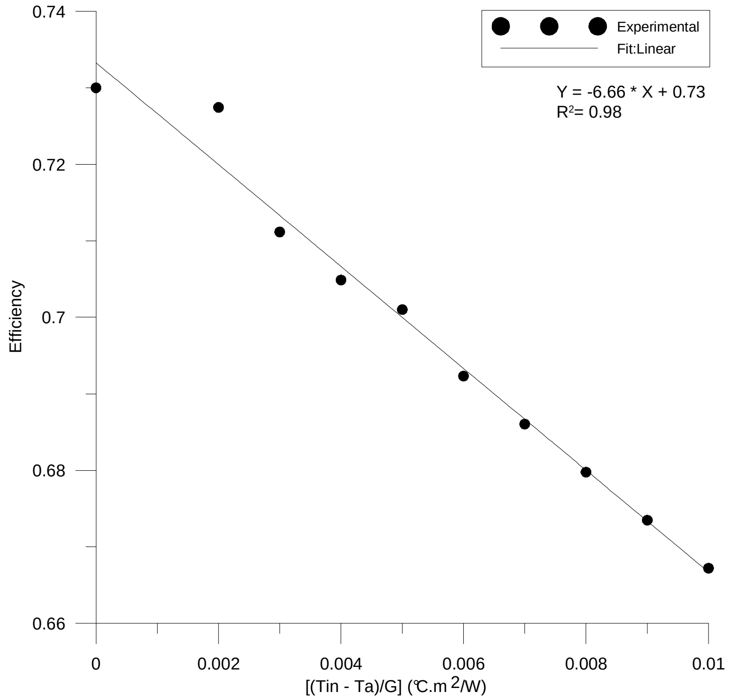

Figure 2. Solar collector efficiency

3. THE APPARATUS

For standard NBR10184 (1988), for realization of the tests in solar collectors, the mass flow rate must be 0.017 kg/s for each m^2 of area of the collector and the inlet temperature of the water in solar collector must be controlled to provide an equal value to the one of the ambient temperature, with tolerance of ± 2°C and the system of tests must provide adjustments of values of up to 30 °C with respect to the ambient temperature and know the incident radiation on the absorber.

In this way, with the necessity to provide to technical conditions applied by the Brazilian standard, there was developed, in the Laboratory of Solar Energy of the Federal University of Paraiba, one technical apparatus, which integrated to a solar collector under test, is able to provide the control of mass flow rate and temperature of the circulating water in the hydraulical system, through a system of instrumentation and supervised control. In the Fig. 3 presents the interface of the system of supervision and control of the apparatus. Through this interface, the user has the information in real time of the inlet water temperature and outlet water temperature of the solar collector, the units of refrigeration and heating and also of the ambient temperature.

The adjustment of mass flow rate is obtained through a virtual instrument, which controls a frequency converter remotely hanging the rotation of the hydraulic pump as setpoint. The incident radiation on the solar collector is measured by a precision Eppley pyranometer, whose data are sampled and stored in a database, for generating of reports.

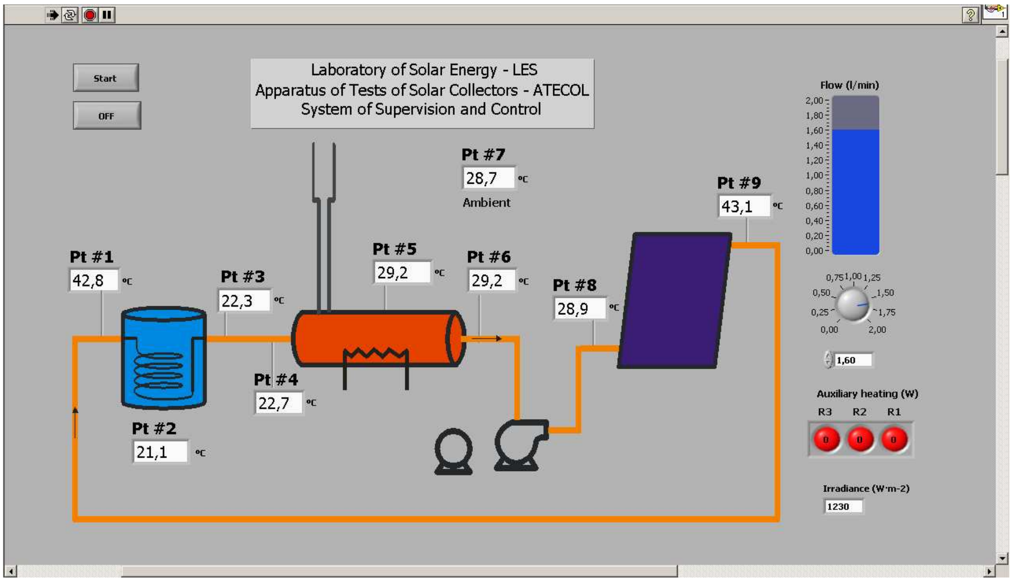

Figure 3. Interface of supervision and control

3.1 Cooling of liquid unit - CLU

The refrigerators of liquids, also called of chillers, or unities of frozen water, are equipments projected to guarantee the continuous supply of water to the temperature adjusted for the cooling of industrial process (Dossat, 2004).

For reuse the circulating water in the system and cooling of the water heated in the collector under test, there was developed a cooling liquid unit (CLU) based on the principle of vapor-compression refrigeration, from the adaptation of a 6.16 kW window air conditioner, with his evaporator immersed in a reservoir of nylon containing 116 kg of water (Souto *et al*., 2008).

The temperature of the thermal bath can be reduced up to 14 °C with a controller of the compressor. Inside this tank is also installed a copper coil for cooling with 10 mm of diameter and 7 m of length, which drives heated water originating from the connection of the solar collector under test, providing an adequate heat exchange to be re-used in the test, without mixture of mass, as shown in Fig.4 and Fig.5.

Figure 4. Compressor and reservoir

Figure 5. Evaporator and copper coil for cooling

The copper coil, immersed in the thermal bath, reduces the heated water by solar collector, resulting in reduction of up to 40 ° C.

For such, a vapor compression refrigeration system was adopted, using the refrigerant gas R-22 as fluid of work. The equipment consists of a compressor type scroll, condenser and evaporator and reservoir of liquid. For specification of the used copper coil in the heat exchanger, has developed a program, based on the LMTD method (logarithmic mean temperature difference).

3.2 Analysis method of the heat exchange in the CLU

According to Incropera and DeWitt (1998) there are two methods of analysis for the heat exchangers, the LMTD (log mean temperature difference) method and ε-NTU (Number of Transfer Units and the Effectiveness - ε) method.

In any situation, both the methods can be used and to get equivalents results. However, depending on the nature of the problem, the ε-NTU method can be easier to implemented. The LMTD method is more appropriate to know inlet and outlet temperatures because the value of ΔTml can easily be calculated. When the inlet and outlet temperatures are not known, the calculation through the LMTD becomes more laborious and demands iterative process. In this case the ε-NTU method is simpler. In this work the LMTD method was adopted. Thus, the thermal load can be represented by the Eq. (6) and Eq.(7)

$$\dot{Q} = \dot{m}.c_p.\Delta T_{ml} \tag{6}$$

where:

$$\Delta T_{ml} = \frac{\Delta T_2 - \Delta T_1}{\ln\left(\frac{\Delta T_2}{\Delta T_1}\right)} \tag{7}$$

Where: ΔT_{ml} or LMTD is the log mean temperature difference

3.3 Axial temperature distribution in the pipe

The axial distribution of average temperature in the pipe for the condition in which the surface temperature remains constant is represented in Eq. (8) and Eq. (9).

$$\frac{dT_m}{dx} = \frac{P}{\dot{m}\,c_p} h \Delta T \tag{8}$$

where:

$$\Delta T = T_s - T_m \tag{9}$$

The total rate of heat transference for convection, under condition where the superficial temperature remains constant is given by Eq.(10).

$$q_{conv} = \bar{h} A_s \Delta T_{lm} \tag{10}$$

$\bar{h}$: average heat transfer coefficient;

A_s : Surface area of the pipe;

ΔT_{lm} : log mean temperature difference.

The Equation (8) can be solved separating the variables and integrating of the input for any point along the axis pipe, resulting in the Eq. (11).

$$\int_{\Delta T_e}^{\Delta T_x} \frac{d(\Delta T)}{\Delta T} = -\frac{P}{\dot{m}\,c_p} \int_0^x h dx \tag{11}$$

The result of this equation is used to find an expression to determine the temperature in an x point (any) of the axial length of the pipe.

3.4 Heating of liquid unit – HLU

For storage and heating water auxiliary was developed a carbon steel boiler with capacity by 23 liters and anti-corrosive treatment. A temperature sensor Pt-100 type is connected to three wires, with stainless steel sheath immersed in the water which is heated by an electric resistance type immersion of stainless steel of 4 kW/220 V, installed inside the boiler. The heating is done directly in the fluid, thereby reducing energy losses and making the system more efficient. Three solid state relays energize the elements of resistance, according to the necessity of thermal power defined by the controller. The tank of heating auxiliary is shown in the Figure 6 which allows the water temperature control in the input of the solar collector, shown in Figure 7.

Figure 6. Boiler of the HLU

Figure 7. Solar collector and pyranometer

3.5 Mass flow rate control

A hydraulic pump is designed to meet a fixed value of the number of turns and the value of the number of rotations, operate with a mass flow rate Q, a lifting height of H, giving a maximum efficiency, η . (MACINTYRE, 1997).

According to MACINTYRE (1997) the power absorbed by the engine that drives the pump varies with the cube of the number of rotations according to Eq. (13).

$$\frac{P_1}{P_2} = \left(\frac{N_1}{N_2}\right)^3 \tag{12}$$

where:

P_1: Initial power consumed;

P_2: Final power consumed;

N_1: Initial speed;

N_2: Final speed.

In low rotation, lesser the power in the axis of the pump and minor the output power of the motor. A reduction of 10% in the speed causes a 27% of reduction on the power consumed for the pump. The mass flow rate is directly proportional to the speed, has the same percentile reduction of the speed, that is, 10%. In this way, for variation of the speed of the joint engine-pump a frequency converter was used that in accordance with the mass flow rate necessity, through a signal of analogical voltage, commanded remotely, can modify the value of mass flow rate of the system.

In the traditional method of control of mass flow rate for valves, a reduction can be obtained, however, the motors continues operating in the same speed - pressuring the fluid on the input of the valve, absorbing the same power. The NBR-10184 (1988) establishes that the mass flow rate for the assay of the collector must be of 0.017 kg/s for each square meter of solar collector. The collector used test in this work has 1.7 m^2 of area.

3.6 The Controller

According to OGATA (2005) a system that establishes a relation of comparison between the output and input reference, using the difference as a means of control, is called feedback control system.

The controllers developed for this work have as function the control of temperature and mass flow rate of the system, being that the main goal of each one is the orientation for the setpoint.

The corrective action happens when the controlled variable deviates from setpoint, independent the type of disturbance, a time that the control system does not require no knowledge of the source or nature of the disturbance. In the feedback control no corrective action is taken until a shunting line in the controlled variable occurs, that is, the disturbance reaches the process and later that the controlled output if moves away from setpoint the control system acts.

This type of control is satisfactory for the process in question.

All temperature sensors were calibrated from 15 to 100 °C, obtaining a precision of ± 0.1ºC and electronic circuits of signal conditioning were developed to convert the variation of resistance of the sensor into function of the voltage variation.

For all process of acquisition of data were used two converters modules with A/D and D/A characteristics with 12 bits of resolution and 10 kS/s (National, 2008), totalizing 16 analogical inputs, 24 digital canals I/O and 4 analogical outputs.

The graphical interfaces were developed in the graphical language LabVIEW^{TM} and the showed data are automatically filed for generation of graphs and reports.

In Fig. 8 is presented the project of used controller and in the Fig. 9 the graphical interface of the controller of the cooling of liquid unit. In Figure 10 an indoor view of apparatus is presented and in the Fig. 11 the electrical command.

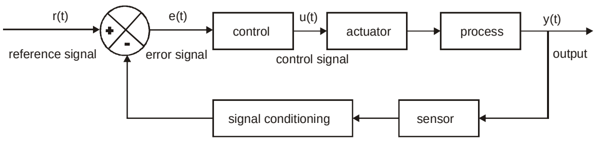

Figure 8. Block diagram of controller

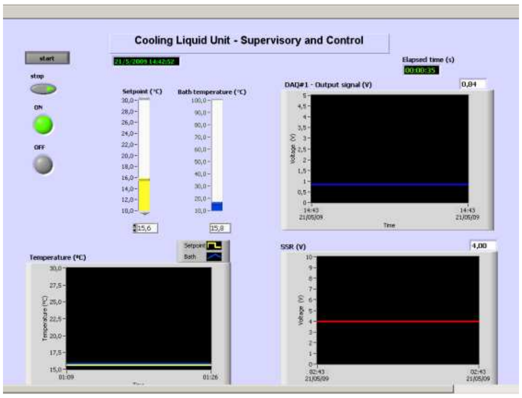

Figure 9. CLU Supervisory and control interface

Figure 10. Apparatus

Figure 11. Electrical command

4. RESULTS AND DISCUSSION

Analyzing individually the components developed for the stages of refrigeration control, heating, and mass flow rate, concludes that the system of acquisition, supervision and control presents stability, versatility and reliability.

The behavior of the unit of liquid heating (HLU) with 23 kg of water and with a resistance of 4 kW/220 V is demonstrated in the Fig. 12. Was noticed that the water temperature increased of 29.3°C for 62.2 °C, that means, a variation of 32.8 °C in 15 min. In 50 min the unit of refrigeration (CLU) reduced the initial temperature of the thermal bath of 28.3 °C for 16.4 °C, for a mass of 116 kg of water, as shown in the Fig. 13. The values reached for HLU are enough for maintenance of a temperature of work, with fast increments the sufficient for the control of the inlet temperature of the collector. With respect to CLU, a reached time the value of the temperature of bath adjusted for 21.0 °C and this maintenance is guaranteed by the raised mass of the reservoir and also by the performance of the controller who qualifies the refrigeration system, keeping the temperature of the water of thermal bath in the value of setpoint.

Using a solar collector with 1.7 m^2 of area, adjusted the mass flow rate for 0.028 kg/s and keeping constant the temperature of the thermal bath of the CLU in 21.1 °C was analyzed the capacity of cooling of the CLU for various values of inlet temperature in the immersed copper coil in the thermal bath. The graph of the Fig. 14 presents the curve of decline of the inlet and outlet temperature of the coil copper cooling, measured for Pt-100 sensors in direct contact with the water.

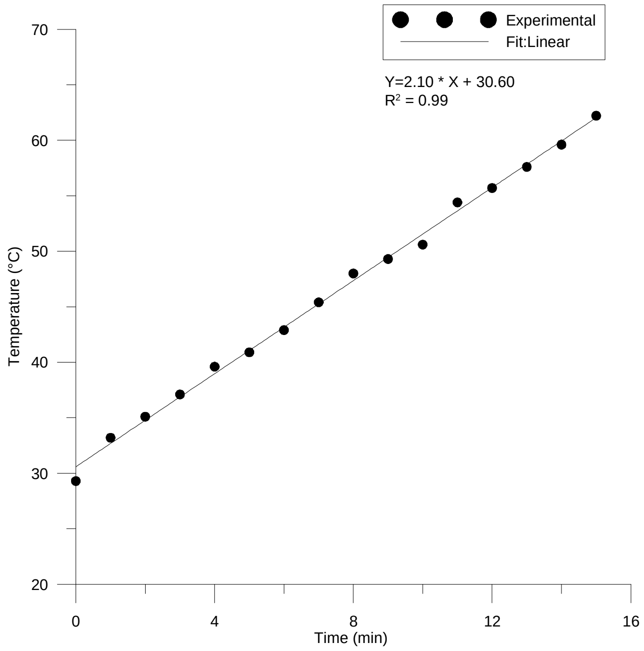

Figure 12. Behavior of the HLU

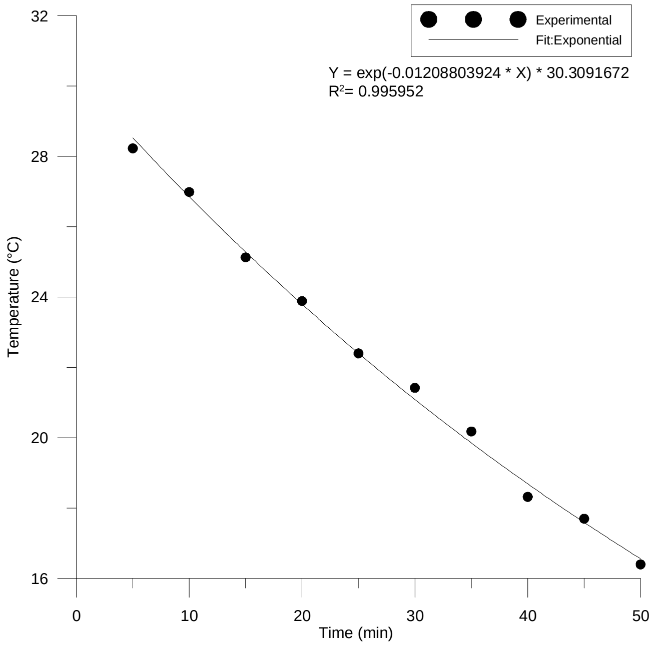

Figure 13. Cooling of thermal bath

Thus, there was a 63.62% reduction in temperature, providing 76.2 kW of water cooled by the copper coil. Considering the equivalent model simulated, there was ± 0.57 ° C average difference for all temperatures, which can be justified by some simplifications in the mathematical model.

Was used a frequency converter to control the motor-pump set and the system mass flow rate, adopting as reference a flowmeter with ± 2% of precision and his correspondent values of the voltage to the control of frequency converter in which results obtained for range of mass flow rate desired were satisfactory, as shown in Figure 15.

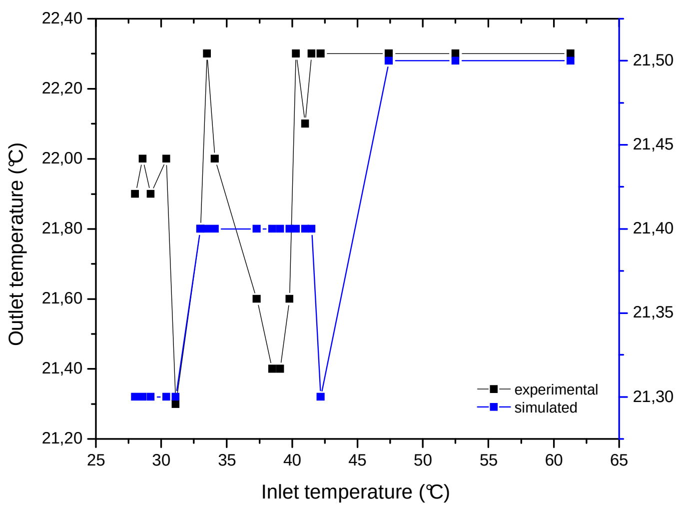

Figure 14. Cooling water output of the collector

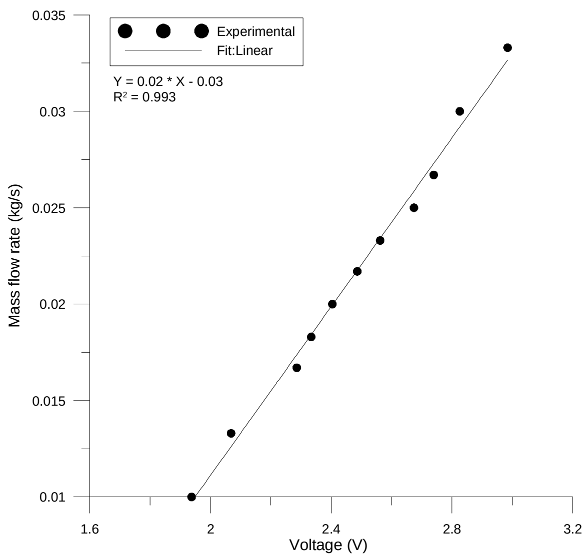

Figure 15. Calibration of flowmeter

5. CONCLUSION

In this work, was presented the resulted from a system of virtual instrumentation, supervision and acquisition of data for tests of performance of solar collectors.

Were developed a system of thermal bath, on the principle of refrigeration the steam, when there is employed an appliance of air conditioner of window of 5.16 kW, which provided 76.2 kW of cold water, in a temperature of the thermal bath of 21.1 ºC. The results also demonstrated that the CLU is able to provide a reduction of temperature of 63.2 % when the temperature of the water is adopted like referential system in the inlet and in the outlet of the CLU.

An auxiliary heating source with capacity for 23 kg of water and resistance of 4 kW/220V, has his thermal power dispersed in the water by setpoint of the controller.

For measurement of the temperature of the circulating water in the circuit there were used sensors Pt-100, which integrated to electronic circuits and analogical/digital converter the integration with a microcomputer, through USB interface.

The control of the mass flow rate, from 0.01 kg/s to 0.033 kg/s, through a frequency converter acting in the joint motor-pump, provided versatility, stability to the hydraulic circuit and economy of energy.

This way, the authors of this work believe in the viability of implantation of the apparatus for integration to the system of analysis of performance of solar collectors.

6. ACKNOWLEDGEMENTS

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