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CONSTRUCTION AND CONTROL OF AN EXPERIMENTAL PHYSICAL MODEL OF LEVEL AND TEMPERATURE BY MEANS OF A PLC

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Abstract: At present, the application of the programmable logic controller (PLC) in automation of industrial processes continues to have enormous opportunities due to its robustness and ease of programming control algorithms, it is also true that there is a shortage of teaching material in higher level schools in this area, usually because of the cost. This work describes the construction and control of a tank or experimental physical model of level and temperature by means of a PLC and the visualization of information in a Human Machine Interface (HMI), an experimental documentary methodology was used. A proportional control with PWM was applied in the PLC to control the variables, level and temperature tests were performed with and without water discharge in the tank. The results showed that the proportional control was sufficient to control the level and temperature of the tank with gain of 3 and 5 with an error ±5 mm or ±2% and± 0.5^{0}C or ±1.56% with discharge respectively, the system is open so it can be applied and test the response under various types of control.
Keywords: Physical model, level control, temperature control, sensors, PLC, HMI.

INTRODUCTION

According to Wang (2006), commented by Villegas et al. (2008), one of the most important activities in modern industries is the monitoring and control of the variables associated with their production processes. Since computers are tools capable of storing, processing and presenting information in an attractive and reliable way, the trend in modern industries is to associate their automated processes to programs that have an environment in which the user can have access to monitor and modify the various elements that make up its control system (Villegas et al, 2008).

Also Distefano (1999), quoted by Villegas et al. (2008), states that this diversification has forced the developers of Control and Data Acquisition Systems (SCADA) to incorporate different types of controllers, seeking to include various manufacturers (Villegas et al, 2008).

Berrojo et al. (2002), cited by Fernández et al. (2019), comments that programmable logic controllers have been for years the basis of automatic industrial process control systems.

Hernandez Perez (2024), implemented a level control system in a 1mts high tank with closed loop PID control for the Automation Laboratory of his University using a PLC, to monitor the information of the variables in real time they used a graphical HMI interface, The results showed a settling time of 6 minutes, a stationary error of ±3%, the system had an overshoot of 15%, and a level measurement range of up to 3 meters.

Likewise, Macafenix (2019), commented by Fernández (2019), mentions that among the advantages of the use of PLC, are factors such as its low cost, reliability, ease in the handling and the reliability granted by having been tested with years of success in its operation. It adapts to both digital and analog inputs and outputs. If you choose the modular configuration can be adapted to situations where the architecture of the control process must undergo modifications due to the increase in the number of inputs and outputs that the closed loop system must process. Another aspect to take into account is the fact that PLC networks have their own communication protocols (Fielbus, Profibus) which gives them the possibility to form dedicated networks for the supervision and control of industrial processes (Fernandez et al., 2019).

The growth experienced in the supply of automatic control systems means that there are numerous manufacturers vying for a niche in this market, which means that these products are continually evolving, resulting in products with better performance (Fernández et al., 2019).

Dueñas and Villegas (2020), cited by Saa (2021), mention that industry 4.0 brings technological advances in the trend of process automation and data exchange, combining the virtual with the physical and incorporating production techniques with intelligent technologies, with the aim of achieving customer satisfaction. Therefore, implementing this new technology is indispensable in organizations both to identify opportunities for innovation and improve their production methods, as well as in decision making (Saa Zamorano, 2021).

Magallanes Bueno and Zambrano Lopez (2024), mention that there are modules in their University related to automation, however, they state that many times they are not used due to malfunctions, inappropriate use, lack of maintenance or outdated. They upgraded a didactic level control module using a Siemens S7-1500 PLC, an HMI and the ET200S peripheral system, which allows connections to the PLC via a fieldbus. They used ultrasonic and capacitive sensors for level control by applying a PID algorithm, the results presented indicated that the module was upgraded and the PID control improved the level control accuracy.

Canduela Ilundain (2022), controlled in a didactic process, the temperature of a box with an Arduino showing the information on a display, used for detection an LM35, a 15W bulb as actuator and fan to distribute the heat, also served as a disturbance. He applied a discrete PID.

Subbaraman et al. (2010) and Radulovic et al. (2012), cited by Fernandez et al. (2019), indicate that one aspect to take into account in everything related to industrial process supervision are SCADA Systems, (Supervisory Control And DataAcquisition), which merges the best of industrial process control technology, the capacity for processing, communication, data storage and graphics management that personal computers have with the ease of performing monitoring and control operations virtually and independent of distances (Fernandez et al., 2019).

Rahmadini et al. (2023), used an Arduino ATmega 328 board for a temperature control, using a water heater to vary the temperature precisely and a continuous PID control. They mention that this method is still reliable and efficient, the temperature is displayed on a 16x2 LCD and applying a PWM to control the output power to the heater, the control was from 34.5 to 41.7$^{(0)\ C}$, the gains that worked best were Kp=10, Ki= 5and Kd= 2, they tested several types of control and suggest that having good understanding of the gains and the process helps to have better tuning.

Guilcamaigua González and Villacis Ortiz (2022), in their work describe a didactic plant that they automated with a Siemens S7-1200 PLC and an HMI, the control was of tank level with a PID algorithm and an ON-OFF temperature control, the sensors used were hydrostatic pressure and a j-type thermocouple, the results were acceptable with the following gain values for Kp=6.5, Kd=0.1, Ki=27.1, technically the derivative gain was cancelled to obtain a good control.

Sanchez Silvera and Goche Infante (2021), in their work automated with a PLC Siemens S7-1200 the level and temperature control of laboratory tanks with industrial sensors, a variable resistance for temperature Pt100 (Resistance Temperature Detector, RTD), an Ultrasonic sensor Echomax XPS-10 for the level and the Hart protocol, the programming was performed in the TIA Portal platform, the PID with gains of Kp=1, Ki=20 and Kd=0.01.

Zhang et al. (2018), proposed a fast and high precision temperature control using a PID algorithm on a STM 32 microcontroller, as a temperature sensor was a pt1000 resistor, for the cooling system they applied an opto--coupled fan to a PWM controlled transistor, this control depended on the desired and actual temperature, the variable was monitored on a computer receiving the data from the microcontroller serially, the error was ± 0.5%^{0}C over a temperature range of 20 to 80$^{(0)\ C}$.

Based on the above information, it can be said that many articles describe the types and control algorithms, there are few that detail the construction of models as a learning support in the area of instrumentation and electronic control. Therefore, it is interesting to describe in more detail the process of building a physical model and its control of some variables involved, which is why in the Faculty of Engineering of the Autonomous University of the State of Mexico an experimental physical model of level and temperature was built and controlled with a Siemens S7-1200 PLC and monitored with a Human Machine Interface (HMI).

DEVELOPMENT

The following methodology was used to build the physical model and its level and temperature control:

1. Documentary research
2. Proposal for the design of the experimental physical model
3. Proposal of the instrumentation system design
4. Selection of materials
5. Construction of the experimental physical model
6. Instrumentation and control of the physical model
7. Tests and analysis of results
8. Conclusions

DESCRIPTION OF THE DESIGN AND CONSTRUCTION

For the assembly of the physical model, the use of a wooden structure on which the tank of the physical model was mounted was proposed, which allowed for easy installation, mobility and future modifications, as opposed to a structure based on ironwork that requires special tools.

Also, for convenience, a vertical system was established to take advantage of gravity to discharge the water tank to be controlled, as long as it has a base with sufficient area to allow good stability in operation, reducing the risk of falls, as shown in Figure 1.

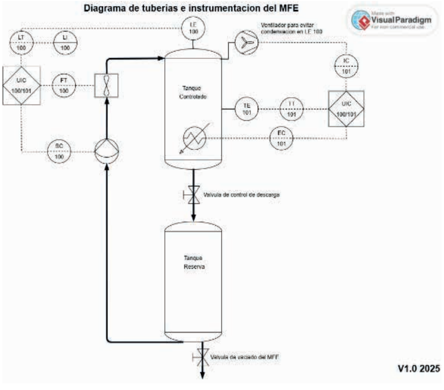

Figure 1. Piping and instrumentation diagram of the experimental physical model. Source: Own elaboration

The dimension of the wooden structure consists of strips cut to one meter of 34 cm (lateral), 30 cm (front) and 122 cm (height).

Thus the vertical model is formed with two tanks, one, in the lower part, as a water reservoir; the other, in the upper part, the tank to be controlled, with a total height of 152 cm. This also allows the water discharge speed to be controlled by means of a valve and the water loading speed to be regulated by means of the pump that will return the water from the lower reservoir.

For the construction of the vessel, 4-inch diameter PVC pipe was used. This decision is also based on the wide availability of complementary elements such as connectors, lids, valves, among others, to reduce the possibility of leakage, as well as an easy implementation and modification of future improvements to the model. It is evident that PVC has a lower maximum operating temperature, so this condition is considered in the configuration of the controller.

The transition connections between the water tanks are made with ½ inch pipe, as it allows sufficient flow for this scale model of a control process. With the help of the discharge valve of the controlled tank, the outflow can be adequately regulated, which the control loop will be able to replenish. The flow sensor, as well as the water pump, are available with this connection diameter, thus avoiding the use of adapters and additional elements in the hydraulic circuit that can be prone to failure.

In order to facilitate the transport of this model, a water discharge valve was incorporated that allows, without tilting the model, the discharge of the liquid, significantly reducing the weight of the system. This implies the need for a type of pump that can resume the flow without requiring an auxiliary preloading action of water in the pump cavities prior to start-up.

The electrical system is based on two types of wiring, for low voltage signals such as those used in the instrumentation and control stages with a 22 gauge, while for the conduction of alternating current at 120 volts a 16 gauge is used. As an additional safety measure, a 3-pole plug incorporating earth ground and a fuse in series on the line was used to eliminate the possibility of an overload. A switch with a pilot light was also incorporated to maintain the operation of the contacts for possible repairs.

The systems that integrate the experimental model are intended to meet the following specific objectives:

1. Use of standardized hydraulic elements for leak prevention and minimum requirement of specialized tools.
2. Appropriate size and weight for experimentation and transport.
3. Easy implementation of improvements or new instrumentation modules at low cost.
4. Centralization of the instrumentation system in one panel to reduce failures.

The installation of a 20 cm base, 17 cm height and 5.5 cm front panel was proposed, which contains the instrumentation circuits, as well as the isolation and indicators on site, in order to prevent damage to them due to vibrations, manipulation or water falling when recharging the hydraulic system. This board incorporates slots that allow ventilation and access to the wiring coming from different points of the model. It also improves the visual appearance of the model by keeping the wiring organized, and the modules were also considered to be removable.

The heating of water in the tank of approximately 2 lts, was performed with a horseshoe resistor as shown in Figure 2, which consumes 590.4 watts, 4.92 amperes and operates at 120 Volts AC. To control the heating of the resistor gradually, a PWM signal sent by the opto--coupled PLC was used and for activation a Solid State Relay (SSR) as shown in Figure 3.

Figure 2. Electrical resistance to heat the water in the tank. Source: Own elaboration.

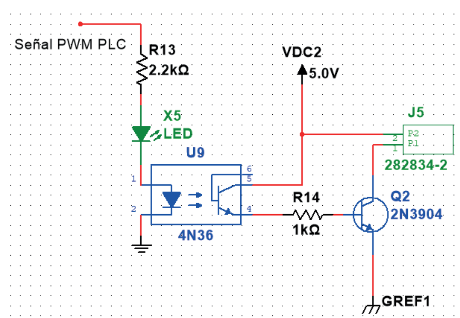

Figure 3. Coupling circuit between PLC and SSR. Source: Own elaboration: Own elaboration.

According to Bolton (2015), who indicates that a PLC can control the rotational speed of a motor by controlling the electronic circuit by varying the width of the voltage pulse, for this case, the water supply in the tank to be controlled was used a ½ inch diaphragm pump, 60 W, at 12 V, and 5 lts/min, controlled with a PWM sent by the PLC, opto-coupled to the H-bridge as pointed out by Bolton (2015), this is observed in Figures 4 and 5.

Figure 4. Electric pump and H-bridge: Own elaboration.

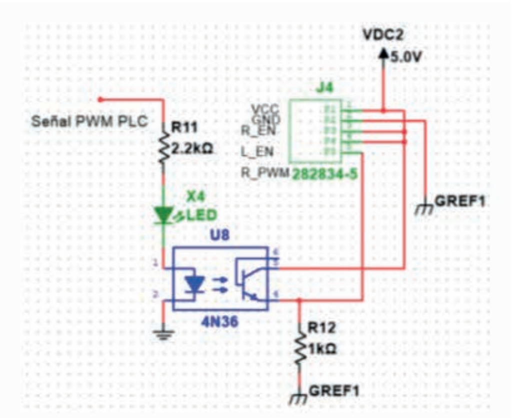

Figure 5. PLC signal opto-coupled to the H-bridge for pump control Source: Own elaboration.

Creus Solé (2011) points out that "the pulsed signal has good penetration and a large measurement range, so it is typically used in industrial applications". Based on this, the water level measurement was performed using a time-of-flight measurement sensor, based on the VL53L0X integrated circuit from ST Semiconductor[MR].

According to Lozano Navarro (2017), this device is a "time-of-flight (ToF) distance sensor that uses a VCSEL (Vertical Cavity Surface Emitting Laser) emitter of 940 nm to generate a pulse of infrared light and this is how the sensor measures the time that takes the light to bounce on an object until it returns, therefore, the distance is calculated from the time of flight of the light. The most striking feature of this sensor, compared to those that perform the same activity, is the sensitivity of ± 1 mm within its measurement range and the dimensions it occupies before the action it performs. This sensor uses the I2C interface which is characterized by a data signal line and a clock signal line, both of which are received by an ATMEGA328P microcontroller on pins 27(SDA) and 28(SCL) shown in Figure 6.

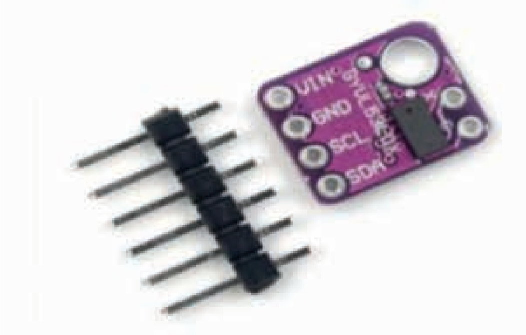

Figure 6. Diagram of the VL53L0X level sensor. Source: Own elaboration.

Due to the properties of the fluid inside the tank that do not allow a complete reflection of the light beam coming from the 940 nm laser, a float consisting of a disk of just 7 mm hollow 3D printed was added to the design, the edges were smoothed and the diameter was reduced to avoid it getting stuck and causing an erroneous reading. A notch was integrated to allow the water feed pipe to be inserted into the tank, this was proposed in order to keep the float with the minimum of ripples that could be caused by the liquid falling from the top as shown in Figure 7. The formula in Equation 1 was applied to adjust the correct level measurement from 0 to 100%, 0 and 240 mm equivalent to 0 and 1.945 lts.

$$Med_{final} = Max_{nivel} - (Med_{actual} - Offset) \qquad \text{Ec. 1}$$

To avoid water condensation on the VL53L0X level sensor, a fan was installed on

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the top cover, which is powered at +12 volts and has a current consumption of 100 mA (see Figures 7 and 8). Its speed was regulated with the help of a transistor by adjusting the current flowing through it.

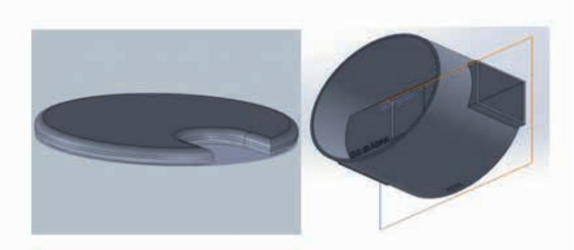

Figure 7. 3D design of the float (left) and fan (right). Source: Own elaboration.

Figure 8. Location of the level sensor inside the air circulation duct. Source: Own elaboration: Own elaboration.

The information from the sensor is sent to a microcontroller to convert the level variable expressed in mm to a PWM signal that will be linearly related by means of Equation 2.

$$\%PWM = \frac{nivel[mm] * 1.0583}{254} * 100 \qquad \text{Ec. 2}$$

Where the constant is obtained from the slope that relates the level reading in mm and the % duty cycle of the PWM signal. Which is the slope obtained from the following endpoints of Equation 3.

$$m = \frac{y_2 - y_1}{x_2 - x_1} \qquad \text{Ec. 3}$$

Applying to Equation 2 for the extremes of points 1 and 2 we have:

$$p_1 = (0{,}0)\ ;\ p_2 = (240{,}254)\ ;\ = \frac{254 - 0}{240 - 0} = 1.0583$$

The level value is displayed in indicators on a 10-position common cathode led bar and a quad display module based on the TM1637 integrated circuit that allows multiplexing the display to 7 segments in order to reduce the number of digital pins, this is done by the microcontroller, each led lights for 10% of the level value, as shown in Figure 9.

Figure 9. LED level indicators and display on the control board. Source: Own elaboration.

The level measurement was performed with an Arduino nano, through a PWM output. This signal was conditioned by means of a single stage passive low-pass filter in order to change a pulsating waveform to a slightly variable value over time, using a first order filter whose mathematical function is indicated in Equation 4, with a cutoff frequency of 1Hz and a capacitor of 1uF, the resistance calculation was 159K .**Ω**

$$f_c = \frac{1}{2\pi RC} \qquad \text{Ec. 4}$$

$$R = \frac{1}{2\pi C f_c} = \frac{1}{2\pi(1\mu F)(1Hz)} = 159k\Omega$$

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With the above, the analog signal is intended to vary from 0 to 5 Volts according to the PWM input from 0 to 100% respectively. This signal was conditioned with a non-inverting amplifier with a gain of 1.88 to ensure that the PLC gets a voltage of 9.4 V to the analog input pin AI0.

For the temperature measurement of the physical model, a thermistor sensor was used, which is a resistance with a reference value at a specific temperature that varies as the temperature rises or falls. A 10kΩ negative temperature coefficient (Negative Temperature Coefficient, NTC) was chosen, connected in series with a 10kΩ resistor. Forming a voltage divider with ends connected to 5 VDC and GND (Figure 10), as the temperature increases in the liquid, the voltage at the intermediate point will increase linearly.

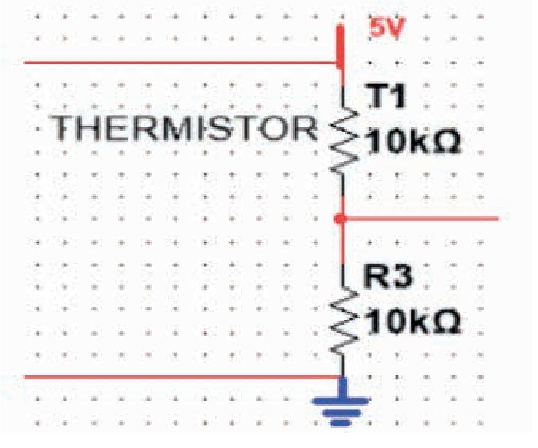

Figure 10. Electrical arrangement of the thermistor to measure temperature. Source: Own elaboration.

When performing a characterization of the thermistor, the voltage variation with respect to temperature was measured as shown in Figure 11, showing linearity.

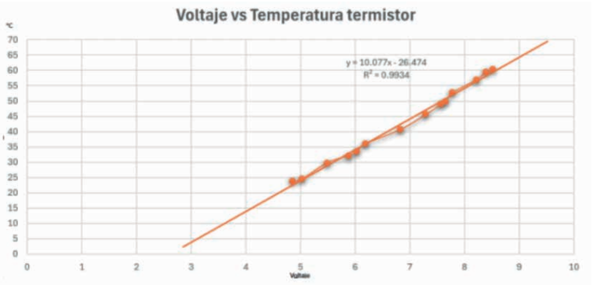

Figure 11. Characterization of the thermistor between voltage vs temperature measurement. Source: Own elaboration.

Equations 5, 6 and 7 were used to calculate the current, voltage and power dissipated by the thermistor, respectively.

$$I_{T1} = \frac{V}{R} = \frac{5v}{20k\Omega} = 0.25x10^{-3}\text{ A} \qquad \text{Ec. 5}$$

$$V_{T1} = \frac{Vi(T_1)}{(T_1 + R_3)} = \frac{5(10k\Omega)}{(10k\Omega + 10k\Omega)} = 2.5\text{ V} \qquad \text{Ec. 6}$$

$$P_{T1} = V * I = 2.5v * 0.25mA = 0.625\text{ mW} \qquad \text{Ec. 7}$$

Due to the fact that when the temperature increases the resistance drops, the voltage drop also drops, then the power dissipated by the thermistor will be lower. With a power of less than one it is possible to rule out that this method of measurement can significantly alter the readings, considering that the electrical resistance to heat the water requires approximately 590 watts. This power represents less than 1% of what the resistance requires to heat the water.

Conditioning was performed with operational amplifiers with a gain of 2.076 to adapt and send this temperature signal to the analog input A11 of the PLC (Figure 12).

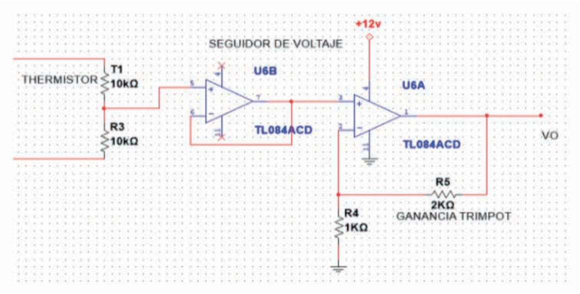

Figure 12. Electrical diagram of the operational array for the temperature signal to the PLC. Source: Own elaboration.

A flowchart was made for programming the microcontroller in the Arduino platform to measure the tank level and send the signals to the PLC as shown in Figures 13 and 14.

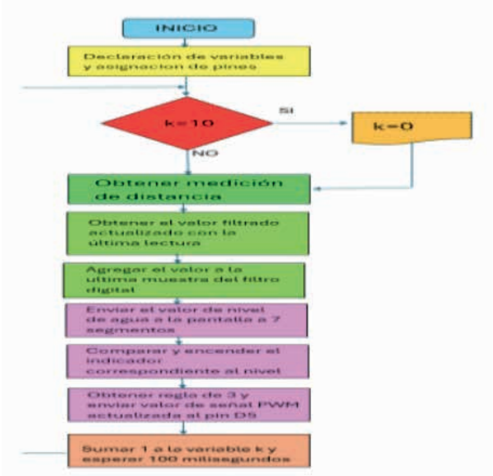

Figure 13. Flowchart for programming the microcontroller for level control. Source: Own elaboration.

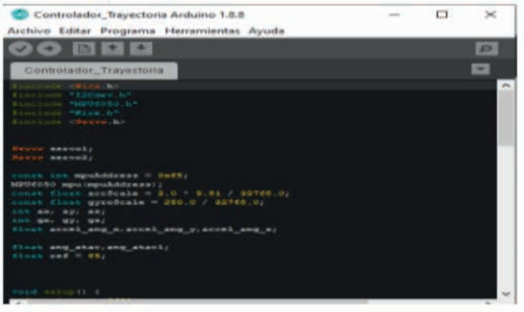

Figure 14. Arduino development environment for microcontroller programming. Source: Own elaboration.

For flow detection, a sensor was considered in the tank supply line, just after the circulation pump. The sensor chosen is the YF-S201 model shown in Figure 15, which has ½ inch diameter connections. This type of sensor requires no maintenance and is completely sealed, reducing the possibility of leakage. It consists of a small wheel with fins that are driven by the flow of water through the sensor, the rotor rotates with a speed directly proportional to the flow rate. A permanent magnet is attached very close to the shaft. Using a Hall effect sensor, the changing magnetic field of the rotating magnet is detected. This generates at the output pin a square signal with variable frequency according to the flow through the sensor and a maximum current of 10 mA.

Figure 15. Exploded view of the YF-S201 flux sensor for the experimental physical model. Source: Own elaboration.

This signal was amplified and opto-coupled to serve as input to the PLC at port DI0 and an LED on the board to indicate the flow at the tank inlet.

An open loop measurement was performed with the system, by circulating a known amount of fluid in a given time, Equation 8 was obtained, which relates the flow rate to the frequency, the pump was used at 85% operation to obtain the flow by filling a vessel.

$$\frac{Q(l/m)}{f\,(Hz)} = 10.2660 \qquad \text{Ec. 8}$$

Where:
Q=flow in liters/minute
f= frequency in Hz

TESTS AND RESULTS

Three tests were performed on the level with a proportional closed loop control with a gain of 3.

Test one, the tank was stabilized with a volume of 12.5%, corresponding to 30 mm of tank height, the discharge valve was kept closed, with Equation 9, the volume was calculated, from there it was taken to 200 mm, at 83.3% or 1.62 lts in a time of 34 sec (Figure 16).

$$\mathrm{Vol} = h * r^2 * \pi \qquad \text{Ec. 9}$$

Where:
h=height of the tank in mm
r= tank radius 50.8 mm

Applying Equation 9, to obtain the volume of water of 30 mm height, in the tank, being the radius constant.

$$\mathrm{Vol} = 30\mathrm{mm} * 50.8^2\mathrm{mm}^2 * \pi = 0.24\,\mathrm{l}$$

Figure 16. HMI graph of tank filling time from 12.5% to 83.3% with closed tap. Source: Own elaboration.

Test two, maintaining the level of 200 mm or 83.3% of tank fill with rapid discharge, it can be seen in the graph in Figure 17, that the level was kept constant only with fluctuations related to the discharge and the speed of the pump to act. The error was 6 mm of height or 2.5%.

Figure 17. Graph in the HMI on the level control at 83.3% with discharge. Source: Own elaboration.

Test three, maintaining the level of 50 mm or 28.8% of tank filling with fast discharge, it can be seen in the graph in Figure 18 how the level drops from 83.3% to 28.8%, here the level remained constant and fluctuations were smaller than in the previous case, related to the discharge due to the speed of the pump to act.

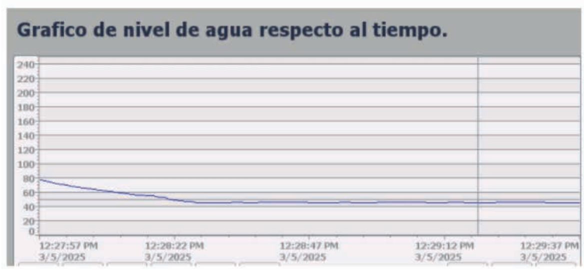

Figure 18. HMI graph of level control from 83.3% to 28.8% with discharge. Source: Own elaboration.

Also, three temperature tests were performed. Test number one consisted of raising the tank water temperature from 22 to 32 $^{(0)\,C}$, with discharge valve open with a level of 200 mm of water height or 83.3% of filling, taking 10 min. with 28 sec. to reach the desired temperature, as shown in the graph in Figure 19, the small fluctuations are due to the combination of cold and hot incoming water from the tank.

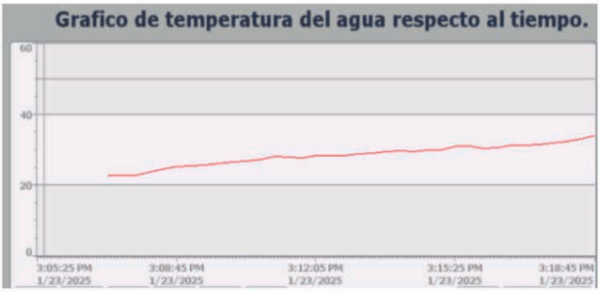

Figure 19. Graph on the HMI shows the heating time from 22 to 32 0C with the tank at 83.3% with discharge. Source: Own elaboration.

Test number two consisted of raising the tank temperature from 24 to 34 $^{(0)\,C}$, with a level of 50 mm or 20.8% full, with the discharge valve closed, taking 5 min. and 57 sec. as shown in the graph in Figure 20, with faster heating due to the closed vent valve.

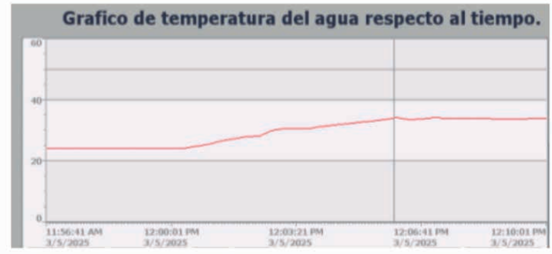

Figure 20. Graph in the HMI shows the heating time from 24 to 34 0C with the tank at 28.8% without discharge. Source: Own elaboration.

Test number three was to maintain the tank temperature at 34$^{(0)\,C}$, with a level of 225 mm or 93.7% full, with the discharge valve open, the proportional control maintained the temperature at 39.9^{0}C with an error of 1% as shown in the graph in Figure 21.

Figure 21. HMI graph showing temperature control at 34 0C with tank at 93.7% with discharge. Source: Own elaboration.

Figure 22 shows the construction of the electronic control circuit for the experimental physical model with all the modules and the Arduino nano.

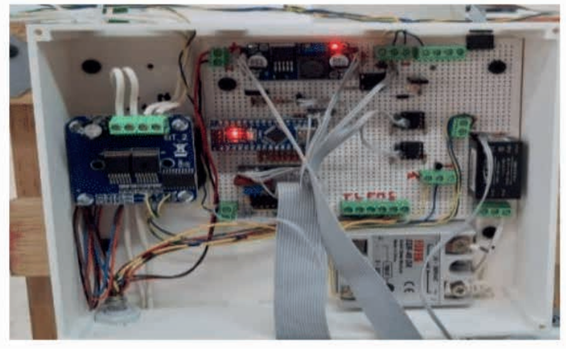

Figure 22. Construction of the control electronics. Source: Own elaboration.

Figure 23 shows the final construction of the experimental physical model with the PLC S7-1200 and the HMI.

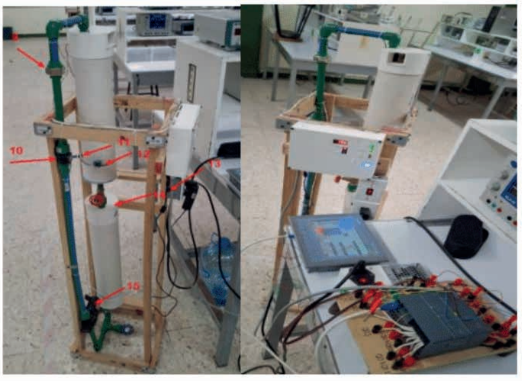

Figure 23. Experimental physical model, PLC S7-1200 and HMI. Source: Own elaboration.

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Figure 24 shows the regions of the physical model, the green color shows the tank to be controlled from 0 to 240 mm, green region.

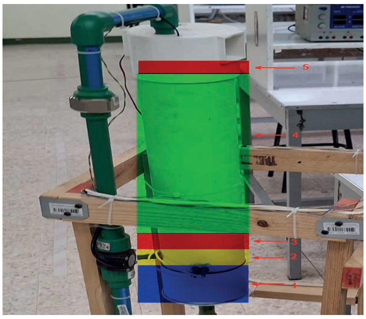

Figure 24. Regions of the experimental physical model. Source: Own elaboration.

Figure 25 shows the diagram of the control system in the HMI, the parameterizations and the real-time measurements of the variables.

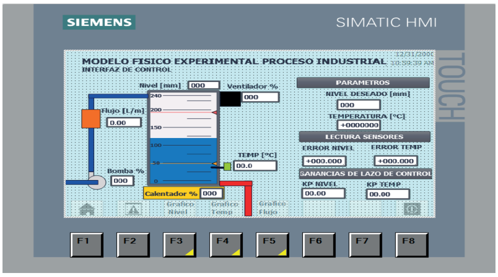

Figure 25. HMI for the control of the experimental physical model. Source: Own elaboration.

CONCLUSIONS

An experimental physical model was built based on a 1,945 lts liquid storage tank that can control its level and temperature.

An Arduino nano microcontroller was used for level indication and to send these opto-electronically coupled signals to a Siemes S7-1200 PLC.

Information about variable measurements and parameter settings can be done through an HMI interface.

A proportional control made in PLC was applied for level and temperature with gain of 3 and 5, the average error was ±5 mm ± 2% and ± 0.5^{0}C or 1.56% respectively with discharge.

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