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DEVELOPMENT OF A REDUCED SCALE PLANT FOR CONTINUOUS INDUSTRIAL PROCESS SIMULATION AND FLUID LEVEL CONTROL IN COMMUNICATING VESSELS

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Abstract. *This paper describes the development process and testing procedures of a reduced scale plant reproducing a continuous process. The fluid level within three communicating vessels is controlled using the PID (Proportional Integrative Derivative) technique. The vessels interconnections as well as the turbulent flow through the pipeline make the process to be controlled non-liner, as expected in several real applications. Three vessels, one horizontal cylindrical, one conical and one squared base prismatic compose system. Pressure sensors are utilized to monitor the fluid level in the tanks and to provide feedback to the PID control block embedded in a PLC (Programmable Logical Controller), which in turn, sends analog signals to an automated valve, built from a servomotor and an ordinary ball valve. The automated valves, then, manipulate the flow moving in and out the vessels, and hence, controlling the fluid level. In addition, a frequency inverter - Power Flex 70 AC – is employed to manipulate the nominal maximum flow the system will work with. A plant model is proposed and the bill of materials employed to build it is described across the steps of the development.*

Keywords: *Reduced scale plant, fluid level control, communicating vessels, continuous process*

1. INTRODUCTION

For the study of process control, it is fundamental to understand how processes behave dynamically. Thus, it is necessary to develop the set of equations that describes the processes (Smith and Corripio, 1985). The mathematical model, then, must be validated. Phenomenological modeling of industrial continuous process consisting of fluid and thermal systems plays an important role in the industry and are essentially employed to predict system behavior as well as outputs under certain input conditions, contributing to make the system more reliable and robust (Ogata, 2000). Prototypes or reduced scale plants are widely employed to generate more consistent data as well as to support either the validation or the improvement of the models. In the present work, a reduced scale plant that represents a continuous industrial process is designed, built and tested. The steps of the project are described in the following sections. The PID control technique was implemented in order to keep the fluid level at a predefined setpoint. Automated valves are employed as actuators and will control the fluid level by adjusting the flow from 0% to 100%. A frequency inverter, model PowerFlex 70 AC, is also employed to control the maximum flow the system works with, and plays a relevant role in the fluid level control as well. The intrinsic non-linearity present in the system due to the interconnections and the turbulent flow are managed by applying linearization techniques at the operation point along with the application of different transfer functions and control gains for specific ranges of the control variable.

2. MATERIALS AND METHODS

A block diagram was drawn to give an overview of the entire process. It is shown in Fig. 1. The process represented in the block diagram by the conical and prismatic tanks is referred to as an interacting system, i.e., the flow between the two vessels depends on the levels in both tanks, each affecting the other (Smith and Corripio, 1985).

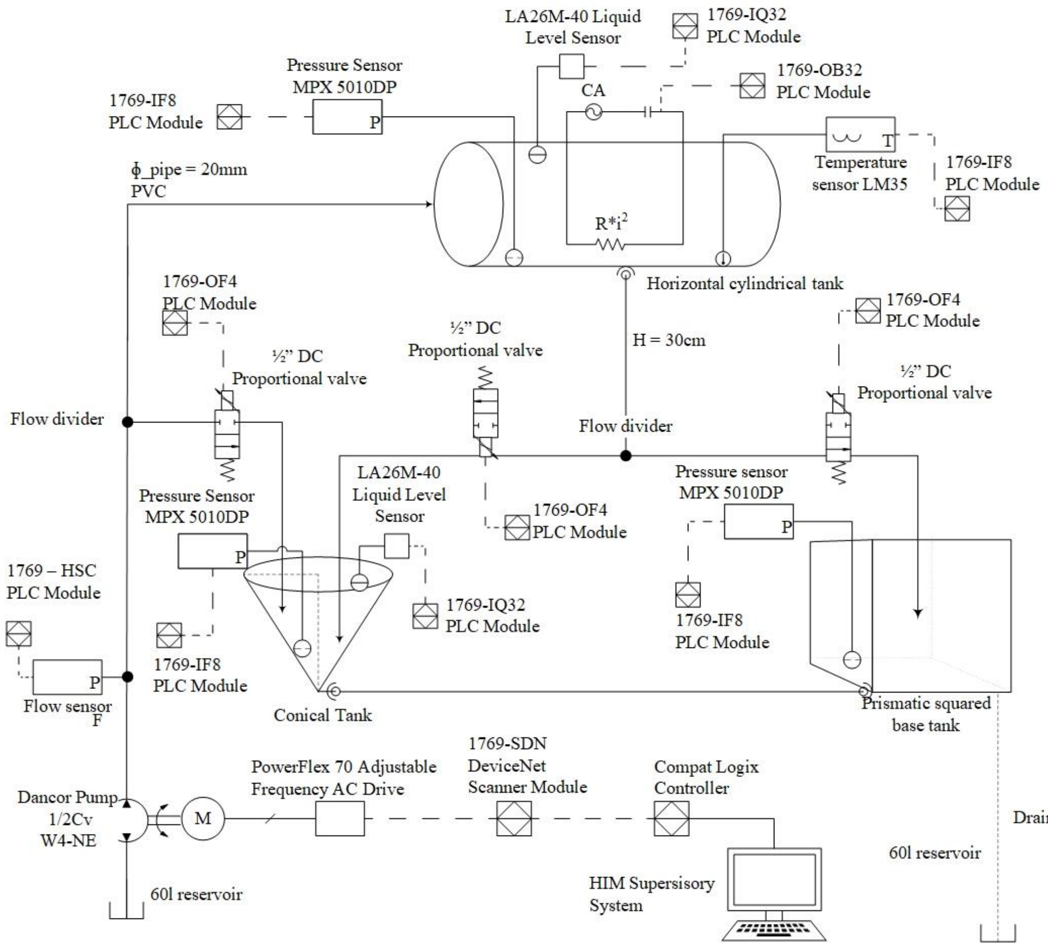

Figure 1. Block diagram of the plant

2.1 Mechanical structure development

The vessels composing the plant were made according to the building complexity and cost. The cone was made of Polylactic Acid (PLA) thermoplastic, which is in general a brittle material with lower impact strength and elongation at break (Sin, *et al.*, 2012). The model and the vessel are shown in Fig. 2.

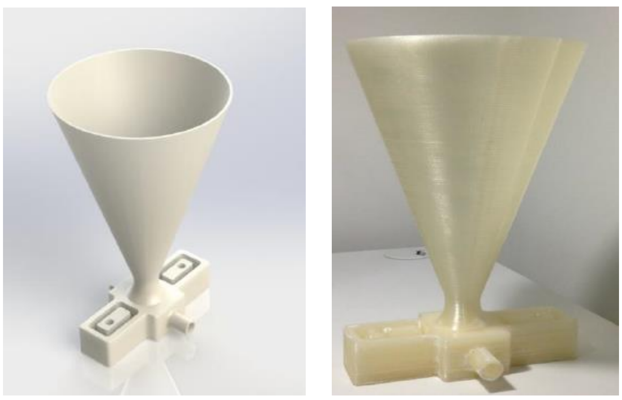

Figure 2. Conical Vessel 3D model and final built frame

The cylindrical vessel was made of transparent acrylic. Two PVC caps were utilized to close the cylinder extremities. The cylinder is placed 0.3 m above the conical and the prismatic vessels. The fluid flows from the cylinder to both vessels by gravity. The vessel is shown in Fig.3.

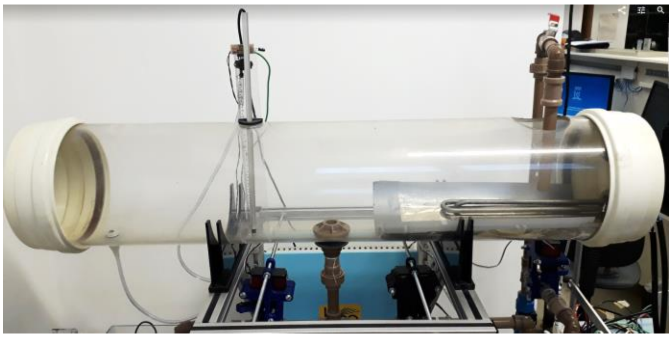

Figure 3. Cylindrical vessel final built frame

The squared base prismatic reservoir was made of polycarbonate. The prismatic and conical vessels are interconnected. The prismatic tank assembled is shown in Fig. 4.

Figure 4. Squared base prismatic vessel final built frame

The reduced scale plant is composed by a frame designed and built with the use of structural aluminum, 30 mm per 30 mm profile. The proposed structure and the frame assembled are shown in Fig. 5.

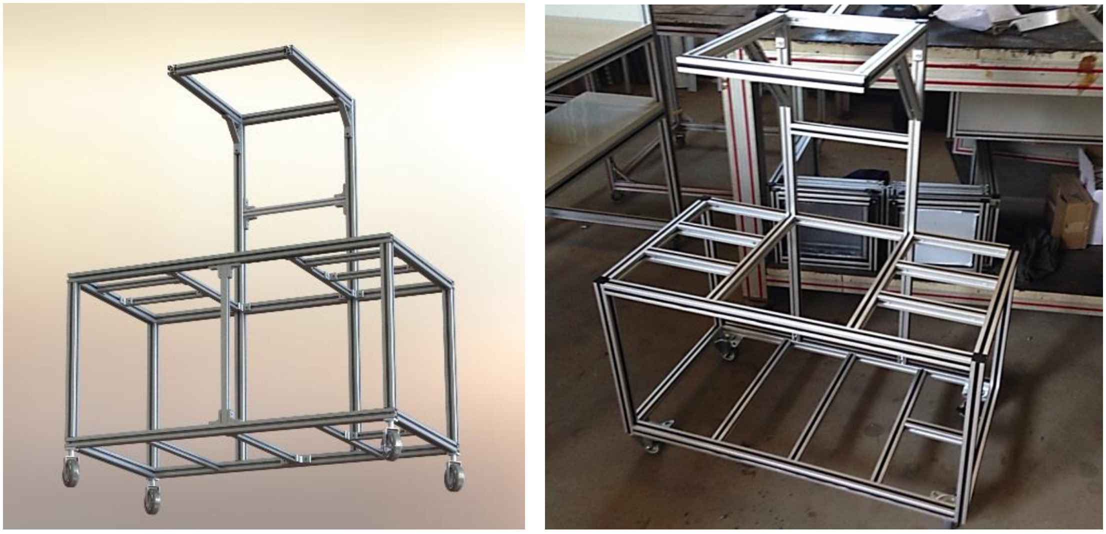

Figure 5. Structural design 3D model and final built frame

The summary of the tanks dimensions and volumes are listed in Tab. 1.

Table 1. Summary of the tanks dimensions and volumes.

Tank	Diameter (m)	Height (m)	L1 (m)	L2(m)	Volume (m^3)
Cylindrical	0.18	0.95	N/A	N/A	2.55 $x10^{-2}$
Conical	0.20	0.30	N/A	N/A	1.05 $x10^{-2}$
Prismatic	N/A	0.40	0,20	0,20	1.60 $x10^{-2}$

In order to provide transport energy to the fluid, a pump, model Dancor CAM-W4-NE 1/2CV, is employed with a frequency inverter, model PowerFlex 70 AC, as a means to manipulate the maximum nominal flow the system will be supplied with. In this case, high pressures are also avoided.

2.2 Sensors and electronic hardware development

Two LM35 temperature sensors were employed, one to check the temperature of the fluid in the cylinder and another one to check the temperature of the fluid in the source reservoir. The last one provides the reference temperature of the system. The LM35 operates within the range between 2°C and 150°C. The output response of this sensor is analog and proportional to the measured temperature variation. In this case, the sensor output varies 10 mV for each 1°C variation, with a maximum non-linearity error of +/- ¼ °C. It Works with power supply range from 4 V to 30 V. The sensor output is, for example, 250 mV if the measured temperature is 25°C and 1500 mV at 150°C. In this case, a LM346 operational amplifier was employed for signal conditioning to the ranges suitable to the 1769-IF8 PLC module. The circuit design of the printed board is shown in Fig. 6.

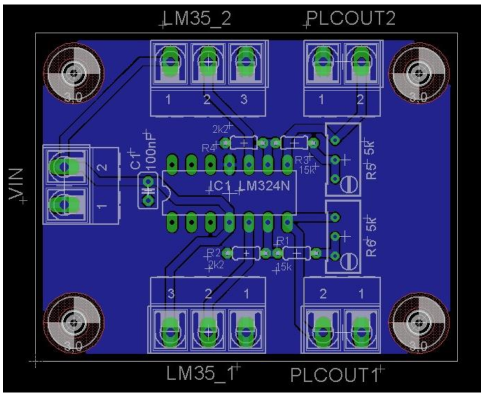

Figure 6. LM35 conditioning circuit design

The pressure sensor MPX5010DP was adapted to monitor the fluid level in the three vessels. This sensor works with a supply voltage of 5 V. The output response is proportional to the measured pressure, and varies from 0.2 V to 4.7 V. The resolution of the sensor is 450 mV for each 1 kPa variation. The MPX5010DP has the output within a range suitable for the PLC module 1769-IF8, then, no additional amplification or attenuation was needed. The printed board circuit that manages the sensor signals is shown in Fig. 7.

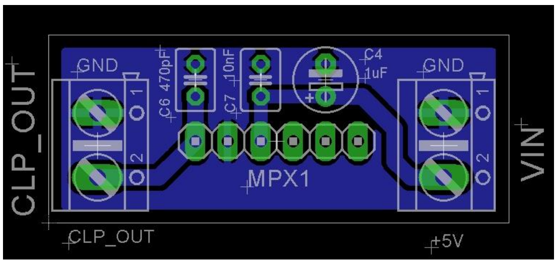

Figure 7. MPX5010DP circuit design

The LA26M-40 is an on-off commutation sensor. It was installed as a security measure in order to prevent overflow of the conical and cylindrical tanks. The two sensors are directly connected to the 1769-OB32 PLC module, which will provide the 24 V power supply, with a 220 Ω and 5 W resistor in series as recommended by the sensor manufacturer.

The flow sensor FSA30004 G3/4", based on hall effect probes, was implemented to monitor the volume per second delivered by the pump. The output of this sensor is sent directly to the special PLC module 1769-HSC (High Speed Counter). The signal conditioning was not needed in this case because the HSC module counts the pulses generated by the flow sensor through the Ladder routing "Current Rate". The routine also converts the counted pulses in the current flow rate in m^3/s, for example. The module 1769-OB32 provides 24 V power supply necessary to make the sensor works.

In order to control the flow, an automated valve was developed from an ordinary cast iron ball valve, linked to a servomotor by 3-D printed structure made of Acrylonitrile Butadiene Styrene (ABS). The servomotor selected was a Trackstar, model TS-700 MG. It presents a good torque range for the proposed application, from 2.72 Nm (at 4.8 V) to 3.3 Nm (at 6.0 V), and a fast-angular speed response, from 5.3 rad/s (at 4.8 V) to 5.8 rad/s (at 6.0 V). A PIC 12F675P - 8-bit microcontroller - is used to control the servomotor axle position through PWM (Pulse Width Modulation) technique. The servomotor works with PWM at the frequency of 60 Hz. The valve is shown in Fig. 8. It is important to point out that the valve is proportional to the electrical signal sent to the valve controller. The control circuit of the servo is shown in Fig. 9.

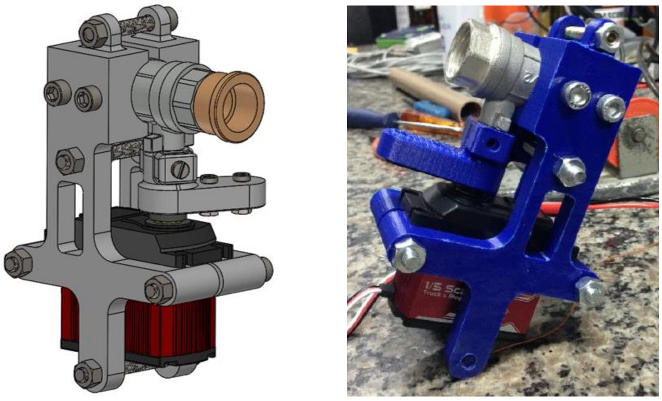

Figure 8. Automated control valve 3-D design and final product released

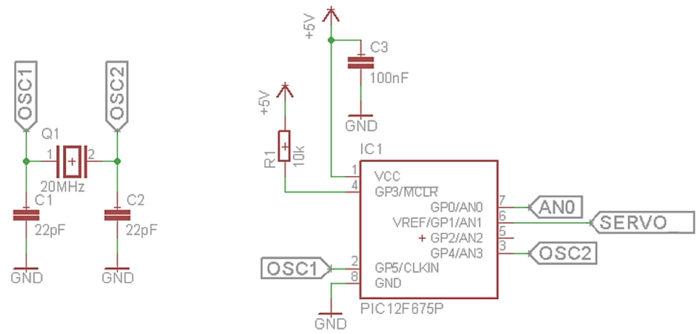

Figure 9. Servomotor control circuit schematic diagram

2.3 Mathematical Modeling

The generic mathematical model considered the fluid level as a function of the flow moving in and out of the control volumes, i.e., a change in the level in (m) will be provoked by a change in the flow rate (m^3/s).

Figure 10 shows the control volume used to define the mathematical model of the mass flow balance in the cylindrical tank.

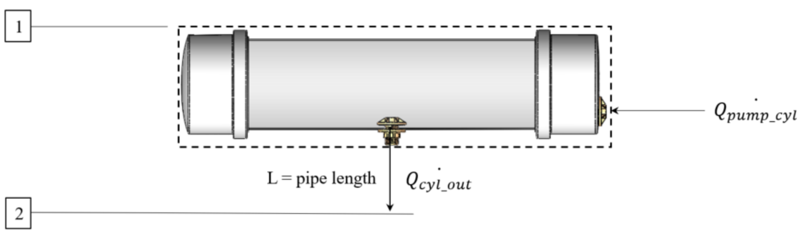

Figure 10. Control volume of the cylindrical tank

Considering $S(h)_{cyl}$ the cross-section surface of the cylinder as a function of the fluid level h_{cyl}, S_{pipe} the cross-section surface of the pipeline, the mass flow balance in the cylindrical tank is, then, given by Eq. (1).

$$\frac{dh_{cyl}}{dt} = \frac{1}{S(h)_{cyl}} \times \left(\dot{Q}_{pump\_cyl} - \dot{Q}_{cyl\_out} \right) \tag{1}$$

The mass flow leaving the cylinder, in this case, is given by Eq. (2).

$$\dot{Q}_{cyl\_out} = S_{pipe} \times \sqrt{2g \times (h_{cyl} + L)} \tag{2}$$

Given that r is the radius of the cylinder and y is its length, the area of the transversal section as a function of the fluid level is given by Eq. (3) (Neto, 2009).

$$S(h)_{cyl} = y \times \left(\frac{r}{1 - \frac{(r - h_{cyl})^2}{r^2}} + \sqrt{r^2 - (r - h_{cyl})^2} - \frac{2 \times (r - h_{cyl})^2}{\sqrt{r^2 - (r - h_{cyl})^2}} \right) \tag{3}$$

Considering $S(h)_{prismatic}$ the cross-section surface of the prismatic tank is constant and denoted by S_0, the mass flow balance in the prismatic tank is given by Eq. (4). Figure 11 shows the control volume of the prismatic vessel.

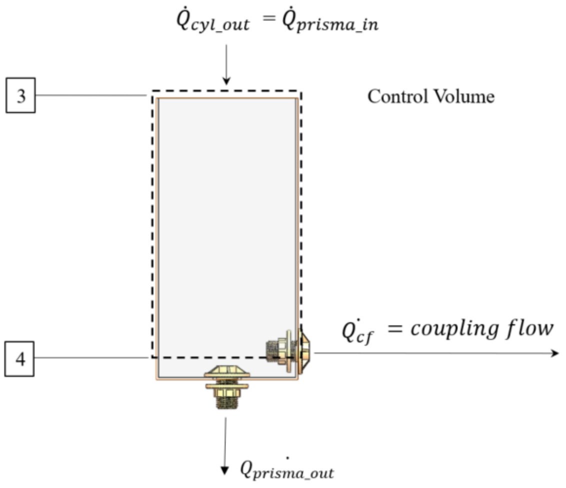

Figure 11. Control volume of the prismatic tank

$$\frac{dh_{prismatic}}{dt} = \frac{1}{S_0} \times \left(\dot{Q}_{cyl\_out} - \dot{Q}_{cf} - \dot{Q}_{prisma\_out} \right) \tag{4}$$

The coupling flow is given by Eq. (5) (Smith and Corripio, 1985). This equation has the assumption that the fluid level in prismatic tank will always be greater than or equal to the fluid level in the conical vessel.

$$\dot{Q}_{cf} = S_{pipe} \times \sqrt{2g \times (h_{prismatic} - h_{conical})} \tag{5}$$

The volume flowing out from the prismatic vessel is given by Eq. (6).

$$\dot{Q}_4 = S_{pipe} \times \sqrt{2g \times (h_3 - h_4)} \tag{6}$$

Considering $S(h)_{cone}$ the cross-section surface of the cone as a function of the fluid level h_{cone}, the mass flow balance in the conical tank is given by Eq. (7). The control volume of the conical vessel is shown in Fig. 12.

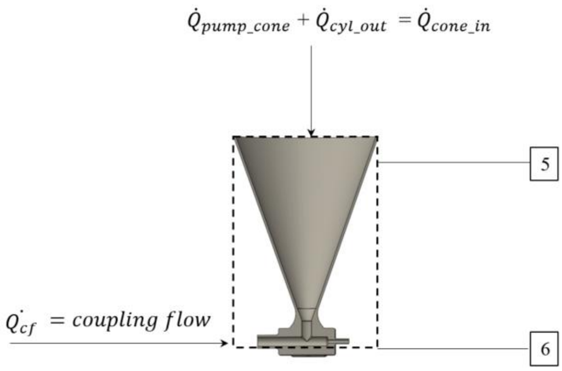

Figure 12. Control volume of the conical tank

$$\frac{dh_{cone}}{dt} = \frac{1}{S(h)_{cone}} \times \left(\dot{Q}_{pump\_cone} + \dot{Q}_{cyl\_out} - \dot{Q}_{cf}\right) \tag{7}$$

The cross-section area of the cone as a function of the fluid level h is given by Eq. (8).

$$S(h)_{cone} = \frac{\pi \times \left(\frac{D}{H} \times h_{cone}\right)}{4} \tag{8}$$

Where D is the nominal diameter of the cone and H is the nominal height.

2.4 Controller Development

The linearization at the operating point was carried out in order to implement the PID controller and to obtain the transfer functions that represent the behavior of the fluid level in each tank. The optimal tuning was obtained by the integral of squared error (ISE) method, slightly adjusted for a better controller performance. This refinement was carried out during the integration between hardware and software.

A unique PID controller for each tank, developed to work in the entire fluid level range did not performed as expected. The controller worked with a poor performance for certain ranges of the control variable in the cylindrical and conical tanks. This happened because of the strong non-linearity presented by both vessels. To overcome this situation, different operating ranges for the control variable were defined, where a pertinent identification along with the tuning process were carried out for each particular operating range. The pertinent PID block is, then, selected by the Ladder routine according to the current value of the setpoint. For the conical vessel, three operating ranges were defined: the first from 0 to 0.09 m, the second from 0.10 m to 0.19 m, and the last one, from 0.20 m to 0.25 m. For the cylindrical tank, two ranges were defined, from 0 to 0.09 m, and from 0.10 m to 0.18 m. The transfer functions for each tank and respective operating ranges are shown in Fig. 13, Fig. 14 and Fig. 15.

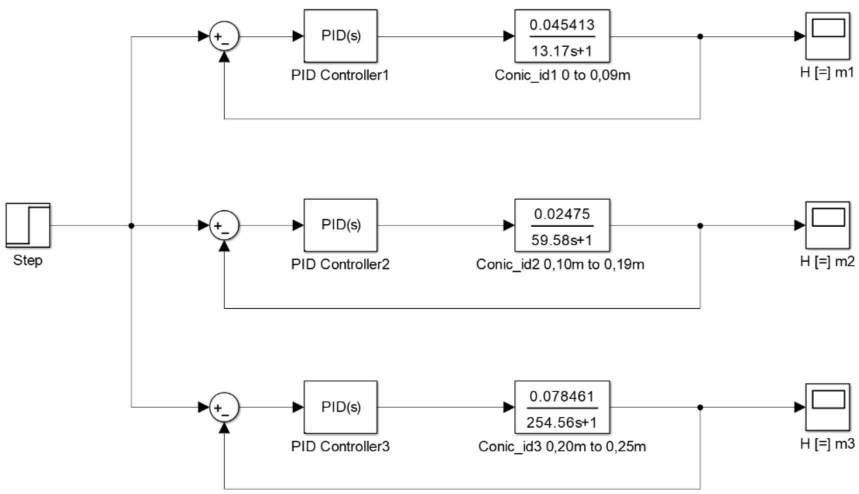

Figure 13. Transfer function of conical tank with PID control

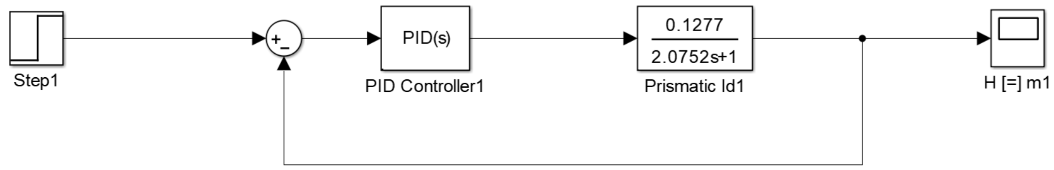

Figure 14. Transfer function of prismatic tank with PID control

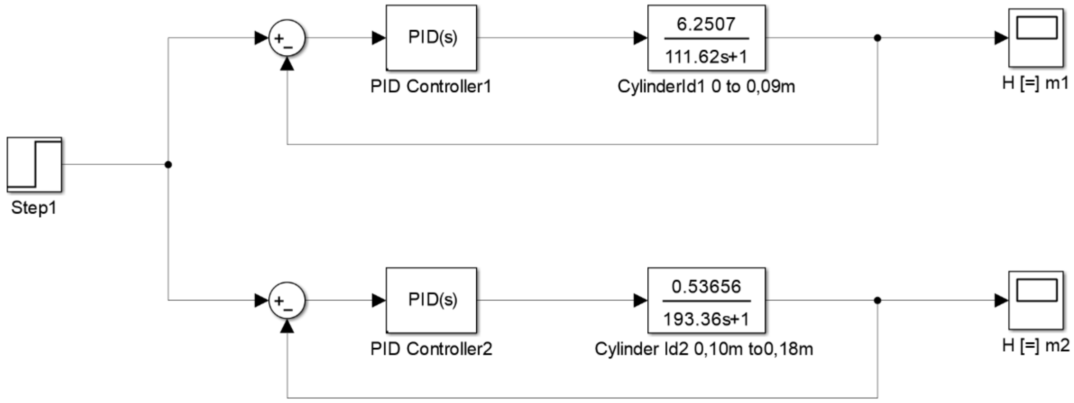

Figure 15. Transfer function of cylindrical tank with PID control

3. RESULTS AND DISCUSSIONS

The 3D of the proposed plant is shown in Fig. 16. The final assembly was built according to the proposed 3D model.

Figure 16. Plant Final Assembly 3-D rendering and plant released

At the point where the controllers were tested, in practices, it was observed for the cylindrical vessel, that due to its constructive design, the tank presented a dead volume in the bottom part, from 0 to 0.03 m, and in the upper part, from 0.15 m. Since the non-linearity at the bottom as well as at the top of the cylinder is more accentuated, the use of a dead volume, eliminating the extremities, improved the performance of the controller. Then, a unique PID control block along with a unique transfer function worked satisfactorily for the entire operating range in the cylinder (PID controller 1, shown in Fig. 14). The dead volume was needed because of the installation of the anti-overflow sensor and a resistance of 12 kW - for future projects that will cover simulations with temperature control. The results of the simulations for the three tanks are shown in Fig. 17 and Fig. 18.

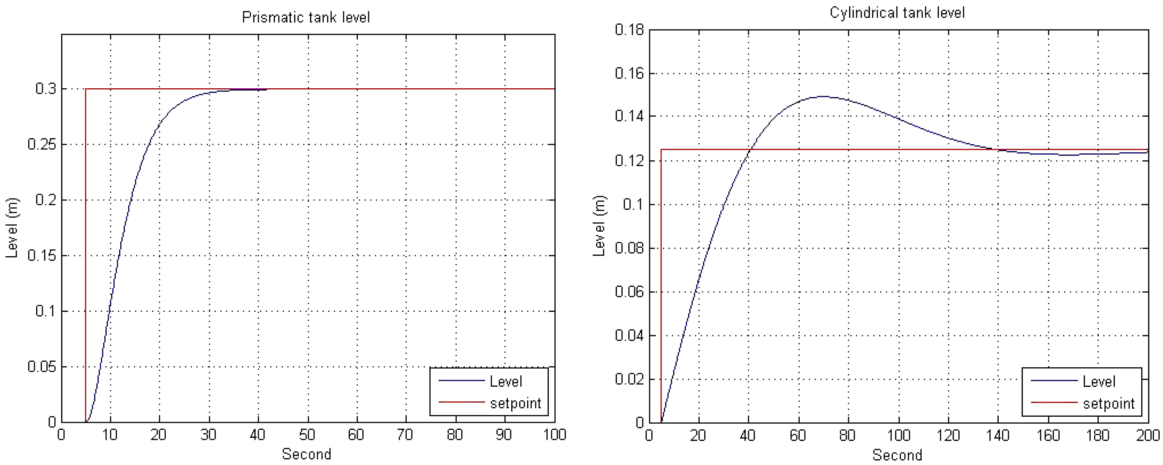

Figure 17. Step response of the prismatic and cylindrical tanks with PID control

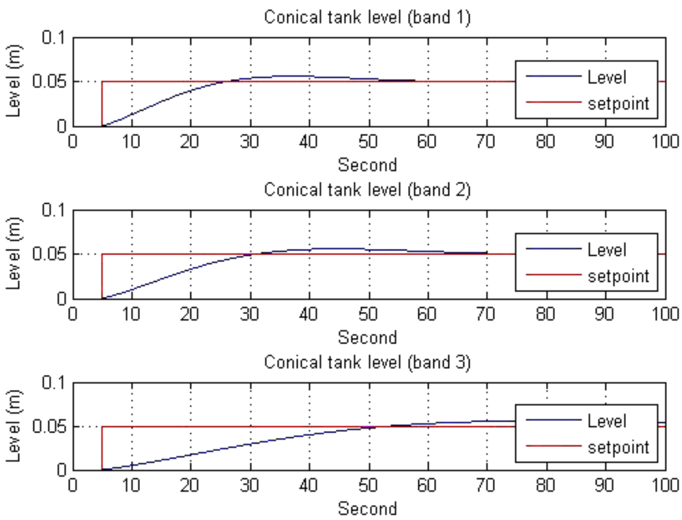

Figure 18. Step response of the conical tank with PID control at different linearization points

The summary of the gains obtained from the simulations and after the tuning process are listed in Tab. 2.

Table 2. Summary of the tanks dimensions and volumes.

Tank	k_p	k_i	k_d
Prismatic	0.001	1240.531	0
Conical id1	0.044	0.284	0
Conical id2	0.064	0.230	0
Conical id3	0.099	0.123	0
Cylindrical id1	0.679	0.041	0
Cylindrical id2	19.385	0.044	0

Three valves were employed to control the flow in the conical and prismatic tanks. In order to control the level at the cylindrical tank, the controller manipulated the frequency delivered by the PowerFlex 70 AC, and hence, the flow at the pump. The valves were placed in the plant as shown in the diagram block, Fig. 1, and in the plant model shown in Fig. 16. A graphical user interface was not developed. Nevertheless, in order to illustrate the mini-plant in operation, the PID blocks from the developed Ladder routines are shown in Fig. 19 and Fig. 20 for setpoints points arbitrarily defined for each operating range. It is important to notice that the process variable is the fluid level in each tank indeed.

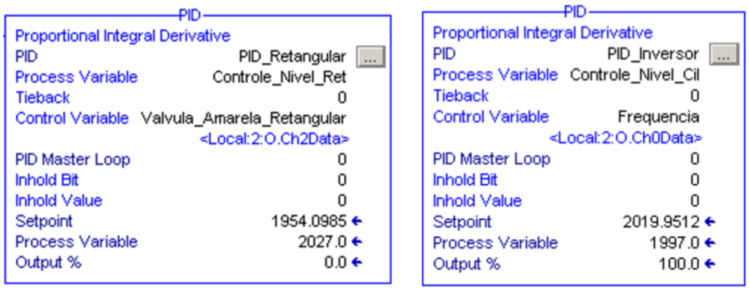

Figure 19. Ladder PID blocks representing the plant for the three operating ranges in the prismatic tank

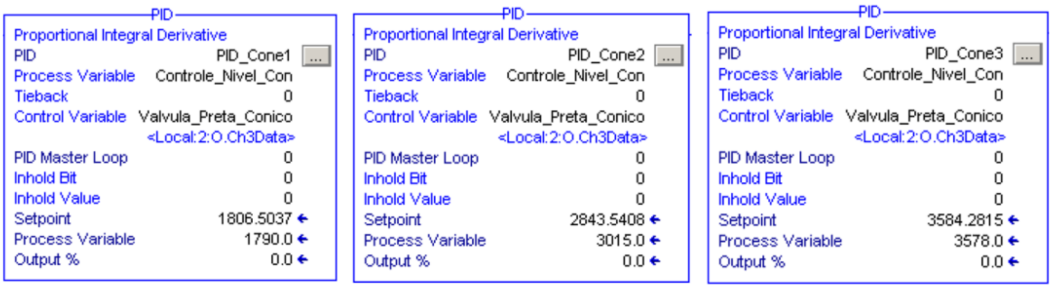

Figure 20. Ladder PID blocks representing the plant for the three operating ranges in the conical tank

The water dropping on the free surface of the fluid in the tanks provoked oscillations transmitted to the PLC trough the pressure (level) sensor. This scenario required more effort from the controllers.

4. CONCLUSIONS

The reduced scale plant was designed, built and successfully tested. The plant may be used to validate mathematical model regarding control strategies for flow and fluid level, either for academic purposes or to support industrial matters, since the modularity of the final assembly gives the mini-plant the possibility to be adapted to different configurations. The installed 12 kW three-phased resistance allows future works involving temperature control to be developed. The implementation of the classical PID technique, along with the ISE tuning, to manage the process variables in non-liner systems could consistently work in the process simulated in the present work, since different gains and transfer functions were implemented for different operating points of the system. In addition, despite the gaussian noise generated by the water falling on the free surface of the fluid in the tanks, the controllers fulfilled the expectations in terms of performance. Other advanced control techniques might also be developed and tested in the proposed project.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

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