SIMULATION OF A PROCESS WITH PID CONTROLLER ON AN EDUCATIONAL APPARATUS USING THE CLASSIC AND MODERN CONTROL THEORY

Lin Chau Jen, linchau@uninove.br
Pedro Augusto Peres, pedro.augusto@uninove.br
University Center Nove de Julho - UNINOVE

Sérgio Ricardo Lourenço, slourenco@uninove.br
University Center Nove de Julho - UNINOVE

Abstract. *Continuous processes of production are important in the industry, so, the knowledge of its control systems is an important activity of engineering students. A project for the construction of an experimental apparatus is going on at Uninove. The system is constituted of mixing tank, pump, heat exchanger, heater, valves, pipes and sensors. The central operation is the mixing of two water flows, with different temperatures. The objective is to keep constant the temperature of the mixed flow, while perturbations are done. The controller acts through the electric heater. The mathematical model of the system dynamic behavior can be based only on the energy balance of each equipment. Simulations using the classical theory of control were done and its results are presented. For a perturbation, bigger than the normal ones, like a temporary turn-off of the heat exchanger, the classical theory cannot be used, because the equations are nonlinear. The option is to use the modern theory of control. Result from this simulation is presented.*

Keywords*: process control, dynamic simulation, engineering education, continuous process.*

1. INTRODUCTION

There are two kinds of production processes: continuous or batch process. The first one has important function in the industry; it is the main process of industries of chemical, petrochemical or steel processes. So, the knowledge of the fundamentals of its control systems is an important activity of engineering students.

A project for the construction of an experimental apparatus is going on at Uninove that will realize the physical simulation of a continuous process, connected to a set of sensors, controllers and action devices that will control the process.

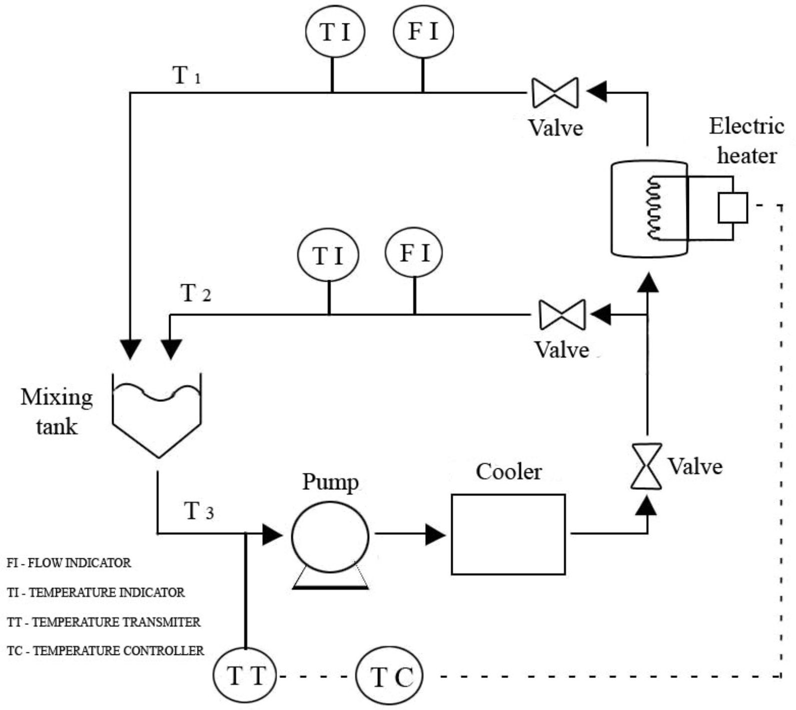

Figure 1. Schematic drawing of the experimental apparatus

Figure 1 presents the schematic drawing of the experimental apparatus. It will be constituted of a mixing tank, a hydraulic pump, a heat exchanger (car radiators), an electrical heater, valves, pipes and sensors. The central operation will be the mixing of two water flows, with different temperatures. The objective will be to keep constant the temperature of the mixing tank flow while the process is submitted to perturbations that can aris e. The controller will act through variation of the electrical heater.

The experimental apparatus is for educational utilization, that will make possible to the students know theory and practically the components of control systems and their interconnections, as well the different kinds of control strategy in use by the many actual processes.

Beside its practical utilization, the apparatus can be the object of simulations that can anticipate its behavior due to variations on operational parameters or randomperturbations.

This paper presents the first simulations, relating the utilized technique to the classic and modern control theories.

2. THE MATHEMATICAL MODEL FOR DYNAMIC SIMULATION

The experimental apparatus is not operational yet. But, its dynamic simulation could be realized, including the controller action, with some simplified hypothesis, those can be revue when the apparatus will operate.

The simulation considers the components those have some function in the process: the mixing tank, the electrical heater and the heat exchanger. It is not necessary to include the sensors.

The circulation of water is closed in the system that means the mass balances of each equipment are assured. So, the mathematical model for the system dynamic can be done based only on the energy balances of each equipment of the system. These equations are presented according to the equipment.

a) The mixing tank

The energy equation gives:

$$\frac{d}{dt}\left(m_T\, c_p\, T_3\right) = c_p\left(\dot{m}_1\, T_1 + \dot{m}_2\, T_2 - \dot{m}_3\, T_3\right) \tag{1}$$

where:

m_T .... is the amount of water contained in the mixing tank

c_p .... is specific heat of water

$\dot{m}_1, \dot{m}_2, \dot{m}_3$ .... are the mass flow rates of the water streams, respectively, the hot and the cold streams and the exit of the mixing tank

T_1, T_2, T_3 .... are the temperatures of the water streams, respectively, the hot and the cold streams and the exit of the mixing tank

This equation can be rearranged to give:

$$V_T\,\frac{dT_3}{dt} = f_1T_1 + f_2T_2 - f_3T_3 \tag{2}$$

where:

V_T .... is the volume of the mixing tank

f_1, f_2, f_3 .... are the volumetric flow rates of the water streams, respectively, the hot and the cold streams and the exit of the mixing tank

The replacement of the variables with the deviation variables (from the steady state) and the application of the Laplace transform gives:

$$T_3^{'} = \frac{f_1/f_3}{t_T s+1}T_1^{'} + \frac{f_2/f_3}{t_T s+1}T_2^{'} \tag{3}$$

where:

s .... is the Laplace transform variable

t_T .... is the system time constant, in this case, equal to the residence time of the tank

b) The electrical heater

The electrical heater will be constituted of two domestic heaters. The energy equation gives:

$$\frac{d}{dt}\left(m_A c_p T_1\right) = \dot{m}_1 c_p \left(T_2 - T_1\right) + Q_A \tag{4}$$

where:
m_A .... is the amount of water contained in the heater
Q_A .... is the heat transfer rate from the heater

This equation can be rearranged to give:

$$\frac{V_A}{f_1}\frac{dT_1}{dt} + T_1 = T_2 + \frac{Q_A}{r\ f_1 c_p} \tag{5}$$

where:
V_A ...... is the volume of the heater

The replacement of the variables with the deviation variables (from the steady state) and the application of the Laplace transform gives:

$$T_1^{'} = \frac{1}{t_A s + 1} T_2^{'} + \frac{\left(r\ f_1 c_p\right)^{-1}}{t_A s + 1} Q^{'} \tag{6}$$

where:
t_A .... is the system time constant

c) The heat exchanger

To realize the cooling of the water flux that arises from the mixing tank, it will be used car radiators. In these equipments, the water flow is cooled through the heat exchange with an air flow, moving by an fan. As the apparatus is not constructed yet, it was not possible to determine the necessary parameters to calculate the heat transfer tax as, par example, the air flow rate and its flow conditions. These parameters can be determined with the preliminary experiments of the apparatus.

Due to this, it was decided to use a simplified hypothesis that accepted as constant the difference between the temperatures of the water and air flow at any point inside the heat exchanger. It was used, also, typical values for the global heat transfer coefficient and for the correction factor (ÇENGEL; TURNER, 2001, p. 901-902).

So, the equation is:

$$\dot{m}_3 c_p \left(T_3 - T_2\right) = U_i A_i F \left(T_2 - T_5\right) \tag{7}$$

where:
U_i .... is the global heat transfer coefficient
A_i .... is the heat transfer surface area
F .... is the correction factor for cross-flow heat exchangers
T_5 .... is the temperature of the environmental air

The rearrangement of the equation gives:

$$T_2 = \frac{\dot{m}_3 c_p}{U_i A_i F + \dot{m}_3 c_p} T_3 + \frac{U_i A_i F}{U_i A_i F + \dot{m}_3 c_p} T_5 \tag{8}$$

The replacement of the variables with the deviation variables (from the steady state) and the application of the Laplace transform gives:

$$T_2^{'} = \frac{\dot{m}_3 c_p}{U_i A_i F + \dot{m}_3 c_p} T_3^{'} + \frac{U_i A_i F}{U_i A_i F + \dot{m}_3 c_p} T_5^{'} \qquad (9)$$

3. SIMULATION USING THE CLASSICAL CONTROL THEORY

In the final equations, Eq. (3), (6) and (9), there is the terms, named transfer functions, used by the techniques of the classical control theory. The transfer functions relate the process variables and, so, make possible to determine the impact on one variable due the variation on another. They are used to determine the impact in the controlled variable due the variations on the operational parameters, having or not an control system. There are two kinds of variations on the operational parameters: (a) a set-point variation that means a change on the desired value of the controlled variable; (b) a random perturbation of the steady state operation.

The block diagram of the apparatus is presented in the next figure.

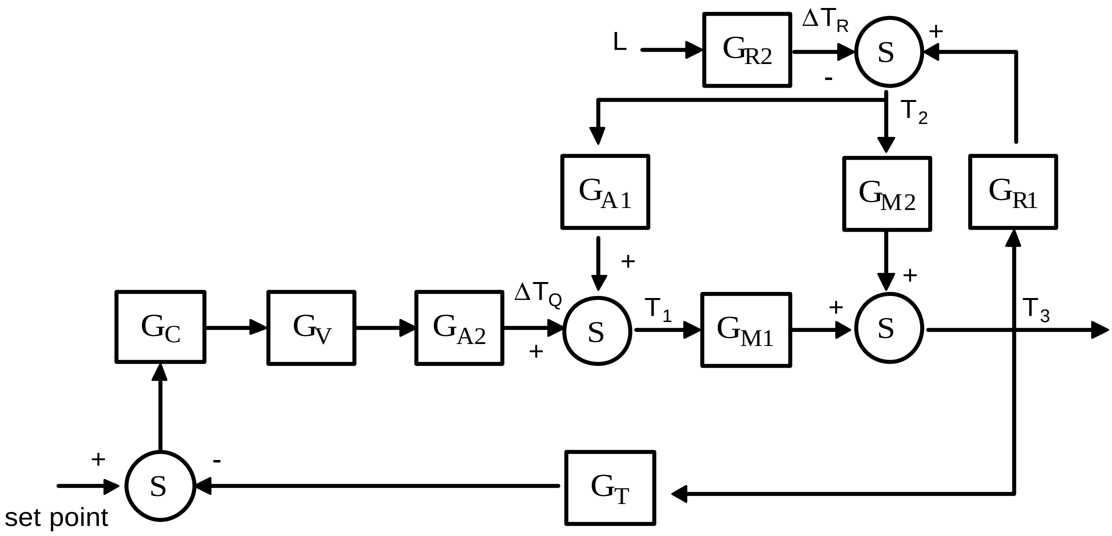

Figure 2. Block diagram of the experimental apparatus, with feedback control (L is the load variable)

In Fig. 2, G_C is the transfer function of the controller, G_V is the transfer function of the action device and G_T is the transfer function of the temperature sensor in the mixing tank. These transfer functions are not presented here because arbitrary values are given to them. The actual values of them can be determined through experiments that will be realized with the apparatus. But, this fact does not invalidate the dynamic response because the effect of the exact values of these functions is compensated by the controller settings. For other values to these transfer functions the controller settings will be others to give the same response.

The other transfer functions relate the process variables and can be extracted from the equations already developed. These are presented in the Tab. 1.

Considering the equations developed and the assumptions done, simulations are realized using the free access program SCILAB.

It is convenient to mention some details of these simulations:

- Values for the operational parameters and the controller settings are attributed.
- The transfer functions are combined, through the technique named “block diagram algebra” (CARVALHO, 2000, p. 65-68; DISTEFANO; STUBBERUD; WILLIAMS, 1979, p. 147-175).
- The program presents the results through two graphics of the variation of the controlled variable, the temperature of the mixing tank: (a) one due a set-point change, and (b) a perturbation on the temperature of the environmental air, that cause a variation on the heat exchanger performance.

Theses results are presented in the Fig. 3:

Table 1. Blocks related to the process

Label	Transfer function	Term
G_{A1}	Temperature of the cold water stream to the heater	$\frac{1}{t_A s+1}$
G_{A2}	Heat transfer rate of the heater	$\frac{(r f_1 c_p)^{-1}}{t_A s+1}$
G_{M1}	Flow rate of the hot water stream to the mixing tank	$\frac{f_1/f_3}{t_T s+1}$
G_{M2}	Flow rate of the cold water stream to the mixing tank	$\frac{f_2/f_3}{t_T s+1}$
G_{R1}	Temperature of the water stream from the mixing tank to the heat exchanger	$\frac{\dot{m}_3 c_p}{U_i A_i F+\dot{m}_3 c_p}$
G_{R2}	Temperature of the environmental air to the heat exchanger	$\frac{U_i A_i F}{U_i A_i F+\dot{m}_3 c_p}$

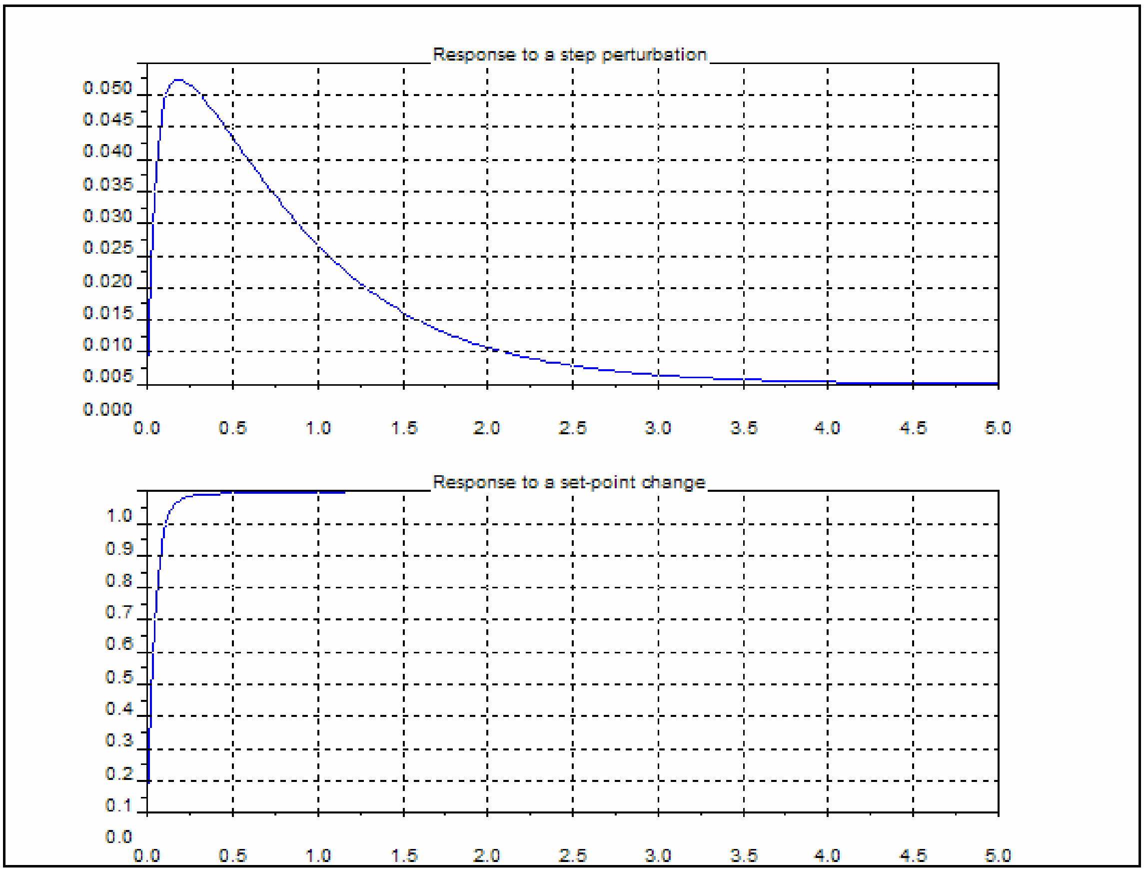

Figure 3. Results using the classical control theory

These results are important to confirm if the equations, based on the described phenomena and the mentioned assumptions, are right. The exact quantitative values mu st be observed with some reservation because operations parameters, those depend on the actual equipment, still will be determined.

4. SIMULATION USING THE MODERN CONTROL THEORY

The classical control theory, as described until now, is limited for the experiments those can be done on the experimental apparatus. The reason is that this theory only accepts linear relations among the variables and, if any relation is not, it must be replaced for a linear one.

For the study of the dynamic response due to the change of the set-point of the controlled variable and due to perturbations on the temperature of the environmental air, with or without the control system, the simulation based on the classical control theory does well.

But for a bigger perturbation, par example, caused by the temporary dysfunction of the car radiators, this perturbation can not be analyzed through a linear equation. Thermal variations seldom have impact that can be analyzed through a linear equation.

So, the attention was put on the modern control theory that distinguishes from the classical control theory on not demanding linear equations, among others points.

In the modern control theory one can uses equations on more flexible forms, linear and nonlinear ones. The equations are evaluated with the utilization of numeric methods that, also, accept any function to determine the process parameters. These methods are named "state-space" ones. In this way, the modern control theory gives the dynamic response through sets of points and not through analytical mathematical expressions.

For the experimental apparatus, a simulation based on the modern theory was done using an MS-Excel worksheet. Equations (2), (5) and (8) are used in this worksheet.

A response from this simulation is presented in the Fig. 4.

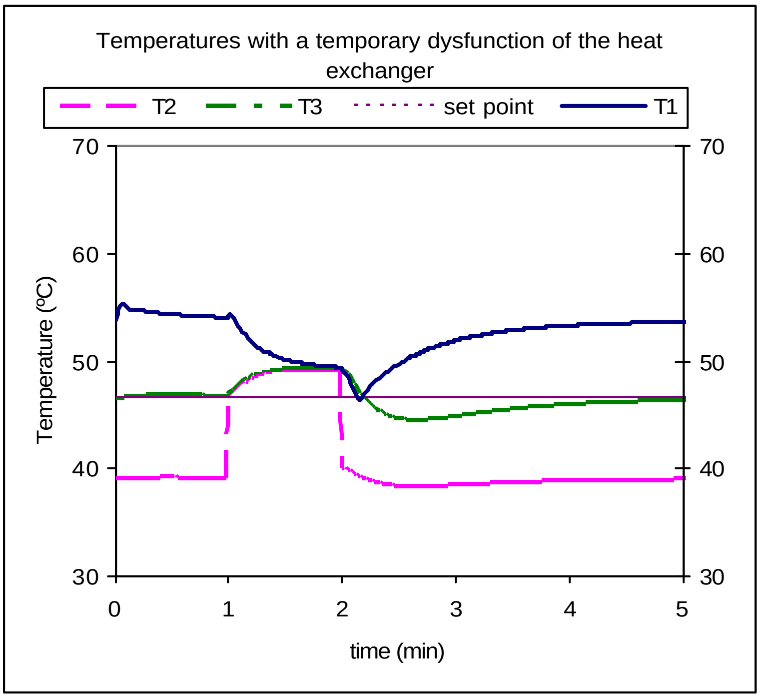

Figure 4. Results of the simulation with the dysfunction of the heat exchanger

This response gives the graphics of the temperatures of the water fluxes in the apparatus due to the temporary turn-off of the heat exchanger, between the minutes 1 and 2. It can noted that, in this time period, the temperatures T2 and T3, at the exit and at the entrance of the heat exchanger, respectively, are practically equal and, also, that the temperature T1, at the exit of the electrical heater, is reducing. These facts show that the controller turned off the electrical heater due this perturbation. The temperature drop is not instantaneous because there was an amount of hot water inside the electrical heater when it was turned off. Soon after the minute 2, when the heat exchanger came back to work, the control system return to act on the electrical heater, and got, in few minutes, the steady-state conditions again.

5. CONCLUSION

This paper described the mathematical model for a simulation of an experimental apparatus that is under construction at Uninove. It will be the basis for future accurate simulations those considerer the actual parameters of transfer functions of the instrumentation and equipments. The experimental apparatus will be available measurements which would be compared with the simulation results. Different types of perturbations would be realized at the experimental apparatus which would be simulated using the classic or the modern control theory.

6. REFERENCES

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