Virtual Training Module for the Production of Rubber Adhesives Through the Production of Cyclopentenol

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Abstract. This article developed a didactic module that presents the evolution of the process of a Perfectly Agitated Reactor to obtain Cyclopentenol, which is used for the production of rubber adhesives. For this process was implemented controllers such as: Numerical Methods, Fuzzy and MPC. The mathematical model of the process as well as the control algorithms are implemented on the Raspberry Pi board which is embedded in the module. The module has connectivity with a computer in which it has a virtual environment that resembles an industrial process which was developed in Unity 3D, the same environment is interactive and immersive for anyone interested in the area of control and virtualization. The virtual environment simulates the process through animations allowing to visualize a process as if it were real showing elements such as: SCADA systems for the control room, industrial instrumentation in the process lines, catastrophic events when an error occurs, sounds of an industrial environment, etc. Finally, the evaluation of each of the controllers implemented in the process was verified.

Keywords: CSTR reactor · Advanced controllers · Virtual reality · Didactic module

1 Introduction

Chemical, food, manufacturing, etc. industries have implemented process automation through the use of various technologies with the objective of controlling a large number of variables involved in a process and in turn limiting human intervention in the processes [1, 2]. The implementation of process automation allows higher productivity and better product quality, decreases the cost of the production process and ensures the safety of operators and equipment in critical and hazardous areas of the industry [3, 4]. Industry 4.0 has climbed to the top of industrial process automation where productive systems are interconnected with the digital society through the use of technologies such as: artificial intelligence, big data, robotics, cloud communication, internet of things, internet of everything, internet of everything, cybersecurity, Wireless industrial automation, industrial networks, nanotechnology, network virtualization, augmented reality and virtual reality [5, 6].

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The industry for process automation has relied on different mathematical software that allow implementing different control strategies in industrial processes among them there are free software (Open Source) such as Arduino, Python [7], C++, C#, Scilab and commercial software Ros, Matlab [8], Maple [9], Labview [10] such software provide the ability to combine symbolic, numerical and graphical calculation. Due to the excessive costs in the implementation of controllers in a real process, the alternative of using 3D graphic engines such as Unity, Un-real Engine, RPG Maker, Godot, the last mentioned software allows the simulation of industrial environments in an immersive way [11, 12].

Augmented reality and virtual reality are immersive technologies that have made inroads in the automotive, food, chemical and medical industries, whose objective is the virtualization of immersive industrial processes, achieving interaction with the process layout, machinery, instrumentation, operating elements, signaling and control. Immersive technologies make it possible to observe the performance of the process and in turn enable personnel to acquire monitoring and manipulation skills and abilities for their subsequent performance in a real plant or process [13]. To develop the virtualization of industrial processes there are currently several ways, as described in [14], in which it uses different forms of modeling and software, which causes greater emphasis to the development of 3D Virtual Reality (VR) environments. VRs are a great tool for training skills as, for example, in the area of the food industry the work presented by [13] presents a VR training system of a pasteurization plant with equipment, structures and other instrumentation. In the manufacturing domain it shows the virtualization of a leather tanning process which is immersive and able to train operators [15]. In the automotive field [16] shows a VR system which is low-cost to simulate vehicle prototypes quickly. The examples are countless as the field of research is advancing daily.

As described above, this work proposes the development of a physical training module for the implementation of different advanced control strategies for the production of cyclopentenol to be used in the production of rubber adhesives. A didactic module was developed which is composed of a control unit (raspberry pi card) which incorporates the advanced control shakers (MPC, Fuzzy and Numerical Methods) and an HMI (led screen) to visualize the performance of the controllers in real time; it is also proposed to develop a 3D virtual environment of the mentioned process using Unity software, which must be interactive and immersive for the user, while incorporating the mathematical model of the process to provide the realism of the animations and the behavior of the process. Finally, experimental tests are carried out with the developed prototype in order to check the usability and performance of the virtual training module of a CSTR reactor for the production of cyclopentenol used for the production of rubber adhesives.

This article consists of Seven Sections, the Sect. 1 contains the Introduction, whereas Sect. 2 describes the training module, the structure of which is governed by the design of the training module. Section 3 consists of the development of the virtual environment, In the Sect. 4, the mathematical model of a perfectly stirred reactor is described in detail. The Sect. 5 consists of the design of advanced controllers (MPC, Fuzzy and Numerical Methods), Sect. 6 details the results obtained through the evolution of the controllers where the user chooses the control algorithm to visualize and analyze the results, finally, the conclusions of the work carried out are described in the Sect. 7.

2 Methodology

Virtual Reality (VR) has provided a great help in the field of research and education in recent years because one of the qualities is to provide experimental data and provide training environments very close to a real industrial system. For the development of the 3D virtualization of the processes, techniques such as modeling, controller design, implementation in a didactic module and inclusion of a virtual environment for the experimentation process are used.

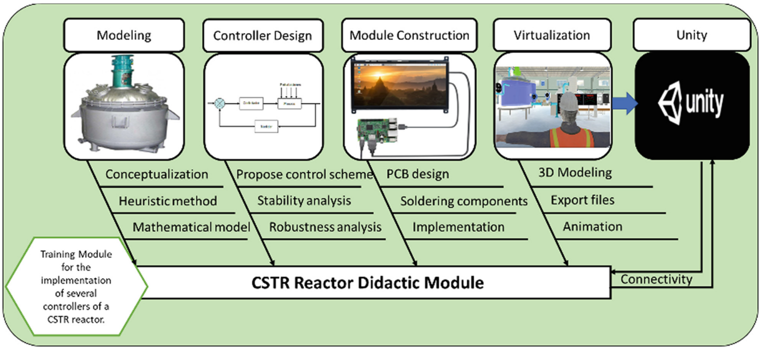


Fig. 1. Methodology for a CSTR reactor training and visualization module.

The scheme shown in Fig. 1 consists of four main stages, which must be consecutive: *(i) Mathematical Modeling* is obtained in order to mathematically represent the process performed by a CSTR reactor for the production of cyclopentenol used as part of the production of rubber adhesives. Therefore, a MIMO mathematical model is considered that represents the characteristics taking into account the inputs as cyclopentadiene flow and temperature flow and as outputs as cyclopentenol flow and internal temperature of the reactor jacket; *(ii) Controller Design*, in the case of this research, advanced control algorithms will be implemented, such as: numerical methods, Fuzzy and finally MPC, considering that it is a MIMO system; *(iii) Construction of the Module* which consists of hardware and software with the HIL (Hardware in the Loop) technique, which allows emulating the behavior of the CSTR reactor, for which a raspberry pi is implemented where the mathematical model of the plant is located, it also has a screen considered an HMI which allows us to observe the behavior of the controllers and the system; *(iiii) Virtualization* of a perfectly agitated reactor together with the elements of the virtual environment are designed in CAD software, based on their real shapes in order to obtain a process with a high degree of realism, we export the files compatible with Unity 3D software; Finally, tests of the training module are performed by applying communication with the virtual environment in order to apply the use of VR (Virtual Reality) in the teaching-learning methodology as an alternative for testing new proposals for advanced control algorithms.

Figure 2 details the schematic of a training system for cyclopentenol production, which consists of a physical module that operates independently. In the module there is a control unit (Raspberry Pi card) in which the mathematical model is implemented as the control algorithms allowing to observe on an LCD screen the performance of the implemented controllers. The prototype has the option to communicate with a computer that contains a virtual environment allowing interaction with the virtualized process. The virtual environment will receive the process variable data sent from the module.

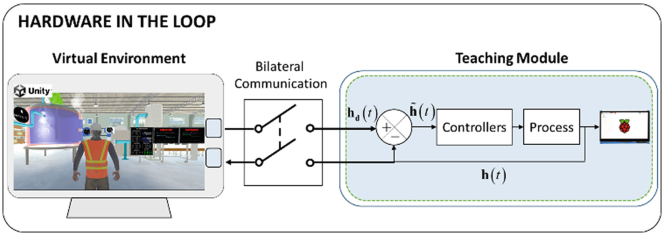


Fig. 2. Diagram of the training module.

3 Virtual Environment

To design the virtual environment of the process, the following procedures were developed as shown in Fig. 3. The industrial environment is based on a real process to be followed in order to perform the virtualization, CAD software is used to create a 3D drawing of the model. Subsequently the 3D model is exported with the sketchup software which allows compatibility with Unity where the different animations are made. In the Unity software it allows the insertion of an avatar, which performs a tour of the entire process environment guided by the user.

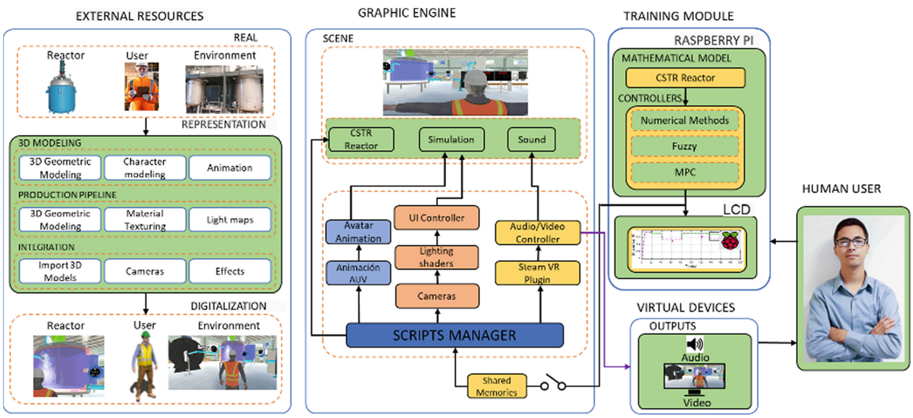


Fig. 3. Virtualization of the process.

4 Modeling of the Process

When automation of industrial processes is performed, mathematical modeling is necessary, which is directly involved in the development of advanced control algorithms. This Section describes the process of a reactor that through temperature-driven reactions allows an input component to undergo a chemical change in order to obtain a product with different properties.

The mathematical model of the CSTR reactor is composed of a stirring system which maintains a continuous motion that performs a constant movement inside the reactor, which allows stirring to produce several reactions in series and in parallel described by the Diels-Alder principle which allow the production of cyclopentenol by chemical intervention of cyclopentadiene [11]. Figure 4 describes the process of a perfectly stirred reactor, by means of the inputs and outputs the mathematical model was obtained, which is composed of an internal tank which is covered by an external structure with an intermediate vacuum between the two structures through which the heat flow Q enters to transmit the temperature to the inside of the reactor T_k, to obtain the cyclopentenol concentrate, several chemical reactions are provoked inside the reactor by the variation of the inlet flow C_{ao} and the temperature.

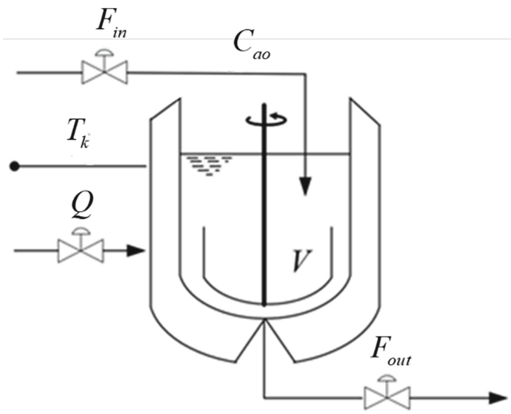


Fig. 4. Process of a CSTR reactor

For the product of the Cyclopentadiene balance input, the following equation is considered:

$$\frac{dC_A}{dt} = \frac{F}{V}(C_{A0} - C_A) - k_1 C_A - k_3 C_A^2 \tag{1}$$

To obtain the desired product, the Ciclopentenol balance is obtained:

$$\frac{dC_B}{dt} = -\frac{F}{V} C_B + k_1 C_A - k_2 C_B \tag{2}$$

To determine the temperature of the system, the temperature mass balance is obtained:

$$\frac{dT}{dt} = \frac{1}{\rho C_\rho}\left[k_1 C_A(-\Delta H_{RAB}) + k_2 C_B(-\Delta H_{RBC}) + k_3 C_A^2(-\Delta H_{RAD})\right] + \frac{F}{V}(T_0 - T) + \frac{k_w A_R}{\rho C_\rho V}(T_k - T) \quad (3)$$

The parameters of the reaction rates k_1, k_2 and k_3 depend on the temperature by means of the Arrhenius law. The above equations of the process were based on the work [11]. By placing (1), (2) and (3) into state variables gives the following equation:

$$\begin{bmatrix} \dot{C}_B \\ \dot{T} \end{bmatrix} = \begin{bmatrix} -C_B & 0 \\ T_0 - T & \frac{K_w A_R}{C_\rho \rho V} \end{bmatrix} \begin{bmatrix} F_{in} \\ Q \end{bmatrix} + \begin{bmatrix} P_{C_B} \\ P_T \end{bmatrix} \quad (4)$$

where, cyclopentenol is defined as C_B; T is the reactor temperature; K_w is the heat transfer coefficient; A_R is the surface area of the reactor; C_ρ is the heating capacity; ρ is the constant density of the liquid and V is the reactor volume. Equation (4) can be compactly described as

$$\dot{\mathbf{h}} = Hv + P \quad (5)$$

where **v** defines the control actions (variations of: cyclopentadiene flow and heat flow); **P** are the disturbances that exist in the process; $\dot{\mathbf{h}}$ represents the rate of change of the process output; **H** is the matrix representing the behavior inside the reactor.

5 Controllers Design

In this Section advanced controllers such as: Fuzzy, MPC and Numerical Methods were implemented which can be selected in order to evaluate the process behavior as detailed in the diagram in Fig. 5

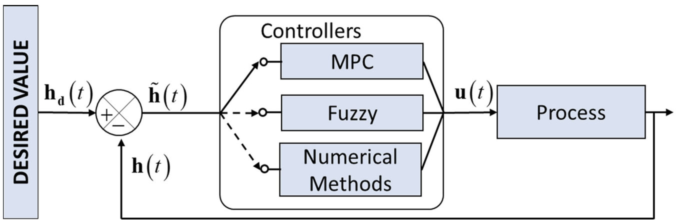


Fig. 5. General scheme of proposed controllers

where: $\mathbf{h_d}$ are desired values such as (ciclopentenol flow and reactor temperature); **h** are real values of the process; $\tilde{\mathbf{h}}$ are errors that enter the controllers and finally **u** are the control actions (cyclopentadiene flow and heat flow).

5.1 Control of Numerical Methods

To obtain cyclopentenol by means of a control based on numerical methods, the variables of temperature flow and cyclopentadiene concentration flow are considered. The process is represented by a matrix structure in which theorems and axioms of linear algebra are applied.

Discretizing (4) through Euler's method we have:

$$\mathbf{h}(k+1) = t_s(\mathbf{H}(k)\mathbf{v}(k) + \mathbf{P}(k)) + \mathbf{h}(k) \tag{6}$$

where t_s represents the proposed sampling time according to the Nyquist theorem and k is discrete time for which its evolution in an instant of time is $k+1$.

By implementing the Markov Chain, it is possible to establish the evolution of the variables to be controlled after they have undergone a sampling period as shown below: $\mathbf{h}(k+1) = \mathbf{h_d}(k+1) - \mathbf{W}[\mathbf{h_d}(k) - \mathbf{h}(k)]$. From here, the control law can be defined on the basis of [17]:

$$\mathbf{v_c}(k) = \frac{1}{t_s}\mathbf{H}^{-1}[\mathbf{h_d}(k+1) - \mathbf{W}[\mathbf{h_d}(k) - \mathbf{h}(k)] - \mathbf{h}(k)] - \mathbf{P}(k) \tag{7}$$

in (7), defined as $\tilde{\mathbf{h}} = \mathbf{h_d} - \mathbf{h}$; $\mathbf{h_d} = [\mathrm{C}_{bd}\ \mathrm{T}_d]^T$ and finally the diagonal gain matrix is defined as $\mathbf{W} \in R^{2x2}$ which weights the control errors of the process and contains values between zero and one, when the gain matrix takes values close to zero the system behaves stably and if they take values close to one the behavior is unstable.

5.2 Control of Fuzzy

To control temperature and ciclopentenol flow with fuzzy logic, the following linguistic variables were considered $\tilde{\mathbf{h}}(t)$ and $\mathbf{u}(t)$. The 7 control rules are used where the input flows will respond according to the error that enters the controller.

With the help of the inference method, the membership function is obtained:

$$\mu_{\mathbf{B'_i}}(\mathbf{u}(t)) = \vee_{\tilde{\mathbf{h}}(t)}\left[\mu_{\mathbf{A'_i}}\left(\tilde{\mathbf{h}}(t)\right) \wedge \mu_{\mathbf{R'_i}}\left(\tilde{\mathbf{h}}(t), \mathbf{u}(t)\right)\right] \tag{8}$$

considering that $\mathbf{A}'$ is a singleton set, the following expression is obtained:

$$\mu_{\mathbf{B'_i}}(\mathbf{u}(t)) = \mu_{\mathbf{A'_i}}\left(\tilde{\mathbf{h}}_0(t)\right) \wedge \mu_{\mathbf{B'_i}}(\mathbf{u}(t)) \tag{9}$$

where $\mathbf{A_i}$ is a linguistic term for the input to the controller known as the error; $\mathbf{B_i}$ is the ligustic term obtained at the output of the controller; $\wedge\mu_{\mathbf{R'_i}}$ the minimum value of the ratio of the Cartesian product of the membership function of the input is considered and output is considered.;$\vee_{\tilde{\mathbf{h}}(t)}$ refers to the maximum values of temperature and cyclpentenol error occurring in the Reactor, and finally $\tilde{\mathbf{h}}_0(t)$ the first small value that takes the value of the membership known as a merging value of the antecedent of the input to the controller.

5.3 Control MPC

The MPC controller is applicable for multi-input and multi-output processes (MIMO), which seeks to minimize the cyclopentenol error and temperature error. Therefore, it can be said that it seeks to minimize the abrupt control actions of temperature flow and cyclopentadiene concentration flow, therefore the simultaneous control of two process variables is performed to determine the control actions as shown in the following equation:

$$\mathbf{J}(k) = \sum_{i=N_w}^{N_p} \delta(k) \left\| \hat{\mathbf{h}}(k+i|k) - \mathbf{h_d}(k+i|k) \right\|_{\mathbf{D}}^2 + \sum_{i=0}^{N_{C-1}} \lambda(k) \| \Delta\mathbf{u}(k+i-1) \|_{\mathbf{F}}^2 \quad (10)$$

Subject to:

$$\Delta\mathbf{u}_{\min} \leq \Delta\mathbf{u} \leq \Delta\mathbf{u}_{\max} \quad (11)$$

$$\mathbf{h}_{\min} \leq \mathbf{h} \leq \mathbf{h}_{\max} \quad (12)$$

where N_w y N_p is defined as the start of the prediction horizon and the number of samples of the prediction horizon respectively; N_c as the control horizon, which must always be shorter than the prediction horizon; $\hat{\mathbf{h}}$ are the predicted outputs of cyclopentenol flow and reactor temperature.

For process optimization, there are control action constraints such as cyclopetadiene concentrate flow and temperature flow defined as $\Delta\mathbf{u}$. The same is true for the maximum and minimum limits of the process outputs represented by $\mathbf{h}$. The constants δ and λ correspond to the weight of the error and the weight of the variations of the control actions respectively.

6 Experimental Results

This Section defines the operation of the training module in conjunction with the virtualized process where the user can interact and analyze the evolution of the various control algorithms proposed for the production of cyclopentenol by means of a perfectly stirred reactor.

6.1 Module Construction

The didactic training module is composed of a Raspberry Pi card as a control unit and has a display for visualizing the performance of the controllers. The module is powered by a portable power source in this case is a Lipo battery and has protections against over current, also has an Xbee card which allows wireless communication with the virtual environment. Figure 6 shows the electrical diagram of the didactic module.

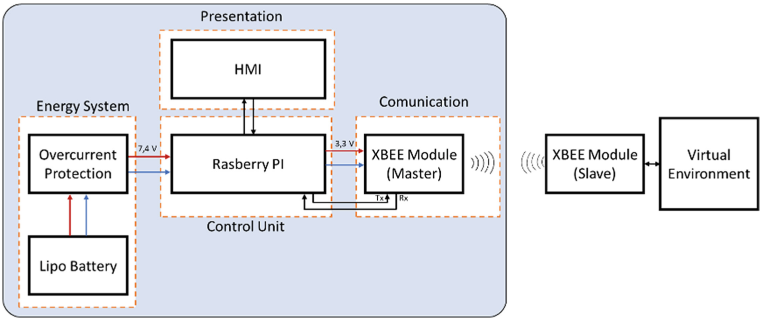


Fig. 6. Training module electrical schematic

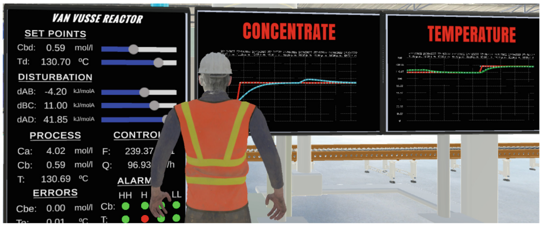
Once the electrical connections of the elements and the programming in the control unit have been made, several tests can be performed. Figure 7 shows the results of the tests performed on the module in conjunction with the virtual environment, where the evolution of the controller in the module's HMI and its communication with the virtual environment can be seen.

Fig. 7. Operation of the training module

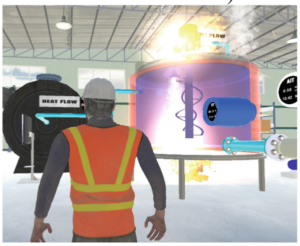
6.2 Virtual Environment

In order to allow the user to analyze the performance and recognize the Cyclopentenol production process, a virtual environment was developed (see Fig. 8), which represents the production of this concentrate, the user can navigate represented by an avatar that can move throughout the industrial process: exploring and visualizing the existing industrial instrumentation in the process line, SCADA system that allows modifying the desired values and in turn provides real-time information on the variables to be controlled. The virtual environment contains safety and caution signs throughout the cyclopentenol production area making it an immersive environment.

a) CSTR Reactor



b) Control and monitoring screen



c) Process in critical state.

Fig. 8. Virtualized process industrial environment

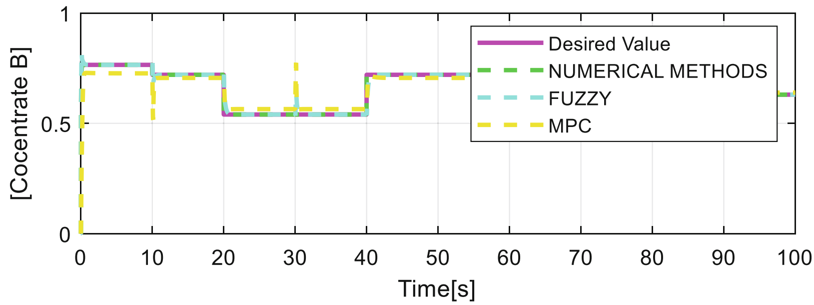
After the product obtained from the process will be sent to a packaging process in industrial tanks which will be sent for further manufacturing spindle in solvents and rubber adhesives as shown in Fig. 9.

Fig. 9. Packaging area of cyclopentenol concéntrate.

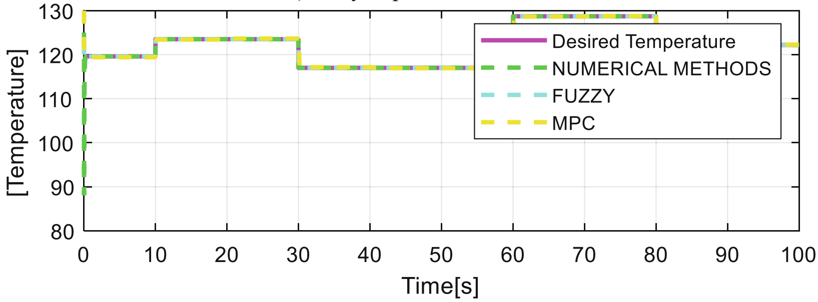
6.3 Controllers Performance

The implemented controllers have a correct operation so that when evolving the process variables reach the desired value in the course of time, due to this the control errors approach the value of zero in each of the variations of the desired value.

The performance of the controllers is similar between them, but when varying the set point of concentrate B (cyclopentenol), there are differences due to the existence of over impulses when implementing the MPC and Fuzzy controllers. The percentage of overshoot of the MPC controller is higher with respect to the overshoot of the Fuzzy controller as opposed to the Numerical Methods controller which has no overshoot. As for the performance of the controllers in the temperature variable, there is no evident difference between them, it should be noted that the production of cyclopentenol depends directly on the temperature flow as can be seen in Fig. 10.



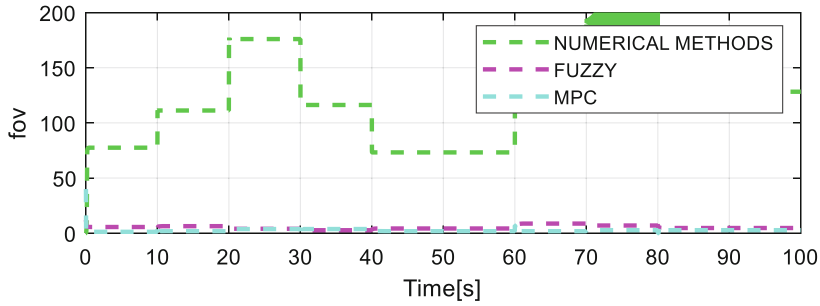
a) Cyclopentenol evolution



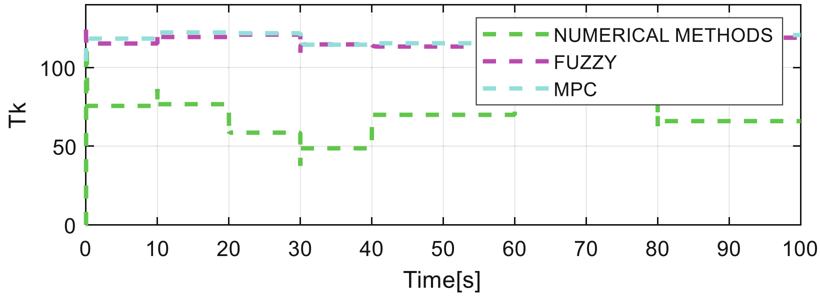
b) Reactor internal temperatura

Fig. 10. Process desired values.

The Numerical Methods based control actions have abrupt changes in the control actions for both the input flow (cyclopentadiene) and temperature flow, unlike the control actions of the MPC and Fuzzy controllers whose changes are of smaller magnitude so they are suitable for the final control elements as indicated in Fig. 11.



a) Cyclopentadiene concentration flow



b) Temperature flow

Fig. 11. Process control actions.

7 Conclusions

In this work we presented the didactic module for the user interaction where it will be possible to visualize the performance of the proposed control algorithms for process, through a communication channel is connected to a VR of an industrial process, which interacts in parallel with the didactic module. The virtual environment is focused on a chemical industry where CSTR reactors and process instrumentation are managed. To create the virtual environment, different techniques were implemented, one of which is to obtain the mathematical representation of the reactor and then advanced control algorithms were developed, such as: Numerical Methods, Fuzzy and MPC. When these algorithms were implemented, satisfactory performance was achieved, given that the desired values of the cyclopentenol concentrate flow and the internal temperature of the reactor were reached, while the control errors tended to stabilize at values close to zero.

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