Control de un sistema integrado en cascada con un calderín alimentador de vapor constante a un reactor para la producción de cloruro de aluminio virtualizado usando una estrategia de control predictivo basado en modelos MPC

Amores Daniel, Villagómez Javier

Departamento de Eléctrica y Electrónica

Carrera de ingeniería en Electrónica e Instrumentación

Articulo académico, previo a la obtención del título de ingeniería en Electrónica e Instrumentación

Ing. Llanos Proaño, Jacqueline del Rosario

5 de diciembre del 2022

Latacunga

Control of a Virtual Cascade Integrated System with Constant Steam Feed Boiler to a Reactor for the Production of Aluminum Chloride Using a Model Predictive Control MPC

David Amores, Javier Villagómez, Jacqueline Llanos, and Diego Ortiz

***Abstract*—This research work models, virtualizes and controls an integrated cascade system for the production of aluminum chloride, based on the implementation of a boiler, which aims to produce constant steam at a certain temperature, the same that is coupled to the jacket of a continuous stirred reactor, which aims to produce aluminum chloride by the entry of hydrochloric acid inside which is deposited aluminum. Once the two processes are coupled, control strategies are designed based on traditional PID algorithms, one to control the steam temperature at the boiler outlet, and the other to control the aluminum chloride concentration at the reactor outlet. In addition, a model-based predictive control (MPC) algorithm is designed, with four control objectives: the first one is to bring the steam temperature to the desired value, which in turn indirectly controls the internal temperature in the reactor; the second one controls the concentration error; the third and fourth ones guarantee that the variations of the control actions are minimal, thus preserving the useful life of the actuators.**

***Keywords*—— Cascade, Boiler, Reactor, PID, MPC**

I. Introduction

The degree of industrialization in all regions of the world has continued to increase and the resulting production volume has also increased, which means that there may be multiple variables that need to be controlled in a working environment. The increase in tasks to be performed and rising equipment costs, as well as higher requirements for quality, precision and efficiency, clearly show that the idea of using only operators to control is not sufficient. Therefore, automatic control has become a solution [1].

In this research, the production of aluminum chloride from a constant steam feed boiler to a reactor, which are connected in cascade, is analyzed.

The resulting chemical (aluminum chloride) is probably the most widely used Lewis acid and also one of the most potent. Its application in the chemical industry is in a catalyst for Friedel-Crafts reactions, both acylations and alkylations [2].

Manuscript received July 31, 2022; revised September 19, 2022; accepted.

D. Amores and J. Villagómez, J. Llanos and D. Ortiz are with the Electrical and Electronic Department of Universidad de las Fuerzas Armadas ESPE, Av. General Rumiñahui s/n, Sangolqui, Ecuador, P.O.BOX: 171-5-231B, e-mail: ddamores@espe.edu.ec, javillagomez1@espe.edu.ec, jdllanos1@espe.edu.ec, ddortiz5@espe.edu.ec.

The most important products where aluminum chloride is used are detergents. This chemical is also used for polymerization and isomerization reactions of hydrocarbons such as production of ethylbenzene, which is used to manufacture styrene, polystyrene and also the production of dodecylbenzene [3].

To carry out this task one of the most used industrial equipment are the reactors, which are fed by a certain product and need a constant temperature inside the jacket of the reactor, so that the temperature remains within a certain range of values it is proposed to implement a constant steam producing reboiler in cascade with the reactor.

Stirred tank reactors are vessels with a large volume, which provides a long residence time, coupled with the isothermal nature of the reactor, resulting in the reactor operating at an optimum temperature and with a large reaction time. Continuous reactors are used in liquid phase systems at low to medium pressures. They can be used when the heat of reaction is high, but only if the temperature level in isothermal operation is adequate, such as, for example, that the temperature is not so high as to jeopardize the safety of the reactor [4].

In several industrial applications, advanced controllers have been shown to perform better than traditional PI or PID controllers in industrial chemical processes with nonlinear and multivariable dynamics, for example, the implementation of a controller using an online recursive least squares identification method based on ARX to have a good understanding of the dynamic behavior of the system [5]. Other controllers used to stabilize the dynamics of nonlinear reactors are strategies based on model predictive controls (MPC), which try to find the most optimal control action respecting the established constraints [6]. On the other hand, boilers are equipment used at industrial level, their main purpose is to generate heat, which can then be used in different processes at a given point. This heat is transferred in the form of steam, which can be used for many purposes. The steam produced is conducted through pipes that must be insulated, with respect to the different specific points of the process [7].

Among the most relevant applications of boilers are the following: Use of the steam produced by the boiler as a generating plant (power plant), combined cycle thermal power plant [8], [9]. Development of heat exchangers through constant steam at the boiler outlet, power supply in desalination plants [10], etc. Within some published works, and related to the control of a boiler plant, it can be observed that different controllers are implemented in order to stabilize such plant. There are some similar controllers reported in which a system based on adaptive inverse control strategies is observed through a neural network which adopts the steam flow signal for the inverse controller taking into account the influence of load changes [11]. Two-dimensional fuzzy logic-based controllers can also be taken into consideration to stabilize the steam pressure and obtain the closed-loop control variable of fuel dryness [12]. Another control strategy used to stabilize the steam pressure is the Smith predictor (SP) with PID and PI controllers based on the application of different performance indices [13].

On the other hand, in the academy it is difficult to find systems or laboratories of these processes and less with elements necessary to couple two systems in cascade, presenting virtual laboratories as options. Virtual reality is an environment in which people can interact with a series of events within a computer-generated world, it can also be considered highly real through the use of computers; currently, this tool has a wide application because it allows users to interact with a simulated environment which allows activating multiple senses that lead the operator to experience the sensation of performing an activity only in an artificial environment [14].

In the academy, modeling and implementing controls in industrial processes with the appropriate instrumentation is almost impossible due to its high costs, which prevents future professionals from acquiring skills in this area, on the other hand, controlling this type of real industrial processes is very complicated, but thanks to the advancement of technology, it is possible to opt for systems that emulate the real performance of these physical processes. This has been reflected in published research, such as the implementation of a two-phase separator within an immersive industrial environment that requires advanced automatic control strategies [15]. Another case where the use of this technology can be observed is shown in the design and advanced control of the Festo virtual workstation, in which a high level of detail in the virtual elements is considered [16], [17].

In this work, the modeling and design of control algorithms of the cascade system consisting of a reboiler and a reactor to generate aluminum chloride is carried out. The cascade system where the control algorithms are implemented has a virtualized environment with realism, and the processes have dynamics similar to the real ones. First, a traditional control strategy is designed for the two coupled systems, based on PID controls, evaluating its performance in cascade operation. After that, an advanced model-based control (MPC) is proposed to the cascade system that controls the steam boiler with constant temperature and the reactor to generate aluminum chloride as final product. The overall performance of the cascade system is validated within a virtual environment. For the development of the virtual environment, we intend to use a program that allows us to export data to other platforms and also allows the development of a virtual environment to simulate the behavior of a real industrial system, using the software's own graphical tools.

The main contributions of this research work are: i) The modeling that integrates two cascade systems, ii) A virtualization methodology applied to an industrial process that can be replicable in academic applications, iii) Implementation of traditional and advanced predictive controllers based on models, iv) The proposal of a centralized predictive control MPC that allows controlling the two cascade processes.

II. Description and Modeling of the Integrated System of a Boiler and a Cascade Reactor for the Production of Aluminum Chloride.

The cascade system consists of two integrated processes. The first one corresponds to a boiler that has the purpose of maintaining a constant steam temperature at the outlet, which will serve as input for the following multivariable cascade process that corresponds to a continuous reactor for the production of aluminum chloride.

Fig. 1 shows the cascade integrated system, it can be observed the coupling of the output of the $tr(t)$ boiler as an external source to the reactor, which represents the constant steam input at a certain temperature to the $tr(t)$ input of the reactor, therefore the output of the boiler is the steam input of the reactor, in this way the two processes are integrated in cascade, it can also be observed the implementation of a closed loop controller based on traditional (PID) and advanced (MPC) control strategies, which allows to control the system by varying the control valves corresponding to the input flow (high pressure water) of the boiler and the input flow (hydrochloric acid) of the reactor. The variables $tr(t)$, $T(t)$, and $C_B(t)$ are measured, which represent the temperature of the output steam SH (high pressure steam) of the reboiler, the internal temperature of the reactor, and the concentration of aluminum chloride at the output of the continuous reactor, respectively. It should be noted that the variable $tr(t)$ depends on the temperature $T(t)$, this is due to the fact that the boiler output produces a constant steam flow at a certain temperature, which enters the reactor jacket in the form of steam; this temperature is required to ensure that the internal temperature of the reactor is maintained at a desired value. In [4] and [5], they show that the constant temperature towards the reactor and the temperature that I know it generates inside the reactor are proportional. Therefore, the steam temperature at the output of the boiler feeding the reactor can be equal to the reactor internal temperature $T(t)$ multiplied by a transfer factor F_a. This factor represents the heat transfer from the reactor jacket to the interior, and also the heat transfer coming from the chain reactions produced at the moment of contact between the chemicals implemented inside the reactor, in this case hydrochloric acid and aluminum, as well as losses that could be produced by the distances between the boiler and the reactor. Therefore, in the integrated system it is important to ensure that the temperature entering the reactor is adequate for the reaction inside the reactor.

It should be noted that the steam generation process through the boiler has a Q transfer due to the fuel input, which allows generating steam and producing aluminum chloride as the final product at the output of the C_B reactor. This is due to the reactions produced between hydrochloric acid and the aluminum scrap inside the reactor.

A steam boiler is a sealed vessel in which pressurized water ($BFWH$) is transformed into steam (SH) as shown in Fig. 1, by applying the heat resulting from the combustion of combustible gases, liquids or solids. When the conversion of water to steam begins, the temperature remains constant, although heat continues to be added. The fluid is at saturation pressure/temperature conditions throughout the water-to-steam conversion [7].

The continuous stirred tank reactor consists of a tank with almost perfect agitation as shown in Fig. 1, in which there is a continuous flow of reactant material and from which the reacted material (produced material) continuously exits. The agitated condition is not so difficult to achieve as long as the liquid phase is not too viscous. The purpose of achieving a good agitation is to achieve a good mixing of the materials inside the tank, in order to ensure that the entire volume of the vessel is used to carry out the reaction, and that there are no dead spaces [18].

A. *Mathematical Modeling of an Integrated Cascade System for Aluminum Chloride Production.*

For the mathematical model of the boiler, it is taken into consideration that the boiler has an input of feed water $BFWH$ and the output of saturated steam SH (See Fig. 1).

The two variables are measured in tons per hour [T/h], therefore their difference must be integrated in order to obtain the total mass (M_c) stored in the boiler as indicated in (1).

In order to obtain the model that expresses the dynamics of a boiler, the variations of specific density of water (ρ_w) and steam (ρ_s) as a function of pressure are taken into consideration, since they are very important aspects to take into account in the behavior of the boiler dynamics, as described in equations (2) and (3) respectively. Where it is

$$M_c = \int BFWH - SH. \tag{1}$$

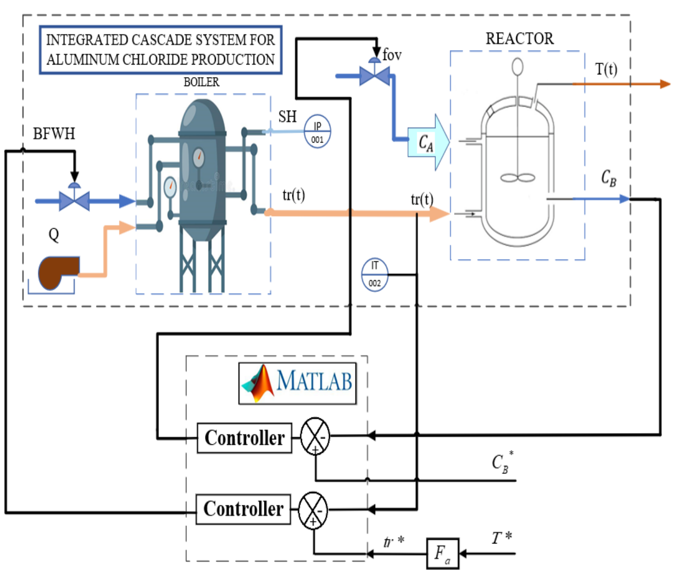

Fig. 1. Integrated cascade system for closed-loop aluminum chloride production.

observed that their units are expressed in tons per cubic meter $\left(\frac{\mathrm{T}}{\mathrm{m}^3}\right)$ and P represents the internal pressure of the boiler.

$$\rho_w = 0.9768 - 9.0803\times10^{-3}P + 1.134\times10^{-4}P^2. \tag{2}$$

$$\rho_s = 7.21\times10^{-5} + 4.996\times10^{-4}P + 3\times10^{-5}P^2. \tag{3}$$

Equations (2) and (3) do not consider the enthalpies used h_w and h_s, that is to say, the energy released corresponding to the steam and water present in the development of the process in the production of steam. Due to these new considerations, it is necessary to obtain new equations where the behavior of the enthalpies that are part of the process is expressed. Subsequently, and in the same way as in the previous case, the equations are obtained through operations in tables and a spreadsheet, which allow obtaining equations (4) and (5) for each enthalpy as a function of pressure. The units in which these differential equations are expressed are given in (kJ/T) kilo Joules over tons.

$$h_w = 0.2769 + 48.949\times10^{-3}P - 7.054\times10^{-4}P^2. \tag{4}$$

$$h_s = 2.6196 + 15.941\times10^{-3}P - 2.806\times10^{-4}P^2. \tag{5}$$

The enthalpy of condensation (h_c) is defined by the difference between the enthalpy (h_s) and the enthalpy of water (h_w) as shown in (6).

$$h_c = h_s - h_w. \tag{6}$$

In (7) the temperature behavior of the boiler is determined, for which the pressure value of the vessel must be known at each moment. This is done by taking into account each of the set values of saturated pressure and temperature, which are previously entered in a spreadsheet [7].

$$t_r = 103.67P^{0.2392}. \tag{7}$$

To determine the model that describes the behavior of the reactor, the principle of conservation of matter is applied considering that the momentum of the continuous reactor does not change under any operating condition, to obtain the total mass balance of the system, where the mass accumulation is equal to the total mass input found in the input flow, minus the total mass output of the output flow with respect to time. The mass consumed by the system must also be considered.

Considering the mass balance of the first component and the mass accumulation we can obtain (8), where the derivative with respect to time of C_A is the mass balance of the C_A component (hydrochloric acid), F is the constant flow at the input and output of the reactor and V is the volume that is considered constant inside the reactor, C_A represents the output flow and C_{A0} the flow at the input, and the chemical reactions produced in series for this case are given by k_1 and k_3. It should be noted that this differential equation is expressed as a function of the internal temperature T of the reactor.

$$\frac{d(C_A)}{dt} = \frac{F}{V}(C_{A0} - C_A) - k_1(T)C_A - k_3(T)C_A^2. \quad (8)$$

In the same way (9) can be obtained, where the derivative with respect to time of C_B is the mass balance of the C_B (aluminum chloride) component, C_B is the aluminum chloride flux at the reactor output and the series reactions produced are expressed through k_1 and k_2.

$$\frac{d(C_B)}{dt} = -\frac{F}{V}C_B + k_1(T)C_A - k_2(T)C_B. \quad (9)$$

The dynamics of the thermal jacket of the reactor is defined by (10). In this case the derivative with respect to time of T corresponding to the dynamics of the temperature inside the reactor, it can be observed the intervention of k_1, k_2, k_3 and corresponding to all the series reactions produced inside the reactor, in the same way the flux density ρ and the heat capacity C_ρ, on the other hand taking into account the heat introduced to the reactor it can be observed that, k_W is the heat transfer coefficient and A_R is the surface area of the reactor, as well as: $(-\Delta H_{RAB})$, $(-\Delta H_{RAD})$, $(-\Delta H_{RBC})$, are the reaction temperatures, T_k which is the temperature in the reactor jacket and T_0 as the initial temperature of the reactor.

$$\frac{d(T)}{dt} = \frac{1}{\rho C_\rho}\begin{bmatrix} k_1(T)C_A(-\Delta H_{RAB}) + \\ k_2(T)C_B(-\Delta H_{RBC}) + \\ k_3(T)C_A^2(-\Delta H_{RAD}) \end{bmatrix} + \frac{F}{V}(T_0 - T) + \frac{k_w A_R}{\rho C_\rho V}(T_k - T). \quad (10)$$

Therefore, the differential equations expressed in (8), (9) and (10) allow modeling the dynamic behavior of the reactor [19].

B. *Methodology for the virtualization of a cascade integrated system for aluminum chloride production.*

In the virtualization of the integrated cascade system for the production of aluminum chloride, the stages shown in Fig. 2 are followed, first all the individual elements of the process (such as sensors, actuators, pipes, tanks) must be modeled in 3D in a CAD software, then assembled and connected correctly to carry out the data export through a connection with the Unity software. The next stage is to integrate the animation and mathematical models developed to carry out the process in Unity, this is done using Visual Studio, then the control algorithms designed within the Matlab software are implemented and the connection between Unity and Matlab is established, using shared memories [16].

III. Design of the Controllers Applied to an Integrated Cascade System

A. *PID Controller Design*

A traditional proportional integral derivative (PID) control strategy is designed for the coupled systems, evaluating their performance in operation when integrated in cascade. For this purpose, the structure of a PID controller is considered as shown in Fig. 3. The variables to be controlled are the steam

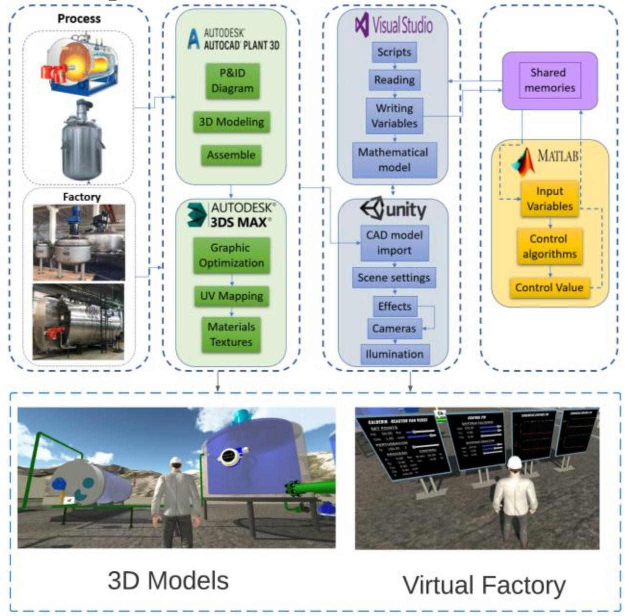

Fig. 2. Methodology of cascading integrated system virtualization.

temperature at the boiler output, which is related to the internal temperature of the reactor. Therefore, $T(t)$ is indirectly controlled. In addition, the C_B concentration of the reactor is controlled. This controller allows manipulation of the input valves corresponding to the $(BFWH)$ high pressure water flow and the (C_A) hydrochloric acid flow.

Within the implemented PID control, k_p represents the proportional gain, T_i the integral gain of the error $e(s)$, and T_d the derivative time constant. To obtain the value of the gains, the Lambda tuning method is used. This requires a transfer function representing the process described in (11), which contains the parameters, representing the process gain K, the open-loop time constant of the process g and the delay τ.

$$G(s) = \frac{K}{1+gs}e^{-\tau s}. \quad (11)$$

Fig. 3 shows the implementation diagram of the PID controllers to the cascade integrated system.

B. *Design of a Predictive Controller Based on MPC Models*

Subsequently, an advanced model-based control (MPC) is designed for the two variables to be controlled $tr(t)$, which indirectly controls $T(t)$ and the (C_B) concentration. Predictive control uses a process model to obtain the prediction of the dynamic variables in function of which the control signals are obtained by minimizing an objective function. This structure has the following elements: (i) the explicit use of the model to predict the evolution of the process at future times; (ii) the minimization of the cost function respecting the restrictions in its formulation; (iii) the use of a limited and sliding control range, which means calculating the control sequence for the whole range, and

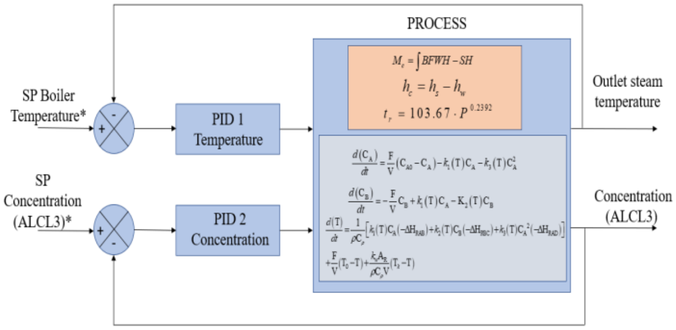

Fig. 3. PID controller structure.

applying the first signal of the sequence, as well as repeating the whole process at subsequent sampling times [15].

The models are used to predict the evolution of the process outputs or states from known input and output signals. The predicted variables are the boiler output steam temperature $\hat{tr}$ and concentration ($\hat{C}_B$), obtained from the prediction model. These obtain the prediction vectors, all in the same prediction horizon (N_p) which are inputs to the optimization problem. Next, the future control actions are calculated using an optimizer that includes an objective function subject to constraints. In (12) the objective function is detailed, which seeks to minimize the quadratic error of temperature at the output of the boiler tr, as well as the quadratic error of the concentration C_B, while minimizing the control action changes Δ_{u1} and Δ_{u2} for tr and C_B, respectively.

$$J(k)_{u1,u2} = \sum_{i=1}^{N_p}\left[\begin{array}{l}\delta_1(k)\left[\hat{tr}(k+i|k)-tr^*(k+i|k)\right]^2+\\ \delta_2(k)\left[\hat{C}_B(k+i|k)-C_B^*(k+i|k)\right]^2\end{array}\right]+\sum_{i=1}^{N_u}\lambda_1(k)\left[\Delta_{u1}(k+i-1)\right]^2+\lambda_2(k)\left[\Delta_{u2}(k+i-1)\right]^2. \quad (12)$$

Where N_p and N_u are the prediction and control horizon respectively, $\delta(k)$ and $\lambda(j)$ are the weights given to each control target, $\hat{tr}(k+i|k)$ is the temperature prediction at the boiler output , with i steps ahead calculated with known data at time instant k, $tr^*(k+i|k)$ is the future temperature reference trajectory at the boiler output, while $\hat{C}_B(k+i|k)$ is the predicted aluminum chloride concentration at the reactor output, $C_B^*(k+i|k)$ is the concentration reference trajectory in the reactor, $[\Delta_{u1}(k+i-1)]$ is the control action that manipulates the opening percentage of the high pressure water valve, and $[\Delta_{u2}(k+i-1)]$ is the control action that manipulates the opening percentage of the hydrochloric acid valve at the reactor input. It should be clarified that the control actions are given by a vector of values, but in real life only the first value of each of the vectors corresponding to the control actions is taken into consideration. The objective function for the MIMO system, detailed in (12), seeks to minimize the temperature error at the boiler output and the concentration error. At the same time, the variations of the actuator control action.

There are limitations of the plant which in the optimization problem are the inequality restrictions, the first restriction of the optimization problem is indicated in equation (13) are the opening percentage of the liquid valve defined as Δ_{u1}, responsible for handling the flow of high pressure water and Δ_{u2} which is responsible for handling the flow of hydrochloric acid entering the reactor, these being the control actions, it should be noted that the two have the maximum value $\Delta_{u\max}=1$ and the minimum value $\Delta_{u\min}=0$.

$$\begin{array}{l}\Delta_{u\min} \le \Delta_{u1} \le \Delta_{u\max}\\ \Delta_{u\max} \le \Delta_{u2} \le \Delta_{u\max}.\end{array} \quad (13)$$

$$\hat{tr}_{\min} \le \hat{tr} \le \hat{tr}_{\max}. \quad (14)$$

$$\hat{C}_{B\min} \le \hat{C}_B \le \hat{C}_{B\max}. \quad (15)$$

The second inequality constraint in equation (14) describes the temperature limits at the boiler output in this case are $tr_{\min}=140$ [C°] and $tr_{\max}=395$ [C°], the third inequality constraint is shown in (15) which describes the reactor aluminum chloride concentration limits $C_{B\min}=0$ [mol/m³] and $C_B=2.5$ [mol/m³]. It is important to note that the prediction horizon needs to be larger than the control horizon. The control horizon is small because it has better control actions. In Fig. 4, the implementation diagram of the MPC predictive controller to the cascade integrated system is shown.

IV. Results

A. *Virtual environment of the integrated system of a boiler and a cascade reactor for aluminum chloride production*

This section presents the implementation of a virtual environment for the production of aluminum chloride from a boiler integrated in cascade to a continuously stirred (Fig. 5).

The virtualization methodology of section I is applied where the mathematical models of section II describing the dynamics of the boiler and the cascade reactor are applied. The virtual environment is incorporated, as well as visualization and control screens, instrumentation components and animations of its elements. The virtual environment is created in the Unity tool. While the control algorithms are contained in a script in the Matlab mathematical laboratory, the bilateral communication between the process and the controller is done through shared memories created through the "smClient64.dll" library in Matlab, which allows writing data corresponding to the control actions, and in turn allows reading the set point changes, perturbations and tuning parameters for PID and MPC controllers.

An immersive industrial environment that closely resembles reality is obtained, which includes a control center in the virtual environment, through which the process can be controlled through the computer peripherals, which in turn control an avatar that can move around the workstation according to the applied configuration. This makes it possible

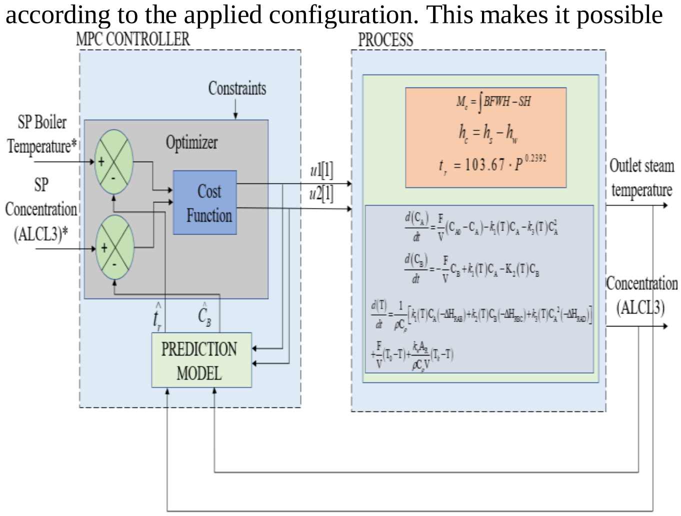

Fig. 4. Structure of the advanced controller based on MPC models

Fig. 5. Virtualization of industrial elements (boiler and reactor).

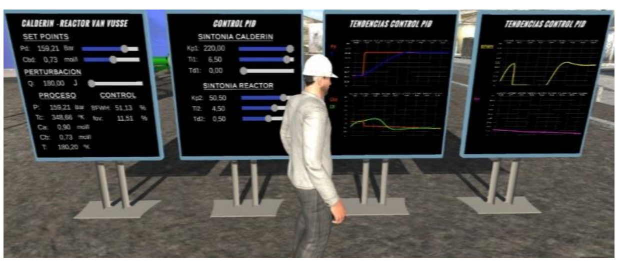

Fig. 6. Trends to PID and MPC controller responses

TABLE I
PARAMETERS USED IN THE REACTOR AND THE BOILER

Parameters	Value	Unit
k_{10} / k_{20}	1.287×10^{12}	h^{-1}
k_{30}	9.043×10^{09}	L/molA.h
($-E_1/R$) / $-E_2/R$)	–9758.3	K
$-E_3/R$	–8560.0	K
$-\Delta H_{RAB}$	–4.20	kJ/molA
$-\Delta H_{RBC}$	11	kJ/molB
$-\Delta H_{RAD}$	41.85	kJ/molA
ρ	0.9342	Kg/L
C_p	3.01	kJ/kgK
k_w	4032.0	$kJ/h.K.m^2$
A_R	0.215	M^2
V	10	L
T_0 / F_a	130.0 / 1.0120	°C
T_k	128.95	K
C_{A0}	5.10	molA/L

to visualize the evolution of the variables on an HMI interface as shown in Fig. 6.

The values of the parameters used for the reboiler and the reactor are shown below [7], [19].

B. *Performance of the designed drivers*

This section analyzes the control strategies applied to the integrated system of a boiler and a cascade reactor for the production of aluminum chloride. The temperature and concentration variables are controlled, reaching their respective set point.

For the analysis of the cascade system performance, PID and MPC controllers are compared. Two PID controllers are designed, one for the steam temperature variable at the reboiler outlet, whose gains are: PID: $k_p = 200$, $T_i = 6.5$, $T_d = 0.0002$ and another for the aluminum chloride concentration variable at the reactor outlet, whose PID design gains are: $k_p = 50.5$, $T_i = 4.5$, $T_d = 0.0002$. While for the centralized MPC controller that controls the two variables, the following tuning parameters are defined, where the prediction horizon takes 12 samples $N_w = 12$ and the control horizon takes 4 samples $N_c = 4$, every 0.1 second, the weight related to temperature error $\delta_1 = 30$, weight related to temperature error $\delta_2 = 30$, weight related to the variation of pressure control actions $\lambda_1 = 0{,}0000001$, and the weight related to the variation of temperature control actions $\lambda_2 = 0{,}0000001$.

C. *Analysis of the boiler process*

In II shows the comparative results of the performance of the steam temperature variable at the boiler outlet, and an analysis is performed in transient state such as settling time, rise time, maximum peak overshoot and in steady state the steady state error.

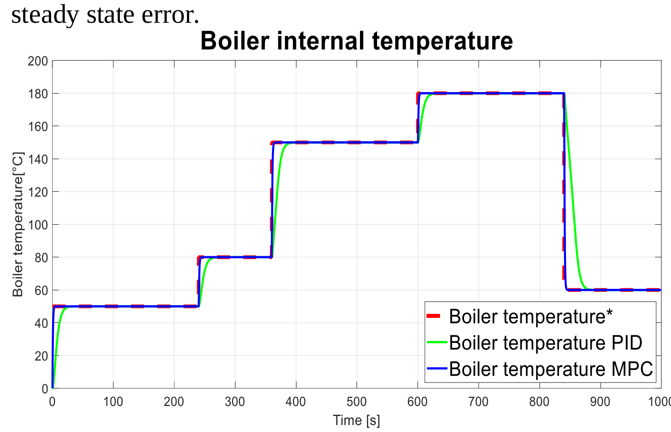

Fig. 7. Steam temperature at the boiler outlet, when PID and MPC controllers are applied.

TABLE II
DYNAMIC BOILER TEMPERATURE CHARACTERISTICS

Parameters	PID	MPC
% Over impulse	0.0873%	0%

Settlement time	42 s	6.9 s
Rise time	10.8 s	1.3 s
Error in stable state	0 bar	0 bar

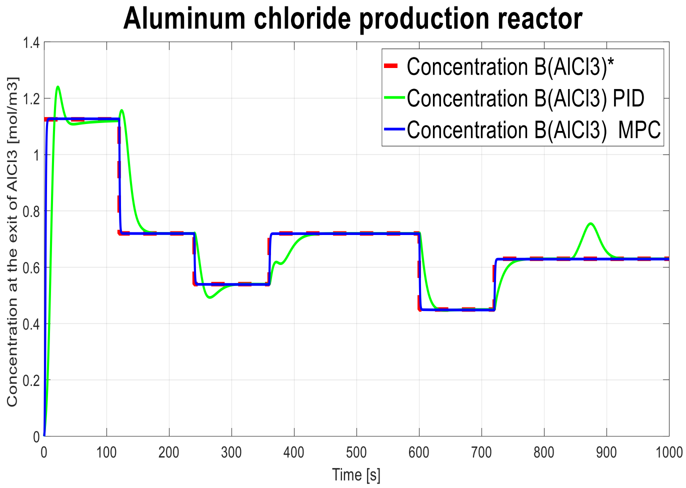

Fig. 8. Aluminum chloride concentration at reactor outlet, when applying PID and MPC control.

TABLE III
DYNAMIC CHARACTERISTICS OF THE REACTOR CONCENTRATION

Parameters	PID	MPC
% Over impulse	7.73 %	0 %
Settlement time	877.9 s	7.8 s
Rise time	41 s	2 s
Error in stable state	0.0004 mol/m^3	0.08 mol/m^3

It is possible to observe a correct performance of the two control strategies in the face of changes in the pressure of the reference boiler. However, it can be noted that the MPC controller has better dynamic characteristics compared to those of a traditional PID controller.

Fig. 7 shows a comparison of the two control strategies verifying that the MPC controller has better dynamic

D. Analysis of the reactor process

For the second system corresponding to the behavior of a perfectly stirred reactor which will allow the production of the chemical component aluminum chloride which in turn is a chemical that has a great variety within the industry. In order to carry out the task, a traditional PID controller was implemented and compared with an MPC in order to stabilize the internal temperature of the reactor which is fed with a constant steam flow at a certain temperature produced.

As can be seen in Fig. 8, the green trend represents the behavior of the aluminum chloride concentration at the reactor outlet once a traditional PID controller is implemented with different set point changes, where it can be seen that the controller is able to stabilize the system adequately, once implemented, the dynamic characteristics of this controller can be observed, which are detailed in III.

As can be seen in the following Fig. 8, the predictive controller is much faster than the traditional PID controller, that is that it has a shorter rise time compared to the rise time of the traditional controller, and it has no overshoot, in short, the MPC controller has several dynamic characteristics which are better compared to the traditional PID controller, these dynamic characteristics can be seen in III. The model-based MPC controller has better performance for this cascade system.

E. Performance of PID and MPC controllers against constrains entered into the reboiler

In order to analyze the robustness to constrains in the cascade system, a constrain is applied to the boiler, corresponding to a change in the fuel flow valve, at 1000 seconds and 1800 seconds inside the boiler as shown in Fig. 9. When entering this constrain it is observed that the steam temperature output at the outlet of the boiler implemented the traditional PID controller suffers a transient in its signal, on the other hand, the response of the MPC controller are negligible alterations in its signal after having entered constrains in the same time instances.

F. PID and MPC Controller Response against Constrains Inside the Reactor

In the same way that external constrains are implemented in the reboiler, a constrain is introduced into the reactor system fed in cascade by the reboiler, this constrain corresponds to an alteration in the hydrochloric acid flow valve, which is one of the reactor inlets.

As shown in Fig. 10, the behavior of the aluminum chloride concentration once the traditional PID controller is implemented, a constrain can be noticed at 1004 seconds, which causes an alteration in the behavior of the

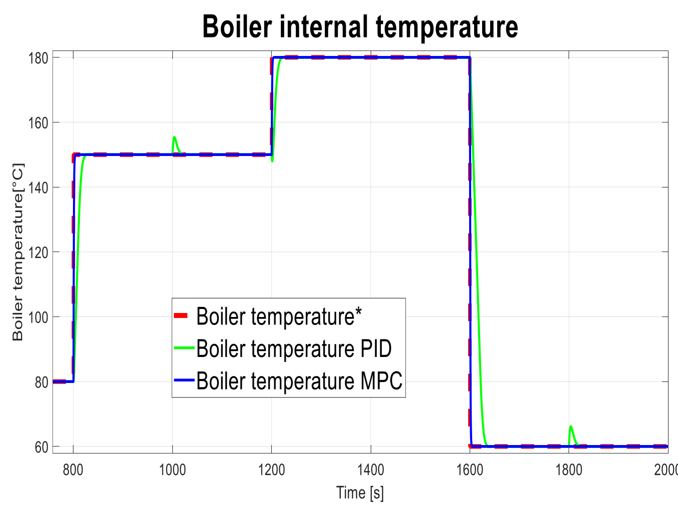

Fig. 9. Steam temperature at the boiler outlet, when applying PID control, MPC and external constrains.

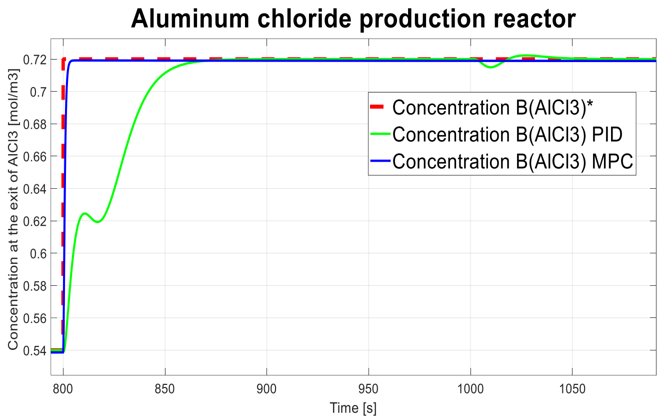

Fig. 10. Aluminum chloride concentration at the reactor outlet, when applying PID and MPC controllers and external constrains.

concentration. Meanwhile, when the same constrain is introduced in the system once the MPC predictive controller is implemented, it can be observed that the concentration behavior at the reactor output presents insignificant transient alterations, therefore, the MPC controller is more robust to external constrains than a traditional PID controller.

V. Conclusions

VI. In this work, the performance of an integrated system in cascade of two processes is evaluated, a boiler connected to a continuous stirred reactor to produce aluminum chloride, the system is virtualized by observing the dynamics of the variables close to the real one in an immersive industrial environment, user friendly, to achieve this it is necessary a nonlinear mathematical model of the integrated system. The system is flexible to operate in open loop as well as in closed loop. The virtual plant is used to evaluate traditional and advanced control algorithms, with the use of shared variables. By applying two control techniques PID and MPC, it can be evidenced that the advanced MPC controller presents a better performance in terms of maximum over impulse, settling time and steady state error, compared to a traditional PID controller. In addition, the control actions are not so abrupt which allows to increase the actuator lifetime. On the other hand, the controllers are evaluated against external disturbances in both the boiler and the reactor, noting a rapid recovery of the boiler output steam temperature, as well as the aluminum chloride concentration at the reactor output and indirectly the reactor internal temperature with the MPC controller as opposed to the PID control.

References

[1] N. Agudelo, G. Tano y C. A. Vargas, “Historia de la automatización,” Universidad *ECC,* 2018.

[2] M. Kaneko, R. Hayashi y . G. R. Cook, “Intermolecular Friedel–Crafts reaction catalyzed by InCl3.,” *Elsevier,* p. 3, 2007.

[3] S. Hernández Ostos y J. Useche Cadena, “Balance de energía en un reactor de producción de etilbenceno,” *Universidad Nacional de Colombia,* p. 13, 2013.

[4] A. Diaz, J. Carpintero y J. Fabregas, “Modelado, simulación y control de un reactor en la producción de cloruro de aluminio,” *Prospect.,* vol. 10, nº 2, pp. 31-36, 2012.

[5] D. Mahboobeh , S. Karim y M. Behzad , “Adaptive Generalized Predictive Control And Model Reference Adaptive Control For CSTR Reactor,” *International Conference on Intelligent Control and Information Processing,* p. 5, 2010.

[6] E. Peña T, A. J. Miranda, A. R. Pérez R y J. H. Sánchez L, “Modelado de un reactor químico tipo CSTR y evaluación del control predictivo aplicando Matlab-Simulink,” *Revista Ingeniería UC,* vol. 15, nº 3, p. 17, diciembre 2008.

[7] J. Peñalba , “Modelado y Simulacion de una Caldera convencional,” 2004.

[8] T. Orrala, D. Burgasi, . J. Llanos y D. Ortiz-Villalba, “Model predictive control strategy for a combined-cycle power-plant boiler,” *IEEE International Conference on Automation/XXIV Congress of the Chilean Association of Automatic Control (ICA-ACCA),* p. 1–6, 2021.

[9] B. Dennis, T. Orrala, J. Llanos, D. Ortiz Villalba, D. A, C. Ponce y . A. A, “Fuzzy and PID controllers performance analysis for a combined-,” *XV International Multidisciplinary Congress on Science and Technology,* p. 15, 2020.

[10] L. Barrios y R. Trejo, “Implementación de diferentes esquemas de control para el análisis de las calderas pirotubulares y acuotubulares bajo diferentes condiciones de operación,” Noviembre 2008. [En línea]. Available: http://mriuc.bc.uc.edu.ve/bitstream/handle/123456789/7860/lubarrios.pdf?sequence=1.

[11] D. Peng, H. Zhang, P. Yang, Y. Wang y C. Xu, “Adaptive inverse control for water level of boiler drum based on neural network,” *6th World Congress on Intelligent Control and Automation,* vol. 1, pp. 2911-2915, 2006.

[12] Y. Jianhua, L. Wenqi y L. Wei, “Fuzzy Predictive Control of Steam Dryness for Steam-injection Boiler,” *Chinese Control Conference,* pp. 395-398, 2007.

[13] J. L. Valdés Piñeda , R. Rivas Pérez y G. Rosaines Ayala, “Design of a control system based on the smith predictor of steam pressure in a fire tube bolier,” *xvii convencion t feria internacional 18 international convention and fair,* pp. 1-9, 2022.

[14] K. A. Valencia y L. A. Joaqui, “Realidad Virtual En La Industria: Capacitación Del Personal,” *Programa de Ingeniería Industrial,* 2017.

[15] F. Flores Bungacho, J. Guerrero, J. Llanos, . D. Ortiz Villalba, A. Navas y P. Velasco, “Development and Application of a Virtual Reality Biphasic Separator as a Learning System for Industrial Process Control,” *Electronics,* 2022.

[16] D. . J. Chanchay Gualoto , J. . D. Feijoo Marin , J. Llanos y D. Ortiz Villalba, “Advanced Controllers for Level and Temperature Process Applied to Virtual Festo MPS® PA Workstation,” *Springer,* 2020.

[17] J. D. Chanchay, J. D. Feijoo, J. Llanos y D. Ortiz-Villalba, “Virtual Festo MPS® PA workstation for level and temperature process control,” *International Conference on Intelligent Information Technology,* pp. 164-180, Octubre 2020.

[18] N. R. B. Saravia, “Control de temperatura de un reactor quimico utilizando estrategias de control optimo y adaptlvo,” Callao, 2011.

[19] J. Trierweiler, “A systematic approach to control structure design.,” 1997.

[20] D. D. Amores, E. P. Lema, L. D. Guerrero, V. H. Andaluz, B. A. García, A. V. Guanopatín y J. Varela Aldás, “Virtual Control of a Perfectly Stirred Reactor for Cyclopentene Production,” *Springer Nature Switzerland,* p. 11, 2021.