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Design and fuzzy controller for a crude oil pre-heater in a virtual environment

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ABSTRACT

Crude oil dilatation process is one of the most important and costly for the industry, but it has also a huge gap for the implementation of new tools and techniques to improve quality and efficiency of the process. The furnace pre-heater is a fundamental part of the process; the distillation tower efficiency depends on its performance. For this reason, is highly important to improve the temperature control, by means of digital tools to verify the controller and save time. This work shows the creation of a virtual environment, where several actions of modern control can be proven on the furnace, connecting Unity 3D® and Matlab® by means of a TCP/IP network, developing a CAD model aiming to obtain the mathematical model that represents it, a fuzzy controller is also created and the result graphs of response and error are analyzed to verify the optimal performance. The above is completed aiming to provide guidelines for connected virtual environments development and have a complete learning experience.

KEY WORDS

Pre-heater, control, virtual environment, Unity.

INTRODUCTION

The crude oil distillation is one of the most important and costly techniques, the energy required for the process is considered high in comparison with other petrochemicals processes [1]. The requirement of improvement of this kind of systems, allows the development of new control techniques, to obtain better efficiency and reducing cost by using virtual simulation tools that also shows the plant behavior and allows testing and workshops [2].

The furnace pre heater is an essential piece of the refining process, it increases the fluid temperature by heat transfer of a gaseous state substance [3]. The furnace performance is altered by the thermic unbalance, due to the changes in the stabilization times of the equipment [4].

Due to all of the above, a control system implementation is required to improve the efficiency, keep a stable performance and make better profits by the optimization of the heat transfer process[5].

The fuzzy logic based controllers, are designed to face system's non-linearity and represents an interesting control alternative due to the possibility of adding the process behavior knowledge to the controller actions[6].

Controllers development and simulation, is complemented by the improvement of digital platforms[7]. By means of this tools a mathematical function is simulated and its impact in a virtual model is analyzed to verify its behavior[8].

These virtual environments are used aiming to improve the learning quality and the usage of physical resources. Cutting down training costs and new technique tests like controllers optimization [9].

Some related works are, Virtual laboratory for control and simulation of parallel robots , where the controllers response is studied at dynamic singularity situations of the system[10]; Virtual laboratory for thermoelectric material design, where the behavior of several materials can be compared to different [11]; 3D Virtual World for data acquisition systems, where a tool where developed for the training of operators with specialized equipment.

This work presents de design of a crude oil pre-heater furnace 3D model, the obtainment of the representative mathematical model, and the temperature fuzzy logic controller. Aiming to develop a 3D environment in Unity 3D®, where the furnace is controlled from Matlab®, by the analysis of the software's result graphics in both programs. The first contribution to this work is the development of a virtual environment for direct test from Simulink® to improve the learning experience.

MATERIALS And METHODS

CAD Model:

The furnace model design is based on[12], where some design standards are generated. In figure 1 the furnace measures are defined in mm.

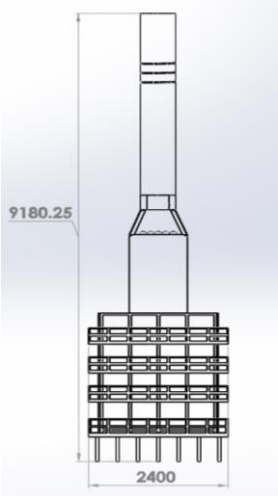

Fig. 1: Furnace measurements

The essential parts of the furnace are modeled as shown in figure 2.

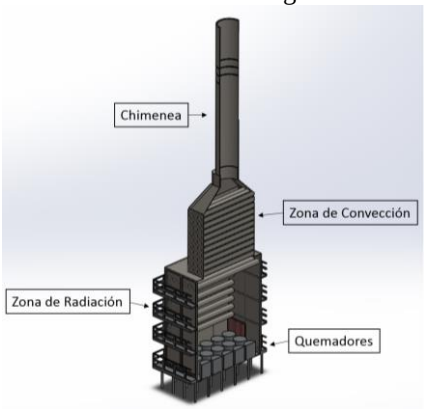

Fig. 2: Pre-heater furnace parts

- Fireplace: Conduit for the expulsion of gases.
- Burner: Combustion of the combustible fluid.
- Radiation and convection zone: 25 tubes arranged horizontally arcuate and tube bank 75 respectively by these zones circulate the working fluid (oil).

Burner mathematical model:

The values for the development of the mathematical model are stablished in table 1.

Table 1: Reference Values

Parameter (unit)	Symb	Value
Process Fluid flow Rate (kg/s)	$\dot{m}_{in}$	73.6
Process Fluid Inlet Temperature (°C)	T_{in}	233
Process Fluid Outlet Temperature (°C)	T_{out}	370
Process Fluid Inlet Pressure (bar)	P_{in}	16.32
Process Fluid Inlet Pressure (bar)	P_{out}	3.22
Combustion Air Pressure (bar)	P_{air}	1.01

Estimated Fuel Gas Flow Rate (kg/s)	$\dot{m}_{fuel}$	0.895
Estimated Combustion Air Flow Rate (kg/s)	$\dot{m}_{air}$	16.46
Fuel Gas Lower Heating Value (MJ/kg)	LHV	47.1
Efficiency of LHV	-	76%
Metal Temperature (°C)	T_a	424
Efficient Process Volume (m^3)	V	4.28
Process Fluid Density (kg/m^3)	ρ	847

The following equation shows the general balance of energy for the burner.

$$\frac{d}{dt}\left[\rho.\mu.V + m_a.C_{p.}T_a\right] = \dot{Q} + \dot{m}_{in}h_{in} - \dot{m}_{out}h_{out} \quad (1)$$

Equaling $\mu = h - p.V$ and considering that que $C_p = \frac{\partial h}{\partial T}P$ y $\frac{dh}{dt} = \left(\frac{\partial h}{\partial T}\right)\left(\frac{dT}{dt}\right)$, we obtain equation 2 assuming that the metal temperature is the same of the process [13].

$$\frac{dTout}{dt} = \frac{1}{\rho.V}\left[\frac{\dot{Q}}{C_p} + \dot{m}_{in}(T_{in} - T_{out})\right] \quad (2)$$

The equation 3 defines enthalpy as the heat released per unit mass.

$$\Delta hR\left(\frac{kJ}{kg_{MIX}}\right) = \left(\frac{m_{fuel}}{m_{fuel}+m_{air}}\right)\Delta hR = \left(\frac{1}{\frac{A}{F}+1}\right)\Delta hR \quad (3)$$

The furnace pressure changes as considered in [14], are expressed in equation 4, where $\frac{A}{F}$ represents the mole fraction of fuel. n_{com} y n_{prss} It is the thermal coefficient of efficiency and burner pressure.

$$\dot{Q} = n_{com}\left(\dot{m}_{fuel}\Delta hR\left(\frac{\frac{A}{F_{com}}+1}{\frac{A}{F_{sto}}+1}\right)\right) - n_{prss}\left(P_{air} - P_{por}\right) \quad (4)$$

The flame height can be estimated according to the equation 5 [15]; where Hf is the height, Q is the heat flux and D the flame diameter.

$$H_f = 0.235\dot{Q}^{2/5} - 1.02D \quad (5)$$

To take into account the system´s pressure drop, in equation 6 Bernoulli's law is stablished, excluding friction losses and height changes.

$$\frac{p}{\rho} + \frac{V^2}{2} = K = constante$$

(62)

In accordance with the above a linear model is obtained, as it is illustrated in figure 7, where u(t) is the fuel flux to the burners and y(t) the temperature of the oil output.

$$G_0(s) = \frac{\Delta Y(s)}{\Delta U(s)} = \frac{K_0}{(1+T_{10}s)(1+T_{20}s)} \quad (7)$$

Stablishing the following values K_0=3.66 °C/% as static gain, $T_{10} = 51.2s$ y $T_{20} = 12.1s$ as time constants, the equation 8 function is obtained.

To be able to program a model that represents the furnace burner in a virtual environment, discretizing the model function is required, Z transform is applied to equation 8, with a zero-order hold and a sample time of 10 seconds, obtaining the following equation.

Calculation the difference equation, the following is obtained:

The system open loop response to the unit impulse is illustrated in figure 3.

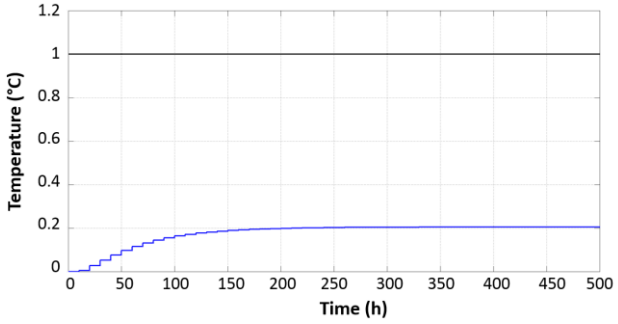

Fig. 3: Open loop system response.

Fuzzy logic controller design:

The fuzzy controller is based in zthe membership functions and the linguistic logic [16]. In this the membership function, can take range values between 0 and 1, the general scheme of the controller is shown in figure 4, it represents a fuzzy PD. The integral constant is not linked to the controller because cero error in stationary state is required.

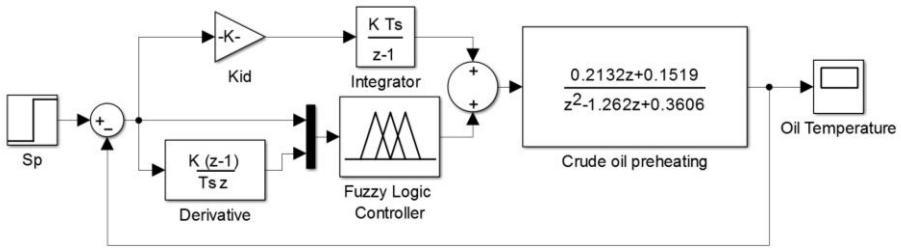

Fig. 4: Fuzzy logic system scheme

The controller starts with the fuzzification that represents the real values, fuzzy values assigned to membership levels to each variable [17]. To obtain the membership level of each parameter, the function in equation 12 is applied, it represents a trapezoidal function.

$$\mu(x) = \begin{cases} \frac{x-a}{b-a} & a < x < b \\ 1 & b < x < c \\ \frac{d-x}{d-b} & c < x < d \\ 0 & x < c \text{ ó } x > d \end{cases} \quad (12)$$

Three membership functions are raised, one for each parameter (Error and speed error). The work ranges of each function are stablished with the knowledge of model of the input variable ranges.

In figure 5 the three membership functions are illustrated for the system error, where a symmetry range is stablished -1000 a 1000 °C.

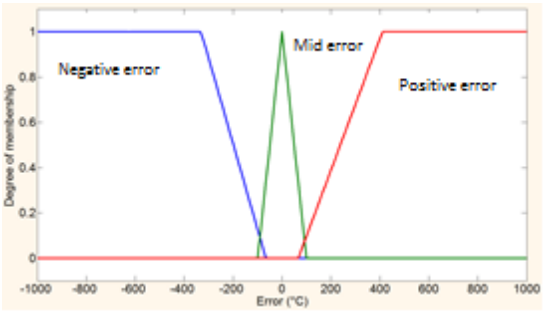

Fig. 5: Membership functions – System error

The rate of change of the error varies from -1.5 to 1.5 °C/s, for this the corresponding membership groups are shown in figure 6.

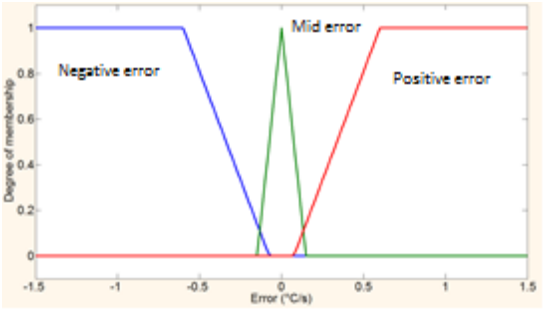

Fig. 6: Membership functions – Error Derivative

The output parametrization is shown in figure 7, where three functions are defined, depending on the range of values of the control signals, this were proposed to relate and crate the fuzzy logic system rules with the inputs.

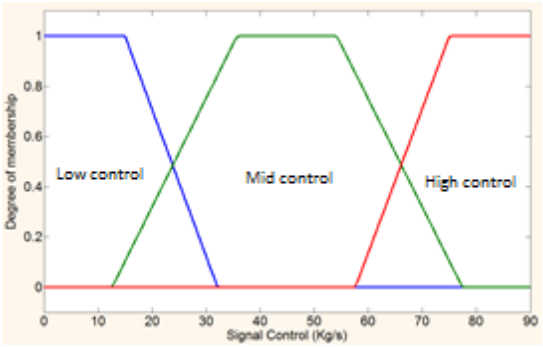

Fig. 7: Trapezoidal output functions

The Mamdani method use (if-else) rules[18], composed by the background and the conclusion, the systems rules are presented in table 2.

Table 2: Fuzzy logic system rules

Error	Derivative error	Control
Negative error	Negative error	Low
Negative error	Mid error	Low
Negative error	Positive error	Low
Mid error	Negative error	Low
Mid error	Mid error	Medium
Mid error	Positive error	Medium
Positive error	Negative error	Medium
Positive error	Mid error	High
Positive error	Positive error	High

The system has 9 rules that link the different I/O functions, the system behavior according to the parametrization shown in figure 8, in the working surface.

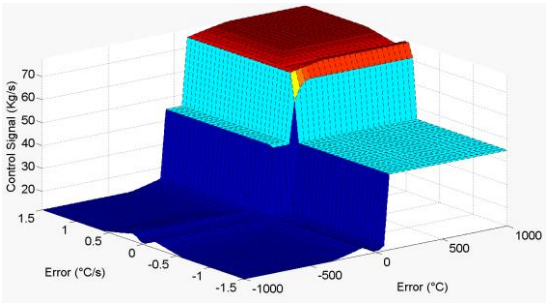

Fig. 8: System working surface

From the above figure, can be noticed that the system responds directly to the error input, the error derived attenuates the control.

The centroid method is used for the process of defuzzification, Its equation is expressed in 13; R is the number of rules, X is the maximum value and $\mu_A(x)$ membership value [19].

In figure 9 the behavior of the controlled system can be observed by the reference of 370°C.

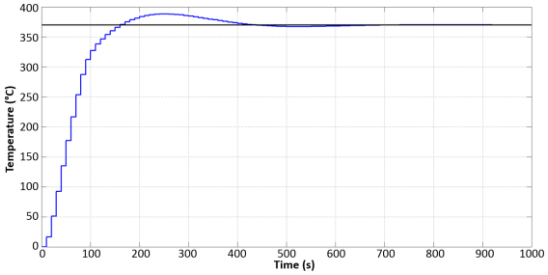

Fig. 9: Controlled system response

Results:

The crude oil pre-heat furnace 3D model is integrated inside a virtual environment, as shown in figure 10. The element has programmed the difference equation that represents it.

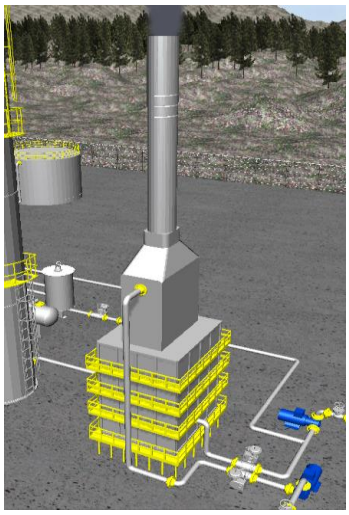

Fig. 10: Unity 3D® furnace model

The scheme in figure 11 represents the integrated system control, it has a reference point, the fuzzy logic controller and the signal conditioning steps for the usage of the TCP/IP communication blocks of Matlab®.

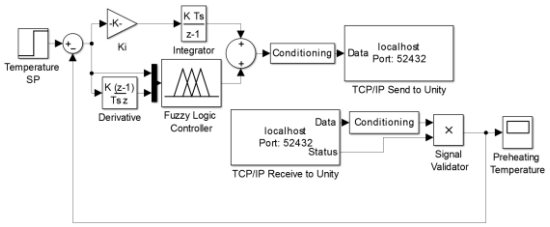

Fig. 11: Control and communication scheme

For the controlled system test, a 370°C desired reference is stablished, the same selected for the output in the mathematical model and 10 seconds of sample time.

In figure 12, the obtained response, using the fuzzy controller can be observed in the virtual environment.

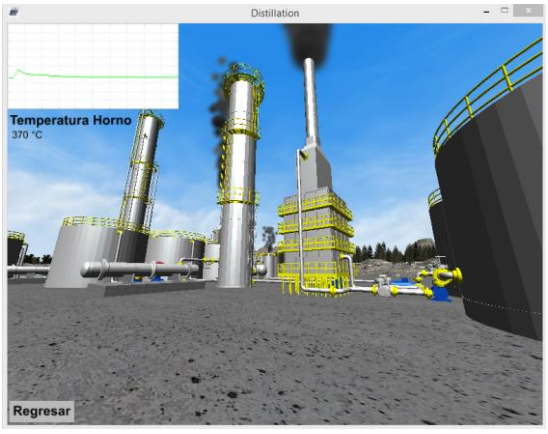

Fig. 12: System response

The stabilization time for the 3D simulation is 550 seconds, which is the same obtained during the controller design. In this way both programs are synchronized, a very important aspect due to the exact sample time used.

The controller works as expected as observed in 13, where the burners input flux can be observed. According to the graphics to heat up the crude oil to 370°C, 130Kg/s of fuel are required.

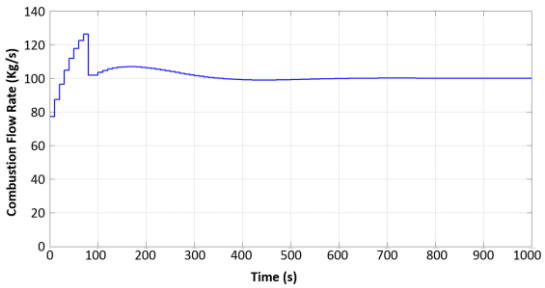

Fig. 13: Control signal

Conclusions:

The oil crude pre-heater furnace model design, and the obtained mathematical model, aiming to include it in a virtual environment and develop the fuzzy logic controller, for the output temperature of the compound. Showed that simulation is a useful tool for the test of industrial processes.

The connection between Matlab® and Unity 3D® proves to be a versatile tool for simulating controllers and test them in virtual environments to evaluate its performance.

The implementation of artificial intelligence controllers requires a systematic process, where the rules and the membership functions can be improved, this is an advantage because any system can be set to its own conditions.

The virtual environments and labs, allows the improvement of new learning techniques and competences, where the student can face, real industrial situations with all the required tools to develop their knowledge.

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