**Fuzzy Control PID in cascade of crude oil preheating furnace**

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**ABSTRACT**

In a furnace is carried out a transfer of heat from one fuel to another, and it is fundamental in the distillation process since it is responsible for heating the crude oil to the required temperature, which prepares for the separation of the components. Due to the importance of the equipment in the process necessary to consider the design of a controller that allows to handle properly the fuel and make the energy consumption caused by perturbations in the system will be reduced with the robustness of a controller type waterfall. In this work we present the model, control and simulation of an industrial oven, typically used for preheating of crude, all this is obtained from the balance sheets and thermodynamic relations. As a result, more important, is the design of a cascade controller type from the dynamic model taking into account two controllers type fuzzy PID, which arise in order to reduce the impact of the shocks, the external controller seeks to rectify the operation of the procedure.

**KEYWORDS**: Furnace, oil, simulation, mathematical modeling

**INTRODUCTION**

The heating furnace is a heat engineering team important in the production of the metallurgical industry, the level of the heater control will directly affect the product quality, performance and consumption of production[1][2].

Based on the distillation of crude oil to warm up to the temperature of the level and requirements in addition to the quality, and under the premise of high performance, maintaining as much as possible the reduction of fuel consumption and reduce the burning of oxidation[3].

The behavior of the oven is not linear, its temperature regulation depends mainly on the control flow of gas, therefore, the establishment of a control of gas flow is reasonable is the key to achieving a smart control of combustion[4].

Currently, classical PID have an increased use in the control of the temperature of the heating furnace of crude, but often cannot be overcome effectively the interference, the shift of the burden or the system parameters and other factors[5]. At the same time, there are many features of the system such as the non-linearity, it heavily engaged, large delay time and other[6].

Then the expectation cannot be achieved by traditional control method. On the basis of a large number of theoretical studies, the diffuse control has a strong application in the system of heating furnace oil[7].

The furnaces are the most important basis to industrial level in units of oil refineries and petrochemical processes. Used in the oil warmed to the desired temperature through the combustion process[8].
The furnaces can have single or multiple flows according to their structures. They are formed from the regions of convection and radiation. The transformation of heat between the gas and oil flows is performed in the regions of convection and radiation. What makes necessary a sufficient amount of oxygen for the control of the process.

In Figure 1 shows a diagram of a preheating oven of crude, in which identifies their parties. Among these are the burners, responsible for entering the air and fuel, coils, consisting of pipes, the area of radiation, where it is carried out the combustion, the convection zone, which retrieves additional energy, and a pipeline of output of gases to the atmosphere.

Among some of the related work, in the area of modeling and diffuse control is the submitted by [13]. In which develops the mathematical model, by means of the thermodynamic principles, and is designing a temperature control system, based on fuzzy logic, for an industrial oven plugs of crude. As the main result is evaluated the control system designed in different points of operation with presence of shocks.

In [14] There is a temperature control system based on a modified Smith predictor. As the main result is presented the mathematical model that describes all the dynamics of the process, in addition to the development of a PI controller embedded in a predictor of Smith, taking into account the refusal to shocks.

With regard to strategies for the control of the temperature variation, this [15], in which it is carried out the description of the operation of the kiln of the Refinery Nico López. As the main result is displayed, the study of control techniques, based on the Smith predictor, also check the results, when the process is subject to external shocks.

Based on the foregoing, in this work is carried out the design of a system of fuzzy control pid type waterfall, and simulation, for a preheating oven of crude. The objective is to minimize the impact of the shocks in the process and improve the energy use of equipment, raising two drivers fuzzy type PID in cascade by means of a rectification by the external controller to internal controller.

**MATERIALS AND METHODS**

The components of the temperature control system for the furnace is shown in figure 1. Where T1C is the primary controller, T2C is the secondary controller, T1T represents the measurement of the temperature at the outlet of the oven and T2T represents the temperature in the heart of the oven.

**Fig. 1:** Suffer from oil preheating furnace

**Fig. 2:** Diagram suffer from oil preheating furnace
The controller output primerio (T1C) is incorporated as the setpoint of the secondary controller (T2C). T2C controls the flow of fuel. In the process, the material that is placed in the coil is heated to a temperature specified. The disruption of load and the quality of the material, are alterations of a type and on the other hand are those related with the fuel, the pressure and the flow of air.

For the modeling of the kiln is applied the equations of thermodynamic laws and the respective balance sheets, taking into account the properties of the Flow[4]. The Equation 1 represents the global energy balance for the oven.

\[
\frac{d}{dt} \left[ \rho \cdot \mu \cdot V + m_a \cdot C_p \cdot T_a \right] = \dot{Q} + m_{in} h_{in} - m_{out} h_{out} \tag{1}
\]

In steady state conditions the temperature of the metal is close to the temperature of the process by which can be despised by the equation 2

\[
\rho \cdot V \cdot C_p \frac{dT}{dt} + m_a \cdot C_p \cdot T_a = \dot{Q} + \dot{m}_{in} (T_{in} - T_{out}) \tag{2}
\]

The model parameters taken in stationary state, applied to the equation 3, allows you to calculate the heat released by the combustion process.

\[
\frac{d\dot{Q}}{dt} = \frac{1}{\rho \cdot V} \left[ \dot{Q} + \dot{m}_{in} (T_{in} - T_{out}) \right] \tag{3}
\]

The combustion process is modeled on the basis of the chemical reaction. A balanced relationship for any fuel system of reaction with air can be represented by the equation 4

\[
C_aH_b + \gamma \left( a + \frac{b}{2} \right) O_2 + 3.76 N_2 \rightarrow aCO_2 + \frac{b}{2} H_2O + dN_2 + eO_2 + fNO_x + gCO + \cdots \tag{4}
\]

To define the enthalpy as the equation 5 the heat released as a unit by mass, can be represented by the equation 6.

\[
\Delta h_R = h_{prod} - h_{react} \tag{5}
\]

\[
\Delta h_R \left( \frac{k_f}{kgMix} \right) = \left( \frac{m_{fuel}}{m_{fuel} + m_{air}} \right) \Delta h_R \left( \frac{1}{f+1} \right) \Delta h_R \tag{6}
\]

In addition, consideration should be given to the empirical function on the absorption efficiency with respect to the height of the flame, which is according to the location as shown in the equation 7, where the parameters \( \lambda \) and \( \alpha \) have a value of 0.61 and 1,012 respectively, taken according to the characteristics of the oven.

\[
\begin{align*}
\eta_{ABS} &= 1 + \lambda \left( \frac{H_f}{H_{nominal}} - 1 \right) \alpha \quad \text{up side} \\
\eta_{ABS} &= 1 - \lambda \left( \frac{H_f}{H_{nominal}} - 1 \right) \alpha \quad \text{bottom side}
\end{align*} \tag{7}
\]

In order to take account of the pressure drop in the process, caused by changes in load, is used the equation of Bernoulli, to leave aside the effects of losses due to friction and differences in height is obtained the equation 8.

\[
\frac{p}{\rho} + \frac{v^2}{2} = K = \text{constante} \tag{8}
\]

The flow rate of each flow is adjusted using control valves. The rate of mass flow (kg/s) of fluid through the control of the valve is related to the drop in pressure (Pa) through a valve fully open as is represented in 9. Where \( CV = 0.4679 \), isthe coefficient of the valve.

\[
\dot{m}_{max} = CV \sqrt{\frac{P_{in} - P_{out}}{\rho}} \tag{9}
\]

By means of this process is an approximate linear model, represented by the equation 10, in which the fuel flow to the burners is the input \( u(t) \) and the temperature of the crude oil at the exit of the oven is the output \( y(t) \).

\[
G_0(s) = \frac{\Delta Y(s)}{\Delta U(s)} = \frac{K_0}{(1+T_{f1}p)(1+T_{f2}p)} \tag{10}
\]
The equations 11 and 12 are the transfer functions that correspond to the process.

\[ G_1(s) = \frac{s^{1/20}}{(s^{1/30})(s^{1/3})} \]

\[ G_2(s) = \frac{s^{1/10}}{(s^{1/20})(s+1)^2} \]  

Figure 3 shows the general approach of the cascade control based on fuzzy controllers pid, in this diagram is encapsulates the controller.

![Fig. 3: Block diagram cascade fuzzy controller](image)

For the design of the fuzzy controller PID is poses a fuzzy controller whose outputs with kp, Kd and alpha and entries are the error and the delta of the error. On the basis of the outputs are applied the mathematical model that allows the obtaining of the controller with equivalent behavior to PID type fuzzy. In the equations 12, 14 and 15 shows the formulae applied to the obtaining of the constants, derivative, proportional and integral.

\[ Kp = Kp_{min} + (Kp_{max} - Kp_{min}) \cdot SalFuzzy \]  

\[ Kd = Kd_{min} + (Kd_{max} - Kd_{min}) \cdot SalFuzzy \]  

\[ Ki = Kp^2 / (Kd \cdot \alpha) \]  

On the other hand, in the equation 16 describes the values of the constants considered according to the desired behavior and in open loop.

\[ Kd_{max} = 2.2854 \]  
\[ Kd_{min} = 1.2189 \]  
\[ Kp_{max} = 2.8042 \]  
\[ Kp_{min} = 1.4956 \]  
\[ K_u = 4.6736 \]  
\[ \alpha = 3.26 \]  

On the other hand, in the equation 16 describes the values of the constants considered according to the desired behavior and in open loop.

Figure 4 shows the internal structure of the fuzzy control PID, which is composed of the fuzzy controller and the associated mathematical model for obtaining the desired behavior.

![Fig. 4: Block diagram Fuzzy PID controller](image)
In Figure 5, is the internal structure of the fuzzy controller, with 2 inputs and 3 outputs and the type of transfer functions that are used for the rules of fuzzification.

The system has as linguistic variables {NB, NM, NS, Z, PS, PB} being these, {Negative Bigger, Negative Medium, Negative Smaller, Zero, Positive Smaller, Positive Bigger}.

Fig. 5: Fuzzy PID controller

The design of the fuzzy controller PID is based on the main structure, in this case you use the inference engine Mamdani[16]. The fuzzy sets are raised according to the behavior of input and output variables, and are associated with linguistic values defined by a word or adjective. In these the role of membership can take values in the range between 0 and 1, and the transition between these is gradual. The employees for the control are described in table 1.

A diffuse collection can be defined with the equation 13 where $\mu$ is the role of membership, $\mu(x)$ is the degree of membership of the variable $x$ and $u$ is the universe. Between is closest to the value 1, the greater will be the membership of $x$ to the set.

\[ A = \{(x, \mu(x)) \mid x \in U\} \quad (17) \]

In the fuzzification are converted the actual values in fuzzy values, so are assigned degrees of belonging to each of the input variables in relation to the fuzzy sets.

Although the driver’s waterfall, pose similar their characteristic parameters of the sets of fuzzification vary by the behavior and the requirements of the system. Basically uses two types of membership rolls, triangular (Figure 3a) and trapezoidal (Figure 3b).

Fig. 6: Membership Roles

For the functions of the figure 4 evaluates the value of $x$, being this membership in the estimated range according to the behavior of the system, the equation 14 corresponds to the triangular and the equation 15 to the trapezoid.

\[ \mu(x) = \begin{cases} \frac{x-p_1}{p_2-p_1} & p_1 < x < p_2 \\ \frac{p_2-x}{p_3-p_2} & p_2 < x < p_3 \\ 0 & x < p_1 \ \text{or} \ x > p_3 \\ 1 & x = p_2 \end{cases} \]

\[ (18) \]

\[ \mu(x) = \begin{cases} \frac{x-p_1}{p_2-p_1} & p_1 < x < p_2 \\ \frac{p_2-x}{p_3-p_2} & p_2 < x < p_3 \\ \frac{p_3-x}{p_4-p_3} & p_3 < x < p_4 \\ 0 & x < p_3 \ \text{or} \ x > p_4 \end{cases} \]

\[ (19) \]
The knowledge base is defined the linguistic rules of control that made the decision-making. According to the ranges of the windows of the fuzzy sets for the inputs and for output, which are posed by the model of the PID.

The method mamdani uses rules type (if-else), composed by the history and the conclusion. Because of the characteristics of the system with three rules per controller is sufficient for the objective. Getting a graphical representation of the surface that reflects the behavior of the driver.

\[ y_{centroide} = \frac{\sum_{i=0}^{R} x_i \mu_A(x)}{\sum_{i=0}^{R} \mu_A(x)} \]

Fig. 7: Surface behavior of the driver

Through the Figure 5 we can evaluate the actual output that is generated by the control depending on the estimated range in entries, so as to check that the operation is the desired according to the design specifications. This value is the result of the process of defuzzification through the centroid method that corresponds to the equation 12, where R is the number of rules.

To evaluate the results obtained is performed a simulation of the system in the Matlab Simulink software module (Figure 6), by means of the block of the toolbox fuzzy in which it is loaded the PID controller.

Fig. 8: Cascade Fuzzy control response

Figure 8 shows the response of the fuzzy control in cascade with a disturbance equivalent to \(0.9e^{-3x}\), whose time of establishment is 6 s, a maximum on momentum of 5.4 % and an error in stationary state of 0.5%.

Fig. 9: Cascade PID control response with disturbance

In Figure 9 you can see the crude oil temperature controlled with the PID cascade, the time of establishment is of 6.4 s with error in stationary state of 0.7%, with an overshoot of 9.7%.
Conclusions:
It was found that the response of a diffuse PID is better than that of a classic PID, since they have a significant difference in the time of establishment equivalent to 347.4 s and the error in stationary state of 1.5%.

It is evidenced that the response of a diffuse PID is better than that of a fuzzy controller, the time of establishment is 10.5% lower, and the error in steady state a 4.7% less significant.

The Diffuse PID controller has a fast response time, a minimum pulse on and closely follows the reference, desired condition in a system of control.

On the basis of the tests performed, highlights the ease of design and better performance of the fuzzy controller, taking into account that requires an expert knowledge of the controlled system to configure the rule base.

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