Simulation

Applications

Simulation: Transactions of the Society for Modeling and Simulation International
1–11

DOI: 10.1177/0037549717692418
journals.sagepub.com/home/sim

Modeling and simulation of furnace pulse firing improvements using fuzzy control

Alejandro Cadena-Ramírez[1], Antonio Favela-Contreras[2] and Graciano Dieck-Assad[2]

Abstract
Pulse firing offers significant process and productivity benefits, such as improved temperature uniformity and high heat transfer rates to the product load through maximum system turndown and utilizes the system's burners at their most efficient firing rates. However, overshoot and undershoot is unavoidable. To minimize these effects, the system operates the burner at an enhanced turndown rate. Faster cycle rates improve temperature uniformity but reduce equipment lifetime. Therefore, a tradeoff exists between furnace temperature uniformity and the cycle rate used by the pulse firing control.
This paper proposes models and simulates an advanced technique that improves temperature uniformity while decreasing the cycle time used by the pulse firing control. This provides reliable, safe furnace operating conditions, thereby extending the lifetime of the equipment. After an analysis of a furnace's combustion system that utilizes the pulse firing method to control the heat demand of the furnace, non-linearities were found in the combustion system. To improve the performance of the temperature control, an error-driven function was coupled to the control strategy to compensate the signal error fed to a proportional–integral–derivative controller. The error-driven function was implemented using a fuzzy system, which improved the temperature uniformity and allowed a 60% duty cycle reduction in comparison with similar combustion systems.

Keywords
Power plant simulation, fuzzy systems, modeling and simulation environments, systems dynamics, pulse firing control

1. Introduction

The primary purpose of a furnace is to provide heat to the product load. Production quality requires all parts of the load, no matter where they are located inside the furnace, to reach and stay at the desired temperature. It is more profitable to increase production throughput by rapidly heating the load to its desired temperature. Therefore, uniformity and high heat transfer rates are critical furnace characteristics. In the past, schemes such as burner tilting and sequential control were used to provide equilibrium between the radiant heat transfer and the appropriate load distribution into the burner system.[1,2]

Delivering heat to the product load is accomplished by transferring heat from the burners to the load. The heat transfer from the flame and hot combustion gases to the load depends on the difference in temperature and the barriers that impede the transfer, and then in order to sustain the desired temperature, the combustion control system has to vary the heat input to the process. This paper describes a method to adjust the heat input to the furnace by pulse firing control.

2. Pulse firing control

Pulse firing is a combustion heating control method developed in Europe in the early 1970s. In a pulse firing control method, the burners are switched between two states. Cycling the burners controls the heat input to the process. Pulse firing utilizing the on/off control method allows the use of burners with limited turndown, as opposed to an amplitude modulating control. Pulse firing occurs

[1]Electrical & Automation department at Primetals Technologies, USA
[2]Tecnologico de Monterrey, México

Corresponding author:
Graciano Dieck-Assad, Tecnologico de Monterrey, Campus Monterrey, Av. Eugenio Garza Sada 2501 Sur, Monterrey, N.L., 64849, México.
Email: graciano.dieck.assad@itesm.mx

throughout individual control valves at each burner where it is possible to cycle burners independently for the greatest control flexibility.[3]

Pulse firing offers significant process and productivity benefits, such as improved temperature uniformity, versatile control scheme, and improved turndown. To achieve these goals, pulse firing operates the burners close to the ratio of their most efficient firing setting, creating ideal operating conditions that result in maximum heat transfer with minimal fuel input. Pulse fired systems can be designed to accommodate even the most stringent temperature uniformity and application requirements, through maximum system turndown, and utilize the system's burners at their most efficient firing rates to transfer maximum energy to the furnace load in the least amount of time. However, pulse firing does come at a price and increase in system complexity.

It is advantageous at all times to provide heat to the furnace under maximum input conditions. In other words, it is imperative to run the burners at their maximum design setting for as great a proportion and for the time that is necessary to meet the furnace mean heat demand, and for the remainder of the time to run the burners at their lowest possible input. However, owing to the effect of the time delay from the switching, the system causes the temperature to follow a sinusoidal pattern – a continually rising and falling temperature. Overshoot and undershoot is unavoidable, making it difficult for the system to achieve a consistent product. To minimize these effects, the system operates the burner at an enhanced turndown, typically 20:1.

In furnace radiative heat transfer systems, two control actions are available that affect the temperature profile of the system.[1,3,4] The translucent flame surface can be changed in equivalent areas by sequential activation of burner valves and this control action depends upon the load demand. The second control action is the flame position with respect to the heat transfer surfaces.[1] Pongrance[5] and Hauck Manufacturing[6] show applications with high production load variability and temperature uniformity requirements to $+/-5°C$, where 6 s duty cycles are used to assure product quality. Because of the increased on/off cycling, a number of specialized equipment is required. Figure 1 shows the main components of a pulse firing burner.

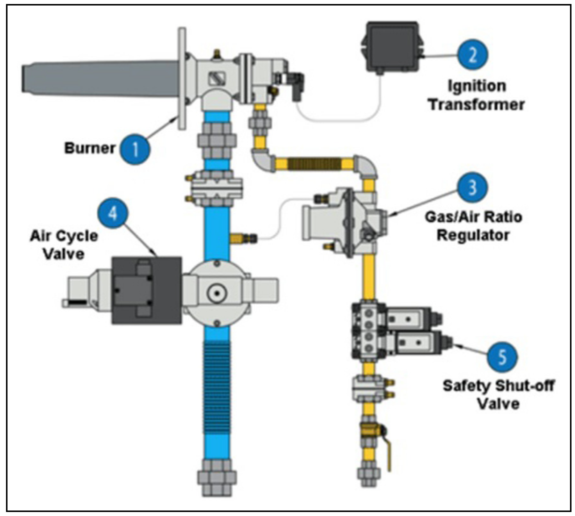

Figure 1. Typical pulse firing burner.[7]

3. Equipment considerations

It can be considered that faster cycle rates improve temperature uniformity at the cost of reduced equipment lifetime.[3]

High cycle rates apply to control equipment such as control devices and their contact ratings. The lifetime of a contact depends on the number of operations, the current flow, and the type of load. Loads such as solenoid valves and ignition transformers are highly inductive and create sparks on the contacts. These sparks erode the metal in the contacts and shorten their life. The air and gas valves selected need to be designed specifically for high frequency.[3] At a frequency of 10 cycles per minute, the valves can be subjected to more than 2 million cycles per year. Standard solenoid valves will last a few months under those operating conditions.

It is also critical to install a ratio regulator to minimize variations of the air–gas ratio and to size it properly. An excessive variation of the inlet pressure into the ratio regulator can affect ignition reliability. Moreover, high-velocity gas burners and specialized controllers dedicated for pulse control, such as Programmable Logic Controllers (PLCs), are needed.

Additional safety concerns apply to the burner's equipment regarding the cycle rates used by the combustion system. The minimum on and off times are dependent on the response times and delays of the control devices, such as the flame safeguard, valve actuation, and burner ignition. During the off time, a valve failure could lead to a collection of unburned fuel. The National Fire Protection Association (NFPA) limits the off time based on a calculation of the defined gas-valve leakage rate. In addition, NFPA requires enhanced maintenance schedules and monitoring of usage. The minimum on is determined by the flame safeguard. It has a start-up delay time before it energizes the ignition and gas-valve output. The on time must be longer than the trial for the ignition time plus the flame failure-response time. Otherwise, each subsequent attempt to light a burner that does not produce a flame will allow discrete pockets of unburned fuel to collect in the furnace without achieving a flame-safeguard alarm and a lockout condition.[3]

Therefore, a tradeoff between furnace temperature uniformity and the cycle rate used by the pulse firing control must be observed. Advanced combustion control techniques are available that allow a reliable uniform temperature regulation by a proper redistribution of heat transfer surfaces in the furnace.[8–12] In this paper we show that advanced control can improve temperature uniformity and at the same time decrease the cycle time used by the pulse firing control, providing a reliable and safety furnace operation that allows extending the equipment lifetime.

4. Normalized heat treatment process

A normalizing furnace is designed to heat plates to the required temperature while the plates are moved through the furnace. A combustion control system using a pulse firing method is responsible for all facets of the plate heating process. Carbon steel plates from a previous milling process, with dimensions of 4.5–50.8 mm thick, 1500–3048 mm width, and 3000–16,000 mm length, are charged into the furnace to be heated to the appropriate temperature and hold it at this temperature in an atmosphere of nitrogen.[13]

The normalizing heat treatment process is basically an annealing process that is used to remove the hardness caused by other process to repair the defects caused by plastic deformation to produce a uniform microstructure. Normalizing heat treatment is used to give the steel structure technological characteristics that are considered the natural or final state of the material that was subjected to the forge and/or milling processes and produces a more uniform final product. This involves heating the steel between 30°C and 50°C above its critical temperature and holding it for a period of time long enough for transformation to occur and for later cooling it in air.[14] The normalizing process can be established by a Time–Temperature–Transformation (TTT) diagram or an S-Curve that shows the initial and final temperature transition-transformations for austenite. Figure 2 shows a typical TTT diagram for the heating process in steel. The transformation from B to A where the red line that runs between the two curves marks the beginning and end of isothermal transformations.

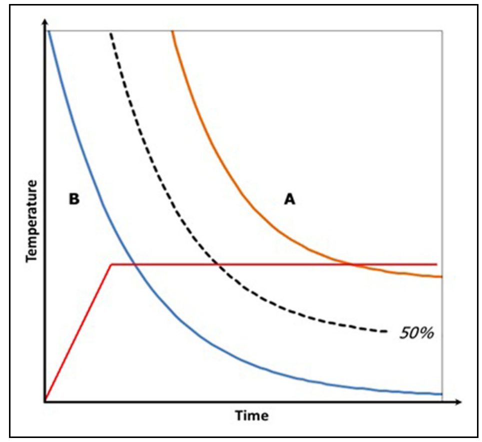

Figure 2. Isothermal transformation Time–Temperature–Transformation diagram. (Color online only.)

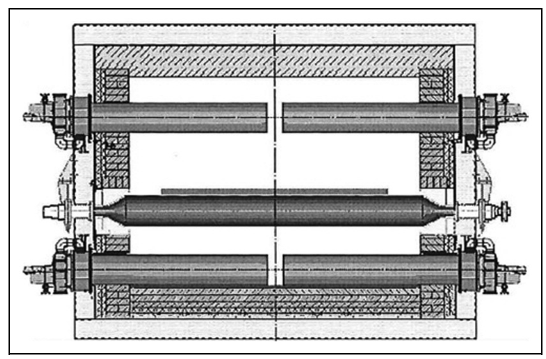

Figure 3. Burner zone schematic.[13]

5. Furnace combustion system

The combustion system consists of 16 combustion zones with a total quantity of 316 pulse firing burners. The burners are arranged in burner zones with four burners for each zone. To keep the products of combustion isolated from the furnace atmosphere, combustion will take place in radiant tubes where it draws approximately 100% of the flue products back through the burner to preheat the combustion air. The burner zones are evenly spaced along the length of the furnace modules and evenly distributed above and below the pass line. The radiant tubes are self-supporting and extend from each side of the furnace in, toward the centerline.[13] Figure 3 shows a schematic of a typical arrangement for a burner zone.

Due to the minimum time that a burner can be on and the minimum time that it can be off, it must be noticed that turndown capability is not infinite. The minimum allowable duty cycle period must be larger than the minimum burner on-period in order to maintain a usable power output range. For the burners used in the normalizing furnace, the on-period can be established at 15 s. The usable power range is defined as the range of firing rates where the burners are pulsing on and off. Ideally, this should be maximized while maintaining acceptable product temperature uniformity. The lower limit of the usable power range, causing the burners to fire for the minimum burner on-period, is defined by the following equation:

$$Lower\ limit = \left(\frac{Min - On\ Period}{Duty\ Cycle}\right) \times 100 \qquad (1)$$

Each burner will have a burner control unit, which will interface between the combustion control system and the

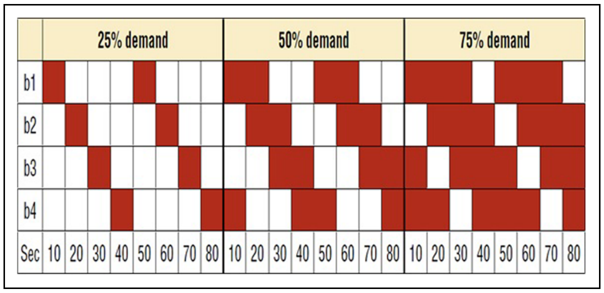

Figure 4. Fixed cycle time with duty cycle by heat demand.[3]

burner trim (solenoid valves, spark igniter, flame sensor, etc.). During normal operation, the zone temperature controller utilizes feedback from a zone thermocouple to adjust the firing rate for each burner in the zone appropriately. When a particular burner is firing, the burner fires at 100% of capacity and the input to the zone is varied by the amount of time each burner is being fired. The burner firing sequence times will be evenly spaced between the four burners in the zone to assure an even distribution of heat to the zone. Figure 4 shows the timing of four burners fired in a pulse sequence at three different heat input rates.

Following this control scheme, the combustion control system implements a sequencer that develops appropriate firing rates for all burners in the zone. The sequencer uses a Pulse Width Modulator (PWM) function to modulate the length of time that the burners fire within a given duty cycle, namely the PWM function controls the average heat power transferred to the production load.

6. Temperature control

To control the normalizing process, it is necessary to control the temperature for each plate loaded into the furnace. Then, for the temperature control a temperature deviation can be seen as having two different contributors: (1) the furnace owns a thermal load regarding the furnace characteristics and (2) the plate thermal load is added once a plate is charged inside the furnace. To manage these two different dynamic behaviors, the temperature control system uses a thermal model to predict the normalizing temperature and the residence time that the plate has to stay inside the furnace. Because the thermal model assumes a constant temperature in the furnace to perform its calculations, the value is used as a reference by the temperature control. Therefore, the objective of the temperature control is to keep the temperature uniform, manipulating the length of time that the burners fire within a given burner zone.

The requirements of a control system may include many factors, such as response to command signals, insensitivity to measurement noise, process variations, and rejection of load disturbances. The design of a control system also involves aspects of process dynamics, actuator saturation, and disturbance characteristics.[15] The general empirical observation is that most industrial processes can be controlled reasonably well with proportional–integral–derivative (PID) control provided that the demands on the performance of the control are not too high. Temperature control is a typical case where the derivative action can be used to speed up the response, due to the characteristic process dynamics, which include time constants of different magnitudes. An analysis of the combustion control system generates two non-linear phenomena inherent to the combustion system. This is due to actuators' saturation regarding the on/off action of the burners, which introduces an oscillatory mode of the following form:

$$y(t) = (4M/\pi) \times \sin \omega t \tag{2}$$

where M is the amplitude during the on action.

Furthermore, the burners' ignition time introduces time delay dominance with respect to the time constants of the process. The presence of these non-linear phenomena impacts negatively on the system performance.[16] Astrom et al.[15] showed that in the presence of these phenomena, the use of more sophisticated control than PID brings benefits to the system performance. Improvements in the controller performance can be obtained through ''gain scheduling'' techniques to deal with the non-linear phenomena. To use the technique, it is necessary to find measurable variables, called scheduling variables, that correlate well with changes in the process dynamics. This ''gain scheduler'' maps the scheduling variables to get the best control gains according to the current operation point, giving an effective way to control processes whose dynamics change with operating conditions. Finding these variables is not always easy, whereby the gain scheduling development takes a substantial engineering effort and the representation of the non-linear function is limited by an interpolation table.

A fuzzy system may be considered as a way to represent a non-linear function. This representation is enlarged in comparison to an interpolation table through its membership functions, which accurately map the variables used to represent the function. Furthermore, the representation of a system as a collection of rules for linguistic variables has a strong intuitive appeal. Also, explaining heuristically how the system works can be useful in communicating control strategies to persons with little formal training.[15] The temperature control for the normalizing furnace implements a PID controller that calculates the usable power signal fed to the sequencer to develop an appropriate firing rate for burners and a fuzzy system is adopted to determine the value of the error signal during the transient response in order to decrease the rise time, and at the same time the overshoot and reducing the settling time as well.[17]

Figure 5 shows a block diagram of the temperature control implementation for the normalizing furnace. This control scheme is implemented for each burner zone available

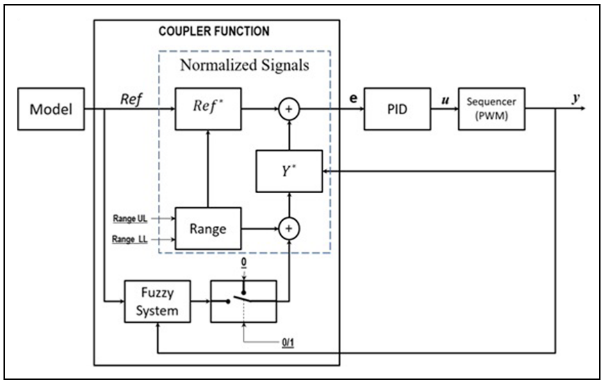

Figure 5. Temperature control block diagram. PID: proportional–integral–derivative; PWM: Pulse Width Modulator.

in the furnace. The furnace temperature control was implemented in a PLC controller. A standard PID function block built into the PLC is used as the main controller and an additional logic was built as a coupler function to implement the fuzzy system in the scheme. A selector switch enables or disables the error compensation estimated by the fuzzy system, giving the flexibility to suppress its action.

To standardize the signals used by the PID controller, the operation range values are used. Both the reference and the feedback signals are normalized before they are used to calculate the error signal. Also, the fuzzy system uses the reference and the feedback signals to create a linguistic variable called ''Delta'' to estimate its output, which compensates the range value used by the normalizing function, giving as a result a direct manipulation of the error signal fed to the PID controller. The error compensation has the effect of extending the PID control effort, improving significantly the performance that can be achieved with the PID controller only. The improvement can be seen in all control aspects, such as a reduction in the rise time, reduction of the overshoot, and reduction of the settling time.

7. Furnace temperature model and simulator

Computational models of dynamical systems are used to study the behavior of systems over time. The foundations for modeling dynamical systems are based on the mathematical concepts of derivatives, integrals, and differential equations to describe the behavior of the system they represent. An essential modeling method is to use mathematical entities, such as numbers, functions, and sets, to describe properties and their relationships to real-world systems.[18]

A computational model using the thermodynamic and heat transfer properties of the fluid is applied to represent and converge the non-linear nature of the equations. Then a furnace temperature model is developed to emulate the cyclic operation of the burner's system and is implemented in a PLC microprocessor that takes advantage of its cyclic operation and memory capacity.

Due to the burners' on/off operation it can be assumed that each burner supplies its maximum heat power during its on operation and no heat power during its off operation. From the heat power definition:

$$Heat\ Power = \frac{dq}{dt} \tag{3}$$

where q is the heat energy in [kJ] and heat power is in [kW].

From the derivative definition we have the following:

$$f'_{(x)} = \lim_{h\to 0} \frac{f_{(x+h)} - f_{(x)}}{h} \tag{4}$$

where the difference quotient is the average rate of change of the function over the interval h and the limit when h approaches 0 of the difference quotients is thus the instantaneous rate of change.

Then the heat energy that the burners supply can be estimated throughout the instantaneous heat power at each PLC scan cycle, provided that it is sufficiently small. Assuming the entire furnace atmosphere is nitrogen, the temperature of the furnace can be estimated through the nitrogen's thermal capacity, which is a measurable physical quantity equal to the ratio of the heat added to an object to the resulting temperature change.

Using the basic thermodynamic equation to calculate the amount of heat energy, the final furnace temperature can be estimated through the following equation:

$$Q = m \times c_p \times \left(t_f - t_i\right) \tag{5}$$

where Q is the heat energy in [kJ], m is the nitrogen mass contained in the furnace atmosphere in [kg], c_p is the nitrogen's specific heat in [kj/kg°C], and the temperature difference is in [°C].

One basic assumption is that the temperature is changing at a constant rate (PLC scan). If the temperature is denoted by *öÊ*, the increment is denoted by *ΔöÊ*, and the value of a term is measured at a particular point in time, the increment can be computed as the difference between two consecutives measures and has the value given by the following expression:

$$T_n = T_{n-1} + \Delta T \tag{6}$$

The mathematical model was implemented as an algorithm in a PLC function, which performs the following steps to estimate the furnace temperature:

1. mass calculation: using the furnace dimensions and the nitrogen density value;
2. heat losses calculation: using a heat losses factor;

3. heat energy calculation: estimated from the burner instantaneous heat power at each scan cycle;
4. total energy calculation: estimated from heat energy and heat losses;
5. furnace temperature calculation: estimated from mass calculation, total energy calculation, and nitrogen thermal capacity.

To simulate the system's dynamic behavior, the furnace temperature simulator uses two first-order filters and a first in, first out (FIFO) array that is populated at each scan cycle and is used to handle the dead time in the simulation. Figure 6 shows the block diagram used by the furnace temperature simulator.

8. Temperature control modeling and implementation

To design the PID controller, a step test in an open loop was performed to identify the process dynamics following the Ziegler–Nichols standard method to obtain the tuning gains. Figure 7 shows the results of the test. The PID tuning gains were calculated as follows:

$$K_c = 1.2(\Delta U/a) \tag{7}$$

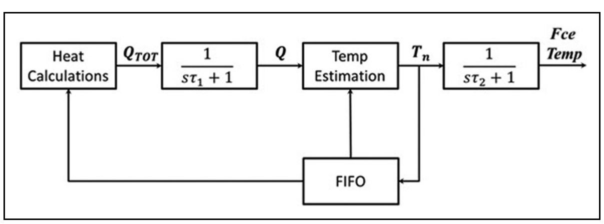

Figure 6. Furnace temperature simulator block diagram. FIFO: first in, first out.

$$T_i = 2L \tag{8}$$

$$T_d = L/2 \tag{9}$$

where the adjusted PID controller gains are as follows: (1) the proportional gain K_c = 0.64; (2) integral time T_i = 80 s; and (3) derivative time T_d = 20 s.

It is well established that the presence of dead time in processes adversely affects the stability and therefore the performance of control systems. The longer the dead time, the less aggressively the controller must be tuned to maintain stability.[19] The time needed to ignite a burner (minimum on time) and the minimum off time can be seen as additional dead time, which adversely impacts the controller performance. This situation worsens when the temperature reference goes from a higher to a lower temperature. Since all physical values are limited, it is useful to have limiting devices in control systems too.[15] Therefore, and knowing that the on/off action of the burners is tied to the usable power range, Equation (1) is used to limit the PID output to avoid delays during the burner operation.

9. Fuzzy system model

The temperature control implements an error-driven function through a fuzzy system based on Mamdani's model, which makes use of heuristic knowledge obtained by experimentation through simple rules. The fuzzy system includes three basic functions as follows[20]:

1. fuzzification: convert the measured quantities from the process into fuzzy sets to be used by the inference mechanism;
2. inference mechanism: determine the degree of firing of each rule in the rule base;
3. defuzzification: convert the recommendations of all rules into a crisp output.

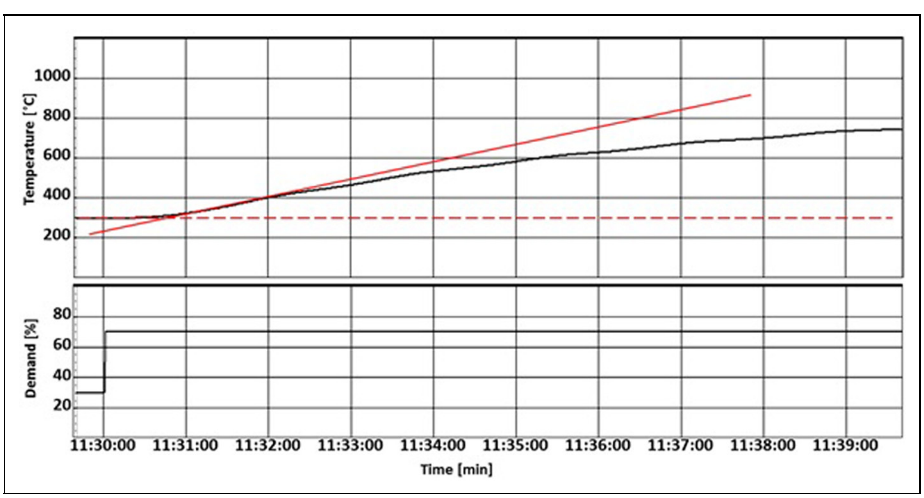

Figure 7. Process identification by the Ziegler–Nichols method.

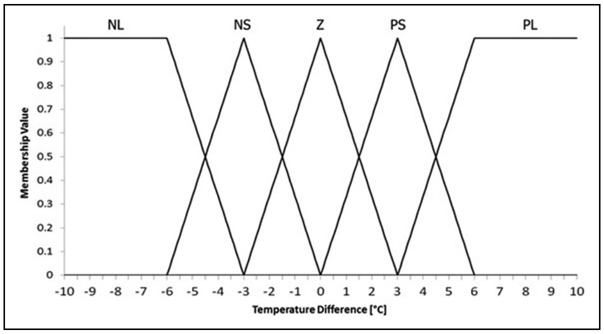

Figure 8. Fuzzy sets for the linguistic variable Delta. NL: Negative Large; NS: Negative Small; Z: Zero; PS: Positive Small; PL: Positive Large.

The design of the fuzzy system follows the minimum computation effort's criterion, because the PLC controller is used not only by the furnace temperature control but also the combustion system in general, limiting the computation load.

Thus, for each of the basic functions used by the fuzzy system a minimum set of values remains to maintain a low computation load, but at the same time allowing sufficient resolution to achieve the objectives of the system. The fuzzification function is defined by five fuzzy sets for a linguistic variable called ''Delta'' with the following defined values:

- Negative Large (NL);
- Negative Small (NS);
- Zero (Z);
- Positive Small (PS);
- Positive Large (PL).

The fuzzy sets are characterized by the triangular membership functions shown in Figure 8. The variable Delta is the difference between the set point signal and the process signal as follows:

$$Delta = |Ref| - |y| \tag{10}$$

A rule base of nine rules is used as the inference mechanism. To keep the calculation at the minimum, the set of rules uses the membership values estimated for the linguistic variable and the use of algebraic operations.

The set of rules that the fuzzy system uses as the inference mechanism are as follows:

- R1 = If NL Then Q1;
- R2 = If NL or NS Then Q2;
- R3 = If NS Then Q3;
- R4 = If NS or Z Then Q4;
- R5 = If Z Then Q5;
- R6 = If PS or Z Then Q6;
- R7 = If PS Then Q7;
- R8 = If PS or PL Then Q8;
- R9 = If PL Then Q9.

The defuzzification function is defined by nine fuzzy sets of the singleton type with values from Q1 to Q9. Moreover, two extra values are added for extreme compensation in the case where the linguistic variable ''Delta'' is mapped where the membership functions are saturated. These two values are *QXN* for an extreme negative value and *QXP* for an extreme positive value. The function calculates an extreme compensation value using the limit value to map the linguistic variable by the fuzzification function and the current estimation of the linguistic variable, calculated as follows:

$$XCOMP = \frac{Delta}{Limit\ Value} \tag{11}$$

To apply the extreme compensation into the error compensation, a parameter used as a threshold is compared with the membership functions values NL and PL, namely, if the membership value is greater than or equal to the threshold, its value is used to calculate a factor as follows:

$$XNF = NL \times XCOMP \tag{12}$$

$$XPF = PL \times XCOMP \tag{13}$$

If the condition is not satisfied the factor is overridden to zero, removing the extreme compensation from the total compensation calculation. As an example, if the temperature set point is 700°C and the process temperature is 694.2°C, the estimation for Delta is 5.8. Using Equation (9), the extreme compensation value estimated according with this data is *XCOMP* = 5.8/10 = 0.58.

As can be seen in Figure 7, the membership function PL = 0.9333 and the membership function NL = 0 for this Delta. Considering the threshold was set to 0.9 and due to PL is above this value, only the extreme compensation factor *XPF* = *XCOMP** 0.9333 = 0.5413 is applied to the total compensation and the *XNF* factor is overridden to zero due to its value being below the threshold. Assuming the next instant, an increment in the process temperature from 694.2°C to 694.4°C, the Delta estimated is 5.6 and the membership function PL = 0.8666 and membership function NL = 0, which results in *XNF* = 0 and *XPF* = 0, since the membership function values are below the threshold.

The crisp output calculated by the defuzzification function is the sum of all singleton values multiplied by its firing value plus the extreme compensation value multiplied by its extreme compensation factor:

$$COMP = \sum_{i=1}^{9} R_i \times Q_i + [QXN \times XNF] + [QXP \times XPF] \tag{14}$$

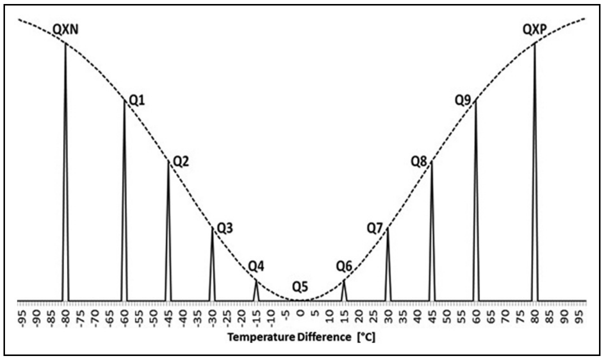

Figure 9. Singleton output fuzzy sets using an inverted normal curve.

The main idea behind the error compensation is to increase the PID control effort to stabilize the process variable as quickly as possible. So, to support this idea the error compensation must increase if the process variable comes away from the reference value and tends to zero if these two variables are close to each other.

This idea can be thought of using an inverse normal distribution curve, where a value tends to the middle and its position from this point can be measured in regards to standard deviations. To set the singleton values, the control range values that establish the settling times are used as the standard deviation and the subsequent values are multiples of this value. Then the fuzzy set values used by the defuzzification function are selected with an inverted distribution curve, as shown in Figure 9.

10. Fuzzy system design using the minimum effort criterion

The design of the fuzzy system follows a minimum computation effort criterion, because the furnace temperature control was implemented in a PLC controller. Also, the same PLC is in charge for all the systems that support the combustion and the furnace systems, such as the combustion air system, exhaust gas system, atmosphere system, nitrogen injection system, natural gas injection system, and burner management system for the normalizing furnace, limiting the computation load in the micro controller. The temperature control of the normalizing furnace consists of 316 pulse firing burners distributed among 105 heating zones that give the flexibility to the furnace temperature control to fit minimum heat demands and at the same time to respond fast enough to load variations. To support this scheme, the heating zones are grouped dynamically, giving as a result the implementation of one PID controller and one fuzzy compensator for each heating zone. During the fuzzy controller design, we conclude that using five fuzzy sets for the linguistic variable obtains satisfactory results in compliance with the performance requirements for the application. This minimum set of values remains to maintain a low computation load, while allowing sufficient resolution to achieve the computational effort, granularity, resolution, and specifications of the control system.

11. Comparative analysis

The performance for the control scheme proposed for the furnace control temperature was measured through comparative analysis against the PID controller action only. The performance test for each control scheme was conducted using the following conditions.

1. The temperature controller must follow the temperature reference sent by the thermal model, and therefore two step tests to change the control reference for each control scheme were performed.
2. As initial point, the furnace temperature was set at 450°C, and once the temperature stabilized at this value a change in reference to 750°C was carried out. When the temperature stabilized at this value the control reference was returned to 450°C.

To measure the performance of both control strategies, the next criteria were used:

- raise time;
- peak time;
- overshoot;
- settling time.

The range established for the settling time was 5% or $+/-15$ °C. Figures 10 and 11 show the temperature response against a step change in temperature set point from 450°C to 750°C for each control strategy. It can be seen that there is a substantial improvement in control aspects, such as raise time, overshoot, and settling time, for the fuzzy system scheme. It is well known that the presence of dead time in processes adversely affects the stability and therefore the performance of control systems.

The longer the dead time, the less aggressive the controller must be tuned to maintain stability.[19,21,22] Due to the effects of the system's non-linearities, the PID controller's performance over the process was limited. Table 1 illustrates the comparative data for test 1 for each control strategy.

Figures 12 and 13 show the temperature response against a step change in temperature set point from 750°C to 450°C for each control strategy. In both cases, the usable power range limit helps to avoid a larger temperature drop due to the burners' off action. Table 2 illustrates the comparative data for test 2 for each control strategy.

Both tests show a significant improvement by using the fuzzy system. The improvements are reflected in the

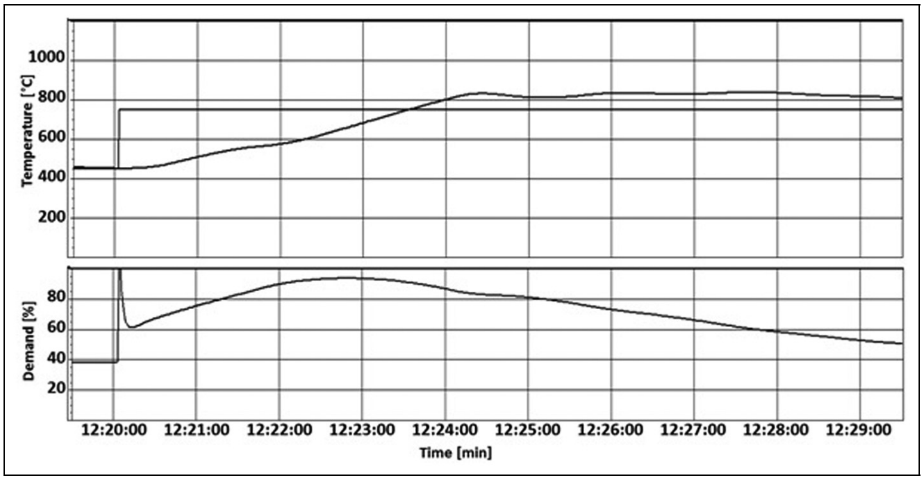

Figure 10. Proportional–integral–derivative step test 1: 450°C to 750°C.

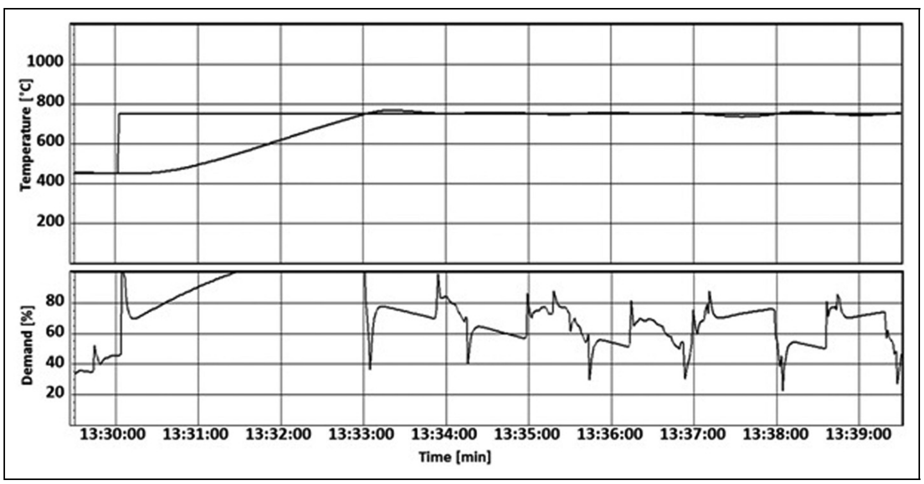

Figure 11. Fuzzy system step test 1: 450°C to 750°C.

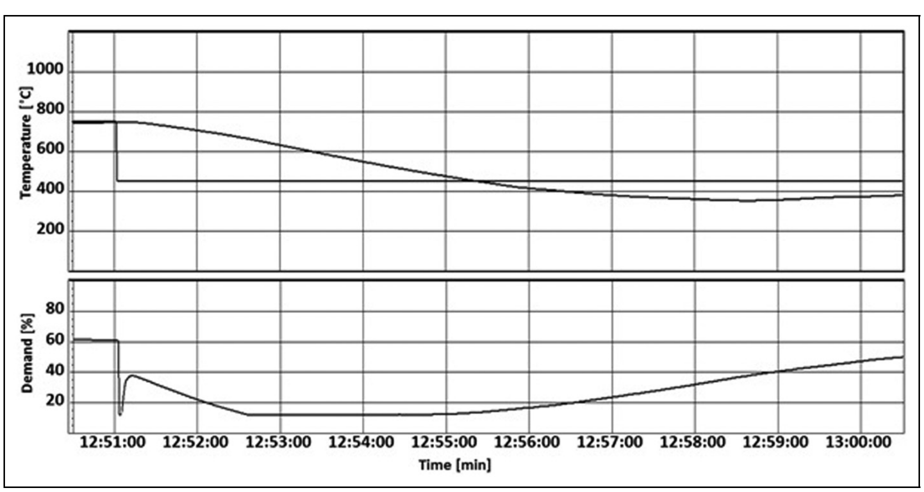

Figure 12. Proportional–integral–derivative step test 2: 750°C to 450°C.

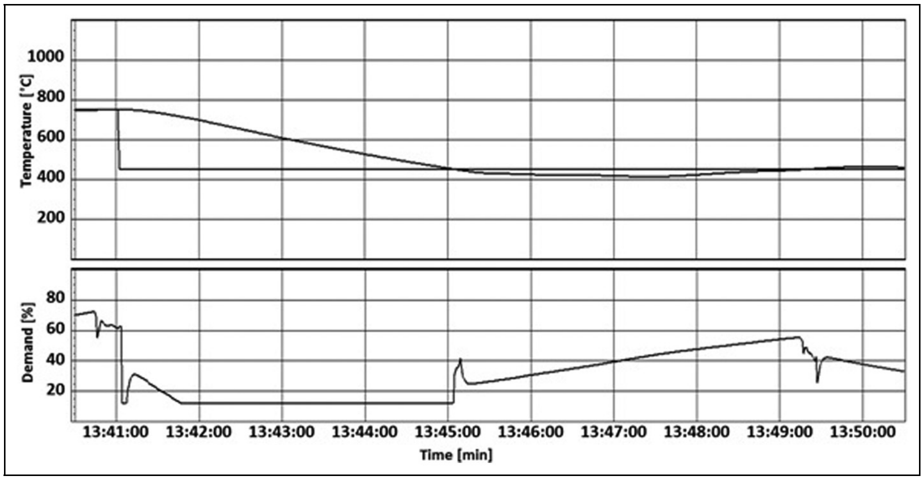

Figure 13. Fuzzy system step test 2: 750°C to 450°C.

Table 1. Comparative data for step test 1.

Data – PID controller		Data – fuzzy system	
Raise time	3:30 min	Raise time	3:00 min
Peak time	4:27 min	Peak time	3:20 min
Settling time	25:00 min	Settling time	4:00 min
Settling range	+/– 15°C	Settling range	+/– 5°C
Overshoot	90 C	Overshoot	13°C

PID: proportional–integral–derivative.

Table 2. Comparative data for step test 2.

Data – PID controller		Data – fuzzy system	
Raise time	4:20 min	Raise time	4:00 min
Peak time	7:39 min	Peak time	6:27 min
Settling time	24:00 min	Settling time	8:00 min
Settling range	+/– 15°C	Settling range	+/– 5°C
Overshoot	98°C	Overshoot	35°C

PID: proportional–integral–derivative.

overshoot correction, reduction on the settling time, and a better settling temperature range.

It must be notice that the step tests performed on the temperature control are not representative of the furnace operation. The step values were used to reflect the worst scenario to emphasize the improvements of the fuzzy system usage.

Furthermore, the implementation of sophisticated control strategies, such as that proposed, open up the possibility to widen the production ranges and increment the production throughput by rapidly heating the load to its desired temperature, maintaining temperature uniformity and high heat transfer rates.

12. Conclusions

The performance of many control systems can be quantified by the variance in the control error. Sophisticated control configurations, other than simple feedback systems, reduce this variance. Modeling and simulation of the thermodynamics process and the sequential cyclic operation of the burner pulse firing scheme allowed a better understanding and a more reliable determination of the advantages in the control strategy. Narrowing the variance in the control error translates directly into more consistent process operations, and significant economic incentives exist to operate the process more efficiently. Usually, this entails improving the control performance so that the process can be operated closer to a limiting condition.

Other than modeling and simulation of the pulse firing methodology, this paper analyzed the behavior of the combustion system for a normalizing furnace and proposes a fuzzy control strategy to enhance its dynamic performance. The method takes advantage of the PLC digital controller used by the combustion control system and its PID controller implemented as a function block. The temperature control of the normalizing furnace incorporates additional logic to enhance the control performance. After performing step tests on the control reference to the furnace temperature control, it is concluded that the use of fuzzy systems coupled to PID controllers improves significantly the performance that can be achieved with a classical control scheme in the presence of non-linearities.

The improvement can be seen in all control aspects, such as a reduction in the raise time, a reduction in the overshoot from 90°C to 13°C and from 98°C to 35°C, a reduction in the settling time from 25 to 4 minutes and from 24 to 8 minutes, and a better settling temperature range from +/−15°C to +/−5°C in the tests performed and having as a result better furnace temperature uniformity. Finally, the duty cycle used by the combustion control system was reduced 60% in comparison to similar combustion systems, improving the reliability and safety of the furnace operation along with a significant increment in equipment lifetime.

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

References

1. Dieck-Assad G, Masada GY and Hopkins D. A method for estimating burner tilt angles in a boiler furnace. *Technical Report*, University of Texas At Austin, January 1983, pp. J2-1-27-83.
2. Dieck-Assad G. Development of a State space boiler model for process optimization. *Simulation* 1990; 55: 201–213.
3. Curry D. The basics of pulse-firing. Eclipse, Inc., IL, http://www.eclipsenet.com (2011, accessed: 2 June 2015).
4. Dieck-Assad G, Masada GY and Flake RH. Optimal set-point scheduling in a boiler-turbine system. *IEEE Trans Energ Convers* 1987; EC-2: 388–395.
5. Pongrance D. *Pulse-firing technology. Combustion system retrofit at superior forge*, Hauck Manufacturing Company, PA, http://www.hauckburner.com/3598.0.html (2008, accessed: 15 June 2015).
6. Hauck Manufacturing. Pulse-firing delivers performance on multi-purpose heat treat furnace. Hauck Manufacturing Company, PA, http://www.hauckburner.com/3611.0.html (1999, accessed: 25 June 2015).
7. b-olstrad. Pulse-Fire 101 – an introduction to pulse-fire combustion systems, http://www.combustion911.com/blog/industrial-burners/pulse-fire-101-introduction (2012, accessed: 28 May 2015).
8. Cates L. Advanced oxy-fuel burners and controls improve fuel savings and uniform heating. *Int J Forging Bus Technol* 2011; 1: 8–11.
9. Krishna CR and Butcher TA. *Variable firing rate oil burner using pulse fuel flow control*. Brookhaven National Laboratory, BNL-73723–2005-IR, October 2004.
10. Gough B. *Advanced control of steam superheat temperature on a utility boiler*. Richmond: Universal Dynamics Technologies Inc., 2000.
11. Ghaffari A, Ali S, Moosavian A, et al. Experimental fuzzy modeling and control of a once-through boiler. In: *Proceedings of the IEEE international conference on mechatronics & automation*, Niagara Falls, Canada, 29 July–1 August 2005, pp.1340–1345. New York: IEEE Publications.
12. Arriaga-de-Valle E and Dieck-Assad G. Modeling and simulation of a fuzzy supervisory controller for an industrial boiler. *Simulation* 2006; 82: 841–850.
13. Safford GC and Sox V. The AHMSA plate normalizing line. In: *2015 AISTech conference proceedings*, Cleveland, USA, 15–17 May 2015. Warrendale, PA: AIST Digital Library.
14. Apraiz Barreiro J. Steel thermal treatments, http://www.scribd.com/doc/219606882/Tratamientos-Termicos-de-Los-Aceros-Apraiz-Barreiro-scribd (1949, accessed: 20 June 2015).
15. Astrom K, et al. *PID controllers: theory, design and tuning*. 2nd ed. USA: ISA, 1995, pp.109–116, 234–237, 287–295, 298–304.
16. Ogata K. *Modern control engineering*. 5th ed. New York, USA: Pearson Education, 2010, pp.695–700.
17. Visioli A. *Practical PID control*. London: Springer, 2006, pp.72–86.
18. Garrido JM. *Introduction to computational modeling using C and open source-tools*. New York, USA: CRC Press, Taylor & Francis Group, 2014, pp.1–2, 161, 261.
19. Smith CA. *Automated continuous process control*. New York: John Wiley & Sons, Inc, 2002, pp.174–179.
20. Lilly JH. *Fuzzy control and identification*. Hoboken, NJ: John Wiley & Sons, Inc, 2010, pp.27–41.
21. Favela A and Dieck Assad G. A fuzzy set point state feedback controller for a temperature process. In: *Proceedings of the NAFIPS conference 1999*, New York City, 10–12 June 1999. New York: IEEE Publishing.
22. Ramírez-Barajas J, Soto R and Dieck-Assad G. A fuzzy logic based AGC algorithm for a radio communication system. In: *Proceedings of the FUZZ-IEEE-2000 conference*, San Antonio, TX, 7–10 May 2000. New York: IEEE Publishing.

Author biographies

Alejandro Cadena-Ramírez is a Senior System Engineer for the Electrical & Automation department at Primetals Technologies, USA. His main research interests are advanced control applications, industrial process control, and energy efficiency. He is part of the Mechatronics Department at the Tecnológico de Monterrey (ITESM), Monterrey Campus.

Antonio Favela Contreras is a Professor of the Department of Mechatronics and Automation at Tecnológico de Monterrey, a member of the Mexican National Research System, and a member of the Mexican Academy of Science. He was chair of the Department of Mechatronics and Automation at ITESM, Monterrey Campus, for the period 2002–2006. His main research interests include adaptive and predictive control, analysis and control of hybrid systems, control of mechatronics systems, control systems on a chip, and industrial process control.

Graciano Dieck-Assad is a Professor of Electrical and Electronics Engineering at ITESM. From 1994 to 2003 he was the EE chair at ITESM, Monterrey Campus. From August 2006 to July 2014 he was the Director of Research and Graduate Studies in Electronics and Information Technology School at ITESM, Monterrey Campus. Presently, he is the ECE chair and his research interests are bioinstrumentation, Microsystems, and energy systems modeling.