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A Neuro-Fuzzy Controller for Rotary Cement Kilns

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Abstract: In this paper, we design a neurofuzzy controller to control several variables of a rotary cement kilns. The variables are back-end temperature, pre-heater temperature, oxygen content and CO2 gas content of the kiln. The fuzzy control system, as an advanced control option for the kilns, is intended to minimize the operator interaction in the control process. The proposed fuzzy controller uses a neural network to optimize TSK-type fuzzy controller. Since there is no generally applicable analytical model for cement kilns, we use the real data derived from Saveh cement factory for the plant identification. A model, which is very similar to the real plant, is identified then; and the identified model is used for control design and simulations. Extensive simulation studies justify the effectiveness and applicability of the proposed control scheme in intelligent control of cement plant.

1. INTRODUCTION

Cement production is a complex process, composed of a series of activities requiring substantial technological support (Akalp *et al*, 1994). The basic process in a cement production plant is baking of the raw material mix in a kiln. Cement kiln exhibits time-varying nonlinear behavior which both physical and chemical reactions occurred in the kiln, have complicated its dynamic equations. The corresponding equations have not been derived completely and accurately while a lot of present variables are discarded in the equations (Noshirvani, 2005). It is obvious that this fact may cause some problems in designing the controller for rotary kiln.

Although cement is the final product of a cement factory, the output product of kiln is called clinker. Producing the clinker with high quality is lead to efficiency improvement in energy consuming, input material, and final benefit of the factory. These are all achievable by deploying a desirable and appropriate kiln controller. Producing neither over-burning nor under-burning clinker is acceptable for a rotary kiln. Some factors such as flame shape, secondary air temperature, ID fan speed and etc all have considerable effects of the clinker quality.

Most of the worldwide cement factories are being controlled by the direct knowledge of the expert kiln operators. Therefore, having the accurate knowledge of the situation and the states of the burning zone is critical for a kiln operator.

Fuzzy controller of cement kilns has been one of the first successful applications of the fuzzy control in industry. In 1978, Holmblad and Ostergaard used the first fuzzy controller for a complex industry process, cement kiln. They saw that the results were much better than when the kiln was directly controlled by human (Wang, 1994). Nowadays, the cases of using the fuzzy logic controllers for controlling the cement kilns have been increased. This is based on this fact that the fuzzy logic controllers do not need an accurate model of the plant. By fuzzy logic controller, a remarkable improvement of the cement quality and a decline in the production expenses has been achieved. Several designs of such controllers have been proposed and/or implemented in (Devedzic, 1995), (Bo *et al*, 1997), (Ruby, 1997) and (Tayel *et al*, 1997), which have been designed based on the knowledge of the operators. There is also a practical description about the industrial concepts of Onoda's Cement Plant in (Aizawa, 1992). Image processing has been proposed as a solution to control a cement kiln in (Jing *et al*, 1997).

The purpose of this paper is to outline a structure for a fuzzy logic controller designed for practical rotary cement kilns based on the real behavior of a cement kiln. Initially, a summary of the cement production process is discussed. Then, the issues and variables to be defined and controlled in a rotary kiln are pointed out. An overview of the proposed neural-fuzzy controller (NFC) for the rotary cement kiln is presented in the later section. Finally, the designed controller is applied on the identified plant model of the kiln and the simulation results, as well as the controller functionality and performance, will be reported.

2. CEMENT PRODUCTION PROCESS

Fig. 1 shows the structure of a rotary kiln with the most important variables used for control purposes in a simplified way (Akalp *et al*, 1994), (Fallahpour *et al*, 2007). The kiln is a long and complex tunnel, generally with a cylindrical shape. The load, constituted by material pieces that have been molded and partially dried, is introduced at one of the ends and carried along the kiln at a very low speed. The input materials (MAT) are included of carbonates and silicates

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which should be burned to generate solid oxides and combustion gases. Burning process, denoted to all activities which are done on the raw materials up to make the final clinker, is done in three places, as follows (Noshirvani, 2005):

- Pre-heater
- Kiln
- Cooler

Raw meal must be preheated and completely dried up before it is fed into the kiln. Hot smokes generated in the kiln during the clinker production are used to do that. Pre-heater is responsible to acquire the remained moisture of the raw material and break up silicates, as well as calcinate partially the present carbonates in the material.

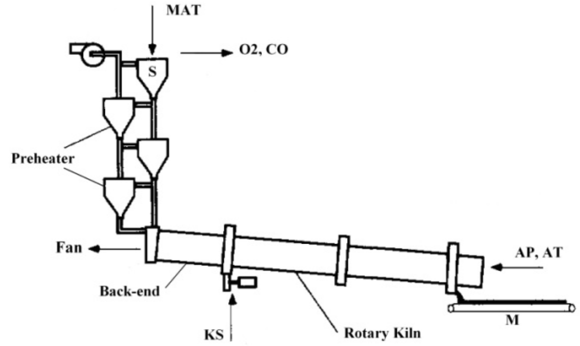

Fig. 1: A rotary kiln plant

The main part of the burning action is done by the kiln. The materials baked in two place of the kiln. First baking is occurred at the back-end and the second is done at the burning zone. The back-end is responsible for calcification the materials before the main baking. If the temperature of the back-end be more than the legal range, it causes that the backing has been done soon before to enter the burning zone. On the other hand, the low back-end temperature causes an incomplete backing of the materials.

The cement kiln is a huge cylindrical tunnel which the sizes of its length and diameter have a direct proportional to the factory capacity. In general, the length and diameter of a cement kiln is 60 and 4 meters, respectively. The cylinder, with a steep about 4 percent, rotates around its axis and the raw meal dust sticks adhesively to its walls. There it gradually gets burned and baked to produce clinker, coarse-grained pieces of cement which are then transported away from the kiln and milled in a special mill, to get the cement dust. The cylinder is slightly inclined down its axis from the raw meal fill end to the clinker output end. So, the raw meal and subsequently the clinker slowly slip towards the cylinder output.

Suction fans are installed near the pre-heater which cause entering the air from the other end of the kiln. This has an influence on the flame direction and the route orientation of combustion gases. On this side of the kiln, a flame has been installed to provide the required temperature over the temperature 1400 °C (Azizian, 1986). Also, a secondary air is forced from this side of the tunnel, i.e. in counter-current. This air, which increases the oxygen content of the kiln, has been already warmed in the cooling process done on the output clinker. In fact, the flow value of the input air is represented as secondary air pressure. Meanwhile, near the middle of the kiln is the firing zone, where gas burners are placed to impose the given temperature profile (Mota *et al*, 1993).

Calcification is the first action done on the raw mill at the kiln by such high temperature. The high temperature at the burning zone melts the input materials. Then, main burning is gradually started and chemical reactions are done between silicates and the present oxygen of the air. *CO* gas includes the main part of the combustion smokes. Finally, the cement crystals are made and go out from the kiln as the clinker (Noshirvani, 2005).

The output clinker has a temperature from 1000 to 1200 °C and it should be cooled at the end of the kiln (M) to be transferred. Cooling the clinker has a perfect effect on its quality as well.

The main goal of the kiln control is producing high quality clinker. On the other hand, a perfect control of the burning zone temperature is one of the most important factors for the quality of the clinker. Unfortunately, the real data of this part of the kiln was not available and we obligatorily used the available data of the back-end temperature of the kiln rather than the burning one. The control variables will be discussed in the next section.

3. EFFECTIVE VARIABLES IN THE CONTROL

The input and output variables effective in the control of a kiln have been shown in the Fig. 1. As previously mentioned, some variables of the kiln such as the ID fan speed (*Fan*), secondary air pressure (*Ap*) and the temperature of the secondary air (*At*), have all significant effects on the clinker quality. These variables along with feed rate of raw mix (*Mat)*, fuel feed rate (*Fuel)*, rotational kiln speed (*Ks)* conclude the control variables. The output variables of the kiln, the controlled variables, are back-end temperature (*Be*), pre-heater temperature (*Pre*), oxygen content (*O*2), the electrical current of the kiln (*Ka*) and *CO* contents of combustion gases. These variables are shown in tables 1 & 2.

It should be noted that in cement kiln systems, the dependency degrees of inputs to outputs are not the same for all variables. Therefore, to control an output, it is reasonable to consider that inputs that have more effect on it. In this case, the inputs which have either little influence or no influence on an output should be discarded.

Table 1: Control variables

Output variables of controller	Variable name
feed rate of raw mix	*Mat*
fuel feed rate	*Fuel*
rotational kiln speed	*Ks*
ID fan speed	*Fan*
secondary air pressure	*Ap*
secondary air temperature	*At*

Table 2: Controlled variables

Controlled variables	Variable name
Back-end temperature	*Be*
Pre-heater temperature	*Pre*
*O*2 (oxygen) content	*O2*
CO content	*CO*
Kiln Ampere	*Ka*

This categorization is done based on the physical behavior of the kiln and the real knowledge of the operators. For the involved kiln, how the outputs are affected by the effective input variables is briefly described as follow, which have been summarized in the table 3:

- Back-end temperature, *Be*: all of input variables are effective on this variable.
- Pre-heater temperature, *Pre*: In fact, all of the variables effective on the back-end temperature may have same behavior on this variable. Except that the effects are applied with tardiness and the efficacy level decreases versus the kiln length. Therefore, the inputs which have little effects of the back-end temperature don't have remarkable effects on the pre-heater one and they can be ignored. Finally, we should consider the main variables including ID fan speed, fuel and secondary air pressure to control properly the pre-heater temperature.
- Electrical current of the kiln in ampere, *Ka*: It's obvious that the electrical current which the kiln consumes, is proportional to the amount of both kiln load and kiln speed.
- CO gas content, *CO*: How much the CO gas is present in the kiln is related directly to the burning situation in the kiln. So, it depends on ID fan speed, fuel and secondary air pressure in the kiln.
- Oxygen gas content, *O2*: The dependence relations for oxygen gas are as same as CO gas. So, it depends on ID fan speed, fuel and secondary air pressure in the kiln, as well.

The relations and dependencies of input variables and the outputs have been summarized in the table3.

Table 3: Categorization of output and input variables

Type	*Be* Temp	*Pre* Temp	Kiln Amp	*CO*	*O2*
Material	*		*		
Fan	*	*		*	*
Kiln Speed	*		*		
Fuel	*	*		*	*
Air Pres.	*			*	*
Air Temp.	*	*			

4. NEURAL-FUZZY CONTROLLER

The structure of the controller system for the cement kiln has been shown in Fig. 2. Designing the intelligent controller of the kiln is done based on the fuzzy logic. As previously mentioned, the design needs an identified model of the plant which has a perfect representation of the real characteristics of the kiln (Fallahpour, 2007). Because of the heavy calculations done for plant identification and this fact that identification is not the goal of this paper, the identification details are neglected to be described here. It is just noted that the model is a five MISO system which has six inputs and one output.

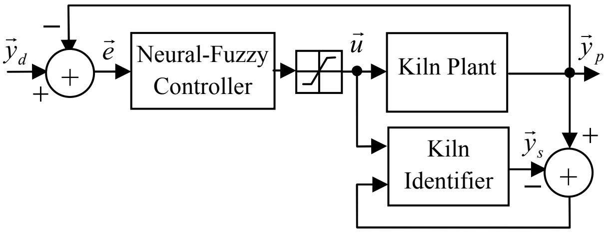

Fig. 2: Kiln controller system

It should be noted that there is no reference setpoints (y_d) for three variables including oxygen, *CO* and electrical current of the kiln. Since, reaching to a specific reference input for these variables at the controller is not a target for the control scheme. However, some authorized ranges are been defined for these variables and they should be measured to be kept in the normal ranges such that having upper values may cause problems in cement production. The authorized ranges have been listed in the table 4.

Table 4: Authorized ranges for *Ka*, *CO* and *O2* variables

	Ka	*CO*	*O2*
Maximum	90	0.6	6
Minimum	-	-	2.6

A. Controller Scheme Design

The controller designed based on the above descriptions can be seen in the Fig. 3 (Fallahpour, 2007). In the controller, three distinct NFC controllers are used to control different variables of the kiln. In the first controller, the control effort signals are generated from the error signals of the *Be* and *Pre* temperatures and also, their derivatives. In the second and third controllers, the measured values for *CO*, *O2* and *Ka* are compared with their authorized values. If the values are not in the normal range, the corresponding controller acts and generates the required control signals. Finally, the average of the controller networks is calculated and applied into the kiln plant as the final control signals.

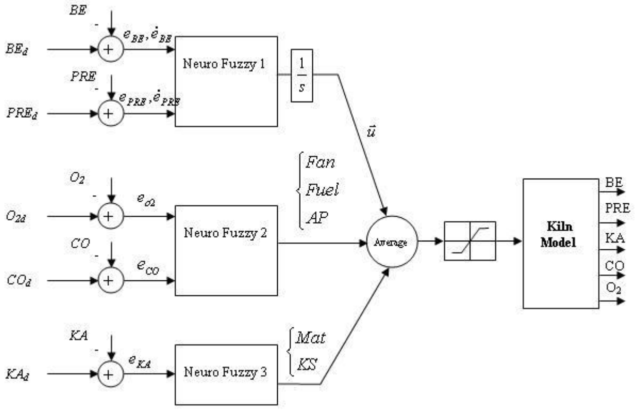

Fig. 3: The controller structure

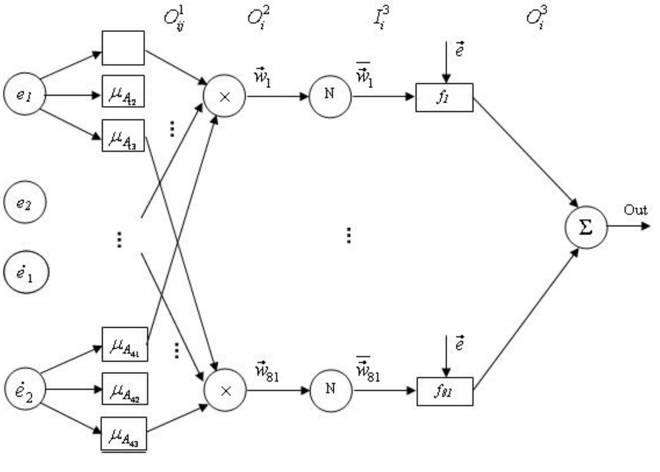

Fig. 4: The structure of the proposed NFC

Each NFC, as illustrated Fig. 4, integrates the basic elements and functions of a conventional fuzzy logic controller (FLC) (membership functions, fuzzy logic rules, fuzzification, and fuzzy implication) into a connectionist structure that has distributed learning ability to learn the membership functions and fuzzy logic rules (Chen & Peng, 1999).

Layer 1: Input layer

The input units in this layer are the transformed process output error ($\vec{e}$) and the transformed change-of-error ($\vec{\dot{e}}$). This layer receives the error signals and uses a Gausian function as a membership function to determine the relative contribution of the observed signals.

Layer 2: Rule layer

Layer 2 implements the links relating preconditions to consequences. The connection criterion is that each rule node has only one antecedent link from a linguistic variable.

Layer 3: Output layer

All consequence links are fully connected to the output nodes and are interpreted directly as the strength of the output action. This layer performs centroid defuzzification to obtain the inference output

Apparently, the NFC presented is equivalent to a simplified fuzzy inference system (Mota *et al*, 1993), where layer 1 corresponds to the antecedent part of the fuzzy control rules, and the layers 2 and 3 correspond to the conclusion part.

B. Learning algorithm for the NFC parameters updating

The adjustment of the parameters can be divided into two tasks, corresponding to the IF (antecedent) part and THEN (consequence) part of the fuzzy logic rules (Chen & Peng, 1999). However, in this paper we only adjusted consequence part, using the gradient-descent-based back-propagation algorithm to adjust the controller parameters. Once the NFC has been constructed, the learning aims at determining appropriate values for the parameters of Sugeno, α and β. Based on minimizing the error function of $E = \frac{1}{2}(y_d - y)^2$, the NFC parameters can be updated by

$$\alpha(k+1) = \alpha(k) - \eta \frac{\partial E}{\partial \alpha}$$

$$\beta(k+1) = \beta(k) - \eta \frac{\partial E}{\partial \beta}$$

The cement kiln has delay in its operation (Makaremi *et al*, 2008). In the other word, the results and effects of input variations may appear in the outputs with different delays. To have a controller with high abilities in the control of the real system, the delays should be considered in the learning of NFC parameters. We just should replace the error vector $e = y_d(t) - y(t)$ with $e = y_d(t - t_{delay}) - y(t)$, where t_{delay} is the delay of affecting each output after variations of inputs.

C. Membership functions

Three membership functions have been considered for handling the error of *Be* and *Pre* input variables, as shown in Fig. 5. Because of the variant difference in the variation range of these variables, using the generated error signals at the input of the network is not reasonable. Hence, to improve the controller performance, design is performed in the normalized state.

The membership functions of *CO*, *O2* and *Ka* variables are shown in Fig. 6. In the subspaces that the membership functions for these variables in their normal range are not defined, they will not have any role and interference for control. However, one of these inputs goes out from its normal range and the corresponding controller overrides the control procedure.

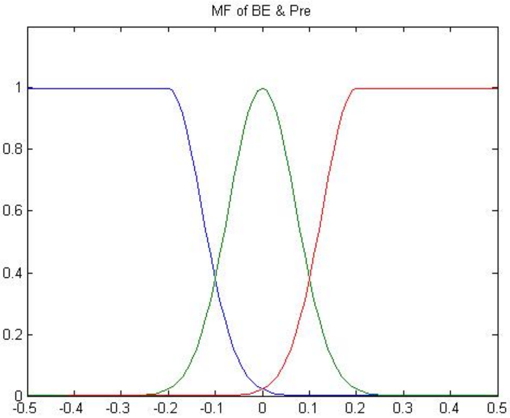

Fig. 5: The membership functions for *Be* and *Pre* variables

5. SIMULATION AND DISCUSSION

In the previous section, we have developed a neural-fuzzy system for the Saveh white cement kiln plant. To demonstrate the applicability and effectiveness of the proposed scheme, in this section we shall implement the controller to the plant simulator. The simulation results of the output variables of the kiln, produced control effort signals and the controller outputs will be depicted.

To evaluate the controller performance, a reference signal with different altitudes, as the setpoint, is applied to the system and the tracking ability of the controller is measured for various control scenarios (Fallahpour, 2007). In the following, the simulation result for one scenario is presented and discussed. As mentioned previously, the tracking ability is evaluated for kiln temperatures including *Be* and *Pre* variables while the controller tries to keep other variables including *CO*, *O2* and *Ka* in their normal ranges. The diagrams of output signals of the kiln for *BE* and *Pre* temperatures are shown in the Fig. 7. Also, the diagrams of *CO*, *O2* and *Ka* variables are drawn in the Fig. 8.

The control effort variables are described in section II as the input parameters of the kiln. The control effort signals which are produced by the controller to achieve the output variables of the kiln are shown in the Fig. 9. These signals are the average of the outputs of three neuro-fuzzy controller networks depicted in Fig. 3, while the output signals are shown separately in Fig. 10, Fig. 11 and Fig. 12.

As it was expected, in the first controller, main changes in the *Be* and *Pre* signals would causes main changes in the kiln fuel and fan speed. When the reference signals of these variables increase, the first controller mainly increases fuel and decreases the fan speed to reach the setpoint. Also, a little increase in the secondary air pressure is seen. The controller functionality is the same as the real reactions when an increase in the temperatures is ordered. In practice, the fuel of the kiln is increased, firstly, for a higher temperature. On the other hand, when the fan speed is reduced, air suction of the kiln decreased and consequently, the flow of stashed air in the kiln become slowly. This causes another increase in the temperatures. Furthermore, increasing the pressure of the secondary air (*Ap*) which enters the air into the kiln, can increase the oxygen content of the kiln and finally, the kiln temperatures.

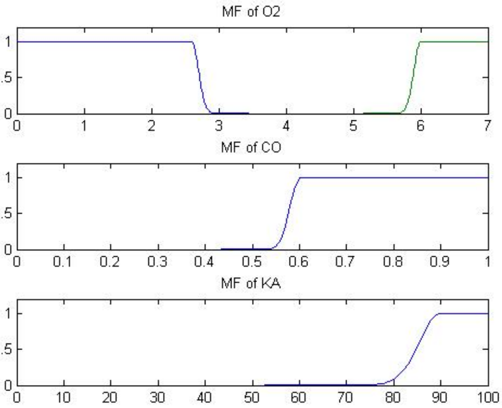

Fig. 6: The membership functions for *CO*, *O2* and *Ka* variables

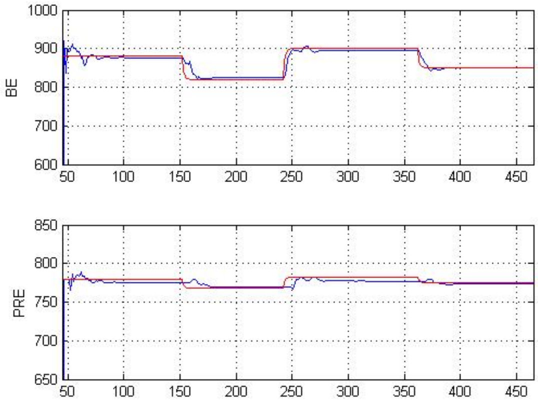

Fig. 7: *Be* and *Pre* output variables

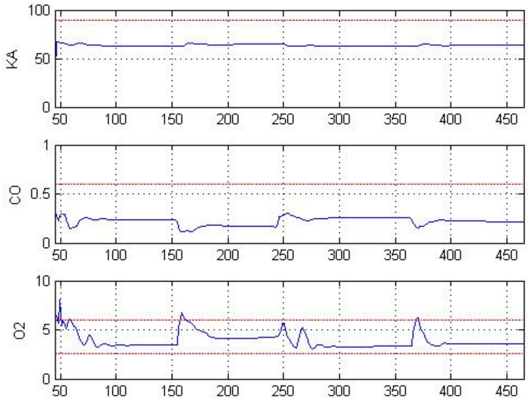

Fig. 8: *CO*, *O2* and *Ka* output variables

Changing in the kiln speed is also a regular way to control the kiln variables. When the kiln speed increases, the hot materials go out rapidly and the temperatures decreases. However, when reference signals changes highly and remarkably, a remarkable change in the kiln speed is occurred.

It should be noted that except than special cases, changing the load of input materials of the kiln is not regular for controlling temperatures. As it can be seen in Fig. 10, this condition has been regarded in the simulator and the controller.

What is so important in the evaluation of the controller performance is the control efforts reaction when there is a sudden change in the reference signals. In this controller, when the reference signal changes suddenly, the control effort signals never go out from the authorized range. However, controller system has been guarded from unauthorized signals by the saturation block installed before the kiln, as in Fig. 3. In this simulation, the control signals were all in authorized range and the saturation block never entered in the control process.

If we have a precise attention at the control effort signals in Fig. 9, it can be observed that the signals have overshoot primarily, when there is a change in the reference signal. The signals rapidly go to steady-state mode and cause the stability behavior in tracking and output signals.

With regard to the *Be* and *Pre* temperatures in the Fig. 7, we can conclude that these two variables have same behavior, with a partial delay for *Pre* temperature. Since the pre-heater temperature is affected by the air which the fan sucks, the air warms the back-end before reaches to the pre-heater. Hence, a delay is expected for the pre-heater temperature to the back-end one.

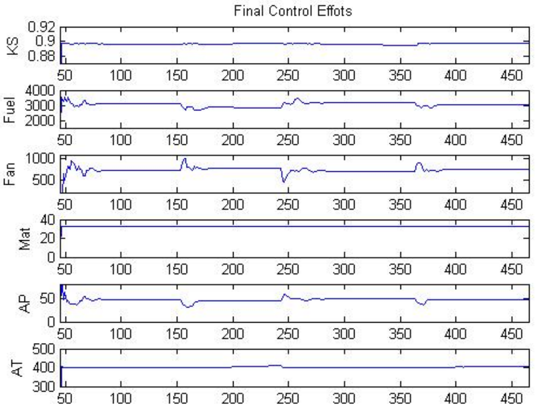

Fig. 9: Control effort signals, input variables of the kiln

The controller functionality for the oxygen variable is also considerable. As mentioned before, fuel, fan speed and secondary air pressure can affect the value of this variable. When the oxygen increases rapidly, increasing the fuel, reducing the fan speed and decreasing the flow of the secondary air, which is represented as reducing the air pressure, can all decrease and adjust the oxygen content in its normal range. Adjusting the oxygen content of the kiln is performed by the controller in the second controller.

The third controller is responsible to maintain the electrical current of the kiln in its normal range. The simulation results show that the *Ka* variable of the kiln has always been in the normal range and the third controller has never worked in the control loop.

To reach an acceptable quality assurance of the controller, it needs more reviews done in the more conditions. The interested readers can refer to (Fallahpour, 2007) for more details.

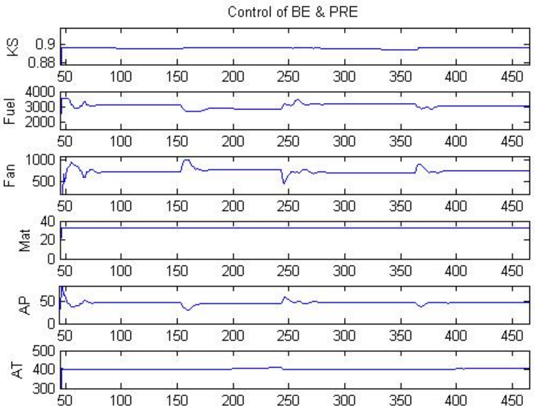
Control of BE & PRE

Fig. 10: The outputs of the first controller

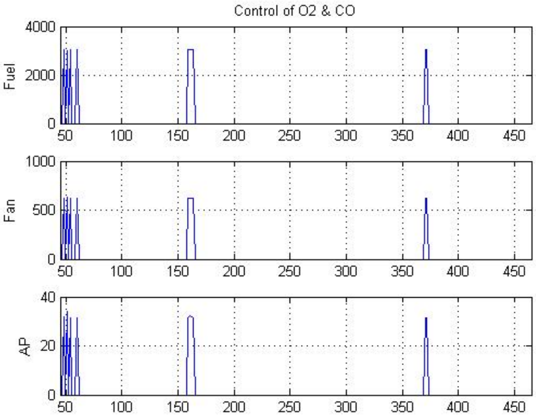
Control of O2 & CO

Fig. 11: The outputs of the second controller

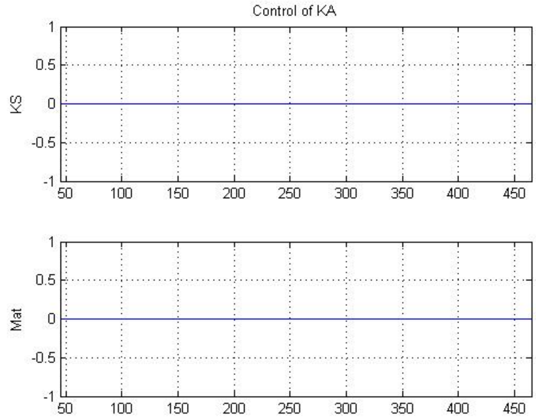
Control of KA

Fig. 12: The outputs of the third controller

6. CONCLUSIONS

Cement production is a complex process, composed of a series of activities and many variables which need to be manipulated and controlled (Fallahpour *et al*, 2007). In this paper, we used the advantages of neural-fuzzy network techniques to develop an intelligent control system for cement kiln process. The NFC was able to learn to control the process by updating the fuzzy rules and membership functions.

With a precise observation on the simulation results of the controller, it can be said that using the intelligent systems for learning the fuzzy networks definitely improve the controller functionality. However, some practical limitations and specifications should be considered for the controller design. For example, the controller's parameters must be defined such that the level of overshoots not to be out of authorized range. Simulation comparison with a supervisory controller clarifies that the proposed controller appears to have less steady state error (Fallahpour, 2007). The difference is more remarkable for the *Pre* variable. Also, the output reaches in a shorter time to its steady state level.

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