Fuzzy Logic Based Cement Kiln Control

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This paper describes the techniques of computer control of rotary cement kiln through fuzzy logic. The automatic kiln control strategy is based on the priority management of different kiln control objectives and sub-objectives. These objectives for the rotary kiln have been developed to control the kiln effectively by tackling the unknown interdependence among the different process variables. The design methodology described in the present paper has been implemented and tested on a 2500 tons per day (tpd) capacity rotary kiln cement plant.

INTRODUCTION

In 1965 fuzzy logic was developed by Lotfi Zadeh[1] of the University of California. It is a very powerful, straight forward method for controlling multivariable nonlinear industrial processes. The cement kiln process is highly nonlinear, time varying, and few process parameters available for its control. Nonlinearity and time varying behaviour of the process can be tackled by predictive control[2] and Self tuning control,[3] respectively. For infrequent measurements of low frequency self tuning controllers may converge very slowly or even may not converge. This is the exact case in a cement kiln process where some measurements like litre weight and free lime samples are not available at regular intervals due to their dependence on laboratory evaluation.[4] Also kilns with identical measurements behave differently. Hence, it is very difficult to establish an accurate mathematical model for the rotary kiln.[4] Human operators control the cement kiln from their experience based on heuristics. These rules are vaguely defined linguistic quantities like, *High, Small, OK etc.* For example, if the cocontent in the exit gas from the kiln at the preheater inlet is *High* then *reduce* the coal feed to the precalciner. By Fuzzy Logic Technique, this type of imprecise, vague linguistic expressions are controlled. The fuzzy logic kiln control system[5, 6] was commercially available in 1980, by F L Smidth (FLS) of Denmark. FLS has developed its own fuzzy programming language: the fuzzy control language[7] (FCL). Till now FLS is working constantly for the further development of a high level fuzzy logic kiln control strategy. This paper deals with the design methodology adopted for the development of a very high level fuzzy logic kiln control system by Ramco Electronics Division, Madras, India.

FUZZY LOGIC PRINCIPLES

The basic structure of the rule based on fuzzy logic system[8] is shown in Fig 1. It is basically consisting of a fuzzifier, inference engine and defuzzifier. Here it would be appropriate to define fuzzy set as a set of ordered pairs, *ie,* $S = \{(u, \mu_F(u) \mid u \in U\}$ with u the generic element and μ_F its grade of membership function, where $0 \leq \mu_F \leq 1$. If $T_i(x)$ is

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FIGURE 1
BLOCK SCHEMATIC OF FUZZY LOGIC PRINCIPLE
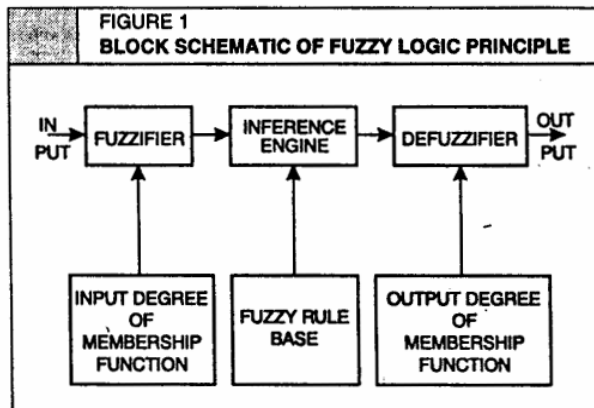
a fuzzy number and $M_i(x)$ in its membership function for all x in a universe of discourse U, then x is called as a linguistic variable, *viz*, temperature, pressure *etc*; and $t_2(x)$ is the term set for x, *viz*, low, medium, high. The fuzzy logic system is a mapping from $U \subset R^n$ to R with the assumption $U = U_1 \times U_2 \times \ldots \ldots \times U_n$, where $U_i \subset R; i = 1, 2, \ldots \ldots, n$, and x means intersection. Now the function of each of the blocks in Fig 1 has been described.

The fuzzifier is a mapping from a crisp input space $x = \{x_1, x_2, \ldots \ldots, x_n\}^T \in U$ to a fuzzy set S in the input universe of discourse U. The fuzzy rule base is a set R of fuzzy IF-THEN rules for a multi-input multi-output (MIMO) system,

$$R = \{R^1_{MIMO}, R^2_{MIMO}, \ldots \ldots R^n_{MIMO}\}$$

where the i-th fuzzy rule is

$$R^i_{MIMO} : \text{IF } (x_1 \text{ is } T_{x_1} \text{ and } \ldots \ldots \text{ and } x_n \text{ is } T_{x_n})$$

$$\text{THEN } (y_1 \text{ is } T_{y_1}, \ldots \ldots, y_n \text{ is } T_{y_n}) \qquad (1)$$

where $X = (x_1, x_2, \ldots \ldots, x_n) \in U$ and $Y = (y_1, y_2, \ldots \ldots, y_n) \in R$ are the input and output of the fuzzy logic system. The precondition of R^i_{MIMO} form a fuzzy set $T_{x_1} \times T_{x_2} \times \ldots \ldots \times T_{x_n}$ and the control action of R^i_{MIMO} is the union of n independent outputs. Here, these rules can be represented by a fuzzy implication[8]:

$$R^i_{MIMO} : \left(T_{x_1} \times T_{x_2} \times \ldots \times T_{xn}\right) \rightarrow \left(T_{y_1} + \ldots + T_{y_n}\right)(2)$$

which is a fuzzy set defined in the product space $U \times R$, where the sign + represents union.

The fuzzy inference engine maps fuzzy sets in U to fuzzy sets in R, based upon the fuzzy IF-THEN rules in the fuzzy rule base and compositional rule of inference[2] *ie*, it matches the preconditions of R^i from a fuzzy set $T_{x_1} \times \ldots \times T_{x_n}$ and perform implication. One example of compositional rule of inference is given in Appendix 1.

The defuzzifier maps fuzzy sets in R to crisp point in R. There are three wide spread methods for defuzzification, amongst these the center of area (COA) method[8] is the superior one. Fuzzy logic control strategy has been selected for cement kiln control, as it utilises all the process information from sensors and human experts, which are imprecise and vague. This method is easy to understand and inexpensive to implement in real time. It is non-parametric and can approximate any nonlinear system in time domain.

FUZZY LOGIC KILN CONTROLLER

The block schematic of the controller implementation of the combined kiln-cooler section of the plant is shown in Fig 2. Kiln-cooler section includes preheater, precalciner, rotary kiln, and cooler. The total control mechanism is divided into two distinct zones one coarse control and the other fine

FIGURE 2
BLOCK SCHEMATIC OF THE KILN CONTROLLER IMPLEMENTATION

FIGURE 3
INPUT OUTPUT DESCRIPTION OF THE FUZZY CONTOLLER
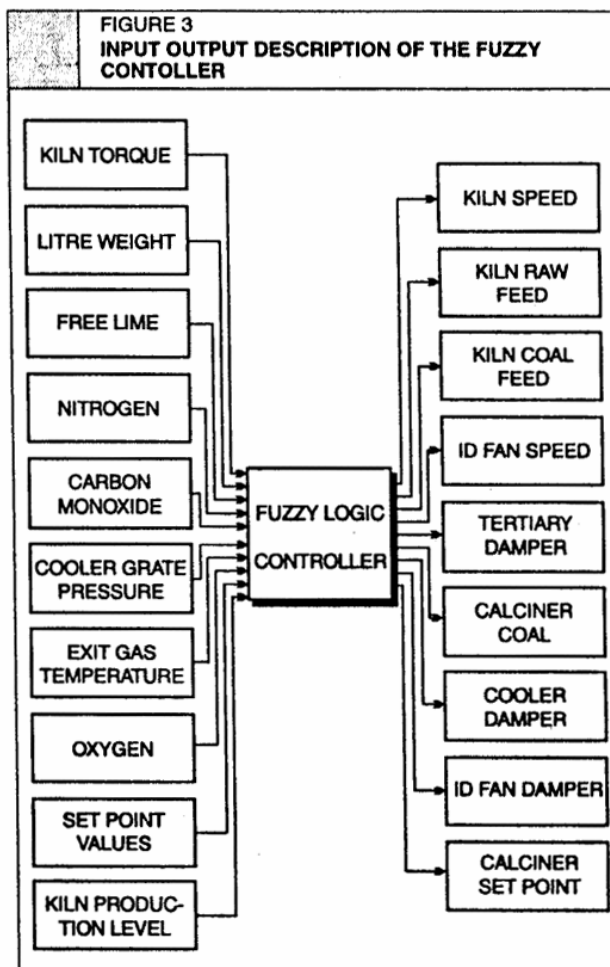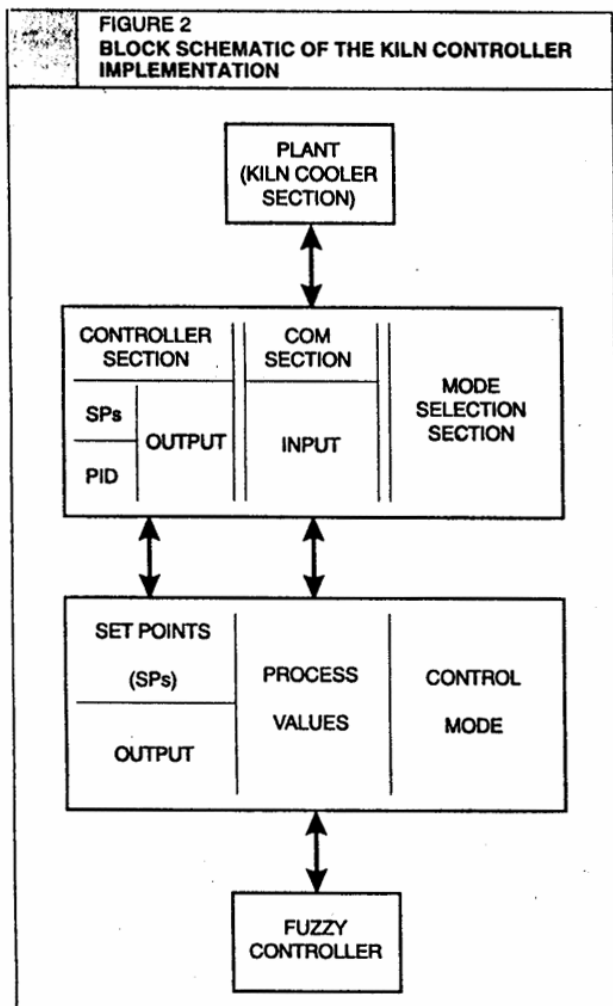
control. Fuzzy controller alone gives the coarse control and the PID controllers provide fine control of the process variable under normal operation periods. But during severe disturbances, the control action for the set point change is drastic which makes the PID controller entirely ineffective. Under these conditions fuzzy control bypasses PID, and gives the control action directly to the kiln,[9] which can be achieved by bumpless transfer,[10] usually followed in practice for a smooth transfer from manual to automatic control without disturbing the plant.

The basic input output details of the controller is shown in Fig 3. This controller is basically designed for a 2500 tpd rotary kiln employing dry process. This controller, of course can be used for any cement kiln control with modification of the rules in the rule base, and the input output membership functions. The input parameters are available from the respective transducers in tems of voltage. All the inputs were normalized to a unit scale. The final normalised output is then scaled to the required range.

KILN CONTROL STRATEGY

The entire kiln operation is very complex, but it is possible to divide this into smaller and simple sub-parts so as to facilitate better control. Now each small part is called an objective. The different objectives to be fulfilled during control mechanism are:

(i)   Sticky kiln

(ii)   Loss of coating

FIGURE 4
KILN CONTROL OBJECTIVE MODULE
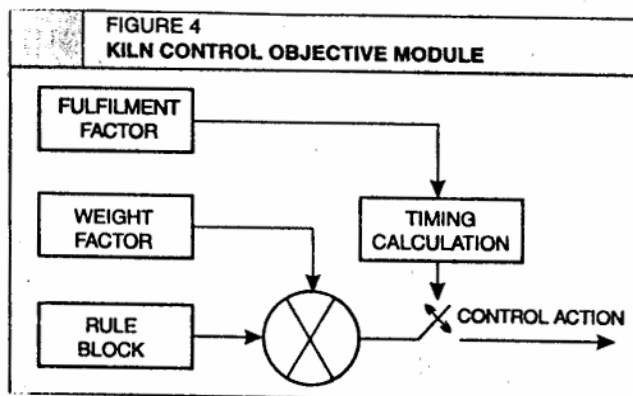
(iii) Stability of the kiln

(iv) Quality of the clinker

(v) Production of the plant

(vi) Carbon monoxide (CO) control

(vii) Oxygen (O₂) control

Out of the above seven objectives first five are material flow objectives and rest two are gas flow objectives. Some of the above objectives are contradictory to each other, like quality or production of clinker, and calorific consumption improvement. A priority to each objective has been assigned. Now a priority management system is required. The priority management system used in this paper checks the highest priority objective which should be fulfilled before next objective is fired. For knowing the fate of objective a fulfillment factor is assigned to each of these objectives. This is called, Grade of Fulfillment (GFF). This priority management system ensures that the particular objective is to be fired, by introducing a factor called Weight Factor (WF). One objective module is described in Fig 4. The basic elements of an objective module are

(i) Fulfillment factor

(ii) Rule block for fulfillment of objective

(iii) Weight factor

(iv) Timing calculation

Fulfillment factor (GFF) indicates the degree of closeness of the particular objective to the actual process value. It is calculated from a set of fuzzy rules giving a value between 0 and 1. For this fuzzy logic controller each objective has its own rule block and the priority management system takes care of the interaction among the rule blocks. The weight factor (WF) close to unity means that all other higher priority objectives are fulfilled. A fuzzy rule base is created for the calculation of weight factor. Timing calculation is one of the important factor in entire control strategy. It determines the time for the next objective rules to be fired. This depends on the fulfillment factor. For this case the timing is chosen as follows

$$t = (GFF \times a + b) \times \text{minimum control action} \qquad (3)$$

where a and b are two constants. This is essentially a time delay in the process objective.

FIGURE 5
PRIORITY MANAGEMENT FOR KILN CONTROL OBJECTIVE
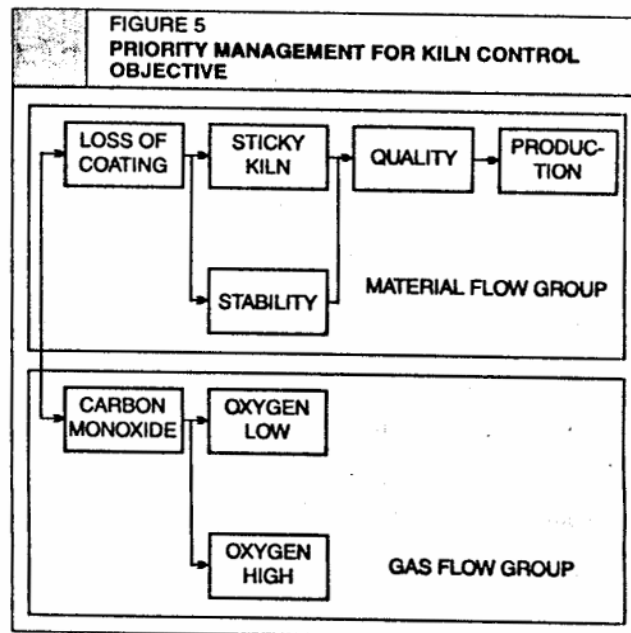
PRIORITY MANAGEMENT SYSTEM FOR OBJECTIVE MODULE

The priority management of different objects are shown in Fig 5. From this figure it is clear that loss of coating (LOC) and carbon monoxide (CO) has got the same priority. Whereas the sticky kiln and stability of the kiln in the material flow group has got the same priority. O₂ low and O₂ high has got the same priority in the priority diagram in the gas flow group. These equal priority to different objectives has been allowed as they will not occur simultaneously. The priority diagram indicates that if LOC is not fulfilled then the control strategy will give less importance to stability of sticky kiln conditions. LOC has been given the highest priority, as when this will occur the kiln has to be stopped, which will in turn hamper rest of the operations. Quality is less important than stability of the kiln, as only a stable kiln can provide good quality clinker. So, quality or production depends on a kiln and its stable running conditions.

Thus, priority scheme is so important for an automatic kiln control, and is the basis for the priority diagram to be set. This priority management system splits a complex problem into small and relatively simple subproblems.

FEATURES OF THE SOFTWARE

The software developed is an integrated package with the major modules, ie,

— Communication module to communicate with plant

— Controller module

— User interface

Amongst the other features the operator can access the history of the plant, on-line trends of different process variables, and alarms for any process deviation.

The data structures used in this software package for implementing the fuzzy control strategy are:

(i) Input Parameters — Name [], Unit [], Week [], Day [], Hour [], Actual Value, Normal Value, Low Limit, High Limit, Previous Value.

(ii) Control Parameters	— Time Last Action, Time Next Action, Along with Input Parameters.
(iii) Main Objective	— Name [], GFF, WF, previous GFF, Time Last Action, Time Next Action, Connected Objective, Preceding Main Objective.
(iv) Sub-objective	— Till Time Next Action, Input Parameters, Output/control Parameters, Parent Objective and all the Data structures of Main Objective.

Objectives and Rule Base — control action, WF, fulfillment factor, timing calculation.

RESULTS AND OBSERVATIONS

The computer program of this control strategy has been developed in C programming language in an Intel 80486 based system. This has tested for a 2500 tons per day (tpd) plant situated at Jayanthipuram, Andhra Pradesh. It has been observed that the plant performance improves dramatically with this control scheme. The clear benefits out of this are:

(i) Higher run factor: up to an extent of 8 to 20 percent increase.

(ii) Improved control performance.

(iii) Longer equipment life time: due to the less intervention of human operator.

(iv) Improved product quality: due to the constant vigil of the fuzzy controller on the process.

(v) Greater production: in respect of the constant supervision of the fuzzy controller.

(vi) Greater operational economy: due to the less human operator interaction.

(vii) Easy maintenance through a much better understanding of the control strategy

All the benefits cited have been derived from the experience of the plant personnel. A clear cut picture can not be drawn without comparing the plant performance between a manual, *ie*, by operators and a fuzzy controller one. This is not possible as two different control strategies can neither be used simultaneously on a running plant nor on two identical kilns as they behave differently. One example of a rule block implementation is given in Appendix 2. It has been observed that with this improved automatic rotary kiln control system, the plant performances such as clinker quality, cement production, *etc* increase significantly. This control strategy is easily maintainable, adaptive to new kiln and operating conditions.

CONCLUSION

This paper deals with the fuzzy logic design technique used for a rotary cement kiln control. This control scheme can be used in many other process industries like refineries, paper mills, polymer plants *etc*. The entire program requires a very few changes for adaptation in other processes.

ACKNOWLEDGEMENT

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APPENDIX 1

COMPOSITIONAL RULE OF INFERENCE

Compositional rule of inference can be interpreted as the matching of two fuzzy subsets or relations (fuzzy set and a relation). If R is a fuzzy relation from universe of discourses (UoD) U to V, then the Fuzzy subset B' in V which is induced by the composition of R and A as

$$B' = A' \, o \, R$$

where o stands for max-min composition.

Alternatively, it can be represented as

$$B'(v) = \text{Sup} \left[\min \left\{ A'(u), R(u, v) \right\} \right]$$

where $u \, \varepsilon \, U$, $v \, \varepsilon \, V$ and A' is fuzzy subset of U.

Let A and B are fuzzy subsets of U and V with

$$A = [0.2 \; 1.0 \; 0.5]$$

and, $B = [0.0 \; 0.3 \; 0.1 \; 0.7]$

Hence,

$$R = \begin{bmatrix} 0.0 & 0.2 & 0.1 & 0.2 \\ 0.0 & 0.3 & 0.1 & 0.7 \\ 0.0 & 0.3 & 0.1 & 0.5 \end{bmatrix}$$

If $A' = [0.1 \; 0.8 \; 0.2]$, then the fuzzy subset B' of V can be calculated by compositional rule of inference as

$$B' = [0.1 \; 0.8 \; 0.2] \begin{bmatrix} 0.0 & 0.2 & 0.1 & 0.2 \\ 0.0 & 0.3 & 0.1 & 0.7 \\ 0.0 & 0.3 & 0.1 & 0.5 \end{bmatrix}$$

$$= [0.0 \; 0.3 \; 0.1 \; 0.7]$$

APPENDIX 2

AN EXAMPLE OF ONE RULE BLOCK

Here INCR and DECR represents Increasing and Decreasing, respectively. Also LDECR, MDECR, SDECR, SINCR, MINCR, LINCR AND BZT represents Large Decrease, Medium Decrease, Small Decrease, Small Increase, Medium Increase, Large Increase and Burning Zone Temperature, respectively.

IF LOW (*FREE LIME*) AND INCR (*KILN SPEED*) THEN SINCR (*BZT*)

IF LOW (*FREE LIME*) AND OK (*KILN SPEED*) THEN MDECR (*BZT*)

IF LOW (*FREE LIME*) AND DECR (*KILN SPEED*) THEN LDECR (*BZT*)

IF OK (*FREE LIME*) AND INCR (*KILN SPEED*) THEN MINCR (*BZT*)

IF OK (*FREE LIME*) AND OK (*KILN SPEED*) THEN ZERO (*BZT*)

IF OK (*FREE LIME*) AND DECR (*KILN SPEED*) THEN MDECR (*BZT*)

IF HIGH (*FREE LIME*) AND INCR (*KILN SPEED*) THEN LINCR (*BZT*)

IF HIGH (*FREE LIME*) AND OK (*KILN SPEED*) THEN MINCR (*BZT*)

IF HIGH (*FREE LIME*) AND DECR (*KILN SPEED*) THEN SDECR (*BZT*)