APPLICATION OF MODEL REFERENCE ADAPTIVE FUZZY SYSTEM FOR CONTROL OF PROCESS PARAMETERS IN SPONGE IRON PRODUCTION PROCESS

EDWELL TAFARA MHARAKURWA

MASTER OF SCIENCE

(Electrical Engineering - Power System Option]

PAN AFRICAN UNIVERSITY

INSTITUTE FOR BASIC SCIENCES TECHNOLOGY AND INNOVATION

2014

APPLICATION OF MODEL REFERENCE ADAPTIVE FUZZY SYSTEM FOR CONTROL OF PROCESS PARAMETERS IN SPONGE IRON PRODUCTION PROCESS

EDWELL TAFARA MHARAKURWA

EE300-0003/12

A thesis submitted to Pan African University Institute for Basic Sciences Technology and Innovation in partial fulfilment of the requirements for the degree of Master of Science in Electrical Engineering

2014

Declaration

I hereby declare that this Thesis is my original work and has not been presented for award of M.Sc. degree in any University.

.... …..

MharakurwaEdwellTafara [EE300-0003/12] Date

This Thesis has been submitted for examination with my approval as a University Supervisor.

....

1. Prof. G. N. Nyakoe Date

Jomo Kenyatta University of Agriculture and Technology, JKUAT, (Department of Mechatronic Engineering)

....

2. Prof. B. W. Ikua Date

Jomo Kenyatta University of Agriculture and Technology, JKUAT, (Department of Mechatronic Engineering)

Dedication

To my beloved mother and brother Talon

Acknowledgements

I would like to express my deepest gratitude and appreciation to Prof. G.N. Nyakoe and Prof. B.W. Ikua who were my supervisors for their support, advice and suggestions throughout the course of this research. I also wish to acknowledgeMr AnadRao, Plant Engineer at Steelmakers Pvt Ltd Company for allowing me to access data for carrying out this research. Without you brother during programming, I would not have sailed through well, I acknowledge your help. I appreciate the efforts of fellow engineering students who played a major role and contributed equally towards the success of this research not forgetting all helpfulRutendoGoboza and my family members for their undeniable support.

This research would not have been possible without the Masters' scholarship of the African Union Commission granted. All funding used for the acquisition of data from the field was acquired through the scholarship.

Table of Contents

Contents

List of Tables

Table of Figures

List of Appendices

List of Abbreviations

ABC	After Burner Chamber
CG	Centre of Gravity
DRC	Democratic Republic of Congo
DRI	Direct Reduced Iron
FIS	Fuzzy Inference System
FL	Fuzzy Logic
FLC	Fuzzy Logic Control
FMRMAC	Fuzzy Multiple Reference Model Adaptive Control
H	High
LO	Low
M	Medium
MIT	Massachusetts Institute of Technology
M-Close	Medium Close
MLO	Medium Low
MRAC	Model Reference Adaptive Control
MRAFS	Model Reference Adaptive Fuzzy System
NB	Negative Big
NM	Negative Medium
NS	Negative Small
PID	Proportional Integral Derivative
PM	Positive Medium

PS	Positive Small
QRT	Quick Response Thermocouple
SCADA	Supervisory Control and Data Acquisition
TPD	Tonnes per Day
VH	Very High
VLO	Very Low
W-Open	Wide Open
ZE	Zero

List of Nomenclature

d_1	kiln diameter after accretion build up
d_0	initial kiln diameter
T	retention time of charge in kiln
R	angle of repose of product
L	length of kiln
D	kiln internal diameter
θ	kiln inclination angle
N	kiln rotational speed
e	tracking error
y_p	plant output
y_m	reference model output
J	loss function
γ	Adaptation gain
G_m	reference model transfer function
G_p	plant transfer function
k_o	model reference constant
k	plant constant
u_c	Control signal
θ_1	plant adaptation parameter
%OS	Maximum Overshoot
t_s	Settling time
ζ	Damping ratio
ω_n	Natural frequency
k	scaling gain for error

g	scaling gain for rate of change of error
r	scaling gain for angle
ec	rate of change of error
v_a	Armature voltage
R_a	Armature resistance
L_a	Armature inductance
I_a	Armature current
e_b	Back emf
K_b	Back emf constant
w	Angular speed
K_t	Torque constant
J_m	Rotor inertia
B_m	Viscous friction coefficient

Abstract

Sponge iron is a product of direct reduction of iron ore in a rotary kiln. The reduction process involves a complex chemical reaction which is based on control of temperature and pressure within the kiln. It needs continuous monitoring and control so as to ensure high product quality and also maintain the safety index of the kiln. This is because fluctuations in temperatures and pressure lead to unstable degree of metallization of the product; causing kiln accretion, hot spots and creation of fines that may compromise product quality and shorten the life of the kiln. The formation of accretions in rotary kilns affects the residence time of the charge, kiln hold-up, and the kiln output to a great extent. However accretion build up in the kiln is difficult to regulate during the reduction process for the sponge iron production due to the nonlinear nature of the process dynamics. Thus methods which utilise partial and imprecise data from temperature and pressure sensors to estimate the performance of the kiln need to be implemented to minimize accretion. In this study, a Fuzzy Logic Controller (FLC) that works in conjunction with Model Reference Adaptive Control (MRAC) based on the MIT-Rule is proposed for control of kiln parameters. A MRAC was designed using a PID algorithm technique, and simulation results showed that it can be used in the process parameter control of a rotary kiln thereby minimizing accretion build up in the kiln. MATLAB/SIMULINK was used to simulate the controller models.Simulation results show that it is possible to reduce accretion build up from 27 % when using PID controller to 14.6 % with the use of Fuzzy control. The results of the simulation also indicate that the Model Reference Adaptive Fuzzy System (MRAFS) provides a faster rate of convergence than the conventional MRAC and PID controller approach so that the process tracks the reference model within a shorter time frame. It was also observed that under the same operating conditions, MRAFS has the best dynamic response, shorter response time, low overshoots and high steady precision. The study shows that the developed MRAFS can be used in rotary kilns to maintain product quality as well as minimize accretion formation in the kiln.

Key words- Accretion, Fuzzy logic, Kiln, Model Reference Adaptive System, Sponge Iron

CHAPTER 1: INTRODUCTION

1.1 Background

The availability of non-coking coal, iron ore reserves and the scarcity of indigenous scrap has led to the mushrooming of sponge iron processing plants within developing nations such as Zimbabwe, Tanzania, Democratic Republic of Congo (DRC), South Africa, Mexico and India. Sponge iron, also called Direct Reduced Iron (DRI) is a recognized alternative to steel scrap as a raw material for the manufacture of various steel products.

Sponge iron is a product of direct reduction of iron ore. This chemical process takes places in a rotary kiln under controlled temperatures and pressures conditions. The objective of the kiln process is to convert iron ore into sponge iron by direct reduction process through the use of non-coking coal and limestone at temperatures below the fusion point of iron while it is still in solid state [1]. The reduction process within the kiln is characterised by complex dynamic and nonlinear behaviour, which calls for a skilled operator to control the working parameters of the processing plant so as to maintain a high metallization rate.

Retention time, kiln temperatures and kiln pressure monitoring and control are vital in sponge iron generation plants and their control is very critical during sponge iron production. Fluctuations in temperatures may lead to unstable degree of metallization. A temperature profile of 700^oC-1050^oC should be maintained within the kiln so as to attain a product of high quality of 90-95% metallization [2]. Unregulated temperatures within the kiln cause kiln accretion, hot spots and creation of fines that may compromise product quality and shorten the life span of the kiln [3].

1.1.1 The Sponge Iron Production Process

The chemical process involved in making sponge iron removes oxygen from iron ore by using a reducing agent in the form of non-coking coal [2]. A simplified flow diagram of sponge iron making is shown in Figure 1.1

The reduction process is carried out in an inclined horizontal rotary kiln, which rotates at a predetermined speed. The kiln is divided into two zones; the pre-heating zone and the reduction zone. For direct reduction in the inclined rotary kiln, ore and coal pass through the inclined kiln in a counter current direction to the oxidizing flue gases in the freeboard. The volatile particles of the coal from the bed material are burnt, over the entire length of the kiln with a controlled amount of air from kiln shell air fans and center burner fan, thereby providing the necessary heat required for the metallization process [1].

This process requires a duration of approximately 8 to 12 hours inside the kiln depending on the capacity of the kiln, during which iron ore undergoes reduction process. The reduced iron is then discharged to a rotary cooler for indirect cooling to a temperature below 100°C before coming out into the finished product separation system[2].The discharge from the cooler consisting of sponge iron, chars and other contaminations are passed on through magnetic separators so that sponge iron can be separated from other impurities [1], [2], [4].The hot gases from the kilnpass through dust settling chamberlocated below the ABC (After Burner Chamber), where heavier particles of dust settle down and the un-burnt carbon monoxide and carbon particles if any are burnt. The gases with finer fraction of dust pass directly through waste gases cleaning system or through waste gas heat recovery boiler.

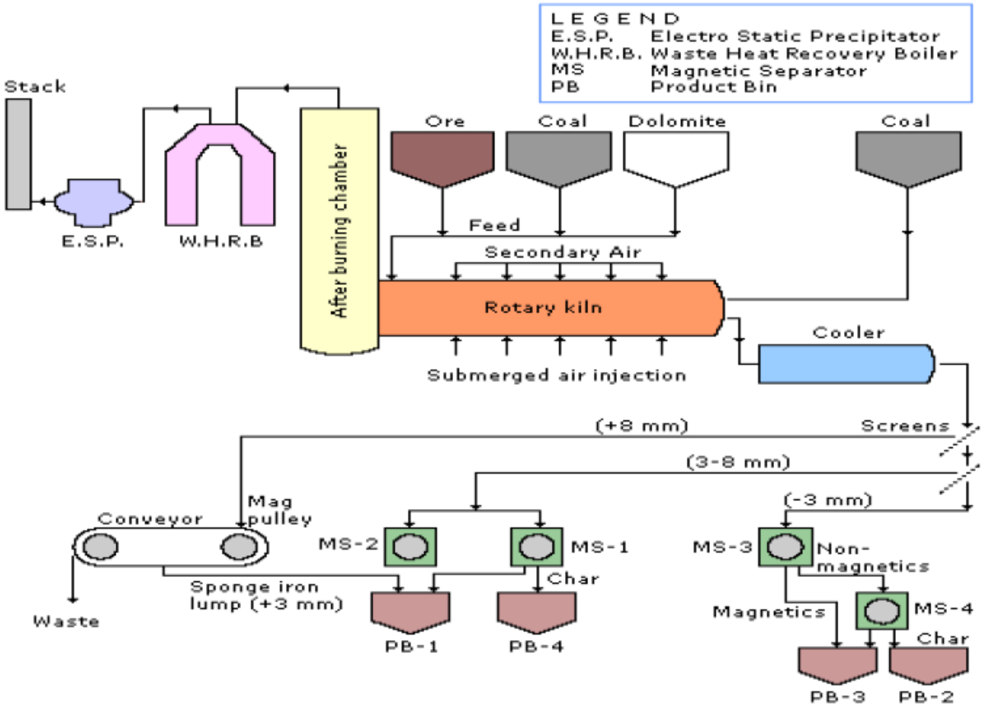

Figure 1.1 DRI Process flow[4]

1.1.2 Direct Reduced Iron (DRI) processvariables

The operating parameters are very important from the view point of energy consumption, coal consumption, productivity of the kiln, campaign life and product quality given by percentage of metallization. Sarangi and Sarangi, [1] noted that DRI production performance is influenced by many parameters which include kiln temperature, kiln pressure, kiln inclination and speed, raw material characteristics, feed rate and charge composition, coal slinging and heat transfer, amount of gas in the kiln, quantity of char in the kiln discharge, speed of rotary cooler and product discharge, composition and temperature of waste gas and its velocity, accretion formation in the kiln and char recycling. Due to the nonlinear dynamic nature of the kiln reduction process, close control and monitoring of working parameters is needed especially kilnpressure and kiln temperatures as they can lead to drop in metallization, formation of kiln hot spots and rings that can necessitate plant closure.

1.1.3 Controltechniques in kiln based processes

Some of the sponge iron rotary kilns are still under manual control where the operator observing the burning status of the different zones of the kiln and exerting appropriate control (human-in-loop control). As a result, it is difficult to maintain consistent product quality and energy consumption is high. In addition, the kiln liner may wear out rapidly and lower the production rate. PID controllers have been used as a control technique in sponge iron plants.However the random changes of the process variables have posed some limitations to this control strategy. Although several advanced control strategies including fuzzy control, neuro-fuzzy control, intelligent control and predictive control have been introduced into process control of rotary kilns, all these researches focused on stabilizing some key controlled variables but are valid for cases where boundary conditions do not change often.

1.2 Problem Statement

Accretion build up in the kiln is difficult to regulate during reduction process due to the complex process dynamics. Current methods in use utilise partial and imprecise data from temperature and pressure sensors to estimate the rate of accretion build up. Many sponge iron plants are producing sponge iron of low quality thus becoming uncompetitive in the market. Thereis a challenge on regulation of machinery for improving sponge iron quality. The main challenge is to maintain kiln temperature and pressure at the desirable values. Theuse of conventional controllers for temperature and pressure control is not effective in maintaining high product quality and plant energy consumption.Unstable temperatures lead to reduction of kiln lifespan and campaign period in sponge iron production due to accretion build up. There is therefore a need to continuously monitor and control the process parameters using modern technologies so as to attain and maintain a product of high quality. This study aims at introducing an intelligent control system to address the problem.

1.3 Objectives

1.3.1 Main Objective

The main objective of this research is to design a Model Reference Adaptive Fuzzy System (MRAFS) for control of process parameters in a kiln-based sponge iron production process.

1.3.2 SpecificObjectives

The specific objectives of the research are as follows:

1. To determine the appropriate working parameters for continuous operation of the kiln.
2. To develop a standalone Fuzzy Logic Control (FLC) system based on temperature and pressure.
3. To design a Model Reference Adaptive Control algorithm based on the determined working parameters.
4. To developand evaluate the performance of a Model Reference Adaptive Fuzzy System through transient analysis.

1.4 Justification

Maintaining good control of the kiln temperature and pressure profiles helps ensure availability of consistently high qualitysponge iron and uniform sponge pellet size that would be acceptable by end users. The safety index and life span of the kiln will be improved since controlled temperatures will minimize chances of hot spots and kiln accretions.The use of an automated system will lead to improved production rate and automatically control the conditions necessary for quality management at minimum labor costs with little or no human intervention. This study seeks to find ways of monitoring, control and maintainkiln operating parameters at the desired levels; in particular how effective and timely temperature and pressure control can affect sponge iron quality while minimizing human intervention within the process thereby achieving a high quality product.

1.5 Scope

The research is a case study for Steelmakers Pvt Ltd (100TPD Plant), SIMBI branch (Zimbabwe). Sponge iron production is affected by many parameters likeraw material quality, kiln temperatures, pressure, gas flow, material flow and mix within the kiln, kiln tilt angle and kiln rotation speed. However, this study only focuses on kiln temperature profile in a rotary kiln and kiln pressure. In this research, the quality aspect of raw materials is considered to be constant and by controlling the process parameters (temperature and pressure), it is expected that the process performance and product quality will also be improved. Further, emphasis is also on the integration of the general PID based system with a Fuzzy Controller cascaded with a Model Reference Adaptive Control system to achieve a Model Reference Adaptive Fuzzy System.

1.6 Thesis outline

This thesis deals with the development of a Model Reference Adaptive Fuzzy system for the control of process parameters in kiln based sponge iron production process and is organized as follows:

Chapter 1 provides an introductory background on the production of sponge iron through kiln based process; the parameters that affect kiln performance and the current control techniques used in kiln control processes. The research problem statement, objectives and significance of the study are also presented.

Chapter 2 describes the different approaches used in accretion minimization in sponge iron production. It also introduces the current techniques used in kiln control and also the technological advancement in industrial automation including Fuzzy Logic, Adaptive control, Model Reference Adaptive control and Model Reference Adaptive Fuzzy control and how these techniques have been implemented in different applications.

Chapter 3 presents the measurements and observations carried out to determine the appropriate working conditions for kiln operation. Also the specification for the design of the fuzzy logic controller for accretion control is presented. The methodology used to develop Model Reference Adaptive control based on MIT rule is also presented. It is in this chapter where MATLAB/Simulink models for Fuzzy Logic, Model Reference Adaptive Control and Model Reference Adaptive Fuzzy System are presented.

Chapter 4 gives the results obtained through simulation of the proposed Model Reference Adaptive Fuzzy system design for kiln parameter control, the analysis and comparisons of these results with the results of the conventional PID and MRAC controllers.

Chapter 5 outlines the main conclusions, thesis contributions and suggestions for the future work.

CHAPTER 2: LITERATURE REVIEW

This chapter establishes the essential theory and critical assessment of the related work needed for the development of the research and it also presents the main findings by different researchers of intelligence systems and how they can be used to regulate kiln temperatures and pressure in sponge manufacturing with aid of Model Reference Adaptive Control System. In this section the reviewed literature concerningaccretion formation, kiln heat transfer, fuzzy logic system, adaptive control, model reference adaptive control techniques, and the impacts caused by intelligent systems in automated sponge iron manufacturing has been presented.

2.1 Accretionformation in Rotary kiln

Some materials adhere to the refractory coating inside the kiln after continual operation of the kiln for several days. Accretion build up or ring formation in the kiln is normally caused by the deposition of low melting complex compounds on the refractory wall of the rotary kiln which gradually increases in thickness thereby, reducing the kiln diameter which ends up hindering material flow in the kiln and hence rate of production and short campaign periods [3], [5], [6]. Some accretion can also form because of the agglomeration of fines nearer to the charge end or because of sintering of sponge iron due to extreme temperatures and low carbon/iron ratio at the charge end of the kiln [1]. It is therefore necessary to minimize the causes attributed to the formation of semi-molten masses in the rotary kiln during processing leading to accretion. According to Venkateswaran, [7] the maximum temperature at which the kiln can be operated is dependent on the ash fusion temperature of the coal; therefore if the kiln is operated beyond this point, accretion develops. Figure 2.1 shows cross-section of kiln showing accretion build up.

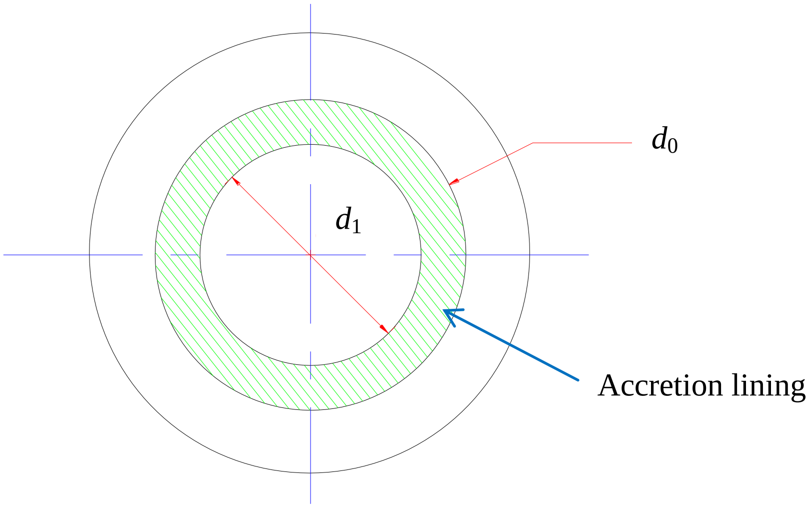

Figure 2.1 Kiln cross-section showing accretion

From Figure 2.1, the shaded section shows the accretion lining in the kiln, whered_0 is the initial kiln diameter, and d_1 is the kiln diameter after the accretion has built up.

Once accretion has been formed in the kiln, it acts as a secondary dam which interferes with the charge movement resulting in poor material flow, increased back spillage at the inlet end,and decrease in effective diameter. The back spillage reduces the working volume resulting in decrease in discharge rate and finally stoppage of the kiln operation [1], [8]. It also adversely effects the kiln availability and economy of the process. Temperature measurement becomes difficult thereby, making the control of the kiln temperature and consequently air profile virtually impossible.Although accretion build up in kiln should be minimized, it should not be totally eliminated because it also helps in refractory capability of the kiln lining.

Rao, [9] in an experimental study of ring formation of sponge iron in a pilot rotary kiln, found that the factors responsible for the ring build up were: the generation of fines during kiln rotation and their tendency to stick to the lining in the presence of moisture at the cold end; formation of cake from coal at 400 to 500° C and agglomeration and sticking tendency to the brick surface as the charge travels, and sticking tendency at higher temperatures above 1050°C due to liquid formation resulting in the fusion of the exposed surface. This appears to be principal cause of the heavy build up. However,Rao[9] suggested that accretion build up could be avoided by eliminating the fines, usage of coal with low alumina and silica, operation of the kiln between 1000°C and 1050°C without any flash of temperature. Venkateswaran, [7], also suggested thatif the generation of dust is avoided and a desired temperature profile ismaintained, the rotary kiln would perform well for solid state reduction of iron ore. However, the challenge within many rotary kiln plants is on how to maintain the required kiln temperature profile along the length of the kiln. This is due to the fact that the thermocouples fail to capture correct temperature when the tips get buried due to accretion build up.

Dash, [6], further articulated another remedy to accretion formation, where they incorporated the use of new refractory technology in sponge iron kilns. The new refractory was designed based on the micro-structural analysis of the accretion refractory interacted interface. They found that newly developed ACCMON DRI showed significantly lower accretion adherence as compared to Andalusite based low cement formulation. To some extent these studies managed to reduce ring formation.

2.2 Rotary Kiln Heat Transfer

Rotary kilns are normally characterized by large scale continuous processes and therefore the key factor of these processes is to keep the thermal regulation stable although it is a fictitious act as fluctuations are unavoidable due to material conditions and equipment working conditions [10]. Rotary kilns are the heart of thermal energy in solid processing plants and one of their important applications is to transfer heat to or from the bed of solids.Heat transfer in kilns is very complex, with radiation, convection and conduction all contributing to energy transfer between the gas, the feed and the refractory material.The relevance of each of heat transfer mechanisms depends on the nature of the flow charge and gaseous dynamics within the kiln.

2.2.1 Heat transfer paths in the transverse direction of a rotary kiln

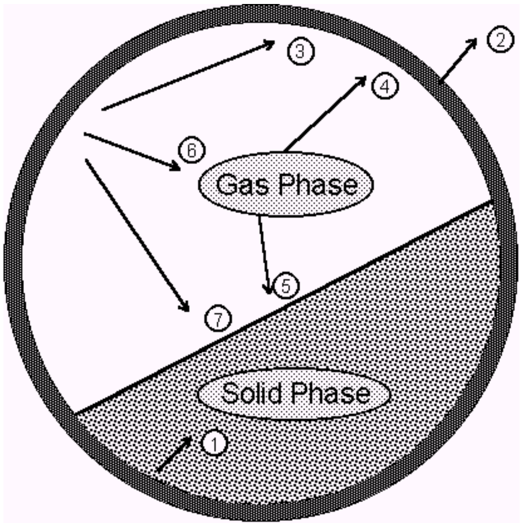

Figure 2.2: Heat transfer paths in the transverse direction of a rotary kiln

Figure 2.2 shows the heat transfer paths in a rotary kiln as defined by Barr, [11]. This shows that heat is transferred to the solid burden in two paths: across the exposed surface of the solid bed and the covered lower surface of the bed.

These paths include:

(1) heat transfer through conduction between the wall and the bed of solids,

(2) heat losses from the outside wall of the kiln,

(3) heat transfer between the inside walls of the kiln via radiation,

(4) radiation heat transfer from the hot gas to the refractory walls,

(5) radiation heat transfer from the hot gas to the burden,

(6) radiation heat transfer from the kiln walls to the gas phase

(7) radiation heat transfer from the kiln walls to the bed of solids.

2.2.2 Related work on rotary kiln heat transfer modeling

The first mathematical model of rotary kiln based on heat transfer alone was developed by Imber and Paschkis, [12] and it was for the purpose of calculating the length of the kiln required to heat solids by a desired amount. Rasul, [13] has presented a model to assess the thermal performance of cement industry with incorporated view to improve the productivity of the plant. The model developed was on the basis of mass, energy and energy balance and was applied to Portland cement industry in Indonesia. Patil, [14] presented a study on heat transfer modeling of rotary kiln for cement plants. Their model showed that there is a scope of at least 12% energy savings in the rotary kilns.

Barr, [11] carried out some measurements for temperature profile of the wall in a gas fired rotary kiln to predict the heat transfer to a rotating bed. The observations made were that rapid heating existed in the kiln initially and the ratio of the heat input to the bed to the heat loss from the bed was dependent on the ratio of the exposed bed surface to the exposed wall surface. Depending on the gas temperatures, the heat transfer from the wall covered by bed to the bed was generally much less than the overall heat transfer rate to the bed. In their experiments the free board temperatures were in the vicinity of 1700 K, which indicates that radiation was the most prominent heat transfer mechanism.

Boateng and Barr, [15] developed a two dimensional grid to determine the temperature profile across the transverse section of the bed of solids in a rotary kiln. They found that in a typically well mixed bed, the thermal conductivity of the bed increased due to particle motion. As the rotational velocity was increased, the bed mixture became more uniform hence the bed temperatures. However the bed mixture was also affected by the bed particle size thus the temperatures were non uniform for a segregated bed.

Chatterjee, [16], described the modelling of rotary kiln based direct reduction and bench-marked their results on experimental results from a pilot plant.The physical modelling was undertaken to understand the influence of various operational variables namely, kiln inclination, rotational speed, kiln geometry (L/D ratio), blockage of the kiln diameter at the discharge end as well as to simulate the phenomenon of accretion build up in DRI kiln. Thus to determine retention time of charge in the rotary kiln, the following expression was used:

$$T = \frac{0.1026RL}{D\theta N} \tag{2.1}$$

Where; T = retention time of charge in kiln, R = angle of repose of product, L = length of kiln, D= kiln internal diameter, θ= kiln inclination angle, N = kiln rotational speed.

The residence time of kiln charge was seen to be affected by accretion build-up in the kiln.To counteract the long residence time, either kiln rotational speed or kiln tilt angle was increased.

2.3 Automation in Kiln based processes

Every process plant has potential for improvement through identification and removal of constraints. Shunta, [17] recommends taking advantage of the power of the new digital systems to upgrade the control strategies inorder to gain solid business reimbursement and not just to ensure steady operation of equipment. Therefore, there is need to include Machine Intelligence when designing optimization systems especially for process optimization and quality control. Rotary kilns are found in many processes that involve solids processing. They are employed to carry out a wide range of operations such as the reduction of oxide ore, the reclamation of hydrated lime, the calcinations of petroleum coke and the reclamation of hazardous waste [18]. However, they are much more widely known for their place in the cement industry and lime manufacturing. Some of the sponge iron rotary kilns are still under manual control where a human operator observing the burning status of the different zones of the kiln and taking appropriate control action (human-in-loop control). As a result, it is difficult to maintain consistent product quality, and energy consumption is high. In addition, the kiln liner wears out rapidly and the kiln production rate is low. PID controllers have been used as a control technique in sponge iron plants, however the random changes of the process variables has posed some limitations to this control strategy. Due to complicated working conditions including heat transfer, fuel consumption, material aggregation which makes a rotary kiln a nonlinear system, a lot of research has been done so as to determine the maximum output of rotary kiln process. The first successful application of fuzzy logic controller in kiln based process was in cement kiln by Holmblad and Østergaard in 1975 and they further improved their fuzzy controller in [19]. They found that the fuzzy controller was able to execute the same control actions as of a process operator. There was also greater production in respect of the constant supervision of the fuzzy controller.Garikayi, [5], applied Fuzzy Logic (FL) strategy in trying to minimize accretion in sponge iron kilns. Also neuro-fuzzy techniques have been implemented in parameter control in a Cement manufacturing kiln [20]. Intelligent and predictive control has been also introduced into process control and monitoring of rotary kilns [21].An advancedReinforcement Learning-Based Supervisory Control Strategy for Alumina Rotary Kiln Process is highlighted by Zhou *et al*,[22]. All the researches that were done on kiln control aim at improving the kiln performance by process parameter control. In developing optimization procedures based on intelligent systems, Ross *et al*, [23], suggests that one should first understand the process and know what to achieve then characterize the various forms of uncertainty and finally develop mathematical models to quantify them.

2.4 Fuzzy Logic (FL)

The concept of Fuzzy Logic (FL) was conceived by Zadeh, [24] in 1965. Fuzzy logic control proposed by Zadeh emerged as a tool to deal with uncertain, imprecise or qualitative decision- making problems.Controllers that combine intelligent and conventional techniques are commonly used in the intelligent control of complex dynamic systems. Therefore, embedded fuzzy logic automates what was traditionally a human control activity. Haack, [25] highlighted that FL has emerged as a profitable tool for the controlling and steering of systems and complex industrial processes, as well as for household and entertainment electronics. Moreover, Godoy andFriedhofer, [26] showed that fuzzy logic control is a practical alternative for a variety of challenging control applications since it provides a convenient method for constructing nonlinear controllers via use of heuristic information. Fuzzy logic control also provides a formal methodology for presenting, manipulating, and implementing a human's heuristic knowledge about how to control a system. Such heuristic information may come from an operator who has acted as a human-in-loop controller for a process. FL is a non-linear problem-solving control system methodology that lends itself to implementation in systems ranging from simple, small, embedded micro-controllers to large networked and multi-channel based data acquisition complex control systems [17].

FL has become one of the most successful techniques for developing sophisticated control systems. The motivation of using such control techniques is that FL addresses complex applications perfectly as it resembles human decision making with an ability to generate precise solutions from certain orapproximate information [27].

Though fuzzy logic controllers have the capability of mimicking the human expert reasoning through measuring and processing inexact and imprecise data, there are still some challenges encountered in using these controllers on their own due to limitations in adaptation capabilities to random changes in both known and unknown process parameters [27], [28].

The essence of fuzzy control is to build a model of human expert capable of controlling the plant without the use of mathematical models [23]. While conventional approaches require accurate equations to model real-world behavior, fuzzy design can accommodate the ambiguities of real-world human language and logic [27]. The fuzzy sets and fuzzy rules can be formulated in terms of linguistic variables, which help the operator to understand the functioning of the controller in terms of *IF, THEN* control rules [28],[29].Industrial control with new techniques of fuzzy algorithm based on active rule selection mechanism to achieve less sampling time ranging from milliseconds in pressure control, and higher sampling time in case of temperature control of larger installations of industrial furnaces has been proposed byHassan *etal*, [30].

Fuzzy logic control as shown in Figure 2.3 gives various advantages over the presently used conventional control in most control systems. These advantages as highlighted by Zadeh [24], Bryan and Bryan [29], include:

a) *Fuzzy logic is conceptually easy to understand*. The mathematical concepts behind fuzzy reasoning are very simple. Fuzzy logic is a more intuitive approach without the far-reaching complexity.

b) *Fuzzy logic is flexible and can be used where data is imprecise.* With any given system, it is easy to lay on more functionality without starting again from scratch.

c) *Fuzzy logic can model nonlinear functions of arbitrary complexity.* You can create a fuzzy system to match any set of input-output data.

d) *Fuzzy logic can be built on top of the experience of experts.* In direct contrast to neural networks, which take training data and generate opaque, impenetrable models, fuzzy logic lets you rely on the experience of people who already understand your system.

e) *Fuzzy logic is based on natural language.* The basis for fuzzy logic is the basis for human communication. Because fuzzy logic is built on the structures of qualitative description used in everyday language, fuzzy logic is easy to use.

However, fuzzy logic control introduces steady-state error in the system which can be reduced by training membership functions and increasing the number of membership function or by adding a learning mechanism.Fuzzy logic is one of the strongest competitors of alternate solutions for non-linear controls among other new approaches because of its ease of use and its exploitation of human experience. Still some applications prefer to use fuzzy control to only tune the parameters of traditional PID controller [28].

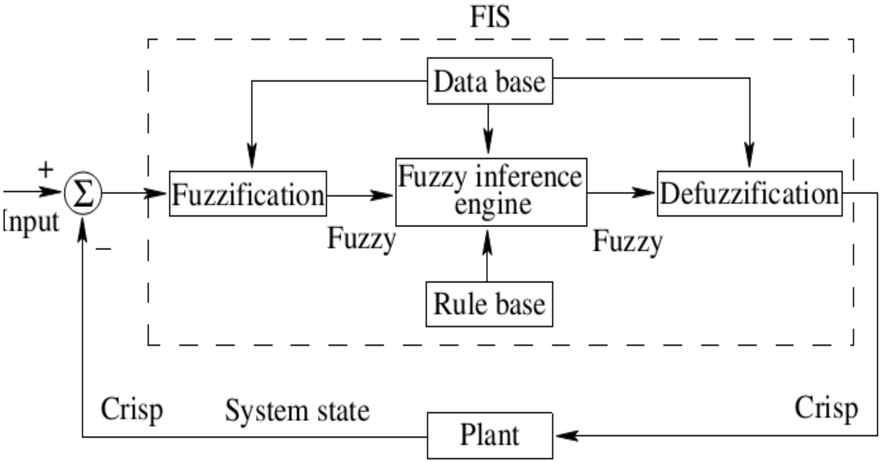

Figure 2.3 Fuzzy Logic Block Diagram

2.5 Adaptive Control System

In a controlled process, if the process parameters are either little known or vary unexpectedly during operation, adaptive control technique can be useful so as to obtain a precise, accurate and safe working control system. Landau, [31] defined adaptive control as a set of techniques for automatic adjustment in real time of controllers in order to achieve or maintain a desired level of performance of a control system when the process parameters are unknown or change with time. Hojati and Gazor, [32]stated that the basic idea in adaptive control is to estimate the uncertainties in the plant (or equivalently, in the corresponding controller) on-line based on the measured signals. Nagrath and Gopal, [33], further defined adaptive controller as a controller that can modify its behavior in response to changes in the dynamics of the process and the disturbances. Bandyopadhyay, [34], defined adaptive control system as a system that is capable of accommodating unpredictable environmental changes and also moderating engineering design errors or uncertainties. These changes may be within the system or external to the system. The adaptation mechanisms are a mimic of adaptation capabilities of living organisms to survive within changing environmental conditions.

Generally, the basic objective of adaptive control is to maintain consistent performance of the control system in the presence of uncertainties. However, conventional adaptive control theory can only deal with the systems with known dynamic structure, without dwelling much in unknown (constant or slowly-varying) parameters [32]. When applied to accretion prevention, a control law is needed that adapts itself to changing conditions such as temperature, raw material flow rate and pressures. Within the sponge iron manufacturing industry, since the process is non-linear, adaptive control can be implemented as a way to adjust the ever changing working variables such as temperature and pressure.

Optimization of a Control Loop using Adaptive method has been reported by Prabhu and Bhaskaran,[35], and the results show that adaptive controllers are very effective to handle the situations where the parameter variations and environment changes as compared to conventional PID controllers. Thus, adaptive control method has a wide number of applications in any field where the plant exhibits non-linear behaviour and when the plant parameters are unknown. The adaptation mechanism helps the controller to maintain a desired point of performance in spite of any noise or fluctuation in the process. Furthermore for an adaptive controller to work efficiently, Bandyopadhyay, [34], stated that the controller must consist of the following three functions: Identification of the dynamic characteristics of the plant; Decision making based on the identification of the plant and Modification or actuation based on the decision made.Figure 2.4shows the general schematic diagram for adaptive control system.

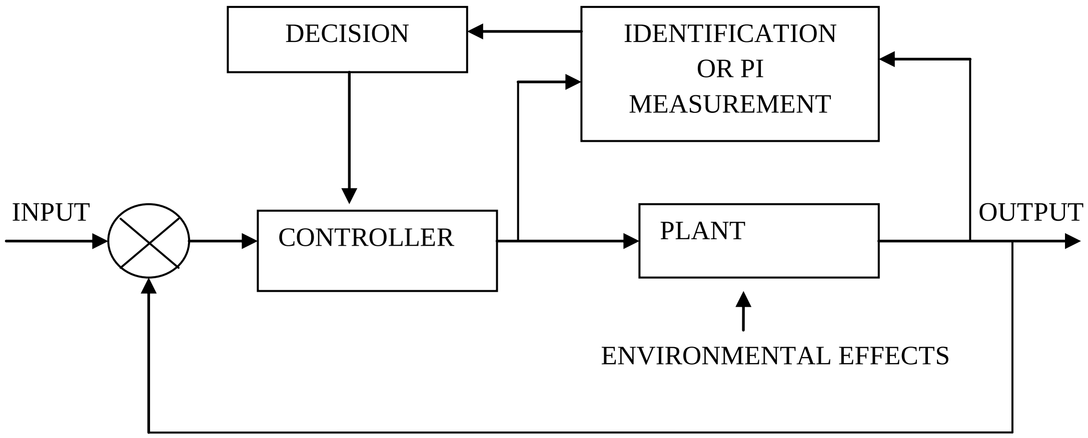

Figure 2.4 Block diagram of Adaptive Control System [34]

2.6 Model Reference Adaptive Control (MRAC)

Model Reference Adaptive Control (MRAC) is one of the main schemes used in adaptive systems. Recently, MRAC has gained popularity among many researchers and many new approaches and techniques have been applied to practical industrial processes [36], [37].Prakash and Anita, [38], based their idea of MRAC design on the fact that the controller is developed to realize plant output converges to reference model output based on the assumption that the plant can be linearized, thus this MRAC scheme is effective for controlling linear plants with unknown parameters. Therefore, one of the weaknesses of conventional MRAC is that it may not be suitable for controlling nonlinear plants with unknown structure.

The notion behind MRAC is to create a closed loop controller where parameters converge to the response of the reference model, and the goal is to minimize error between plant output and reference model output [39]. The controller parameters can be updated by using adaptation mechanism. A novel fuzzy model reference based controller for controlling nonlinear plants is discussed by Prakash[40]. Also moisture restoration in cotton ginning based MRAC system has been highlighted byKhanesarand Teshnehlab[41]. They found that MRAC approach managed to improve many failures of the fixed-gains controller, such as: some large overshoots and undershoots lead to burnout of the devices at the transient, need to retune gains for different operation regions and leading to robustness. A general MRAC block diagram is shown in Figure 2.5

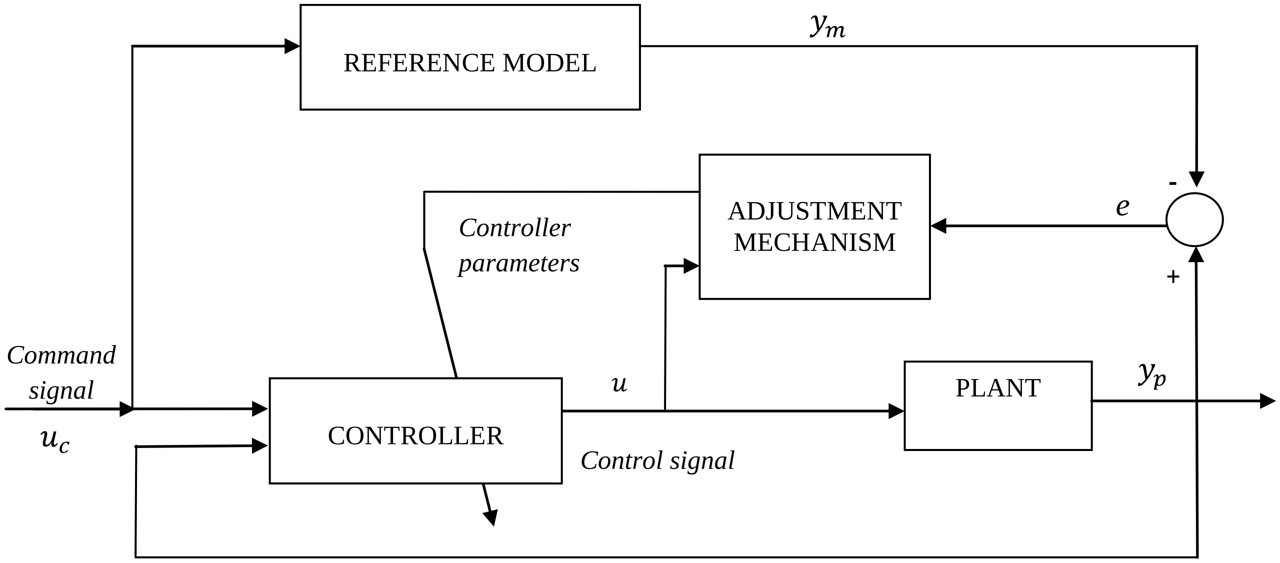

Figure 2.5 MRAC schematic [35]

Benchmarking the approach taken in[42],[35], [41], this study also developed a Model Reference Adaptive Control based on MIT rule for kiln temperature and pressure control so as to minimize accretion build up in a rotary kiln.Adaptation rules for linear MRAC can be derived from guaranteed stability and convergence criteria whilst for non-linear MRAC systems design, the MIT rule and Lyapunov's stability theory are the mostly used adaptation mechanisms [35], [36].

2.6.1 Theoretical Modeling of MRAC using MIT Rule

The MIT rule is the original approach to Model ReferenceAdaptive Control. The name is derived from the fact that it was developed at the Instrumentation Laboratory at Massachusetts Institute of Technology (MIT), U.S.A.

The adaptation law helps in obtaining a set of parameters that minimize the error between the plant and the model outputs. Hence the parameters of the controller are adjusted until the error becomes zero. MRAC begins by defining the tracking error, (e), which is the difference between plant output and the reference model output [35].

To present the MIT rule, both inner and outer loops of the system are considered in which the controller has two adjustable parameters. The desired closed loop response is specified by a model output (y_m). The tracking error (e) is difference between the output of the system (y_p) and the output of the reference model (y_m).The tracking error (e) is given by equation

$$e = y_p - y_m \tag{2.2}$$

To reduce the error, one possibility is to adjust parameters in such a way that the loss function $J(\theta)$ is minimized

$$J(\theta) = \frac{1}{2} e^2(\theta) \tag{2.3}$$

where θ is the plant adaptation parameter.

To minimize$J(\theta)$, the parameters are changed in the direction of negative gradient of J. That is the cost function chosen previously above is:

$$\frac{d\theta}{dt} = -\gamma \frac{\partial J}{\partial \theta} = \gamma e \frac{\partial e}{\partial \theta} \qquad \text{(MIT rule)} \tag{2.4}$$

The partial derivative $e\frac{\partial e}{\partial \theta}$ is called the sensitivity derivative of the system which tells how the error is influenced by the adjustable parameter. γ, is the adaptation gain[36],[41].

2.6.2 Adaptive MIT Algorithm

To see how the MIT rule can be used to form an adaptive controller, a system with an adaptive feed forward and feedback gain is considered. The block diagram is shown in Figure 2.6In this system,G_m and $G_p$is used as the model and plant transfer functions; $k_o$and k as the model and plant constants respectively.The input to output relationship is determined basing on the transfer functions within the adaptive control strategy. The constant k for this plant is unknown. However, a reference model was formed with a desired value of k, and through adaptation of a feed-forward gain, the response of the plant can be made to match this model[41].The reference model is therefore chosen as the plant multiplied by a desired constant $k_{o:}$

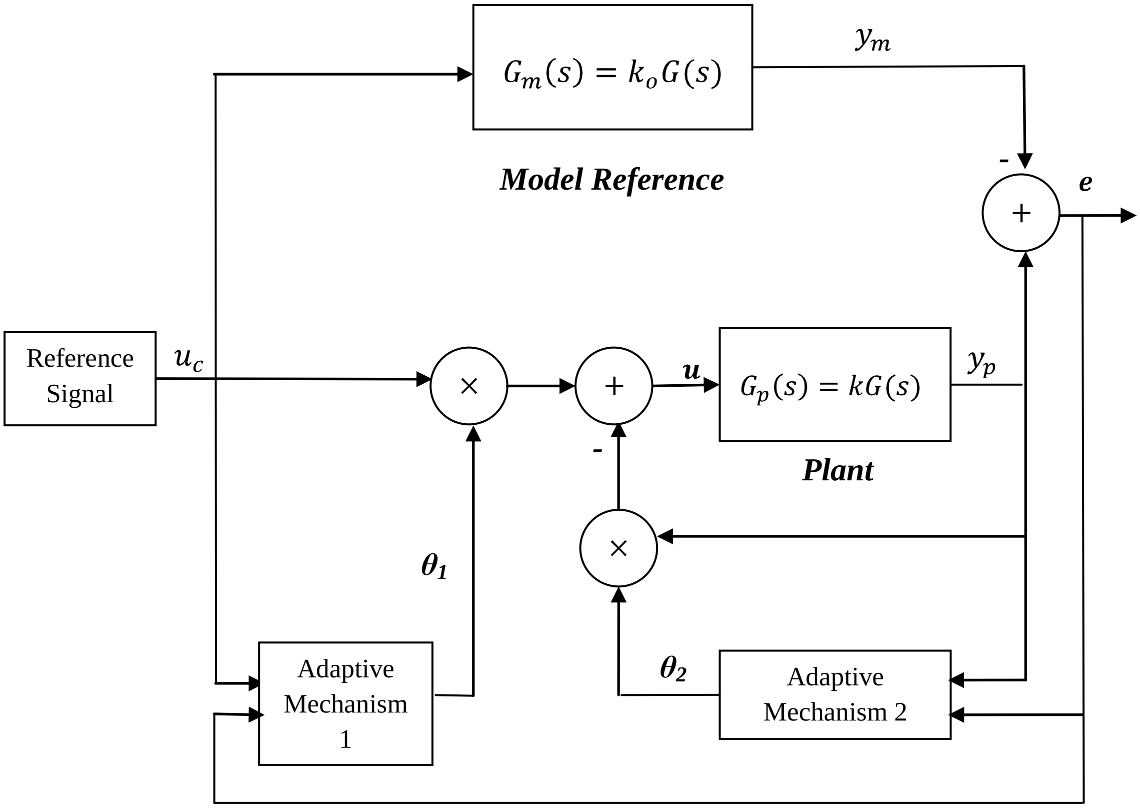

Figure 2.6 Block diagram of Adaptive Control System

From Figure 2.6, the following expressions are formulated:

$$\frac{Y_p(s)}{U(s)} = G_p(s) = kG(s) \tag{2.5}$$

$$\frac{Y_m(s)}{U_c(s)} = G_m(s) = k_oG(s) \tag{2.6}$$

However using the same cost function in equation (2.3)

We have $$J(\theta) = \frac{1}{2}e^2(\theta) \quad \rightarrow \quad \frac{d\theta}{dt} = -\gamma e\frac{\partial e}{\partial \theta} \tag{2.7}$$

The error in equation (2.2) is then restated in terms of the transfer functions multiplied by their inputs.

$$e = kGu - G_m u_c \tag{2.8}$$

$$e = kG\theta u_c - k_o G u_c \tag{2.9}$$

To determine the update rule, the sensitivity derivative was calculated and restated in terms of the model output:

$$\frac{\partial e}{\partial \theta} = kGu_c \tag{2.10}$$

But $$kGu_c = \frac{k}{k_o} y_m \tag{2.11}$$

Therefore $$\frac{\partial e}{\partial \theta} = \frac{k}{k_o} y_m \tag{2.12}$$

The MIT rule is applied to give an expression for updatingθ. The constants k and k_o are combined into *gamma*.

$$\frac{d\theta}{dt} = -\gamma' \frac{k}{k_o} y_m e = -\gamma y_m e \tag{2.13}$$

It is assumed that the controller has both an adaptive feed forward θ_1 and an adaptive feedback θ_2 gain as illustrated in Figure 2.6.

2.7 Model Reference Adaptive Fuzzy Control (MRAFC)

The purpose of the model reference adaptive fuzzy control (MRAFC) is to modify the fuzzy logic controller (FLC) rules and membership functions according to the result between the reference model output signal and system output. The MRAFC is composed of the fuzzy inverse model and a knowledge base adjuster [43]. MRAFC has fast learning features and good tracking characteristics even under severe variations of system parameters due to its improved adaptation algorithm. The learning mechanism observes the plant outputs and adjusts the rules in a direct fuzzy controller, so that the overall system behaves like a reference model, which characterizes the desired behavior, thus minimizing the error.

Fuzzy control systems based on model reference adaptive control have been reported by a number of researchers; Control for Permanent Magnetic Synchronous Motor Drives [43],A Novel Fuzzy Multiple Reference Model Adaptive Controller Design [44],MRAC designed based on Fuzzy inference system and its application on automatic gauge control system [45], and others.Investigation results by Kamalasadan and Ghandakly, [44] showed that the proposed FMRMAC scheme outperformed both traditional and single reference model adaptive controllers. The scheme in [44] provides soft switched fuzzy reference model and was found stable, especially at the modal boundaries when the 'hard switching' mathematical approach fails. Furthermore, the scheme is computationally feasible, and fault tolerant. The MRAFC main components are the reference model, a fuzzy logic controller (FLC), and an adaptation mechanism and the plant. The reference model embodies the desired performance characteristics of the whole system. The purpose of the adaptation mechanism is to update the characteristic of the FLC in response to the errorbetween the outputs of reference model and plant, in order to minimize that error automatically.

It has been noted that fuzzy controllers, like conventional PID controller, cannot adapt themselves to changes in operations such as varying mechanical parameters. To ensure optimum control performance over wide range of parameter variations and load conditions some form of adaptation is required [46].

Zadeh’s work on Fuzzy Logic and Mamdani’s Inference System contributed a lot on the development of Neuro-fuzzy systems. However, the development of the adaptive law facilitated further development of Model Reference Adaptive Systems, though much work has been done at MIT, who developed the MIT-Rule.However the development of Model Reference Adaptive Fuzzy Control systems and their related application seems to be taking a great step as extensive work has been done but they are based on individual appliances like electric motors and drives.

2.8 Summary

The main challenge within many manufacturing and processing industries is the ability of the process controllers to reason or make decisions with imprecise or available partial data. Fuzzy Logic has proved to be the main controller which can handle decision making with minimum available data. However, when there is a reasonably good model of the plant, which satisfies the necessary assumptions, then conventional control is more widely used than fuzzy logic control.Fusion of Fuzzy logic and Adaptive control can improve plant performances. However, researchers such as Zadeh argue that fuzzy systems alone have the ability to optimize process performance. From the review, it can be seen that there has been significant research into modern techniques in kiln control strategies. Focus has been on kiln parameter control but not much emphasis has been made in accretion control. Although different studies have been conducted in accretion control through use of refractory materials, improvement in raw material quality, this study seeks to minimize ring formation, agglomeration and maintain high product quality through the use of intelligent control techniques.

CHAPTER 3: METHODOLOGY

This chapter highlights the steps and procedures employed in carrying out the research. Firstly field process parameters measurements are presented. Then methods used to design the fuzzy logic based kiln controller for accretion control process, the MRAC and the proposed MRAFS are also presented.

3.1 Determination of working parameters for kiln operation

Real time process measurements including, kiln temperatures, kiln pressure, air flow, and raw material feed rate during sponge iron processing were carried out. The purpose for process measurements was to formulate and justify the necessity for process control of the kiln process. The appropriate working values for temperature and pressure were determined by averaging the measured values. However values were varying depending on the type of raw materials used.

3.1.1 Temperature measurement

The efficiency of the rotary kiln operation is governed by effectiveness of temperature control in the bed as well as in the gas phase. The kiln temperatures were measured with fixed K-type thermocouples, Quick Response Thermocouples (QRT) and a radiation pyrometer. The fixed thermocouples are located along the length of the kiln so that temperatures at various sections of the kiln can be monitored. QRTs were used to measure the kiln gas temperatures for different kiln zones. Figure 3.1 shows some of the essential features of a sponge iron rotary kiln and how the thermocouples are aligned along the kiln length.Kiln shell temperatures which help to determine the rate at which accretion is building up in the kiln were measured by a radiation pyrometer. Supervisory Control and Data Acquisition (SCADA) system was used to capture the temperatures measured by the thermocouples. Real time SCADA plant monitoring is depicted in Figure 3.2. The K-type thermocouple used had a range of (-200°C to 1260°C), sensitivity of 41µV/°C.

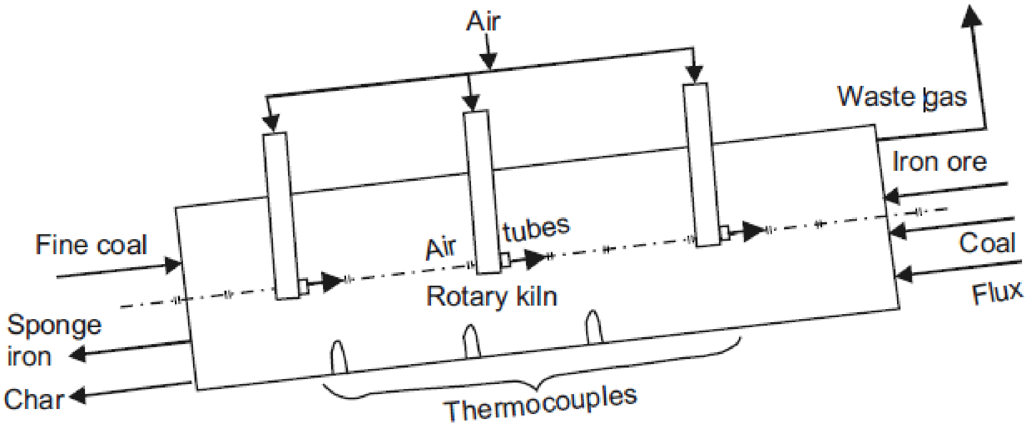

Figure 3.1 Essential features of a sponge iron rotary kiln

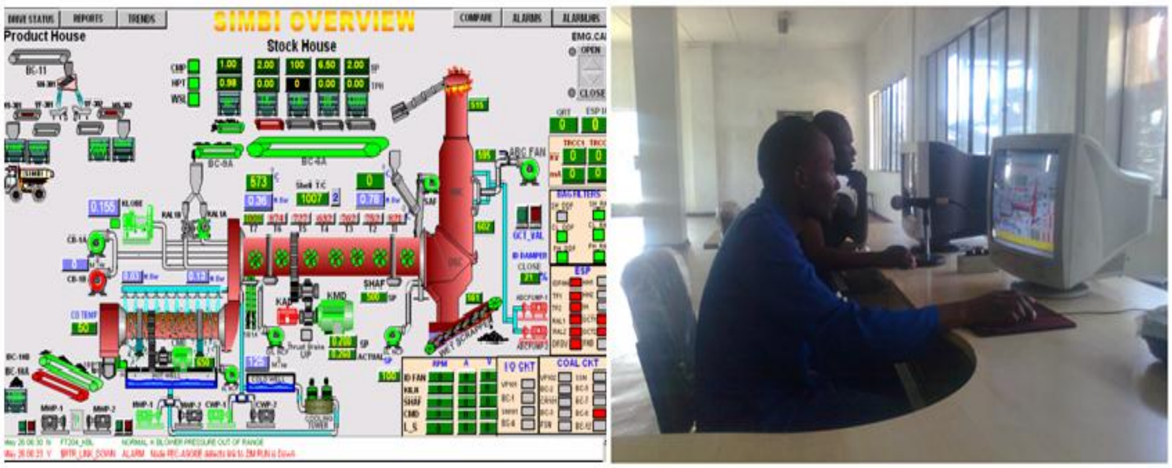

Figure 3.2 SCADA plant monitoring

3.1.2 Measurement of kiln pressure

The gas pressure in the kiln was regulated by use of a manual control valve to eliminate any air entrance which can lead to excess air conditions in the kiln. Kiln pressure measurements were done using Honeywell ST300 Smart Pressure transmitters. The gas pressure inside the kiln was controlled using the Stack Cap control loop so as to have a slight positive pressure of the order of 0.28 to 0.65 mbar at the kiln outlet. This was ensured by continuous monitoring of the damper of the I.D. fan/speed of the I.D. fan. High gas pressure of more than 1.0mbar at the kiln outlet is unacceptable because it affects the quality of the product hence there is need for regulation.

3.1.3 Accretion measurement in the kiln

Determination of accretion build up in a kiln is a bit complicated since it forms inside the kiln. However in this study the rate at which accretion was building up was determined indirectly by measuring kiln shell temperatures. Using the experimental results (charts) done before at the plant, the measured kiln shell temperatures were compared to the corresponding diameters related to the measured temperatures. After every week of continuous operation, kiln shell temperatures were measured using a radiation pyrometer. Also kiln diameter was measured at the end of each campaign period so as to determine how much accretion had built up.

3.2 Development of Fuzzy Logic Controller

The basic structure of the proposed design of kiln accretion control consists of kiln shell air fan, damper valve, a hydraulic actuated cylinder stack cap and fuzzy logic control system. Seven shell air fans are mounted along the length of the kiln, for the 42m long 100TPD kiln. These air fans provide air for combustion inside the kiln. The damper acts as an actuator to control the amount of air entry in to the kiln, thus regulating both temperatures and pressure inside the kiln. The Stack cap is connected to the pressure loop, in such a way that when kiln pressure is very high it opens and releases pressure to the outside environment. The temperature and pressure sensors with amplification transmitter unit are connected to the fuzzifier of the fuzzy logic controller. There are three outputs of defuzzifiers: displacement angle of damper opening, displacement of stack cap cylinder and Accretion. Figure 3.3 shows the block diagram of the proposed structure.

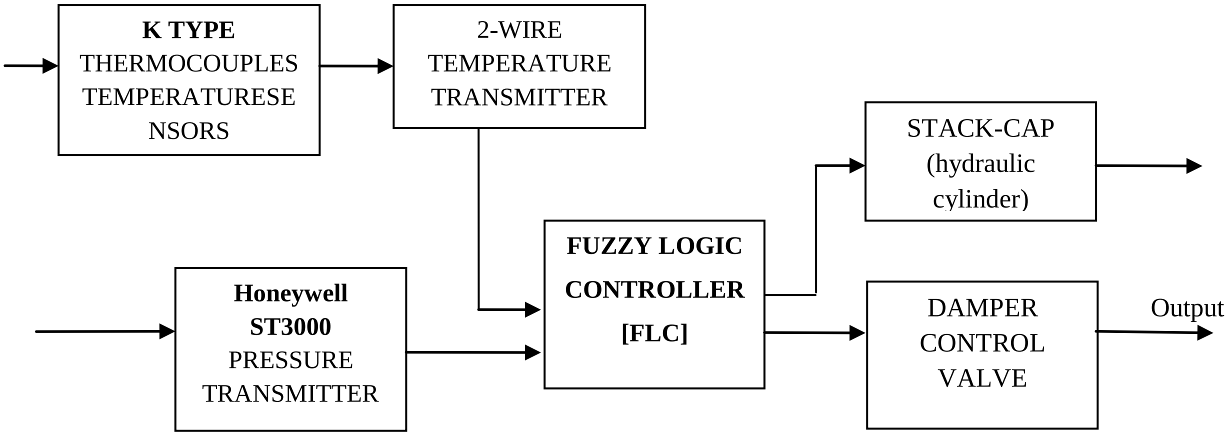

Figure 3.3 Block diagram of designed Fuzzy structure

3.2.1 Fuzzy Logic Algorithm

In this study, the fuzzy control linguistic rule base was used to program the fuzzy control application. The input information consists of real process variables measured from the plant. The main components of fuzzy control comprise of the fuzzifier, linguistic rules base, the inference engine and the defuzzifier. This algorithm is used to design the fuzzifier, inference engine, rule base and defuzzifier for the accretion control system according to the control strategy of the processing plant to achieve the quantity and quality of the desired necessities to improve the kiln performance.

3.2.1.1 Fuzzification

Temperature and pressure are the two input variables in to the fuzzy input block function. Within these inputs block functions, after testing different membership functions it was observed that two trapezoidal and three triangular membership functions for both temperature and pressure are giving satisfactory results.

Temperature input variable: Using the fuzzy sets, the operation of fuzzy controller is to determine the angle of displacement (degree) of damper valve for each pressure level to control the rate of accretion build up in the kiln. The membership function of temperature comprise of five fuzzy labels that was defined by linguistic terms: Low (LO), Medium Low (MLO), Medium (M), High (H) and Very High (VH) as shown in Figure 3.4.

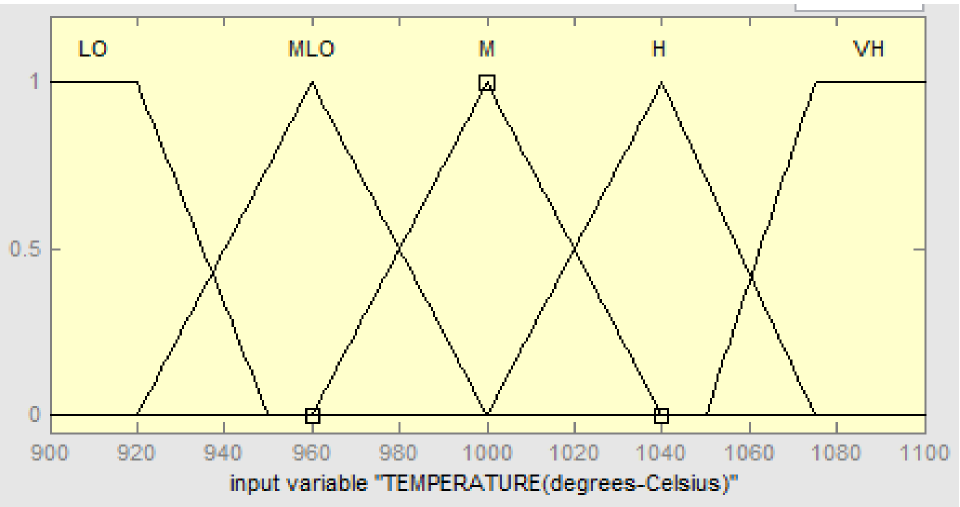

Figure 3.4 Membership Functions for Temperature

Pressure input variable: Also for the level of pressure the operation of fuzzy controller is to determine the angle of displacement of damper valve opening and closing for each temperature value to control the rate of accretion build up in the kiln. The membership function was divided into five levels, Very Low (VLO), Low (LO), Medium (M), High (H) and Very High (VH). The membership functions for pressure are represented in Figure 3.5

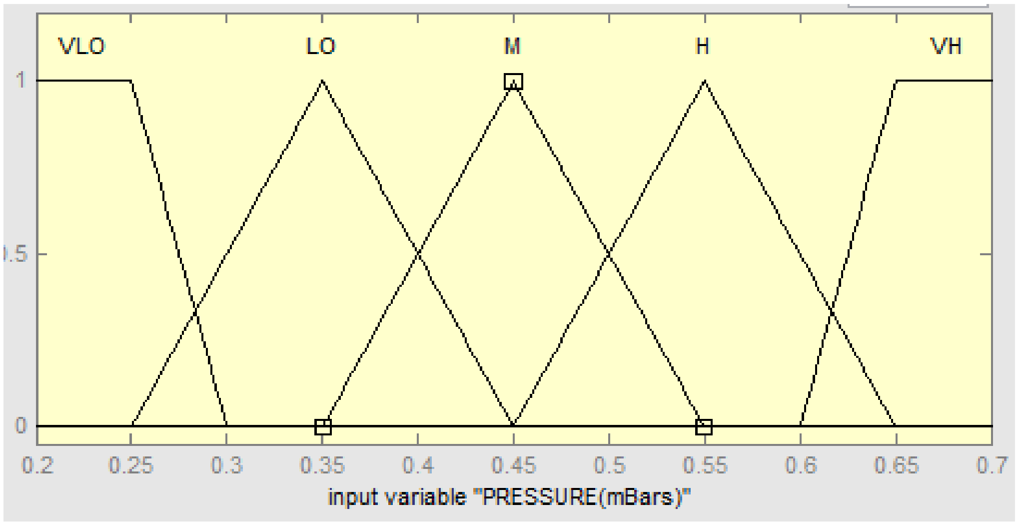

Figure 3.5 Membership Functions for Pressure

3.2.1.2 Formulation of Rule Base

Lists of intuitive rules that govern the accretion control system were made. Contrasting to the conventional control method which uses a mathematical model, the rules are developed in linguistic form of *IF–THEN* statements. Table 3.1 shows the 25 rules that were formulated whilstFigure 3.6 represents the Rule Viewer of the formulated control rules modelled with MATLAB.

The rules can be read as shown by few examples here:

IF (TEMPERATURE is LO) and (PRESSURE is VLO) THEN (Damper-opening is Closed) (Stack Cap-opening is Open) (Accretion is Low)

IF (TEMPERATURE is M) and (PRESSURE is M) THEN (Damper-opening is Medium) (Stack Cap-opening is Medium) (Accretion is Moderate)

TABLE 3.1 Fuzzy Rule Base

INPUT VARIABLES		OUTPUT VARIABLES		
TEMPERATURE (degrees Celsius)	PRESSURE (mBar)	DAMPER-OPENING(degrees)	STACK-CAP OPENING(m)	ACCRETION %
LO	VLO	Closed	Open	Low
LO	LO	Closed	Open	Low
LO	M	M-Close	Medium	Low
LO	H	Medium	Medium	Low
LO	VH	Medium	Closed	Moderate
MLO	VLO	Closed	Open	Low
MLO	LO	M-Close	Open	Low
MLO	M	Medium	Medium	Moderate
MLO	H	Medium	Closed	Moderate
MLO	VH	Medium	Closed	Moderate
M	VLO	Closed	Open	Low
M	LO	M-Close	Open	Moderate
M	M	Medium	Medium	Moderate
M	H	Open	Closed	Moderate
M	VH	Open	Closed	High
H	VLO	M-Close	Open	Moderate
H	LO	Medium	Open	Moderate
H	M	Open	Medium	Moderate
H	H	W-Open	Closed	High
H	VH	W-Open	Closed	High
VH	VLO	M-Close	Open	Moderate
VH	LO	Medium	Open	Moderate
VH	M	Open	Medium	High
VH	H	W-Open	Closed	Very High
VH	VH	W-Open	Closed	Very High

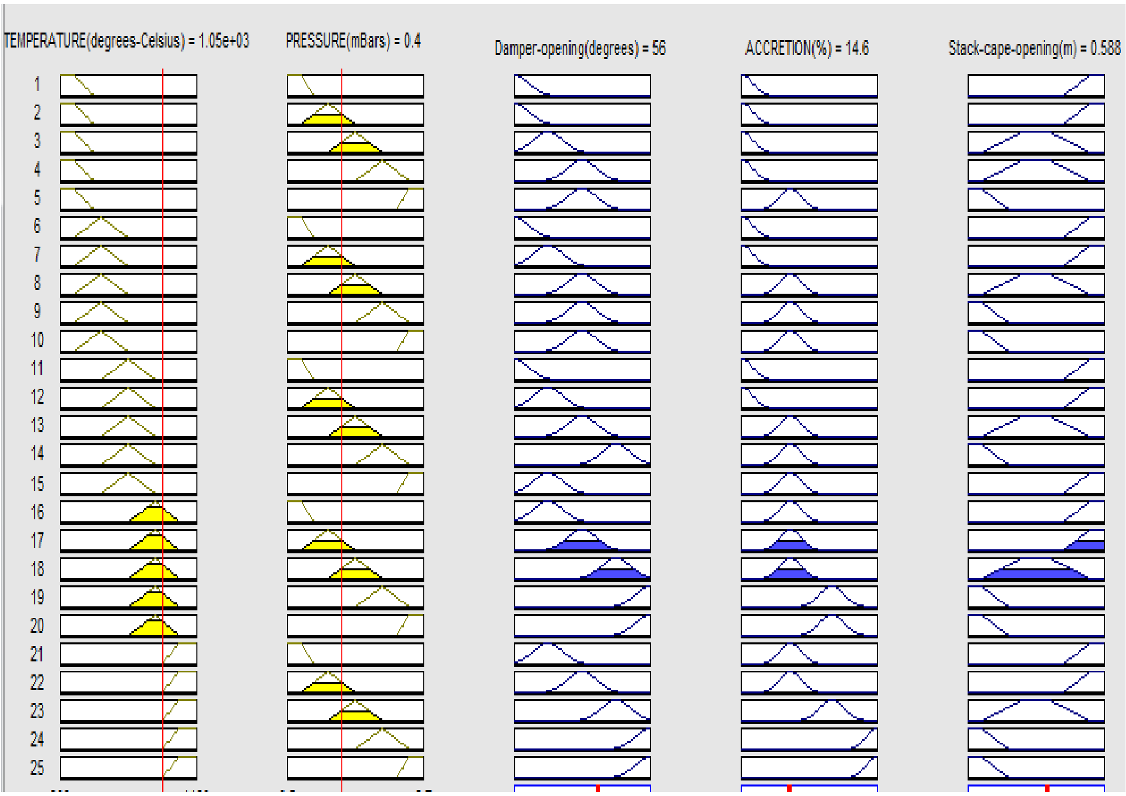

Figure 3.6 Fuzzy Model Rules

3.2.1.3 Defuzification

A Mamdani-type fuzzy inference system (FIS) was used in this study. The “centre of gravity” or the “centroid” method of defuzzification was chosen, since it weighs the effect of each input variable towards the calculation of the output [27], [28]. Input fuzzy sets and rules are converted into an output fuzzy set, and then into a crisp output for controlling the damper, stack cap and accretion percentage. Through the firing of control rules, an output value is decoded by the deffuzifier component to give a crisp value.

Damper-openingoutput variable: the fuzzy output Gaussian membership function was defined into linguistic variable representing the required degree of damper valve opening: Closed,Medium-Close (M-Close), Medium, Open, and Wide-Open (W-Open). The damper opening angle was in degrees.The membership functions for damper-opening are shown in Figure 3.7 Gaussian membership function was used because it can allow room for approximation.

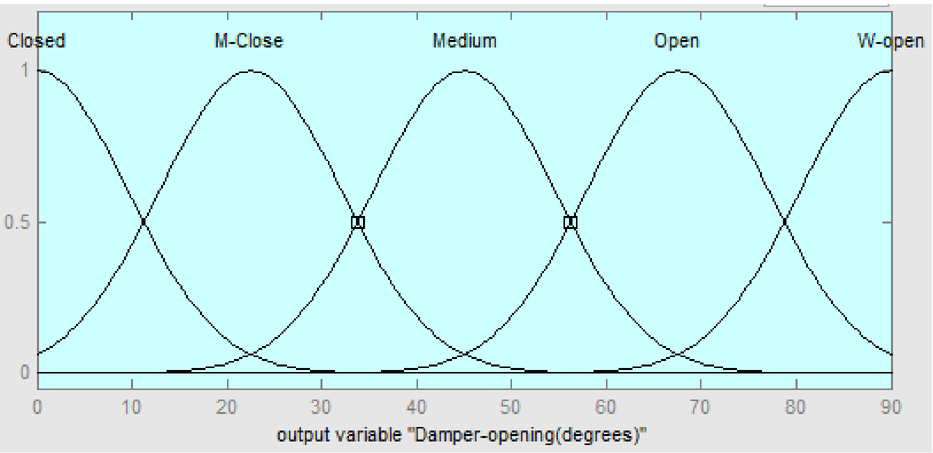

Figure 3.7 Membership Functions for Damper-opening

Stack Cap-opening output variable: the stack cap opening was determined by pressure values inside the kiln, thus the opening was actuated by a hydraulic cylinder arm displacement. Linguistic labels used for the membership function are Closed, Medium and Open. The stack cap displacement is in meters (m).The membership functions for Stack cap-opening are represented in Figure 3.8

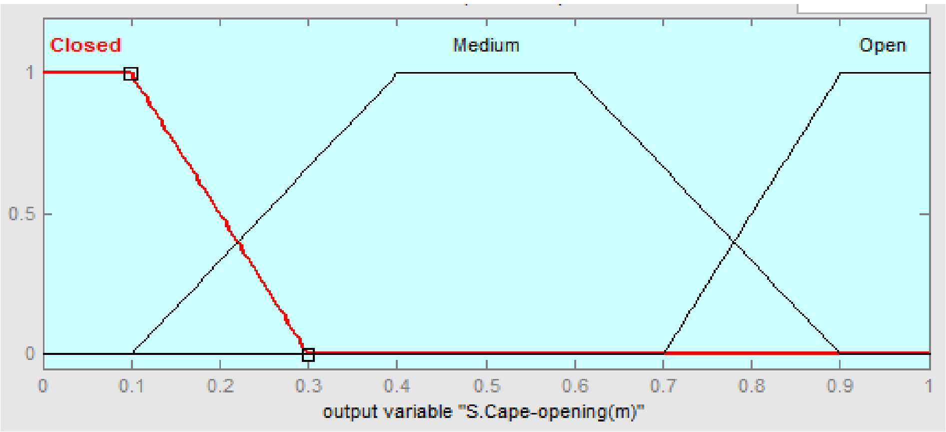

Figure 3.8 Membership Function for Stack Cap-opening

Accretion output variable: accretion build up is determined by the temperature and pressure values which are being controlled by the opening of the Shell Air fan damper valve and the Stack cap. The membership functions of Accretion were defined using the linguistic terms: Low, Moderate, High and Very High as shown by Figure 3.9.

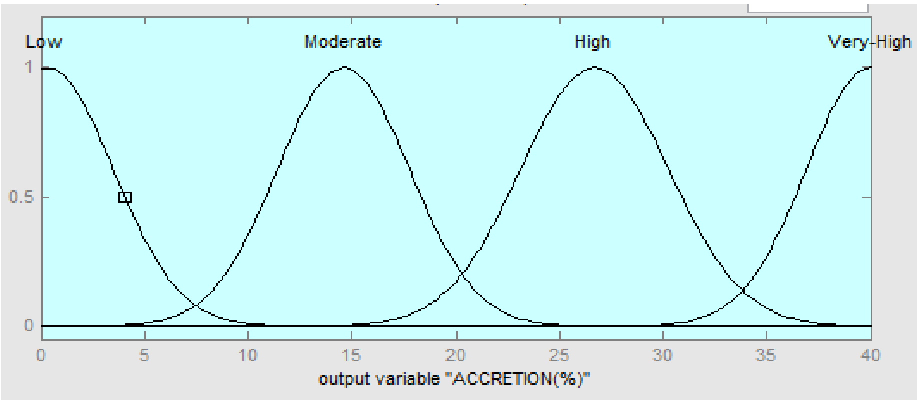

Figure 3.9 Membership Functions for Accretion

3.3 Formulation of the Model Reference Adaptive Control Algorithm

In this study, Model Reference Adaptive Control Modeling is defined as a method of designing a closed loop controller with parameters that can be updated to change the response of the system to match a desired model. In designing a MRAC using the MIT rule, the designer has to select: the reference model, the controller structure and the tuning gains for the adjustment mechanism.

To determine the adaptive control, process transfer function was formulated first. However in this study a motorized damper valve is used to model the process and is approximated to take the linear form. Thus the nonlinearity of the complex process is assumed to be linear so as to formulate the MRAC. The transfer function of the plant is represented below (Check Appendix for the mathematical formulation):

$$G_p(s) = \left(\frac{b}{a_1 s^2 + a_2 s + a_3}\right) \qquad (3.1)$$

where b,a_1 , $a_2$and a_3 are positive and are the process parameters.

Considering the adaptive control highlighted in Figure 2.6, the following expressions were formulated:

$$u = \theta_1 u_c - \theta_2 y_p \qquad \text{(Control law)} \qquad (3.2)$$

$$e = y_p - y_m = G_p u - G_m u_c \qquad (3.3)$$

$$y_p = G_p u = \frac{b}{a_1 s^2 + a_2 s + a_3}\left(\theta_1 u_c - \theta_2 y_p\right) \qquad (3.4)$$

The closed loop transfer function related to the output and the input with the controller in the loop is given by:

$$\frac{y_p}{u_c} = \left(\frac{b\theta_1}{a_1 s^2 + a_2 s + a_3 + b\theta_2}\right) u_c \qquad (3.5)$$

The error was later written with the adaptive terms included.Considering the partial derivative of the error with respect to θ_1 and θ_2 gives the sensitivity derivatives, having in mind that u_c does not include either parameter, and therefore is inconsequential when evaluating the derivative.

$$e = \left(\frac{b\theta_1}{a_1s^2+a_2s+a_3+b\theta_2}\right)u_c - G_mu_c \qquad (3.6)$$

$$\frac{\partial e}{\partial \theta_1} = \left(\frac{b\theta_1}{a_1s^2+a_2s+a_3+b\theta_2}\right)u_c \qquad (3.7)$$

$$\frac{\partial e}{\partial \theta_2} = -\left(\frac{b^2\theta_1}{(a_1s^2+a_2s+a_3+b\theta_2)^2}\right)u_c \qquad (3.8)$$

$$\frac{\partial e}{\partial \theta_2} = -\frac{b\theta_1}{a_1s^2+a_2s+a_3+b\theta_2}y_p \qquad (3.9)$$

Thecontroller parameters are updated by the adaptation mechanism such that the process output follows the model output equation:

$$G_m(s) = \left(\frac{K}{s^2+x_{1a}s+x_{0a}}\right) \qquad (3.10)$$

where$K$,x_{1a} and $x_{0a}$are the model reference parameters.

The sensitivity derivatives obtained contain the parameters from the plant. The premise of design with MRAC assumes that the plant characteristics were not absolutely known. The goal was to make the plant approach the model. If the model is close to the actual plant, the model characteristics we approximated that:

$$a_1s^2 + a_2s + a_3 + b\theta_2 \approx s^2 + x_{1a}s + x_{0a} \qquad (3.11)$$

Taking the derivative of the feed forward loop of the MRAC we have;

$$\frac{\partial e}{\partial \theta_1} = \frac{x_{1a}s+x_{0a}}{s^2+x_{1a}s+x_{0a}}u_c \qquad (3.12)$$

$$\frac{\partial e}{\partial \theta_2} = -\frac{x_{1a}s+x_{0a}}{s^2+x_{1a}s+x_{0a}}y_p \qquad (3.13)$$

Then, applying the MIT rule (2.4), the update rule for each theta is:

$$\frac{d\theta_1}{dt} = -\gamma \frac{\partial e}{\partial \theta_1} e = -\gamma \left(\frac{x_{1a}s + x_{0a}}{s^2 + x_{1a}s + x_{0a}} u_c \right) e \qquad (3.14)$$

$$\frac{d\theta_2}{dt} = -\gamma \frac{\partial e}{\partial \theta_2} e = \gamma \left(\frac{x_{1a}s + x_{0a}}{s^2 + x_{1a}s + x_{0a}} y_p \right) e \qquad (3.15)$$

Figure 3.10 shows the MRAC schematic system after incorporating adaptation mechanism using the MIT rule.

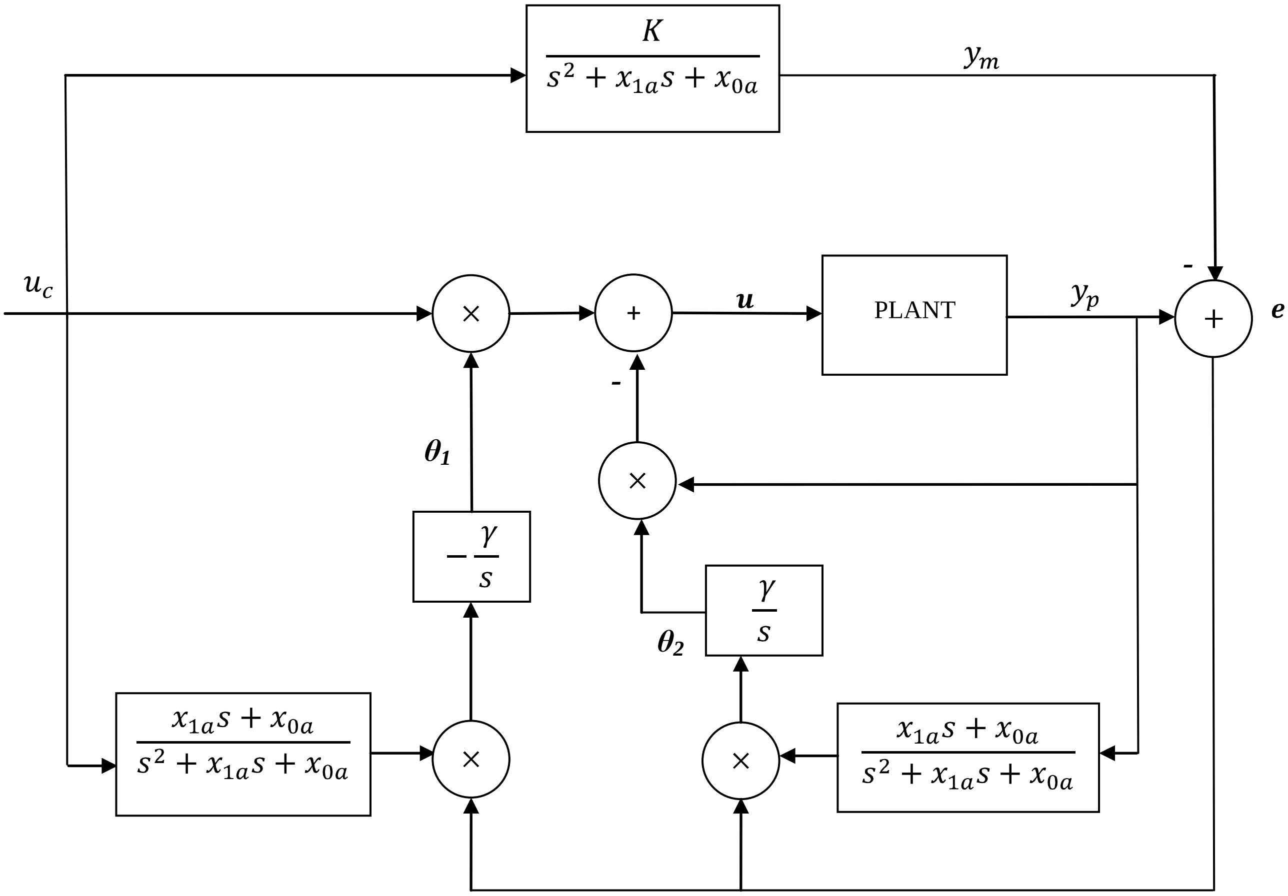

Figure 3.10 MRAC Scheme with MIT Rule

3.3.1 Determination of the Model Reference Transfer function

Considering the assumption of linearity of our process (motorised damper valve), the process will be a second order system. The standard form of second order system is given by the following expression:

$$G_m(s) = \frac{\omega_n^2}{s^2+2\zeta\omega_n s+\omega_n^2} \tag{3.16}$$

The required specifications for the temperature and pressure control system are assumed to be a maximum Overshoot (%OS) of 2 % and a settling time (t_s) of less than 3 seconds. The main aim was to determine the damping ratio and natural frequency for the system such that the transient response to step input satisfy the stated conditions ($t_s \leq$ 3sec and %OS $\leq$ 2%).

The percentage overshoot is supposed to be less than 2%, hence;

$$\%OS = e^{-\frac{\zeta\pi}{\sqrt{1-\zeta^2}}} \times 100\% = 2\,\% \tag{3.17}$$

From this we obtain $\zeta = 0.7447$

The undamped natural frequency was determined using the condition $t_s <$ 3sec such that;

$$t_s = \frac{4}{\zeta\omega_n} \tag{3.18}$$

Thus

$$\frac{4}{\zeta\omega_n} \leq 3 \qquad \rightarrow \omega_n \geq \frac{4}{3\zeta} \tag{3.19}$$

From which we obtain:$\omega_n \geq 1.7904$rads^{-1}

Inserting the values in the transfer function we get:

$$G_m(s) = \frac{3.21}{s^2+2.667s+3.21} \tag{3.20}$$

The formulated model reference transfer function was then incorporated in to the Simulink model for simulation purpose. The Simulink model is shown in Figure 3.11

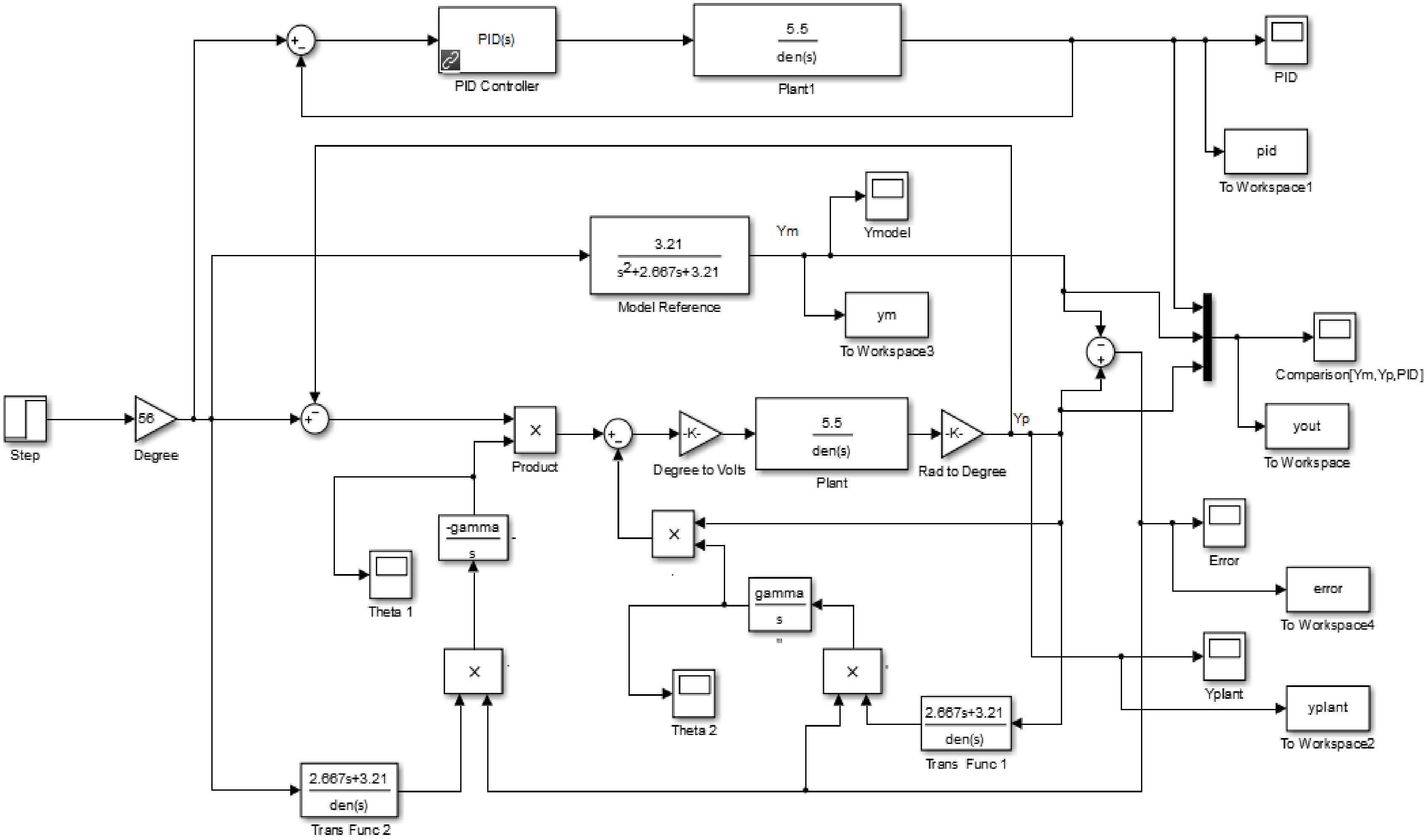

Figure 3.11 Simulink Model of MRAC

3.3.2 Simulation of MRAC

The Model Reference Adaptive Controller Simulinkmodel is shown in Figure 3.11. It has the step input signal, reference model transfer function, process transfer function and adaptation gain value. A step signal of magnitude of 56^o is introduced as the command signal thus the controller's main aim is to maintain the damper opening position at this angle.A damper angle of 56^o should be maintained because it gives minimum accretion build up in the kiln. The transfer function implemented is the actual process including several gains added around the plant so that the plant receives a voltage command not the assumed angle command. The error signal is produced from the difference between process output and reference model output values. The controller parameters ($\theta_1$and θ_2) values depend on the reference input signal, transfer function of the reference model, error signal (e) and adaptation gain values.The system's performance test was done through transient analysis and results were recorded.

3.4 Development of Model Reference Adaptive Fuzzy System

The main goal of the Model Reference Adaptive Fuzzy System (MRAFS) is to change the rules definition in the direct fuzzy logic controller (FLC) and rule base according to the comparison between the reference model output signal with the desired ideal plant set-points for kiln temperature and pressure and system output.

A Fuzzy Logic Controller based Model Reference Adaptive System scheme is proposed to improve the system performance and make it robust when under process disturbances. The controller structure proposed in this study for the MRAFS is shown in Figure 3.12. An adaptive fuzzy controller consists of a fuzzy controller and parameters tuner of proportion and quantization factors. Parameters tuner continuously adjusts the proportion and quantization factors of fuzzy controller based on angle error and its rate of change.The fuzzy control rules are also changed and the control variable adjusted automatically. Initially, a direct fuzzy controller is designed then imbedded into the MRAC.

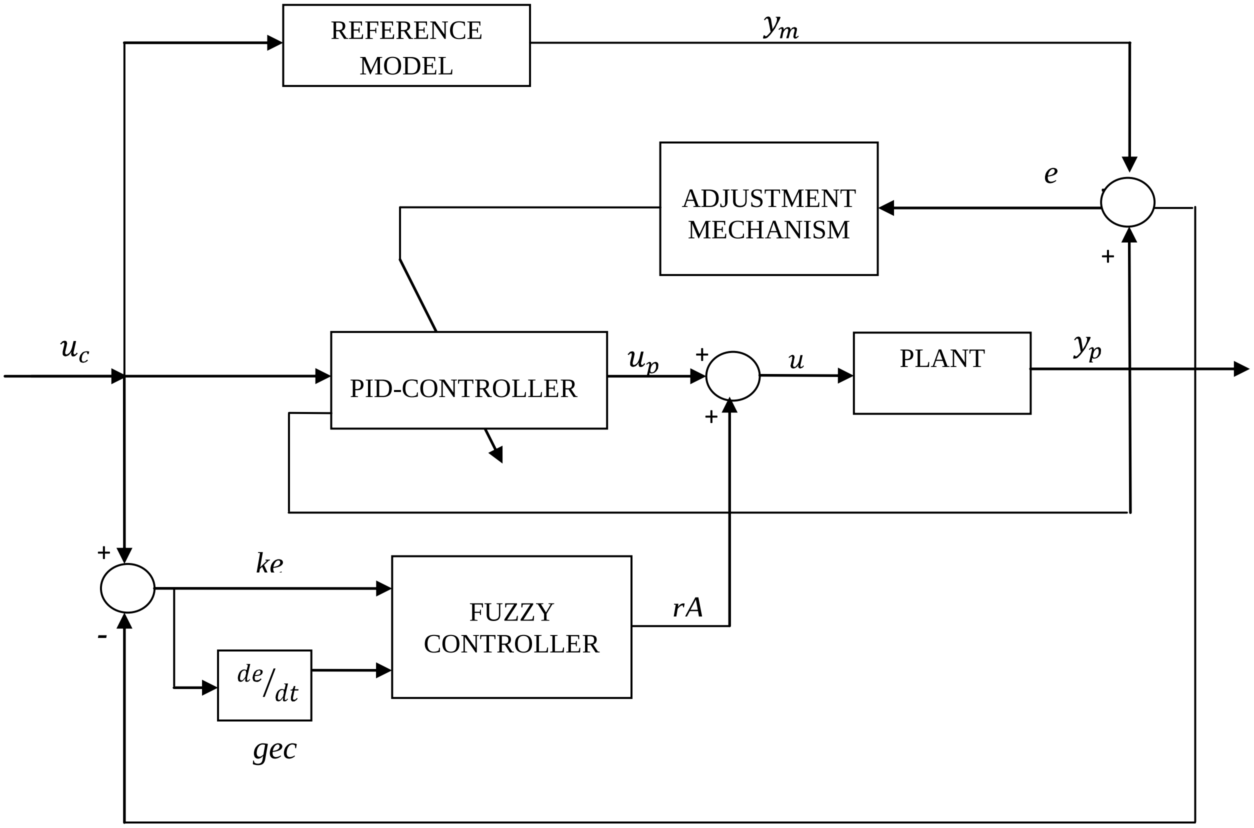

Figure 3.12 Block diagram of proposed MRAFS scheme

3.4.1 Direct Fuzzy Control

The fuzzy controller has a dual-input and single output. The inputs of adaptive fuzzy controller are error signals (e) and the error derivative signals (ec) produced when comparing the plant state to a reference model and the controller output is the damper angle (θ).

$$\left.\begin{aligned} e(t) &= y_p(t) - y_m(t) \\ ec(t) &= \frac{d}{dt}[y_p(t) - y_m(t)] \end{aligned}\right\} \qquad (3.21)$$

The universe of discourse of the variables was normalized to cover a range of [-2, 2] and scaling gains (k, g, r) were used to normalize. A standard choice for the membership functions was used with seven membership functions for the three fuzzy variables (meaning 49 rules in the rule base). These rules were determined heuristically based on the knowledge of the process. An example of *IF-THEN* rule is as shown below:

IF e is negative big (NB) and ec is negative big (NB) THEN θ is positive big (NB)

The resulting rule base is shown in the Table 3.2.

Table 3.2: Rule base for the fuzzy controller

$\boldsymbol{\theta}$		$\boldsymbol{e}$						
		NB	NM	NS	ZE	PS	PM	PB
$\boldsymbol{ec}$	NB	NB	NB	NM	NM	NS	ZE	ZE
	NM	NB	NM	NM	NS	NS	ZE	ZE
	NS	NM	NM	NS	NS	ZE	ZE	PS
	ZE	NM	NS	NS	ZE	PS	PS	PM
	PS	NS	ZE	ZE	PS	PS	PM	PM
	PM	ZE	ZE	PS	PS	PM	PM	PB
	PB	ZE	ZE	PS	PM	PM	PB	PB

The Mamdani-type inference enginewas used. To obtain the crisp output, the centre of gravity (CG)defuzzification method is used. This crisp value is the resulting controller output.

3.4.2 Simulation of MRAFS

Simulink software was used to model the proposed design so as to test the performance of the system through transient response. The Simulink block diagram is shown in Figure 3.13.The fuzzy adaptive mechanism observes the plant output and adjusts the rules in a direct fuzzy controller, so that the overall system behaves like a reference model, which characterizes the desired behaviour. In the proposed scheme, the error and rate of error change measured between the plant (damper angle) and output of the reference model are applied to the fuzzy controller and to the adjustment mechanism loop. The latter will force the system to behave like the signal reference by modifying the knowledge base of the fuzzy logic controller. If the value of *e* and *ec*are all large, the main task of the adaptive tuner is to eliminate the error. Thus the size of *k* and *g* should be smaller to reduce influence of the *e* and *ec* and the value of *r* should be big to reduce the response time and ensure stability of the system. The system's main task is to stabilize as quickly as possible therefore the weight of *k* and *g*was adjusted in a manner to influence quick error elimination.

The goal of the MRAFS is to eliminate error between the model and process within 3 seconds thereby maintaining the damper angle at the required position. Thus the system analysis and evaluation was done through Simulink simulation testing. Transient response in terms of rise time, process overshoot, settling time and stability was used to evaluate the system's performance. The performance of the designed MRAFS was also tested against MRAC and PID conventional controller where much emphasis was on the settling time and oscillations of the controller performance.

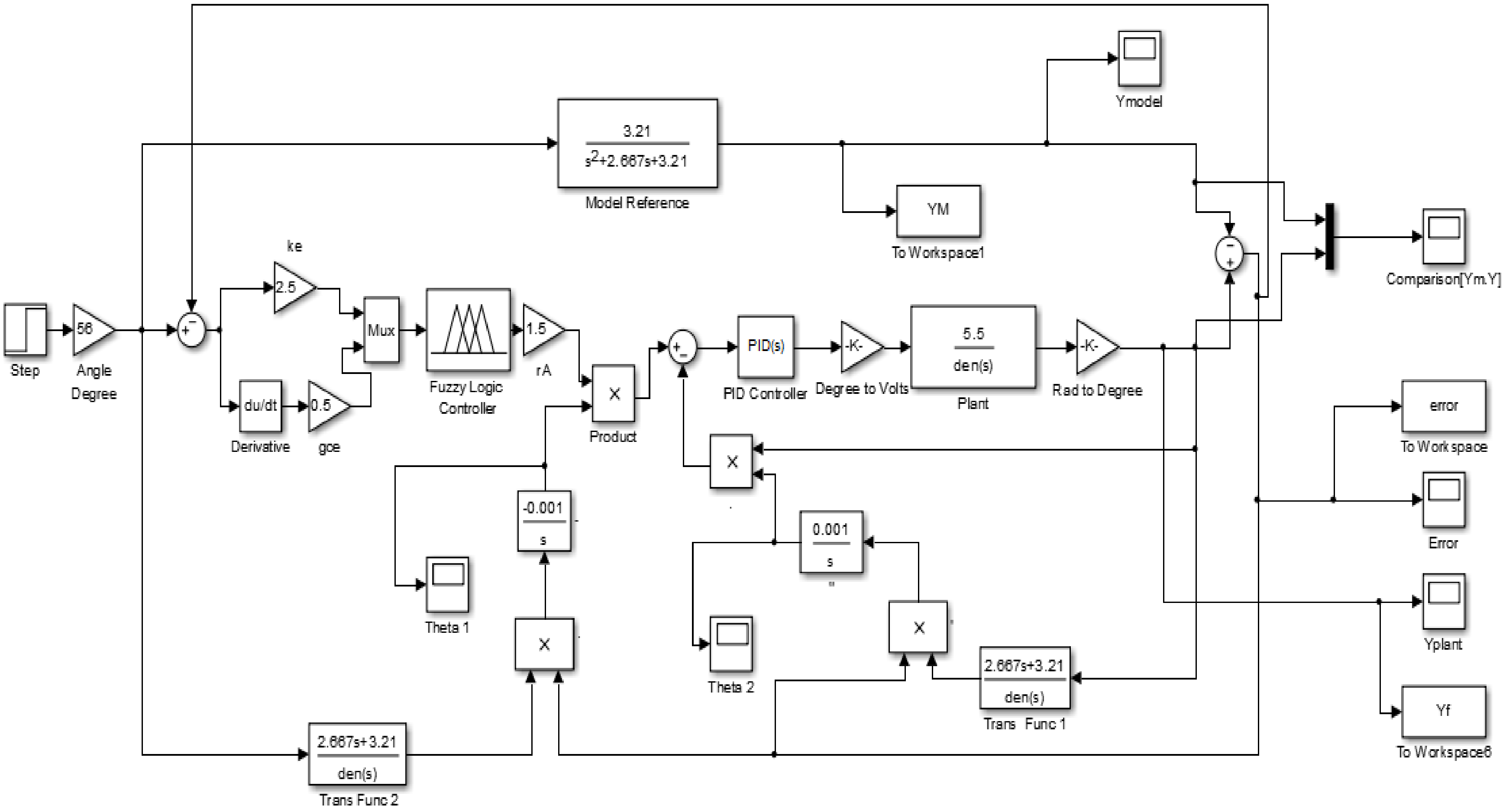

Figure 3.13 Simulink Model MRAFS

CHAPTER 4: RESULTS AND DISCUSSION

This chapter describes the results obtained through process measurements and simulation of the FLC for accretion control and also for the proposed MRAFS for kiln parameter control. The analysis and comparison of these results with results of the conventional PID controller, MRAC and PID-MRAC are presented.

4.1 Process parameter measurements

Process parameter measurements were done so as to determine the appropriate working parameters for continuous operation of the rotary kiln. The parameters measured were kiln temperature, kiln pressure and accretion. However due to the variation in process parameters it was difficult to ascertain the optimal working values because other process parameters could not be held constant such as varying raw material quality and size but the study managed to determine the appropriate operating values.

4.1.1 Kiln Temperature

Figure 4.1 highlights bed charge kiln temperature profile within different kiln zones. From this figure, it can be seen that there is a difference between the measured temperature and the recommended temperatures. The recommended temperature and pressure values were obtained from [47]. During the field measurements, observations were made that the traditional techniques used to measure the temperature of a rotary kiln, due to extreme environmental conditions, heat, vibration and corrosive atmospheres, have some challenges. K Type thermocouples are only stable for short periods at certain temperatures, after which they tend to drift in a positive direction. Challenges in kiln temperature measurements were also experienced as fixedthermocouples were giving high readings as they get coated with ash, ore or accretion as the production process progresses. As seen for the recommended temperatures, measured temperatures are supposed to follow the same trend but Zone 4 (at 24m) shows an anomaly of temperature drop. This is due to the fact that injection coal large particles being thrown into kiln by Key Lobe blower drops in Zone 4 promoting endothermic reactions as the large particles absorb heat from the environment as Magnetite (Fe_3O_4) is reduced to Wustite (FeO). As charge moves down the kiln due to rotational and gravity action, exothermic reactions takes place thus temperature rise is noted in Zone 5 (at 30m) as Hematite (Fe_2O_3) is oxidised to Magnetite (Fe_3O_4) and Wustite (FeO) reduced to sponge iron (Fe). Figure 4.2 shows kiln gas temperatures corresponding to the charge material as it gets reduced down the rotary kiln. The high charge temperatures result in high gas temperature thus the temperatures were increasing as we approach the kiln outlet were final reduction of iron takes place.

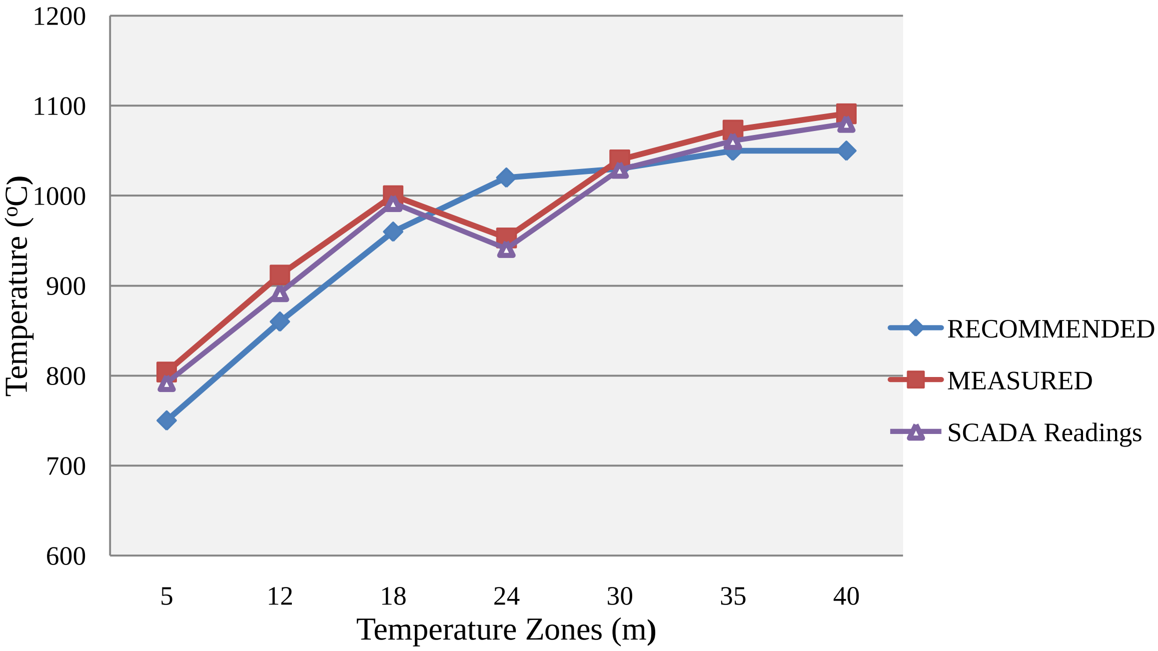

Figure 4.1 Kiln Temperature Profile

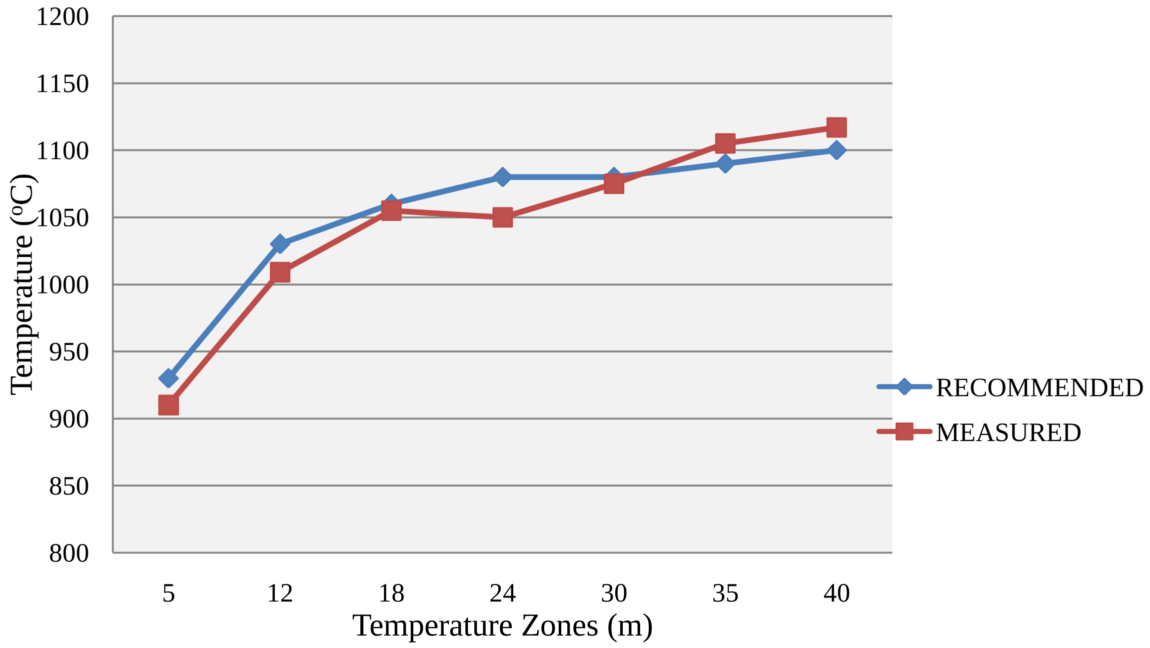

Figure 4.2 Kiln Gas Temperature Profile

4.1.2 Kiln Pressure

Figure 4.3 shows the averaged pressure values obtained on weekly basis at the Steelmakers plant.

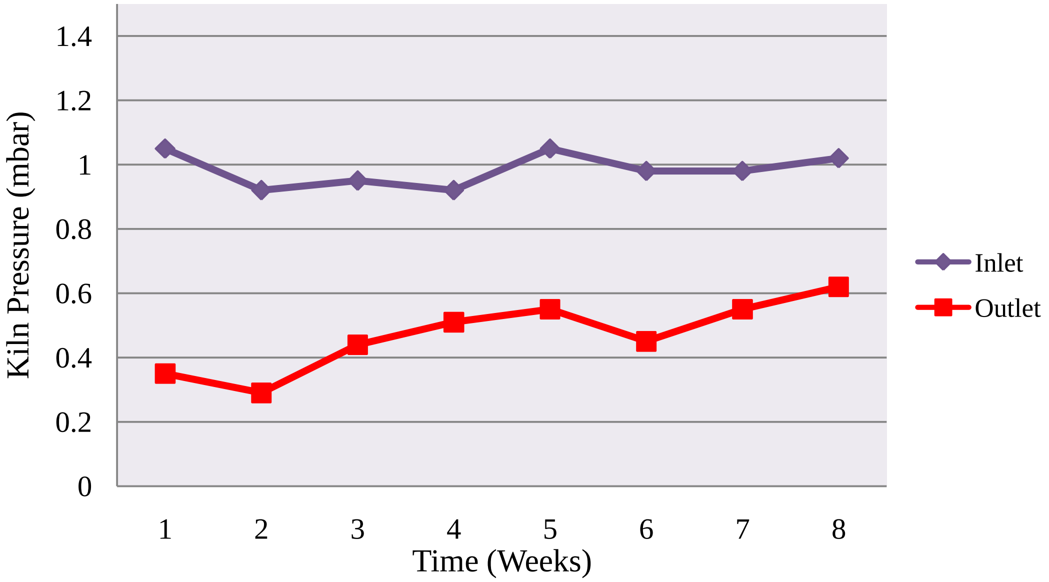

Figure 4.3 Kiln Pressure profile

It is seen that an outlet pressure range of between 0.28-0.65 mbar was maintained in the kiln. These pressure values were within the recommended values for safe kiln operation. In the event of high pressures in the kiln, a linear hydraulic arm controlling movement of the Stack cap was activated torelease excess gasses to the environment.The gas pressure inside the kiln was controlled to have a slight positive pressure of the order of 0.28 to 0.65 mbar at the kiln outlet. This was ensured by continuous monitoring of the damper of the I.D. fan/speed of the I.D. fan.Pressures above 1.0mbar are unacceptable as they affect the product quality and also can lead to accretion build-up since they promote high temperatures inside the kiln.

4.1.3 Accretion in the Kiln

The behaviour of kiln shell temperatures are highlighted in Figure 4.4. The trend shows that the temperatures were decreasing with time for continuous kiln operation. The decrease in shell temperature can be attributed to the decrease in effective diameter of the kiln resulting from molten particles sticking on the wall.

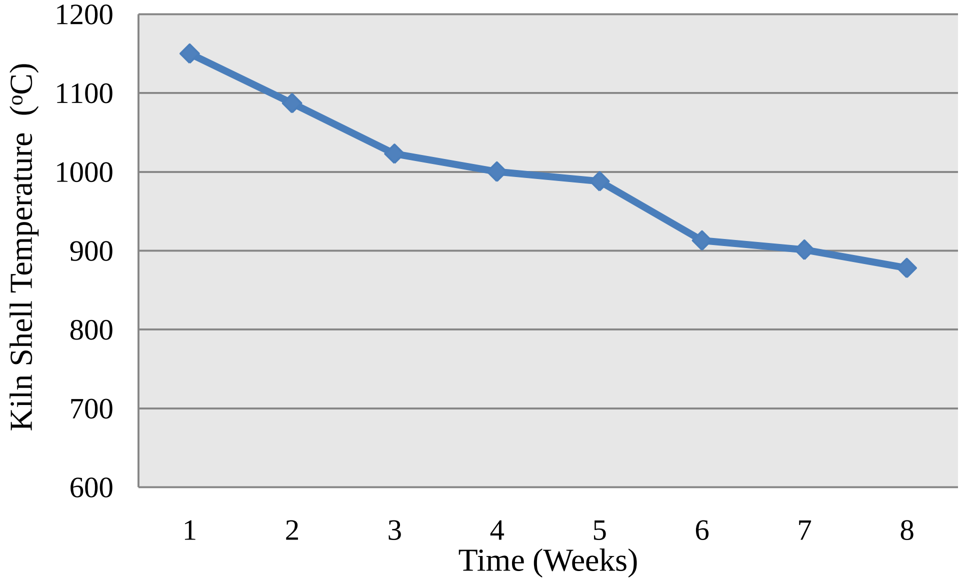

Figure 4.4 Kiln Shell Temperatures

4.2 Simulation results

The designed Fuzzy Logic Control (FLC) system was first simulated without the Model Reference Adaptation characteristics so as to analyse the behaviour of a standalone fuzzy controller in determining the accretion build up in the kiln.Then, a MRAC and MRAFS were simulated. Results are presented in the following sections.

4.2.1 Fuzzy Logic System

Simulation results are presented in MATLAB graphic viewer. From Figure 4.5, it is seen that it is possible to achieve an accretion build up rate of as low as 14.6 % when appropriate process parameters are used, i.e., at kiln maximum temperature of 1050^{o}C and pressure of 0.4 mbar. From this figure, it is also seen that the accretion built up rate of 14.6 % can be maintained if the kiln temperatures are increased up to 1100^{o}C and pressure reduced to 0.35 mbar.However, temperature values within the vicinity of 1100^{o}C are not advisable since they promote material melting that can result in more accretion build up. It also leads to non-uniform metallization which result in poor product quality.

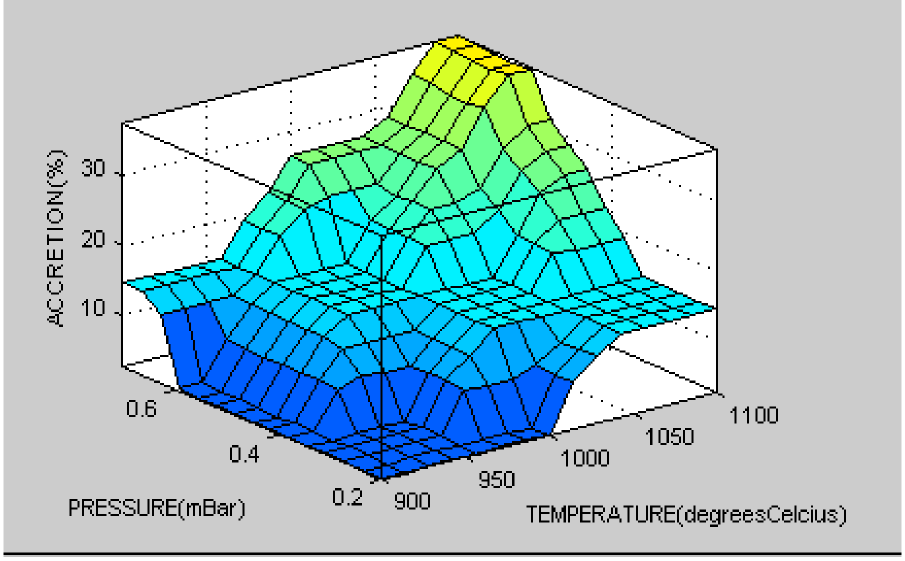

Figure 4.5 Plot of Pressure-Temperature and Accretion

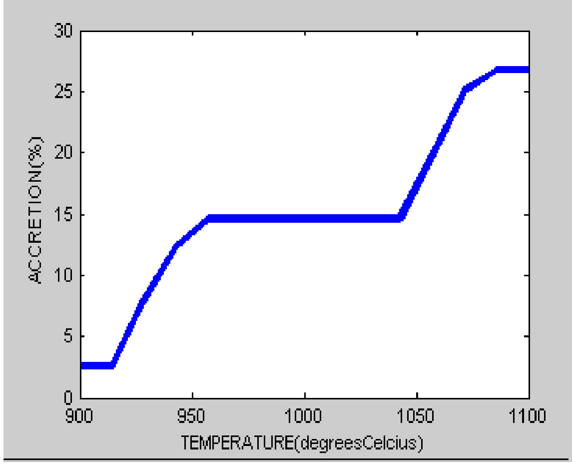

Figure 4.6 Effect of temperature on Accretion

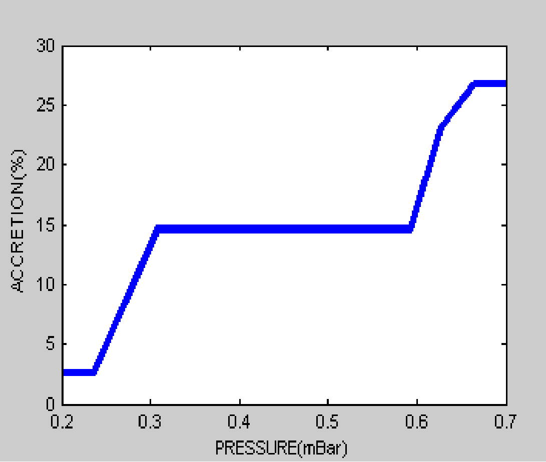

Figure 4.7 Effect of pressure on ring formation

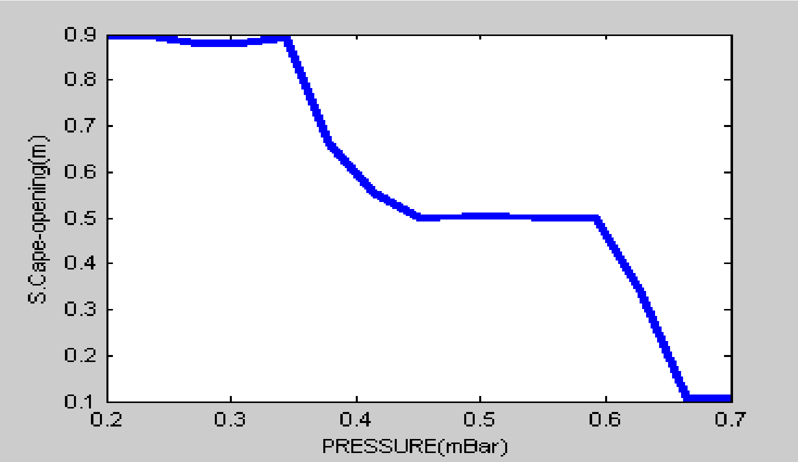

Figure 4.8 Pressure effect on Stack Cap-opening

Figure 4.6 shows that accretion can be reduced below 14.6%, at temperature below 950°C, however, this study suggests that temperature values of 950°C to 1050°C must be maintained in the reduction zone so as to maintain uniform metallization which gives high product quality. From this figure, it is also seen that if kiln temperature is to be raised above 1050°C, it results in increase in accretion build up. This rise in accretion might be due to some coal finesand other minerals melting as the temperatures approach high values within the vicinity of 1100°C. From Figure 4.7, it can be seen that apressure range of 0.3-0.6 mbar managed to maintain accretion build up rate at 14.6%. However, pressures above 0.6 mbar led to increase in accretion. To moderate pressure build up in the kiln, the Stack Cap control loop was linked to the pressure control loop. Figure 4.8 highlights that as the Stack cap opening increases the kiln pressure decreases. Figure 4.5, has shown that temperatures and pressures above the 1050^{o}C and 0.6 mbar respectively cause a sudden increase in ring formation inside the kiln, thus there is need to maintain the reduction zone temperatures within the recommended values.

4.2.2 MRAC Simulation

The designed fuzzy control shows that the damper position of angle of 56^{o}is required to maintain the temperature and pressure in the kiln at the recommended values so as to have minimum accretion as seen from Figure 3.5. The proposed MRAC design was simulated using damper angle of magnitude 56^{o} as the set-point. The results are presented in the following sections.

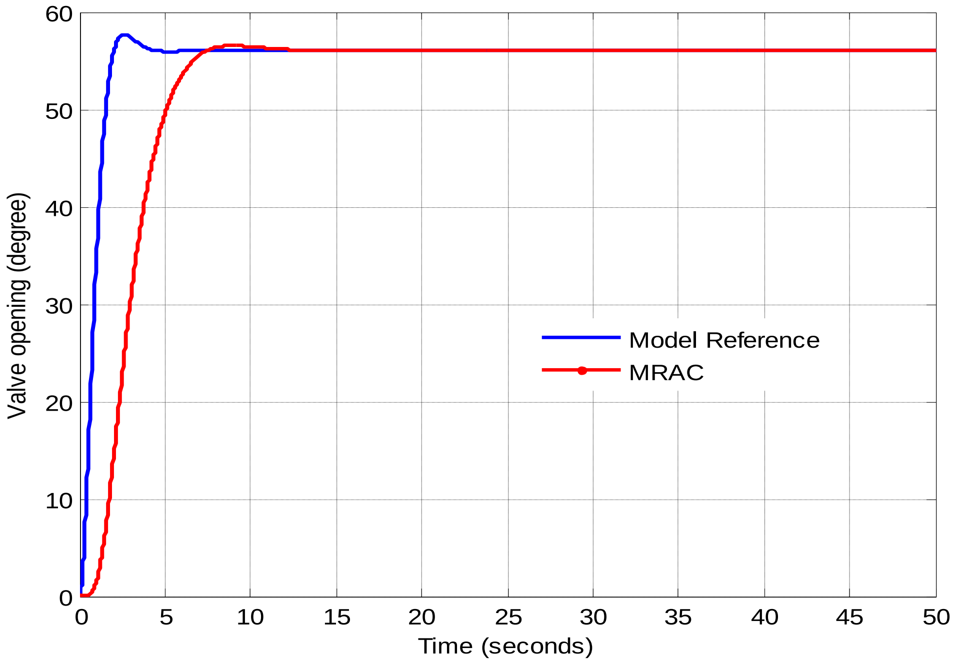

Figure 4.9 MRAC for the desired damper set-point

There are three major objectives of system analysis and design: producing the desired transient response, reducing steady-state error, and achieving stability[48].Figure 4.9 represents the simulation results of MRAC basing on controller performance in terms of transients response: rise time, over shoot and settling time. By using adaptive control, the time taken to reach the set value was 11.6 seconds and the time required for a signal to change from a specified low value to a specified high value was 7.4 seconds for the an adaptation gain of 0.03.The system managed to track the model reference but only to eliminate error at a settling time of about 11.6 seconds. However, it is 7.6 seconds slower than the required time of 3 seconds to eliminate the error. It can be seen that the MRAC system pose no oscillations within the transient response although slow to eliminate error, but it can be used in kiln control where the adaptation mechanism can help to stabilise the system in state of uncertainties' and disturbances.The adaptive control managed to maintain constant dynamic performance in the presence of unpredictable and immeasurable variations.

4.2.3 MRAFS Simulation

The MRAC system was developed first and then the Fuzzy Logic System developed independently; finally the Fuzzy Controller was embedded into the MRAC to form the MRAFS and the system was tested for transient response.The system was tested for step input at 56^{o} set-point and the results obtained are shown in Figure 4.10.

The system was tested using the closed loop function, the initial results without the aid of the PID algorithm shows that the system was oscillating with some overshoots within the first 13.6 seconds as can be seen from Figure 4.10.Reducing the adaptation gain reduces the system overshoot; however this was at the expense of settling time. The system performance was improved by tuning the fuzzy scaling factor and also including PID algorithm tuned to low gain values because at high gain values the system was not converging. It is also seen from Figure 4.11 that the system has low overshoots; the rise time and the settling time have also improved.

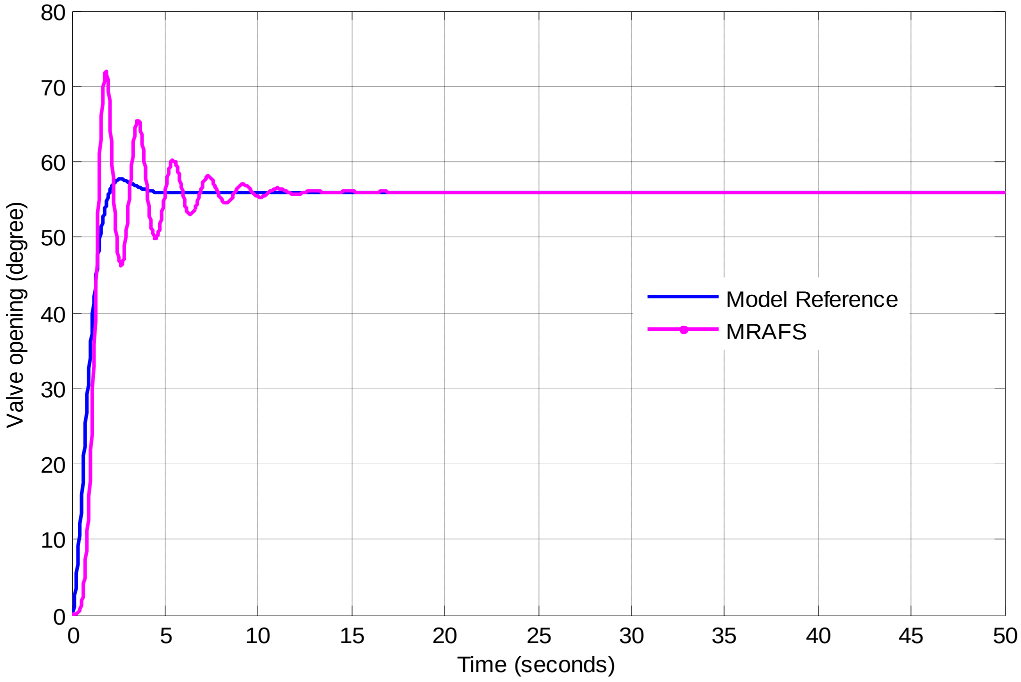

Figure 4.10 MRAFS for the desired damper set-point

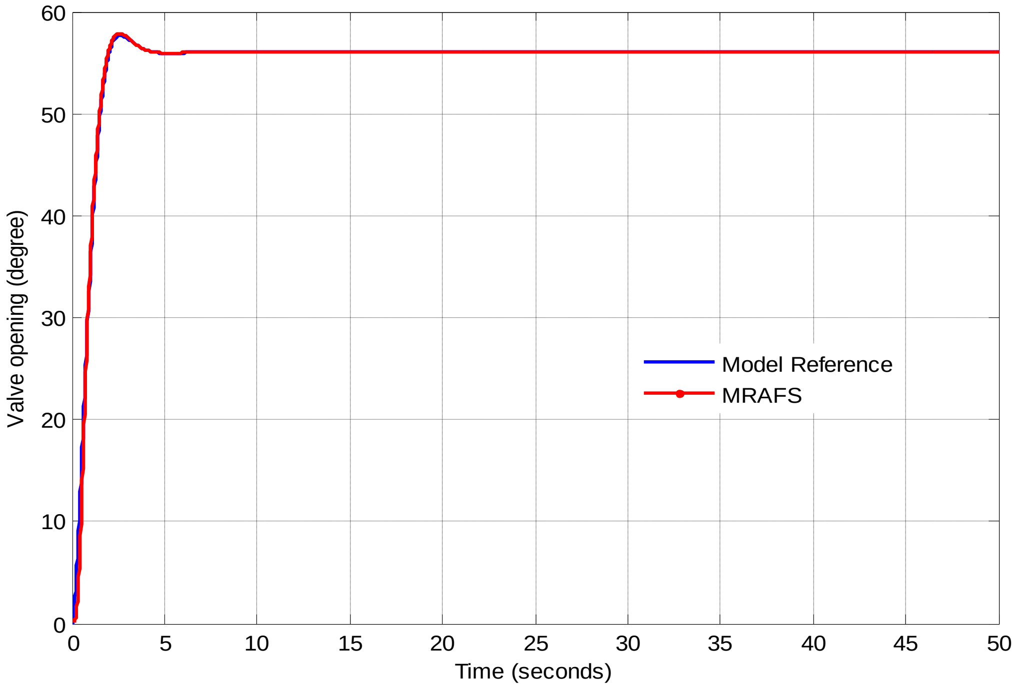

Figure 4.11 Modified MRAFS

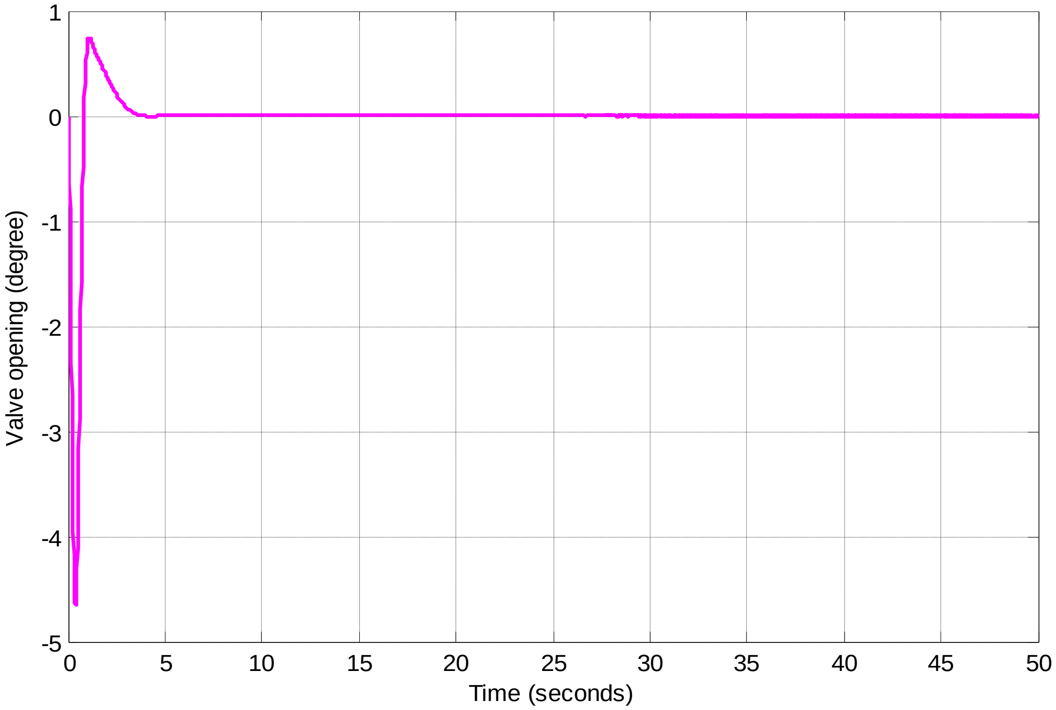

Figure 4.12 MRAFS error tracking

From Figure 4.12 it can be seen that the system managed to eliminate error within 3.6 seconds. There is 0.6 seconds difference from the desired system response. This difference might be due to; during first cycle of fuzzy adaptation the fuzzy membership function area was narrow (near ZE) making the system provide a finer control resolution but at the expense of response time. Making the area far from ZE region wider gives faster control response. Also the system had to self-tune the PID controller for a stable performance. However, the system performed satisfactory as was expected.

The nature of the adaptation mechanism for controlling a system performance is greatly affected by the value of adaptation gain. Every system gives its best for the limited range of the adaptation gain. The study also analysed the effect of adaptation gain on the system's performance. Figure 4.13 shows the system performance by varying the adaptation gain.

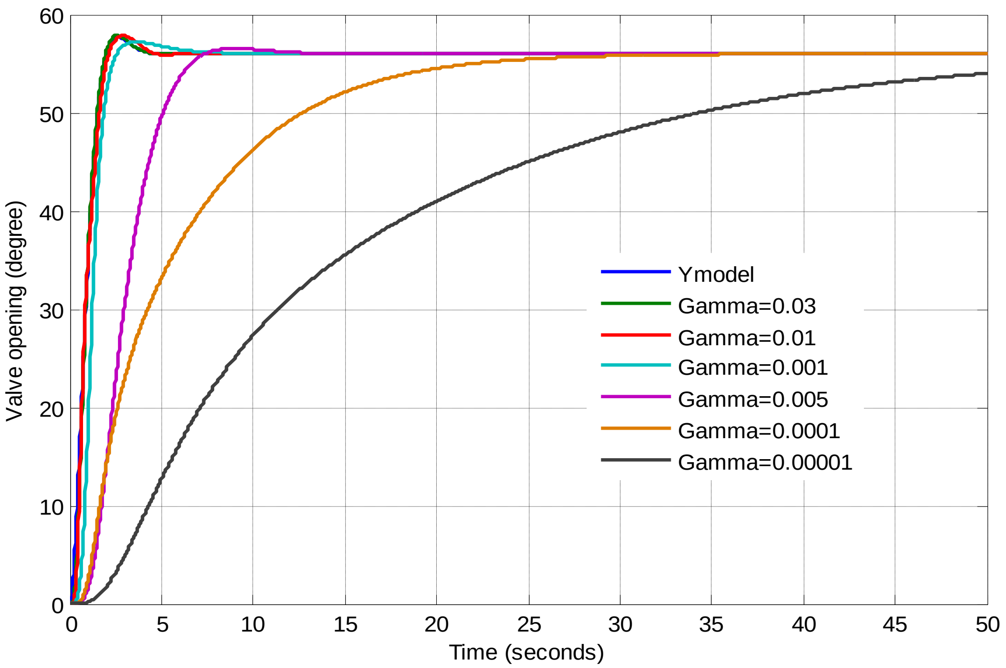

Figure 4.13 System output with different Adaptation gain

From Figure 4.13, it can be seen that if the value of adaptation gain is increased then the settling time, peak time and rise time is reduced. There is improvement in the performance of the system with the increment in adaptation gain. In this study the range of adaptationgain is chosen from 0.0001 to 0.03 for the system under consideration. Beyond this range the system performance is not up to the desired mark. It has been seen that the system response is very slow with the smaller values of adaptation gain (0.00001 and less) but there are no oscillation in the response. Increasing gamma beyond 0.03, the system output experiences severe oscillations leading to undesired behaviour (parameter estimation not converging). The system was becoming unstable for the wrong choice of adaptation gain. Therefore, it was perceived that for suitable values of adaptation gain, the MIT rule can make the plant output as close as possible to the reference model in model reference adaptive fuzzy control scheme.Swarnkar*et al*, [42], also performed the effect of adaptation gain in Model Reference Adaptive controlled Second Order

Systemand they found that an increase in adaptive gain lead to better system response. However the adaptive gain was from a given range, out of that range the system was not converging.

4.2.4 Controller Performance Comparisons

After the MRAFS system was developed, its performance was tested against the conventional PID, MRAC and PIDMRAC as all the controllers were subjected to the same process conditions.

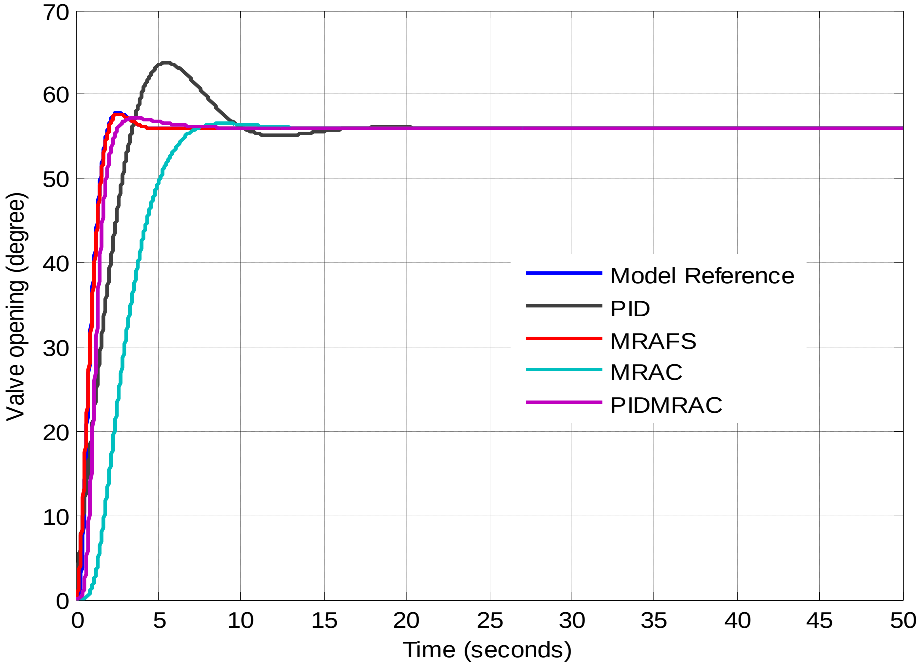

Figure 4.14 Comparisons of Controllers

It can be seen in Figure 4.14 that the conventional PID-plant output is oscillatory with high value of overshoot whereas that of the reference model is smooth and without oscillations. There is a huge dynamic error between these two and this error has to be reduced by using model reference adaptive control scheme. Due to the introduction of adaptation mechanism as shown by MRAC scheme, the oscillations reduced however the system's rise time and settling time is inferior to that of conventional PID controller.

As compared to conventional fixed gain PID controllers, the adaptive controllers proved to be very effective to handle the situations where the parameter variations and environmental changes are frequent. This fact is demonstrated in the results where PID was embedded with MRAC to produce PIDMRAC.The performance is improved by using PID algorithm with MRAC and the tracking error has reduced zero within 8.2 seconds, and no oscillations have occurred. The use of PI control contribution mainly improves the steady state performance by reducing the steady state error whereas PD controller improves the transient period by reducing the maximum overshoot. Through the application of MIT rule in a model reference adaptive control, results clearly show an improvement in system's performance. The tracking error is tending to zero and the performance of the actual plant approaches the performance of the reference model.

However, due to the continuous variation in the system parameters and the operating conditions, in addition to the nonlinearities present in the system, fixed-gain PIDMRAC scheme may not be able to provide the required performance continuously thus the need of adaptive fuzzy control. Figure 4.14 simulation results shows that the settling time for MRAFS is less than the settling time for the other systems and also the rise time for the MRAFS is superior to the rise time for the MRAC.

The greatest strength of the fuzzy controller is in its ability to learn and adapt to dynamic nonlinear conditions and also ability to track the error fast whilst reducing the transient response time. Figure 4.15 clearly illustrates the fastness of MRAFS in tacking and eliminating the error as compared to other controllers. Thus in the case of a MRAFS control scheme the entire dynamic characteristic of the system is improved. Here the controller parameters are adjusted to give a desired closed-loop performance throughout the working of the system. From the simulation results, it can be concluded that the MRAFS is giving better results in terms of transient response.

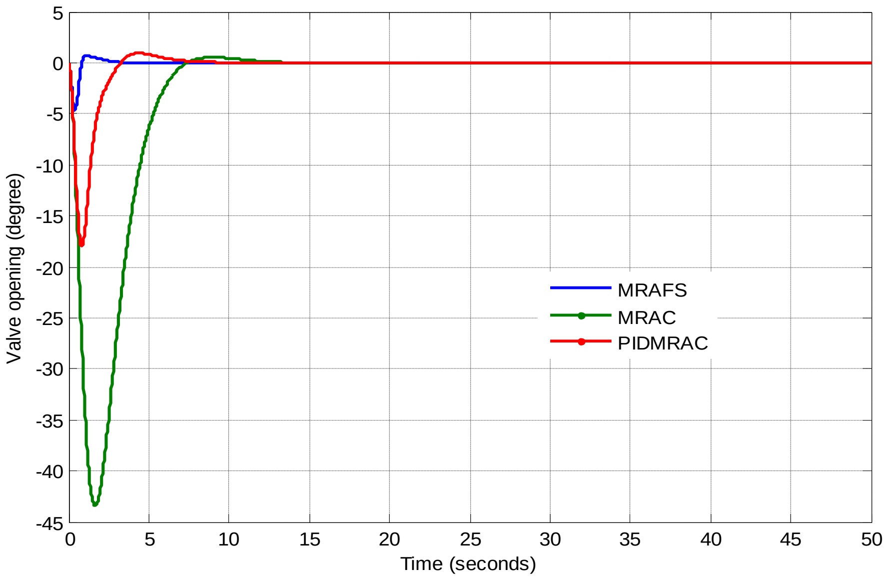

Figure 4.15 Comparisons of Error Tracking

Table 4.1: Summarized Simulation results

Set Point	Controller Type	% Overshoot	Rise time (seconds)	Settling time (seconds)
41^0 [1010^0C]	PID	12.75	3.42	17.3
	MRAC	0.21	16.8	17.5
	PIDMRAC	1.85	2.95	13.8
	MRAFS	2.48	1.93	6.5
45^0 [1020^0C]	PID	12.78	3.42	17.5
	MRAC	0.22	12.75	13.0
	PIDMRAC	1.48	2.80	12.0
	MRAFS	2.44	1.94	5.2
49^0 [1030^0C]	PID	12.77	3.42	16.8
	MRAC	0.34	9.98	12.6
	PIDMRAC	2.04	2.69	11.8
	MRAFS	2.33	1.95	4.6
56^0 [1050^0C]	PID	12.87	3.42	16.8
	MRAC	0.89	7.40	11.6
	PIDMRAC	2.06	2.56	8.2
	MRAFS	2.39	1.96	3.6

Table 4 gives the comparison of MRAFS performance againstPID controller, MRAC controller and PIDMRAC. This comparison is carried out for different set point conditions. The specifications which are taken for comparison are maximum overshoot, settling time, and rise time. From all different set points, MRAFS is giving better results compared to other controllers as rise time and settling time were the main considered aspects of the transients' analysis. The MRAFS showed satisfactory results as there was only a lag time of 0.6seconds of settling time of the system from the initially wanted 3seconds.

The main advantages that the MRAFS seems to offer as an adaptive controller are summarized as follows:

1. A detailed mathematical model of the process is not necessarily needed to develop the MRAFS; the developer only has to know how the process works.
2. The MRAFS provides an automatic method to synthesize the knowledge-base of the direct fuzzy controller while at the same time it ensures that the system will behave in a desirable fashion.
3. The adaptation mechanism in the MRAFS dynamically and continually updates the rule-base in the direct fuzzy controller in response to process parameter variations. If unpredictable changes occur within the plant, the MRAFS can make adjustments to a direct fuzzy controller to maintain sufficient performance levels.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

In this study, the appropriate working values for kiln temperature and pressure for minimizationof accretion formation in sponge iron production were determined. Also, a Fuzzy-based accretion control system and a Model Reference Adaptive Fuzzy system for maintaining appropriate kiln working process parameters were developed. The main aim of this study was to come up with a suitable process controller for improving and maintaining product quality while at the same time minimizing kiln accretion formation. Performance of Model Reference Adaptive Fuzzy system through analysis of transients' analysis in the control of process parameters in sponge iron kiln-based process was assessed.

The simulation results of the fuzzy design were compared to the experimental results done using PID control and they showed that fuzzy controller was able to minimize accretion build up to a low rate than that of PID controller.

By combining adaptive control concepts with fuzzy system theory, a control scheme has been developed which has a fast rate of convergence. As compared to conventional fixed gain PID controllers, the adaptive controllers are more effective in handling situations where the parameter variations and environmental changes are frequent. From the simulation results, it is seenthat, compared with conventional PID and conventional MRAC, MRAFS has the best performance in both transient and steady state response as it gives quick response time with less overshoots.

The proposed control scheme can effectively achieve trajectory tracking even for plant with relatively large amounts of parametric uncertainties. The benefit of the adaptive fuzzy control is that it can implement the reasoning and the experience of the process engineer and is thus able to handle the tasks which are normally implemented by the engineer.

5.2 Recommendations

It can be noted from simulation results that Fuzzy controller for accretion control givesbest results as compared to PID controller. However to validate these simulation results, we recommend the implementation of the Fuzzy logic control in the actual operation of a pilot rotary sponge iron kiln.

Further, although an adaptive controller may control a plant's behaviour to match the one of a predefined reference model in theory, several limitations can be detected in practice. Rigorous testing and simulation with relevant input signals and parameter choices are necessary in order to ensure satisfactory behaviour. Thus, we recommend the use of other parameters like kiln rotational speed as it has influence in the charge mixture and retention time of the product in the kiln.

Also further research should focus on extending this scheme to a predictive model for kiln accretion control system.

REFERENCES

[1] A.Sarangi and B. Sarangi,"Sponge Iron Production in Rotary Kiln", 2011, (*PHI Learning Private Ltd,* New Delhi, ISBN-978-81-203-4099-2, 2011

[2] H.S. Patra, B. Sahoo and B.K. Mishra, "State of sponge iron units in Orisa Vasundhara."2005, Available:http://vasundharaodisha.org/Research%20Reports/Status%20of%20sponge%2 0iron%20plant%20in%20Orissa.pdf, Accessed on 18/12/2013

[3] A.K. Singh, "A Thesis on Preparation and Characterization of Sponge Iron", Master of Technology in Materials Science and Engineering, (2009), *Thapar University*, India.

[4] S.S. Prasad, B.K Rao, K.R Kumar, S.G Sapare, "Cleaner Production and Code of Practice in Sponge Iron Sector", *Information Bulletin, Andhra Pradesh Pollution Control Board, Cleaner Production* Cell, 2006, No.129

[5] T. Garikayi, L. Nyanga, T.Mushiri, S. Mhlanga, P.K. Kuipa, "Designing of an Intelligent Fuzzy Logic System for Accretion prevention in sponge iron SL/RN rotary kiln based 100TPD DRI process", *SAIIE25 Proceedings, 9th–11th of July 2013, Stellenbosch, South Africa* © 2013SAIIE pp. 523_1-523_14

[6] K.K. Dash, V.K.Tiwary and I.N. Chakeaborty, "Refractories solution to accretion problem in Sponge iron kilns", 2007,*Steelworld*, pp. 1-5

[7] V. Venkateswaran, "Mathematical Model of the SL/RN Direct Reduction Process", A Thesis submitted in partial fulfillment of the requirements for the degree of Master of Applied Science, 1972, *Department of Metallurgy*

[8] M. P. Srivastava, A. Bandopadhyay, K.K.Prasda, and B.R. Chavdhury, “Operating Experience of Sponge Pilot-Some aspects”, 1988, *Trans.IIM*, Vol. 41, No 2, pp.177-186

[9] M.R.K.Rao, “A study of ring formation of Sponge iron in the Rotary kiln”, *National Metallurgical Laboratory Jamshedpur*, India, 1967

[10] F. Xiao-hui, W. Yi, C. Xu-ling, “Mathematical models and expert system for grate-kiln process of iron ore oxide pellet production. Part II: Rotary kiln process control”, 2012, *J.Cent.SouthUniv, 19*:pp 1724-1727

[11] P. Barr, J.Brimacombe, A. Watkinson, (1989), “A heat transfer model for the rotary kiln: Part 2. Development of the Cross Section Model”, 1989, *Metall. Trans. B, 20B,* 403-419

[12] M. Imber, and V. Paschkis, “Mathematical model of rotary kiln based on heat transfer”, *International Journal of Heat Mass Transfer*, 1962, Vol. 5, pp.623-638

[13] M.G.Rasul, “Assessment of the thermal performance and energy conservation opportunities of a cement industry in Indonesia”, 2005, *Applied Thermal Engineering 25,* pp.2950-2965

[14] R.K.Patil, M.P.Khond, L.G.Nawale, “Heat Transfer Modeling of Rotary Kiln for Cement Plants”, *International Journal for Advancements in Technical Research and Development,* 2012, IJATRD2012020, Vol. 1, Issue 1, pp,1-11

[15] A. Boateng,and P. Barr, “Modeling of particle mixing and segregation in the transverse plane of the rotary kiln”, 1996,*Chem. Eng. Sci., 51*, 4167-4181.

[16] A. Chatterjee, A.V.Sathe and P.K. Mukhopadhyay, “Modelling of Rotary Kiln Direct Reduction”, *Metallurgical 'Transactions*,1983, Vol. 14B, pp.375-399.

[17] J.P.Shunta, “Achieving World Class Manufacturing”, 1995, *Prentice Hall PTR, Englewood Cliffs*, New Jersey, U.S.A.

[18] A.A.Boeteng, “Rotary Kilns Transport Phenomena and Transport Processes”, 2008, *Butterworth-Heinemann*, ISBN: 978-0-7506-7877-3

[19] L. Holmblad, and J. Østergaard, “The FLS application of Fuzzy logic”, *Fuzzy Sets and Systems*, 1995, Vol. 70, No. 2-3, pp.135-146, ISSN: 0165-0114

[20] M.A.Fallahpour, B. Fatehi, N. Araabi, and M. Azizi, “A Neuro-Fuzzy Controller for Rotary Cement Kilns”,*Proceedings of the 17th World Congress. The International Federation of Automatic Control Seoul, Korea*, 2008, pp.13259-13264.

[21] M. Jarvensivu, K. Saari,and S. Jamsa-Jounela, “Intelligent control system of an Industrial lime kiln process”, *Control Engineering Practice*, 2001, Vol.9, No.6, pp.589-606, ISSN: 0967-0661.

[22] X. Zhou, H. Yue,and T. Chai, “Reinforcement Learning-Based Supervisory Control Strategy for a Rotary Kiln Process”, *Reinforcement Learning, Cornelius Weber, Mark Elshaw and Norbert Michael Mayer (Ed.),*2008, ISBN:978-3-902613-14- 1,InTech,
Available:http://www.intechopen.com/books/reinforcement_learning/reinforcement_lear ningased_supervisory_control_strategy_for_a_rotary_kiln_process

[23] T.J. Ross, J.M.Booker,and W.J.Parkinson, “Fundamentals in Fuzzy Logic and Probability Applications: Bridging the Gap”, *ASA-SIAM Series on Statistics and Applied Probability 11*, 2002.

[24] L.A. Zadeh, “Fuzzy Sets”, *Information and Control*, 1965,Vol. 8, pp. 338- 353

[25] S. Haack,“Do we need fuzzy logic?” *International Journal of Man-machine Studies*, 1979, Vol. 11, pp. 437-445

[26] M.S.Godoy and F. Friedhofer,“An implementation methodology of a fuzzy based decision support algorithm”, *International Journal of knowledge based intelligent engineering systems, Colorado, USA*, 1997, Vol. 1. No. 4, pp.267-275

[27] T.A. Nwodoh, and I.A.Ejimofor, “Implementation of Fuzzy Logic based Temperature- Controlled Heat Exchanger”, *NIGERIAN Journal of Technology*, 2010,Vol. 29 No.1, pp. 94-109

[28] F.O. Karrayand C. De Silva, “Soft Computing and Intelligent Systems Design, Theory, Tools and Applications”, © *Pearson Education Limited*, 2004, ISBN: 0321116178

[29] L.A.Bryan and E.A. Bryan,“Programmable Controllers Theory and Implementation, Second Edition”, Industrial *Text Company Publication*, 1997.

[30] M.Y. Hassan and F.W. Sharif, “Design of FPGA Based PID-like Fuzzy Controller for Industrial Applications”, *IAENG, IJCS.34:2*, 2005

[31] T. Y. Lin, C. Tseng and D. Teo, “Fuzzy Control and Rough Sets,” Proceedings of 1996, International Conference on Circuits and System Sciences, Shanghai, China, June 20-25.

[32] I.D.Landau, R. Lozano and M. M’Saad,“Adaptive Control, Communications and Control Engineering”, DOI 10.1007/978-0-85729-664-1_1, © *Springer-Verlag London Limited*, 2011,(Http://www.springer.com/978-0-85729-663-4)

[33] M. Hojati, and S. Gazor, “Hybrid Adaptive Fuzzy Identification and Control of Nonlinear Systems”, *IEEE Transactions on Fuzzy Systems*, 2002, Vol.10, No. 2, pp.198-210

[34] I.J.Nagrathand M. Gopal, “Control Systems Engineering Fourth Edition”, *New Age International (P) Limited, Publishers, New Delhi*, 2005, ISBN: 81-224-1700-0, pp. 715

[35] M.N.Bandyopadhyay, “Control Engineering theory and Practice”, *PHI learning Private Limited, New Delhi*, 2009,ISBN-978-81-203-1954-7

[36] K.Prabhuand M.V.Bhaskaran,“Optimization of a Control Loop using Adaptive Method”, *International Journal of Engineering and Innovative Technology,*2012, Volume 1,Issue 3, ISSN: 2277-3754, pp.133-138

[37] K.J. Astrom and B. Wittenmark, “Adaptive Control, 2nd Edition”, *Addison-Wesley Publishing Company, Series in Electrical Engineering: Control Engineering, USA*, 1995

[38] P.A. Ioannou, and J. Sun,“Robust Adaptive Control”, *Prentice-Hall, Upper Saddle River, New Jersey*, 1996

[39] R. Prakashand R. Anita,“Modeling and Simulation of Fuzzy Logic Controller-Based Model Reference Adaptive Controller”, *International Journal of Innovative Computing, Information and Control*, 2012, Volume 8, No. 4, ISSN 1349-4198, pp.2533-2550

[40] R. Prakash, “A New Approach to Model Reference Adaptive Control using Fuzzy Logic Controller for Nonlinear Systems”, *International Journal of Innovative Computing, Information and Control*, 2008, pp. 86-93.

[41] M.A. Khanesarand M. Teshnehlab, “Direct fuzzy Model Reference controller for SISO nonlinear plants using observer”, *International Journal of Innovative Computing, Information and Control*, 2010, Vol.6, No.1, pp.297-306.

[42] T. Garikayi1, L. Nyanga, T. Mushiri, S. Mhlanga, A. Muzinda T. Mutangi, “Model Reference Adaptive Control System for Moisture Regulation inCotton ginning”,*SAIIE25 Proceedings, 9th–11th of July 2013, Stellenbosch, South Africa* © *2013SAIIE* pp. 523_1-523_14

[43] P. Swarnkar, J.Shailendra, R.K Nema,“Effect of Adaptation Gain on system Performance for Model Reference Adaptive Control Scheme using MIT Rule”, *World Academy of Science, Engineering and Technology 70*, 2010, pp.621-626

[44] M. Kadjoudj, N. Golea, M.E.H Benbouzid,“Fuzzy Rule – Based Model Reference Adaptive Control for PMSM Drives”, *Serbian Journal of Electrical Engineering,* 2007, Vol. 4, No. 1, pp. 13-22.

[45] S. Kamalasadan and A.A. Ghandakly, “A Novel Fuzzy Multiple Reference Model Adaptive Controller Design”,*International Journal of Fuzzy Systems*, 2006, Vol. 8, No. 3, pp. 165-172

[46] Li-Xin Wang, “Stable Adaptive Fuzzy Control of Nonlinear Systems”,*IEEE Transactions on Fuzzy Systems*, 1993, Vol. 1, No. 2

[47] T.K. Yin, “Fuzzy model reference adaptive control”, *IEEE Trans, On System, Man and Cybernetics*, 1995, Vol.25, No 12

[48] K. Ramu, C.Ramesh, A.Rajasekaran , Technical Aspects of Manufacture of Sponge Iron, *Steel Tech Seminar Taj Bengal Kolkata, India*, 2008,Available on:

http://spongeironinfo.blogspot.com/search?updated-min=2011-01-01T00:00:00-08:00&-updated-max=2012-01-01T00:00:00-08:00&max-results=1

[49] J.J. Jordan, “A DC Motor Drive for a Dyno-Microcontroller and Power Electronics”, *University of Queensland*, Australia, BSc. thesis, Oct. 2001.

[50] H. Ahmed, G. Singh, V. Bhardwaj, S. Saurav, S. Agarwal, “Controlling of D.C. Motor using Fuzzy Logic Controller”, *Conference on Advances in Communication and Control Systems ,2013 (CAC2S 2013), Published by Atlantis Press*

APPENDICES

Appendix A Mathematical Modelling of the Motorized Damper Valve

This section provides brief derivation of a model of an armature control of separately excited DC motor. The DC motor is the driving force of the damper valve linked with a tachometer so as to regulate the valve angle position. The main purpose of this damper valve is to regulate the amount of air entry blown into the kiln by Shell Air Fans along the kiln profile so as to maintain the required temperature and pressure inside the kiln. The damper valve will be receiving an analog control signal from the fuzzy controller then continuously position the valve with reference to angle θ.

In armature control of separately excited DC motors, the voltage applied to the armature of the motor is adjusted without changing the voltage applied to the field. Figure A.1 shows a separately excited DC motor equivalent model.

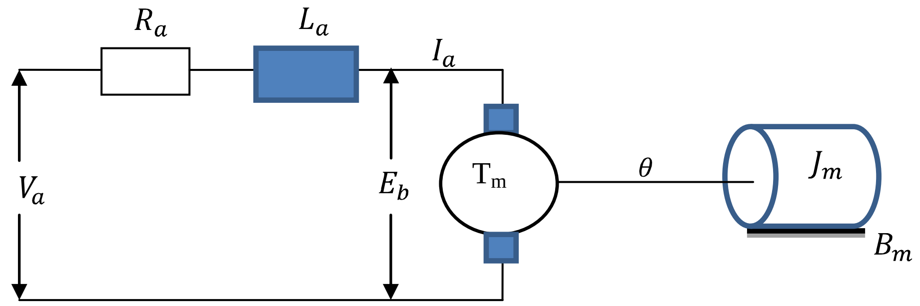

Figure A.1 DC motor model [49]

$$v_a(t) = R_a I_a(t) + L_a \frac{dI_a(t)}{dt} + e_b(t) \tag{A.1}$$

Where v_a= armature voltage, R_a= armature resistance, L_a= armature inductance, I_a = armature current, and $e_b(t)$= back emf and is given by:

$$e_b(t) = K_b w(t) \quad \text{(A.2)}$$

whereK_b= back emf constant and w= angular speed

The motor torque,$T_m(t) = K_t I_a(t)$ (A.3)

Where:K_t = torque constant

The motor torque can be expressed in terms of rotor inertia (J_m) and viscous friction coefficient (B_m) as:

$$T_m(t) = J_m \frac{dw(t)}{dt} + B_m w(t) \quad \text{(A.4)}$$

Substituting equation (A.2) into (A.1) we get:

$$v_a(t) = R_a I_a(t) + L_a \frac{dI_a(t)}{dt} + K_b w(t) \quad \text{(A.5)}$$

Replacing $T_m(t)$ in equation (A.4) by equation (A.3) we obtain:

$$K_t I_a(t) = J_m \frac{dw(t)}{dt} + B_m w(t) \quad \text{(A.6)}$$

Performing Laplace Transform of equations (A.5) and (A.6)

$$V_a(s) = R_a I_a(s) + L_a I_a(s) + K_b W(s) \quad \text{(A.7)}$$

$$K_t I_a(s) = J_m W(s) + B_m W(s) \quad \text{(A.8)}$$

If I_a is obtained in equation (A.8) and substituted in equation (A.7) we obtain the following expression:

$$V_a(s) = W(s) \frac{1}{K_t} [L_a J_m (s^2) + (R_a J_m + L_a B_m)(s) + R_a B_m + K_b K_t] \quad \text{(A.9)}$$

The relation between rotor shaft speed and applied armature voltage is represented by the following transfer function:

$$\frac{W(s)}{V_a(s} = \frac{K_t}{[L_aJ_m(s^2)+(R_aJ_m+L_aB_m)(s)+ R_aB_m+K_bK_t]} \qquad \text{(A.10)}$$

Considering damper valve activated by a DC motor, the transfer function of the plant was formulated as follows:

Equation (A.10) shows the relation between rotor shaft speed and applied armature voltage as a transfer function.However the relation between position and speed is:

$$\theta(s) = \frac{1}{s}W(s) \qquad \text{(A.11)}$$

Combining equation (A.10) and (A.11) we obtained the following transfer function for the plant:

$$\frac{\theta(s)}{V_a(s} = \frac{K_t}{[L_aJ_m\,(s^3)+(R_aJ_m+L_aB_m)(s^2)+ (R_aB_m+K_bK_t)s]} \qquad \text{(A.12)}$$

In this study a separated excited DC motor driven valve was considered. The damper is controlled using a proportional controller with gain K_c and a motor with position (tachometer) and velocity feedback. The different parameters of the system are: K_c= 10, k_t= k_b= 0.55, R_a= 1 Ω, L_a= 0.046H, J_m= 0.093 kgm^2, B_m= 0.08 Nms/rad, torsion damping coefficient of valve k_d= 0.5Nms/rad

Using equation (A.10) and the valve parameters the following transfer function was formulated:

$$G_p(s) = \frac{W(s)}{V_a(s} = \frac{5.5}{[(0.00429s^2)+0.0967(s)+ 0.383]} \qquad \text{(A.13)}$$

Let b = 5.5, a_1= 0.00429, a_2 = 0.0967, a_3 = 0.383

Appendix B Publication

1. E.T. Mharakurwa, G.N. Nyakoe and B.W. Ikua, “Accretion Control in Sponge Iron Production Kiln using Fuzzy”, *Journal of Sustainable Research in Engineering(JSRE)*, 2014, Vol. 2