DESIGNING OF AN INTELLIGENT FUZZY LOGIC SYSTEM FOR ACCRETION PREVENTION IN SPONGE IRON SL/RN ROTARY KILN BASED 100TPD DRI PROCESS

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ABSTRACT

Sponge iron is an intermediate product of steel formed during direct reduction of iron ore with aid of regulated temperatures and pressures within a rotary kiln. The greatest challenge is the direct measurement of kiln shell temperatures due to the catastrophic accumulation of sintered particles of solid bed which form rings at places along the length of the kiln thus hindering material flow. The accretion reduces productivity, damage kiln lining and reduces the production period as well as reduction in product quality. This process requires a controller which will be able to control with imprecise and partial data input; and be able to achieve the desired product quality under dynamic process conditions thus a Fuzzy Controller was used for the proposed design. The main goal of the research was to predict the rate of accretion build up within the kiln and minimize it with aid of a Fuzzy Control System cascaded to an already existing Programmable Logic Controller. A 16.2% build up rate was achieved as compared to the most appreciated 27% thus nearly a 10% decrease, a result which can improve the campaign period by approximately 48 hours which will be a 200 tons of sponge iron.

Key words: Sponge Iron, Fuzzy Logic, Accretion, kiln

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1 INTRODUCTION

The primitive methods of manufacturing, lack of process control and increased down-time has been the greatest effects experienced by manufacturing companies in developing nations. Fuzzy logic is useful just because of its low specificity; it allows a more flexible response to a given input. The output of a fuzzy system is smooth and continuous, ideal for the control of continuously variable systems such as electric motors or positioning systems. The process dynamics of sponge iron production depends largely on kiln rotation, temperature, pressure and feed control. Therefore the intelligence of process control architecture varies directly to the knowledge of the Knowledge Engineer. This research seeks among other things to control the manufacturing process of sponge iron with aid of a fuzzy controller which will be able to reason with imprecise or partial data hence making an informed decision. This controller developed demonstrated superiority in controlling the temperature, pressure and kiln rotational speed. Section 2 presents automation in sponge iron production, section 3 presents the sponge iron production process and section 4 the control parameters and section 5 the development of the fuzzy system.

2 AUTOMATION IN SPONGE IRON PRODUCTION

A report by Rockwell Automation [1] states that the plant floor has been in the past viewed as an “island” in isolation of other elements within the supply chain and the organisation itself. The developments in information technology and the development of e-commerce and e-manufacturing concepts have increased the need for the inventions of new and better methods to keep processes under control and providing information on the factory in the process industry. According to Saha and Grover [2] one of the enablers of e-manufacturing is automation. In developing automation systems based on fuzzy logic Booker [3] suggests one should first sit back and ask fundamental questions about what they are trying to do characterize the various forms of uncertainty and then develop mathematical models to quantify them.

The process of sponge iron making aims to remove oxygen from iron ore. According to Patra et al [4] the quality of sponge iron is primarily ascertained by the percentage of metallization (removal of oxygen), which is the ratio of metallic iron to the total iron present in the product. The characteristics of a kiln based system change significantly with respect to raw material quality, pressure and temperature conditions. In trying to apply the traditional methods of control, difficulties were encountered as the process working condition changes within a large operation range. Control methods such expert systems, fuzzy logic control, neural networks and knowledge-based systems, termed intelligent control were then considered as addition to conventional controllers. Fuzzy Logic (FL) is a nonlinear problem-solving control system methodology that lends itself to implementation in systems [5]. Sponge iron, also called Direct-reduced iron (DRI), is formed, when naturally available Iron Ore which is an oxidized form of Iron (magnetite (Fe_3O_4) or hematite (Fe_2O_3)) is reduced to its metallic form as stated by Kant and Shankar [6].

This reduction process occurs below the melting temperature of both metallic iron and its oxidized form. Though this process is carried out at lower temperature than melting point so that there is less volume reduction a large amount material get eliminated during reduction reaction. It is mandatory to get more understanding of parameters, such as the distributions of gas-solid flow, temperature, and composition of gases and particles within a rotary kiln through mathematical modeling as stated by Bhad et al [7]. The implementation of fuzzy control will enable the process to be optimized with imprecise or partial data hence achieving the desired product quality. However, only few expressions have existed so far for the processes in a cement rotary kiln to model the fuel combustion, heat transfer, and reduction chemistry. This is owing to the complexity of heat transfer that takes place simultaneously along with chemical and mineralogical reactions [7].

Zambak [8] states that in fuzzy logic, exact reasoning is viewed as a limiting case of approximate reasoning. Everything is a matter of degree. Any logical system can be fuzzified thus knowledge is interpreted as a collection of elastic or fuzzy constraint on a collection of variables hence inference is viewed as a process of propagation of elastic constraints.

Fuzzy controller consists of a classifier, fuzzifier, rule base, interface engine. In the fuzzy rule base, various rules are formed according to the problem's requirements. The numerical input values to the fuzzier are converted into fuzzy values. The fuzzy values along with the rule base are fed into the inference engine which produces control values. As the control values are not in usable form, they have to be converted to numerical output values using the defuzzifier summarised by Jeganathan [9].

3 ACCRETION FORMATION

Experimental results done by the researchers revealed that accretion build up or ring formation in the kiln is caused by the deposition of low melting complex compounds on the refractory wall of the rotary kiln which gradually increases in thickness and takes shape of a circular ring, thus, reducing the kiln diameter and hence rate of production and a short campaign period is attained. Sarangi [10] states that, accretion build up occurs at a certain position in the second zone of the kiln when *Wustite* is the stable phase. When the ring formation is above 30% of the diameter of the kiln, the operation of the kiln becomes difficult. The kiln atmosphere must be properly regulated so as to achieve good metallization. The atmosphere above the bed is oxidising and within the bed is reducing. The inside conditions of the kiln are regulated in a manner that the oxidation potential within and just above the bed should be low which will assist in maintaining a strong reducing atmosphere for the reduction of iron ore. Within the second zone the CO: CO_2 ratio of the reducing gas should be more than 2:3. As for the conditions above the bed, the oxidising atmosphere may be controlled by controlled injection of secondary air using shell air fans mounted on the rotary kiln.

There are several factors which affect the isothermal condition in the reaction zone and heat transfer. The time of residence for preheating the charge and the chemical reactions essentially depends on the inclination speed of rotation, and granulometry of the raw materials. Heat release rate, poor heat transfer and lengthy reduction time account for low output of a rotary kiln and the campaign length. With a chosen retention time depending on the length and rotation, the output can be increased by increasing the diameter [11].

The degradation due to self-grinding increases with diameter, while exhaust gas velocity is decreased lowering entrainment of solids. For reasonable reaction rate, an appropriate temperature profile has to be maintained. The reaction temperature is dependent on softening temperature of solids. The reactivity of fuel and reducibility of the ore are the rate determining factors. The degree of metallization depends on the particle size and reducibility of the ore, temperature profile and reactivity of the fuel. All these factors should be considered in designing a model for minimizing accretion build up.

Dash [12] states that coal based process utilizes non-coking coal, lumpy rich grade of iron ore and dolomite as basic raw material. The non-coking coal acts as a reducing agent in this process. The reduction process is carried out in an inclined horizontal rotary kiln, which rotates at a predetermined speed.

Almost all direct reduction kilns operate on counter- current principle where the charge and the fuel are fed at opposite ends and, therefore, the raw materials travel in opposite direction to the flow of the kiln gases, while in co-current kiln the charge and the fuel fed at the same end and consequently the solids and the kiln gases move in the same direction.

The entrainment of fine particles of the charge in the exit gas depends on its velocity; the higher is the gas velocity, the larger will be the amount of fine particles carried away from the kiln. For identical quantity of gas leaving the kiln, the gas velocity decreases with the increase in the diameter of the kiln, which explains the higher length/diameter ratio of the commercial kilns. For gaseous reduction of iron oxide, the reaction rate depends on the flow rate of the gas to sweep away the product gas. Therefore, the rate controlling step of reduction depends on the gas velocity and it cannot be decreased below a definite limit. The velocity of exit gas of 20 m/sec. from a commercial kiln is sufficiently high to sweep the product gas. The extent of the pre-heating zone chiefly depends on the exhaust gas temperature, its volume and the exposed area of the charge. The temperature varies from 800 to 1050°C, while the gas volume varies from 3000 to 5000 Nm^3 ton sponge iron. Higher exhaust gas temperature decreases the thermal efficiency of the kiln and the temperature has to be lowered by admission of air using shell air fans dotted along the kiln length. The admission of the air with aid of shell fans at regular intervals lengthens the combustion zone.

The optimum temperature of operation inside the kiln mainly depends on the softening temperature of the ash of the reductant. As the output of the kiln increases steeply with increase in reaction temperature, the kiln should be operated at the maximum permissible temperature, which should preferably be about 100°C below the ash softening temperature. The softening of fusion of any constituent of the raw material and presence of fines lead to the major problems of balling up of the ingredients and "ring" formation or deposition of accretions on the kiln wall, progressive of operation.

In fact if the "ring" formation can be totally eliminated, a rotary kiln will be an ideal reactor for reduction of iron oxide of which that’s practically impossible. The ash softening temperature of the Zimbabwean non-coking coals is not very high, thereby limiting the maximum operational kiln temperature. The rate of removal of oxygen from iron ore depends on the temperature of reaction. The effect of temperature on gaseous reduction of an iron ore at identical gas flow rate is too complex and will not be used to develop the fuzzy model. A study of the kinetics of removal of oxygen by gaseous reductants reveals that the reaction rate progressively increases from 700°C to 1000°C and the time of 90% reduction, for a particular ore decreases from 145 min. to 70 min. In other words the kinetics of iron ore reduction by gaseous reductants like H_2 or CO at temperature below 800°C is exceedingly slow even when the product of the reaction is swiftly swept away from the reaction front. Consequently, the raw materials in the kiln are to be preheated to an appropriate temperature to assure a reasonable reaction rate as in the presence of large amount of carbon in the charge a significant part of reduction occurs through the agency of solid reductant.

4 CONTROL PARAMETERS

There are several factors and parameters which affect the production of sponge iron, however the research seeks to control only the following parameters so as to minimise accretion build up:

- Feed rate of raw materials from the raw material storage bin with aid of weigh feeder system.
- Kiln Temperature profile along the rotary kiln for both the preheating zone and the reduction zone.
- Kiln Gas pressure
- Kiln rotational speed

Parameters such as raw material quality are difficult to improve with automation; however they have a direct effect on the product quality. Therefore the quality aspect of raw materials is considered to be constant and the design shall seek to optimise the product quality based on the available raw material quality.

5 DEVELOPMENT OF FUZZY LOGIC CONTROL SYSTEM

According to Zadeh [9] and Al-Hadidi et al [14] a Fuzzy Logic Control System provides a simple way to arrive at a definite conclusion based upon vague, ambiguous, imprecise, noisy, or missing input information. FL's approach to control problems mimics how a person would make decisions, only much faster ted by as stated by Sivanandam and Deepa [15]. The FL model is empirically-based, relying on an operator's experience rather than their technical understanding of the system as stated by Priyono et al [16]. The terms are imprecise and yet very descriptive of what must actually happen. The trial-and-error basically formulates the back-bone of the empirical methods implemented during the design of fuzzy systems as shown in Figure 1.

Fuzzy set theory does not permit vagueness in our computations, but shows how to tackle uncertainty, and to handle imprecise information in a complex situation. Fuzzy sets are the core element in Fuzzy Logic. They are characterized by membership functions which are associated with input and output to the fuzzy logic system and terms or words used in the antecedent and consequents of rules as shown in Figure 1.

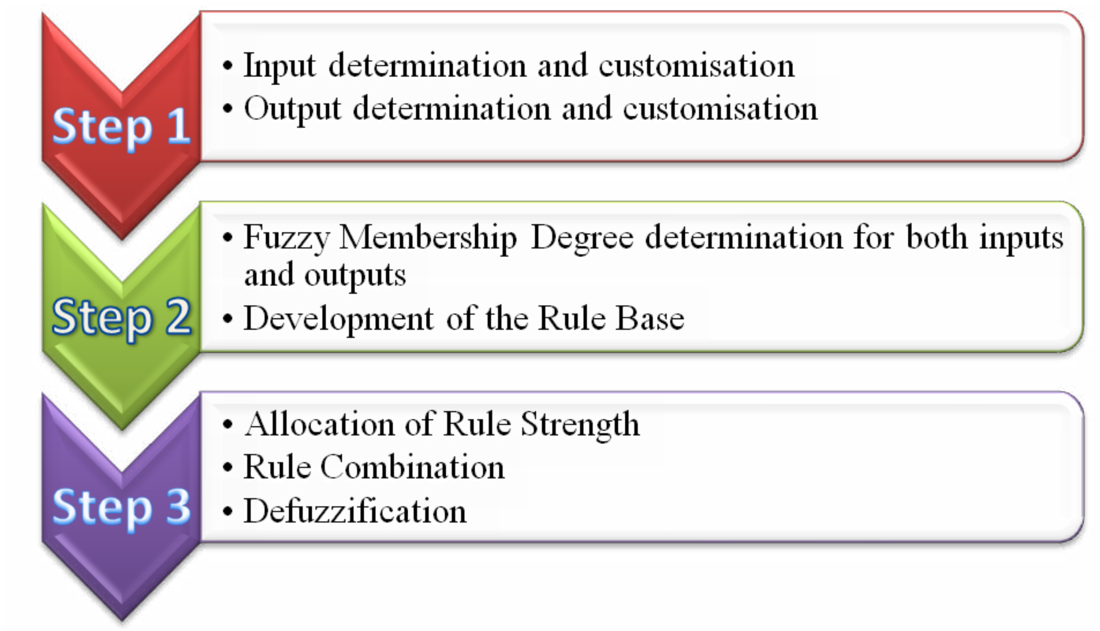

Figure 1 The methodology for designing a fuzzy controller [15]

Fuzzy set theory was originally proposed by Prof. Lotfi A. Zadeh [9] of the University of California at Berkeley to quantitatively and effectively handle problems involving uncertainty, ambiguity and vagueness. The theory, which is now well-established, was specifically designed to mathematically represent uncertainty and vagueness and provide formalized tools for dealing with the imprecision that is intrinsic to many real world problems [17].

The accretion regulation, prediction and prevention are achieved by regulation of the following sets of parameters:

1. Minimising accretion build up by monitoring the temperature profile (**T** /^{o}C) and gas pressure profile inside the kiln (**P** /*mBar*).

The linguistic description provided by the expert can generally be broken into several parts. There will be “linguistic variables” that describe each of the time-varying controller inputs and outputs. Linguistic variables assume "linguistic values". That is, they can be described by the following values:

"Negative High, Negative Low, Zero, Positive Low, and Positive High"

The convention that was used by was such that, a particular linguistic variable is considered positive if it is acting towards the right and negative if it is acting towards the left. Each of the three rules listed above is a *"linguistic rule"* since it is formed solely from linguistic variables and values. Since linguistic values are not precise representations of the underlying quantities that they describe, linguistic rules are not precise either. They are simply abstract ideas about how to achieve good control that could mean somewhat different things to different people. There is no underlying relationship between membership function and a probability density function; hence there is no underlying probability space. By definition "certainty" is the "degree of truth". Zadeh [9] proved that the membership function has no basis to quantify random behavior however it simplymakes less fuzzy the meaning of linguistic descriptions.

Takagi et al [18] explained that the premises (sometimes called "antecedents") are associated with the fuzzy controller inputs and are on the left-hand side of the rules. Note that there is no need to be a premise (consequent) term for each input (output) in each rule, although often there are.

5.1 The fuzzy set theory

Cox [19] summarised that there are two main types of fuzzy logic which are Type-1 and Type-2 fuzzy logic systems. The greater simplicity of implementing a control system with fuzzy logic can reduce design complexity to a point where previously insoluble problems can now be solved. Fuzzy systems typically result in a 10:1 rule reduction, requiring less software to implement the same decision-making capability.

5.1.1 Type-1 Fuzzy

Use full justification Type-1 fuzzy sets are not able to convey the uncertainties about the member ship functions as illustrated on Figure 2. Some typical sources of uncertainties are:

a) The meaning of the words that are used in the antecedents and consequents can be uncertain (words mean different things to different people),
b) Knowledge extracted from a group of experts do not all agree thus the consequents may have a histogram of values associated with them,
c) Inputs or measurements may be noisy

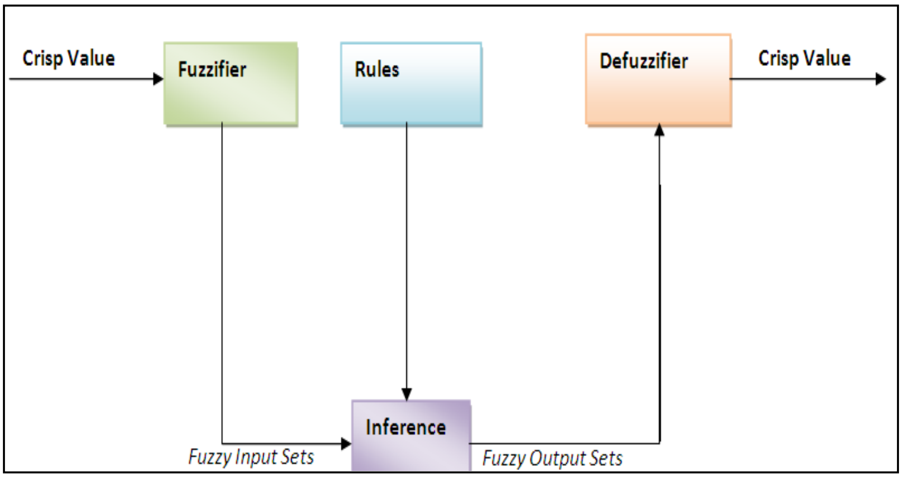

Figure 2: The Type-1 Fuzzy Logic System (FLS)

A type-1 fuzzy set, *A* for a single variable, $x \epsilon X$ is defined as $A = \{(x, \mu_A(x)) | x \epsilon X\}$. Type-1 membership function, $\mu_A(x)$ is constrained to be between 0 and 1 for all $x \epsilon X$, and is a two-dimensional function as summarized by Cox [19]. A fuzzy logic system (FLS) that is described completely in terms of type-1 fuzzy sets is called a type-1 FLS. The system contains four components which are the fuzzifier, rules, inference engine, and defuzzifier.

5.1.2 Type-2 Fuzzy Sets

Unlike type-1 membership functions which are two-dimensional, type-2 fuzzy member ship functions are three-dimensional. The additional degree of freedom offered by the new third dimension enables type-2 fuzzy sets to model the aforementioned uncertainties as illustrated on Figure 3.

Type-2 fuzzy set is formally denoted as Ã and is characterized by a type-2 membership function $x, \mu_{\tilde{A}}(x; u)$ where, $x \epsilon X$ *and* $u \in J_x \subseteq [0,1]$ i.e.

$$\tilde{A} = \{((x, u), u_{\tilde{A}}(x, u)) | \forall x \in X, \quad \forall u \in J_x \subseteq [0,1]\}$$

in which $0 \leq u_{\tilde{A}}(x, u) \leq 1$. The domain of a secondary membership function is called the primary membership of x which is J_x.

For interval type-2 fuzzy set, J_x ,the primary membership of x is reduced to an interval set which is defined above and the secondary grades of Ã are all equal.

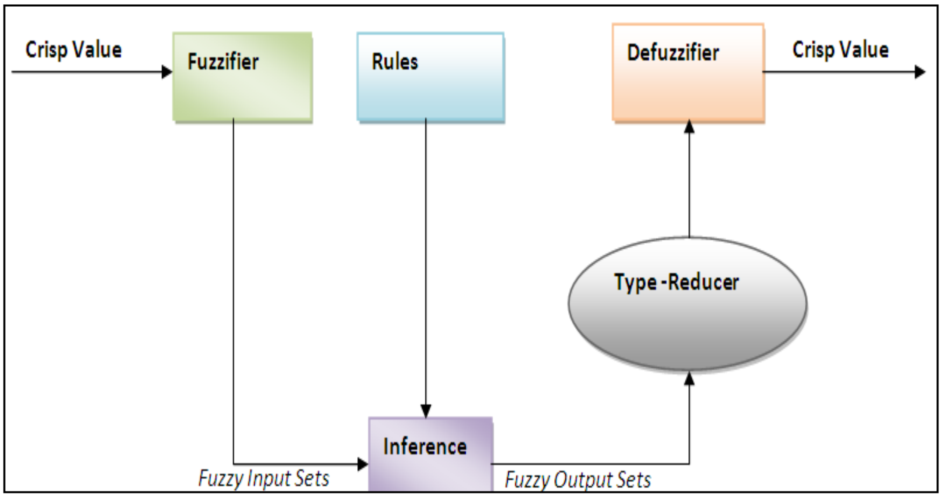

Figure 3: Type-2 fuzzy logic system (FLS)

A FLS that is described using at least one type-2 fuzzy set is called a type-2 FLS. A type-2 FLS is depicted in Figure 3. The first observation is that a type-2 FLS is very similar to a type-1 FLS. The major structural difference is that there exists a type-reducer block before the defuzzifier block. As the name suggests, type-reducer maps a type-2 set into a type-1 set before the defuzzifier performs defuzzification on the later set. Typical type-reduction methods are: centroid, center-of-sums, height, modified height, and center-of sets.

5.2 The fuzzy component design

The ability of Fuzzy Logic to deal with uncertainty and noise has led to its use in controls stated Self **Error! Reference source not found.**, hence sponge iron production is a very dynamic process with several intertwined control loops. Fuzzy logic is inherently robust since it does not require precise, noise-free inputs. It is not limited to a few feedback inputs and one or two control outputs. Fuzzy control is most reliable if the mathematical model of the system to be controlled is unavailable, and the system is known to be significantly nonlinear, time varying, or to have a time delay. Designing a fuzzy controller requires describing the operator's control knowledge/experience linguistically; process operators and control room operators played a major role in development of the control strategy. The controller captures these traits in the form of fuzzy sets, fuzzy logic operations, and fuzzy rules. Thus, Fuzzy logic control can be used to emulate human expert knowledge and experience illustrated Arsene **Error! Reference source not found.**.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.

5.2.1 Fuzzification of inputs

The power and flexibility of fuzzy logic rests on its subjectivity, in that control statements are written in terms of imprecise ideas of what constitutes states of the variable. The values of a fuzzified input execute all the rules in the knowledge repository that as part of their premise have the fuzzified input as proven by Arsene **Error! Reference source not found.**.The process inputs to the fuzzy controller will be the mA from the 4-20mA control signal which will have been converted and conditioned from mV temperature values of the K-Type thermocouples by the 2-wire transmitter. The transmitter is used because millivolts are lost with distance as voltage drops therefore the mA are more accurate to use so as to avoid compensation irregularities. The crisp values from the sensors will be fuzzified accordingly so as to achieve the desired output. Load cell values from weigh-feeders and damper positions from control valves are all the crisp input values which will be fuzzified.

5.2.2 Membership function

Membership Function is a formula used to determine the fuzzy set to which a value belongs and the degree of membership in that set. The uncertainties associated with the membership functions are encapsulated by the footprint of uncertainty (FOU) and it is totally characterized by the upper membership function (UMF) and lower membership function (LMF). To enable designed membership functions (MFs) reflect the data, the researcher analyzed one type of FOU design strategy according to the dispersion of the data. The design comprise of Gaussian MFs with uncertain standard deviations.

5.2.3 Knowledge Base

Knowledge Base consists of a database and a rule base as illustrated on Figure 4. The greater simplicity of implementing a control system with fuzzy logic can reduce design complexity to a point where previously insoluble problems can now be solved. Fuzzy systems typically result in a 10:1 rule reduction, requiring less software to implement the same decision-making capability.

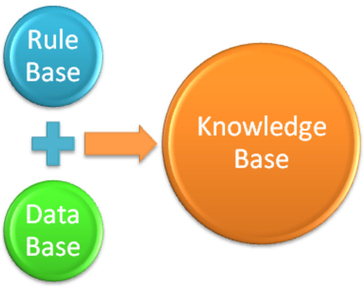

Figure 4: The knowledge base system

i. Data base

The basic function of a database is to provide necessary information for the proper functioning of the Fuzzy Membership (FM), the rule base and the defuzzification module. The basic information includes:

a) Fuzzy sets (membership functions) representing the meaning of the linguistic values of the process and the control output variable.

b) Physical domains and their normalised counter parts together with their normalisation and denormalisation (scaling) factors. For example the K-type thermocouples (temperature sensors) used for the process zone ranges between 0 to 1200 i.e. [0 1200] to be converted to [0 1] will use a scale factor of 0,0008

ii. Rule Base

The basic function of the rule base is to represent in a structured way the control policy of an experienced process operator and/or control engineer in the form of a set of production rules therefore it makes use of antecedent and the consequent.

IF <process state> THEN <Control Output>

E.g. IF <*The Temp is low*> THEN <*The accretion build up is High*>

The rule base is an important component of a fuzzy controller that captures the operator knowledge about the system in the form of fuzzy rules. Developing a rule base is one of the most time consuming part of designing a fuzzy logic controller. Usually it is very difficult to transform human knowledge and experience into a rule base of fuzzy logic controller. Moreover there is a need for developing efficient methods to tune membership functions i.e., to obtain optimal shapes, range and number of member functions.

A fuzzy control rule is a fuzzy conditional statement in which the antecedent is a condition in its application domain and the consequent is a control action for the system under control. The rule provides a convenient way for expressing control policy and domain knowledge.

The source and derivation of fuzzy control rules are:

- Expert experience and control engineering knowledge, achieved by means of heuristic approaches
- Control operator's control actions, as he employs consciously or subconsciously a set of rules to control the process.
- Fuzzy model of a process, used to generate fuzzy control rules.
- Based on learning, refers to self organizing controller (SOC) in which the FLC has the ability to create fuzzy control rules and to modify them based on experience.

Rules for regulating the accretion build up / ring formation:

```
IF (Temp is "zero") THEN (accretion is "average")
IF (Tempis "positive") THEN (accretion is "high")
IF (Pressureis "negative") THEN (accretion is "high")
IF (Pressureis "zero") THEN (accretion is "average")
IF (Pressure is "positive") THEN (accretion is "average")
IF (Temp is "negative") AND (Pressure is "negative" THEN (accretion is "high")
IF (Tempis "zero") AND (Pressure is "zero" THEN (accretion is "average")
IF (Temp is "positive") AND (Pressure is "positive" THEN (accretion is "high")
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IF (Tempis "negative") AND (Pressure is "zero" THEN (accretion is "high")

IF (Temp "negative") AND (Pressure_change is "positive" THEN (accretion is "high")

IF (Tempis "zero") AND (Pressure is "negative" THEN (accretion is "average")
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Figure 5 shows the rule viewer for the rules developed in Matlab. The developed fuzzy rules were largely based on the Operator's discretion however a few rules were also added after investigation and research on recommended practices. The whole set of rules is imprecise hence partial, however the system will be expected to perform well and produce the desired product output.

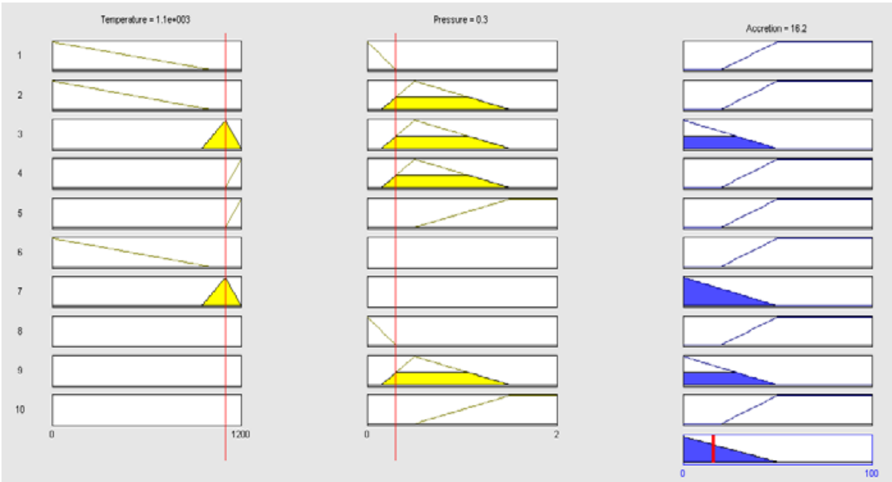

Figure 5: The Rule Viewer

6 MODEL RESULTS ANALYSIS

Accretion build up is an avoidable "evil" hence one cannot achieve total elimination but the rate of buildup can be regulated according to the process design parameters. The research revealed that the best possible rate of ring formation can only be 16.2% using the desired process parameters at the reduction zone of temperature 1100^0C and kiln outlet pressure of 0.3 Bars. Any value less than 16.2% would be achieved during *thermal shock* procedure which is the corrective measure and not a preventative measure hence it is beyond the scope of this research. From the surface view in Figure 6 we can deduce that as the temperatures increase from preheating values to the reduction values of 1100^0C the ring formation gradually decrease to a minimum value of 16.2%

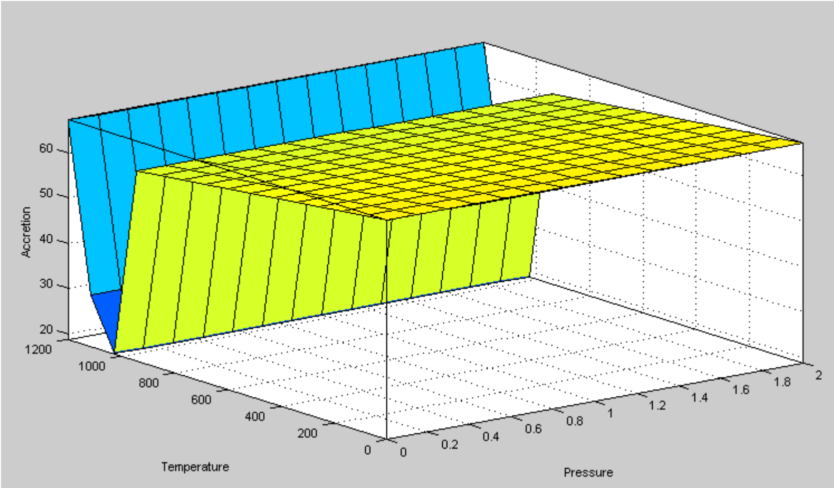

Figure 6: The Surface Model of the Reduction Zone

The results revealed that the most desired temperature of 1100^{0}C at the T7 thermocouple position or the reduction zone can result in high pressure build up. Therefore there is also ring formation, however the use of Induced Draft fan and the Stack Cap Opening and Closing system can be used to regulate the pressure build ups.

6.1 Process parameters

The proposed system was able to maintain the desired process parameters of T=1100 ^{0}C and P =0.3 Bars with a rate of 16.2% on ring formation as shown on Figure 7. Further decrease of the either temperatures or pressure set point was also performed.

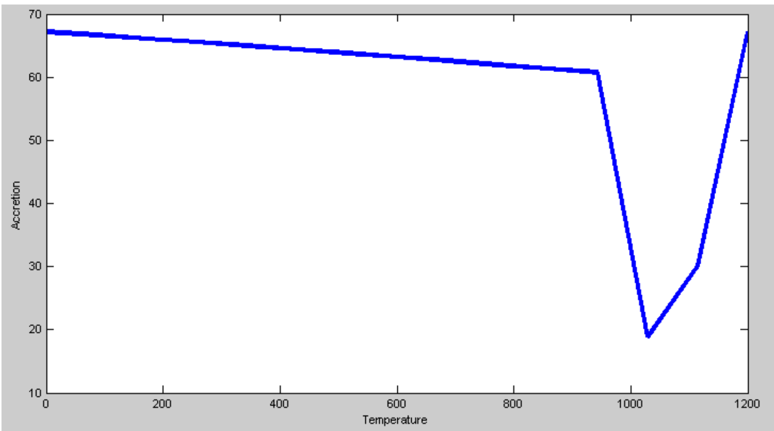

Figure 7 Effect of temperature on ring formation

6.2 The effect of temperature on ring formations

The research has revealed that the gradual change of temperatures from the preheating values to the reduction temperature values will certainly cause ring formation at an average of 63%, therefore there is need to facilitate rate of heat gain from the two zones so as to avoid ring formation. Also increase in temperatures above 1100 ^{0}C will result in sudden increase in accretion build up as sponge iron become steel and the coal fines and other minerals will be melt.

6.3 The effect of pressure on ring formations

The recommended pressure range was 0.3-0.5 mBars, while pressures above 1.5 mBars caused sudden increase in accretion build up as shown in Figure 8. Therefore there is need to have an efficient pressure regulating system such as automated stack cap movement and also variable speed induced draft fan. The central burning fans and the kiln shell air fans are also used to regulate the amount of pressure in the kiln.

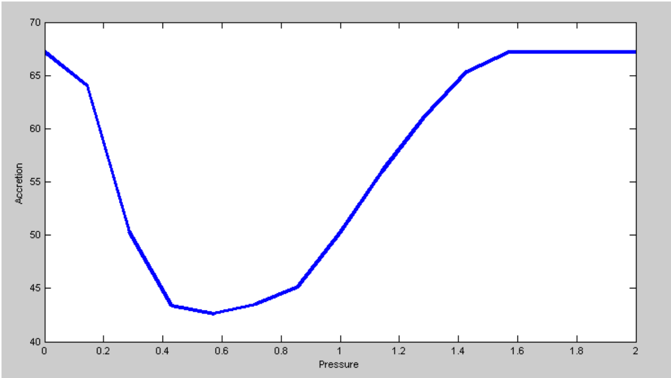

Figure 8:The relationship between pressure build up and accretion formation.

7 CONCLUSION

The fuzzy logic model for accretion build up was designed; however there is need to develop a cascade system of the predictive model and the regulating system. The research revealed that accretion build up was mainly due to pressure and temperature variations within the kiln. Although other factors such as raw material quality, kiln rotational speed and tilt angle had a contribution, it was of less significant. The proposed system managed to maintain the desired process parameters of T=1100 ^{0}C and P =0.3 Bars with a rate of 16.2% on ring formation with a recommended pressure range was 0.3-0.5 mBars. The current plant design consists of a lot of open loop control system with room for human intervention. The temperatures from the kiln zones are simply displayed and the control room operator will determine the best control action, however with the implemented fuzzy logic design, human intervention is minimized and complete automatic control is established.

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