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Valuation of % metallization and % accretion formation in a rotary kiln of sponge iron process based on Fuzzy Logic Inference System

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Abstract: Sponge iron making is a compound process, consisting of a sequence of activities necessitating extensive technological sustenance. An integrated fuzzy inference system model for control of sponge iron rotary kiln performance based on multi-criterion attributes is established in this study. Thus, this paper aims at improving the kiln performance by analyzing the effect of variation of input variables, such as kiln inclination, kiln rotation speed, feed flow rate of iron ore and coal on realizing product % metallization level and estimation of accretion formation inside the rotary kiln, thereby facilitates longevity of kiln life expectancy. Plant data from an operational industrial rotary kiln were used to confirm the functionality of the model. The results reflect that the best angle of inclination, kiln revolution and feed flow rate of iron ore and coal is 2.8^{o}, 4.8rpm, 6.4kg/s and 2.3kg/s, respectively. At these settings, the % metallization is projected as 94.8%, which is 2.93% higher as equated to the obtained industrial practice value. The reduction end temperatures obtained through industrial practice and simulation results were found to be comparable. It was also established that a % accretion value of less than 15% is possible for pressure and temperatures below 0.5mBars and 1060^{o}C, respectively.

Keywords: Accretion, Fuzzy Logic, Metallization, Rotary Kiln, Sponge iron.

1. Introduction

The decline in quantities of scrap for manufacturing of recycled steel has led to birth of other avenues involving carbo-thermal reduction of oxidic ore for production of steel. Through the application of a rotary kiln, a coal-based reduction of iron ore into sponge iron is one of the proficient commercially efficacious carbo-thermal beneficiation processes. Sponge iron has gained popularity in steel making as a substitute for scrap due to its low content of sulphur and also high metallic content of iron. The rotary kiln is the back-bone of sponge iron production. However, the operation of coal based rotary kilns have their difficulties, for instance, not limited to dust generation, reduced thermal efficacy and compromised yield quality, as some of the typical glitches that compromise rotary kiln operations. Although long retention time of the charge inside the kiln, assists in realizing a reasonably uniform product [1], there is still substantial possibilities for refining this aspect of kiln performance.

Different kiln control strategies have been established in diverse manuscripts centered on inferences of different researchers using data obtained from the variables closely related to the operation of the kiln with a mandate to improve kiln yield and product quality [1]-[7]. A model based on heat transfer within the rotary kiln-based process was developed by Boateng and Barr [1]. They based their model on the type of raw materials used, the influence of mixing rate of kiln charge. Results obtained shows that kiln-based process heat transfer is depended on kiln rotation speed, mixing profile of the charge, kiln pressure and temperatures. This has laid foundation for more strategies centered on CFD modelling to assess kiln performance [5], [6]. The attributes that affect the performance of rotary kiln include, but not limited to kiln internal bed and gas temperature profiles, raw material particle size, kiln rotation speed and incline angle, raw material characteristics and feed rate, internal kiln pressure, carbon to gas ratio, thermal combustion of fuel coal, heat transfer characteristics inside the kiln, etc. [4]-[8]. Nevertheless, rotary kiln dynamics and heat transfer is a complex phenomenon which makes sponge iron production analysis challenging. Consequently, variation of these attributes results in diverse kiln performance and yield. This makes it challenging to assess and accurately predict sponge iron rate of metallization and also the end of life of the rotary kiln. Owing to these difficulties, the sponge iron yield is of different percentage metallization and also kiln accretion results due to limiting control factors of the kiln. However, being able to establish a proper control strategy for kiln operation can aid in possibilities of attaining a high product metallization factor and minimum kiln accretion. Due to the dynamic nature of the kiln reduction process, it is of paramount importance to control and monitor the kiln working variables particularly kiln pressure and kiln temperatures as they can lead to drop in metallization, development of kiln hot spots and rings that can necessitate plant closure.

Different authors have highlighted some correlation between different variables that affect kiln performance. It is noted in [9-11] that kiln rotation speed, incline angle and raw material feed rate have an effect on the mixing proportion of charge and also the residence time. It has been observed that long residence of the charge within the kiln favours uniform reduction of iron ore, but at the expense of more materials and energy bills. The ratio of coal to iron ore and particle size of the feed are very important to control the increase of the reduction process in sponge iron making. This is because they affect the internal kiln gas and bed temperature profile which must be regulated to have effective reduction process. Gaurav, and Khanam developed a CDF model to analyse the behaviour of sponge iron kiln performance [6]. Additionally, variation of percentage metallization and temperature profile with different input variables for rotary sponge iron kiln was assessed through 2D CFD model in [7]. The results were closely corresponding well with the industrial data. Also, the effect of pneumatically driven coal injection of different particle size and combustion process for a direct reduction rotary kiln was articulated in [12]. Their results helped in recommending strategies on coal injection optimization techniques, thereby improving efficiency of reduction-based processes.

1.1. Automation in Kiln based processes

Most of the sponge iron rotary kiln plants are still utilizing human in loop control strategies in realising sponge iron output. As a result, it is challenging to retain consistent product quality. Additionally, due to an unstable environment within the kiln, speedy kiln liner wear and tear emanates resulting in lower sponge iron production. PID control has been the most implemented control methodology to improve kiln efficiency. However, the arbitrary variations of the process attributes have posed some limitations to this control strategy. Nevertheless, kiln performance improvement centred on soft-computing strategies have paved ways for better understanding of kiln-based control processes. Due to intricate operational conditions including heat transfer, fuel intake, material aggregation which makes a rotary kiln a nonlinear system, sizeable exploration has been done so as to determine the maximum yield of kiln process.

A fuzzy controlled kiln-based cement process was successfully implemented in [12]. Furthermore, in [13] and [14] a fuzzy logic methodology was applied in a bid to minimize accretion formation. Although, interesting results were attained in reducing accretion formation, some attributes such as kiln rotation speed, the feed rate, raw material particle size etc., that promotes accretion formation were not included in these studies. Additionally, neuro-fuzzy techniques [15], intelligent and predictive control [16], reinforcement learning based supervisory control [17], expert-based systems [18], have been assessed to realize their potential in improving kiln-based processes performance. Even though these soft-computing models detailed in diverse literature have their different opinions concerning the general kiln performance, several of them considered partial parameters for cases where boundary condition do not change often, which are influential in kiln performance, especially in coal-based sponge iron production. Accordingly, implementation of a probable process control strategy for sponge iron kiln-based production, calls for boundless attention in the selection of attributes that have substantial effect on kiln performance outcome such that a high-quality product is realised.

An integrated fuzzy inference system for control of sponge iron kiln performance based on multi-criterion attributes is proposed in this study. Different variables that have direct influence on kiln performance and the quality of output product has been carefully considered for the development of this control strategy. The paper aims at improving the kiln performance, product quality and minimization of accretion formation inside the rotary kiln, thereby facilitates longevity of kiln life expectancy.

2. Rotary kiln operation

The inclined rotary kiln acts as the back-bone of the sponge iron production process. Its efficiency has a paramount effect on the quality of the output product. Depending on capacity, the diameter and length of production sponge iron kiln ranges from 2 to 5m and 40 to 90m, respectively. To enable proper heat transfer and minimize material sticking, the kiln comprises of a cylinder-shaped shell with an internal reinforcement of a robust refractory material. In DRI (Direct Reduced Iron) process, iron ore, dolomite and coal entry to the kiln are from the feed end and gradually travels towards the discharge end where the output product exits the kiln due to gravity and rotation as highlighted in Fig. 1. The kiln generally consists of two operation zones i.e., pre-heating zone and reduction zone. Due to proper material mixture and appropriate heat transfer, the iron reduction materializes in the reduction zone. However, feed material devolatization happens in the pre-heating zone. To control the temperature profile in the kiln, controlled primary and secondary air is injected in the kiln, as per process necessity as shown in Fig. 1.

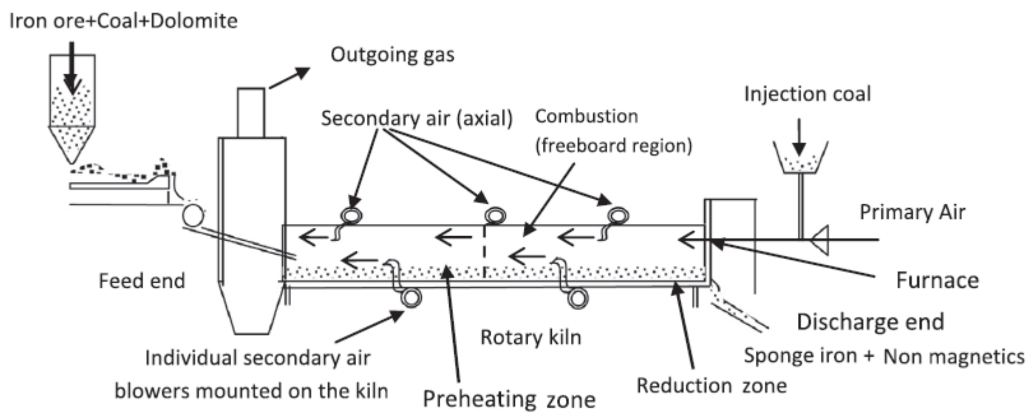

Fig. 1. Typical Rotary Kiln view

The secondary air, mainly for combustion is supplied in the kiln through uniformly mounted air blowers within the periphery of the kiln profile. The number of blowers depend on the kiln productivity range. To enable an effective reduction process, hot gases spread across the kiln in an opposite direction to the kiln charge. The combustion process is initiated through the use of a burner pipe where flame is directed in the kiln. As a result, the iron ore gets pre-heated (850-900°C) in the kiln preheating zone and gradually reduced by the time it reaches the discharged end. To enhance metallization level of iron in kiln, the preheating zone should be kept short. According to [1], the preheating zone should be typically about 40% of the entire kiln length. For continuous combustion of fuel, injection coal is also introduced in different particle sizes at the discharge end of the kiln.

In [4], it is highlighted that for significant pneumatic coal injection, blending of fine coal (< 0.5 mm) and coarse coal is desirable. This DRI 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 yield of the kiln exits it at a temperature range of 1020–1080°C where it is directed to the rotary cooler through a product chute for indirect cooling to a temperature of below 120°C in a non-oxidizing environment [4], [6], [8]. However, to reduce accretion formation, the optimal temperature inside the kiln must not be within the vicinity of 1100°C. Consequently, the discharge constituents from the cooler are transferred to the product section, were magnetic separators and collective systems of screens separate sponge iron from nonmagnetic impurities and contaminants. The hot gases exit the kiln and passes through a dust settling chamber located 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 electrostatic precipitator system or through waste gas heat recovery boiler.

2.1. Process Reaction mechanism

Rotary kiln heat transfer is an intricate phenomenon, with radiation, convection and conduction all contributing to energy transfer between the gas, the feed and the refractory material. Consequently, the reduction and combustion reactions mechanism occur in two sections such as bed and freeboard of the kiln. The chemical reactions, inclusive of temperature ranges and heat of reaction are conveyed in Table 1. The internal kiln operates as a reducing environment where carbon and carbon monoxide propel the reduction of iron oxide as illustrated by equations (1) and (2), Table 1. These reactions are exothermic and they occur in the bed within the reduction zone of the kiln. The combustion reactions, equations (3) to (7) in Table 1, transpire in the freeboard sector of the kiln where exothermic reactions dominate with exemption of equation (3). Reaction (3) is a high-end endothermic reaction mechanism as it also absorbs heat freed by other combustion reactions. Equations (3) and (5) represents bound ward reactions, which are reversible. However, the DRI process is exothermic in nature as portrayed by the reactions.

TABLE 1: Reaction Temperature and its heat of reaction [7], [19]

No	Reaction	Heat of formation ΔH_{298} (KCal/kg-mole)	Heat of reaction, GCal/kmol	Nature of reaction
1	$Fe_2O_3 + CO = 2FeO + CO_2$	−12636	-2.05656GJ/kmol	Exothermic
2	$FeO + CO = Fe + CO_2$	–4136	-0.25738GJ/kmol	Exothermic
3	$CO_2 + C \leftrightarrow 2CO$	+ 53256.4	+75.0GJ/kmol	Endothermic
4	$2CO + O_2 = 2CO_2$	–135262	-135.71417GJ/kmol	Exothermic
5	$C + O_2 \leftrightarrow CO_2$	–94050	-97.994248GJ/kmol	Exothermic
6	$2C + O_2 = 2CO$	–40884	-3.439722GJ/kmol	Exothermic
7	$2H_2 + O_2 = 2H_2O$	–109992.4	-29.8268GJ/kmol	Exothermic

3. Rotary Kiln Control Strategy

Estimation of kiln accretion and % metallization level of the product of kiln process relied on the fuzzy inference platform utilizing the influence of different collective aspects that indicate the rotary kiln operation efficiency is proposed in this paper. Different attributes which are vital in control of a kiln were considered in this study. As earlier stated, some attributes of the kiln such as charge residence time, ID fan speed, kiln pressure and temperature, all have significant effect on the sponge iron quality. These parameters along with feed rate of material mix, injection coal particle size, moisture content in coal, rotational kiln speed, angle of inclination sums the control variables. The controlled outputs of the kiln are reduction zone outlet charge temperature and kiln residence time, which are mapped to highlight the level of % metallization and % accretion.

In sponge iron production plants, the dependency degrees of control inputs to controlled outcome are not equally distributed for all variables. Hence, the control strategy was mapped into sub-model depending on the influence of controlled variables to the realized output. However, it is worth noting that due to different subjective and empirical seasoning in formulating fuzzy logic rules by different designers, it will be difficult to replicate the same results from same data of kiln operation.

3.1. Fuzzy Logic sub-models

Technical expertise, subjective reasoning of the plant operators and the physical orientation of the kiln was used in determining the classification of the designed fuzzy logic sub models.

3.1.1. Kiln Residence Time

The kiln residence time is centred on different attributes whereby, in this study a fuzzy logic inference-based system based on kiln rotational speed, angle of inclination, and the material feed rate are considered. The weigh feeder system was used to control the kiln feed (iron ore and feed coal) tonnage rate. However, a fuzzy logic sub-model for feed-rate was initially considered. In this initial model, the inputs; iron ore and feed coal universe of discourse were partitioned upon an array of 0–10kg/s and 0–5kg/s, respectively. The kiln feed-rate level is mapped on a scale of 0 to 1 and is ranked high within the vicinity of 1. The kiln feed-rate level for different range inputs can be inferred from the surface interpretation, Fig. 2.

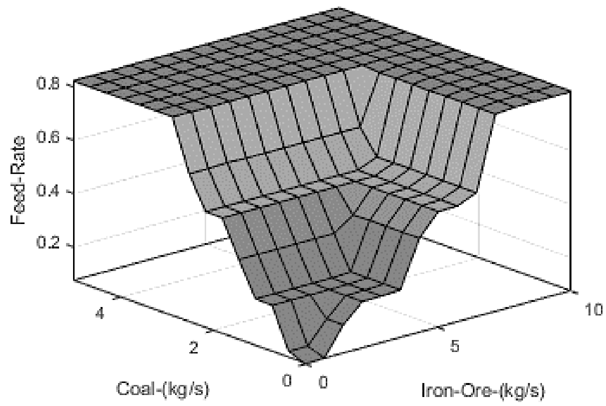

Fig. 2. Surface Graph-Kiln feed-rate.

The output of kiln feed-rate fuzzy logic kiln sub-model was merged with rotational speed and inclination angle as inputs to the kiln residence sub-model. The kiln angle and rotation input variables are within the constraints of 0-6^{o} and 0-5rpm, respectively. The fuzzy logic output, (kiln material residence) membership functions are mapped on a scale of 0 to 16 hours embraced by Fast, Moderate, Normal and Long linguistic labels. The MATLAB/Simulink kiln residence sub-model is highlighted in Fig. 3.

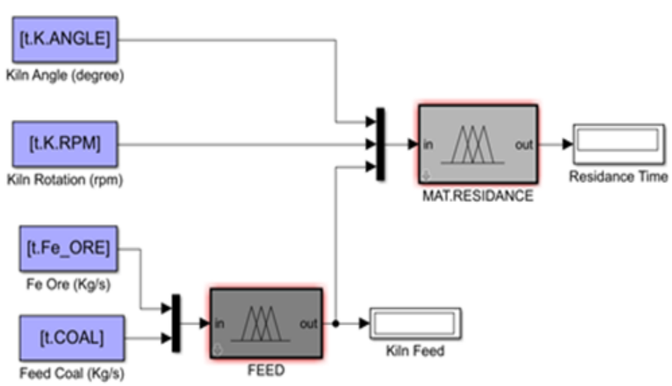

Fig. 3. Kiln Residence Fuzzy logic model

3.1.2. Combustion

One of the critical aspects that influence kiln performance for better sponge iron metallization grade is the combustion rate. A kiln combustion sub-model based on a fuzzy logic inference system was developed based on three attributes. The kiln injection coal, material moisture and secondary air dampers were considered as fuzzy logic inputs. The membership functions for these inputs were spread on a scale of 0-8mm, 0-10% and 0-90^{o}, respectively whilst for the output (kiln burning status) ranges from 0 to 1. The dampers are responsible for secondary kiln air which contributes in combustion of the fuel injection coal. However, the moisture content in the injection coal affects the coal burning state to a greater extend also depending on the injection coal particle size.

3.1.3. Kiln Secondary pressure

Due to entry of primary and secondary air through different entry points, the kiln pressure profile is also affected and this has an effect on the product metallization rate and accretion formation. The magnitude of the kiln pressure is depended on the controllability of ID fan speed, air dampers and kiln stake cape. However, ID fan speed and air damper are considered as the input variables drawn on a scale of 0-1800rpm and 0-90^{o}, respectively. The kiln pressure was drawn on a range of 0 to 1. Pressure level is considered critical as it approaches 1.

3.1.4. Reduction temperature model

Kiln reduction temperature is the main ingredient that influence the perfection of sponge iron metallization rate, and at the same time worsen the kiln accretion. Therefore, this variable needs perfect monitoring and controlling. For the operator to carefully manage the kiln profile temperatures, the inlet temperatures (pre-heating zone) are supposed to be regulated properly. Consequently, in this study, it is assumed that the preheating temperatures are maintained within the acceptable operation range. However, the reduction temperatures influence the reduction process of the iron ore. Henceforth, this study focused mainly on the reduction outlet temperatures to assess % metallization. The establishment of a fuzzy logic inference system for kiln reduction temperature was centered on kiln burning status and kiln pressure as inputs. The subsequent kiln reduction temperature magnitude was achieved by merging the kiln combustion and kiln pressure fuzzy inference sub-systems. Inputs to the kiln temperature model encompass kiln combustion and pressure level, where both input membership functions span between 0 and 1. The kiln reduction temperature membership functions were portioned on a universe of discourse ranging from 900-1150^{o}C. The Fuzzy logic Simulink model and surface interpretation of the kiln reduction temperature are depicted in Fig. 4 and 5, respectively.

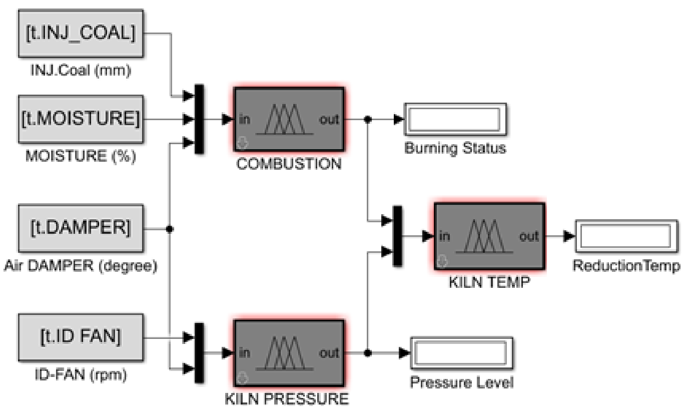

Fig. 4. Kiln Reduction Temperature Fuzzy logic model

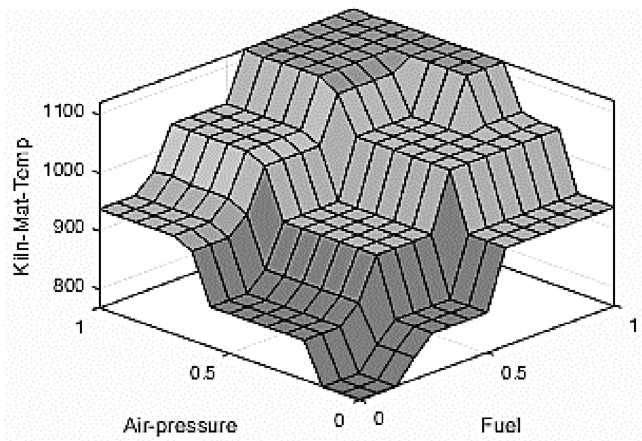

Fig. 5. Surface view graph-Kiln Temperature

3.1.5. Overall Kiln Performance.

In-service industrial rotary sponge iron kiln efficiency is depended on many attributes leading to desired or unwelcoming product yield. The overall sponge iron % metallization and magnitude of accretion build up were obtained after cascading the material residence, reduction temperature and pressure fuzzy inference models. Because of its simplicity and computational efficacy, trapezoidal membership functions were implemented in the model development. However, different linguistic labels were assigned to different variables considered. The overall fuzzy logic model inputs of kiln temperature, pressure and material residence membership functions were mapped across a range of 900^{o}C to 1150^{o}C, 0-1 and 0 to 16 hours, respectively as articulated in Fig. 6, 7 and 8. However, the material residence time depends on the capacity and kiln dimensions, in our case an 80m length and 5 m diameter kiln is considered. Since all the inputs have great influence on the sponge iron % metallization rate and accretion formation, the subjective fuzzy rule formulation weighting criterion was assumed to be comparable. The output % metallization membership functions were mapped across a scale of 60-100% (Ungraded, Grade C to Grade A), whilst the magnitude of accretion formation output membership functions, span from 0–40% (Low, Moderate, High and Critical) as shown in Fig. 9 and 10.

To map the outputs from the inputs through inference system, some linguistic “IF-THEN” rules were established. Samples of the formulated rules for the kiln performance are highlighted as:

IF (MAT.RESIDANCE is Fast) and (KIlN.TEMP is Low) and (Pressure is low) THEN (% METALLIZATION is Ungraded) (% ACCRETION is Low)

IF (MAT.RESIDANCE is Moderate) and (KIlN.TEMP is High) and (Pressure is Moderate) THEN (% METALLIZATION is Grade A) (% ACCRETION is Moderate)

IF (MAT.RESIDANCE is Normal) and (KIlN.TEMP is critical) and (Pressure is High) THEN (% METALLIZATION is Grade A) (% ACCRETION is High)

The crisp values for % metallization and accretion level were attained by centre of gravity defuzzification approach. Though this methodology involves rigorous computational input, it was chosen due to its instinctual acceptability [20], [21]. The developed fuzzy logic model for estimating of % metallization and accretion build up is depicted in Fig. 11, whereas Fig. 12 portrays the rule viewer for the fuzzy logic model.

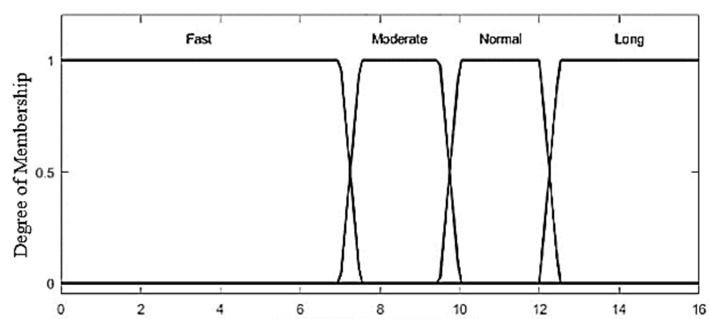

Fig. 6. MF-Material Residence

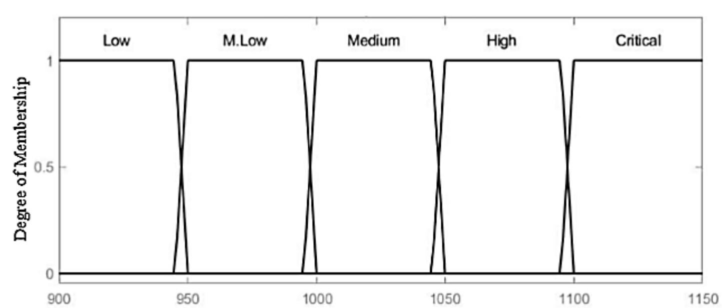

Fig. 7. MF-Kiln Temperature

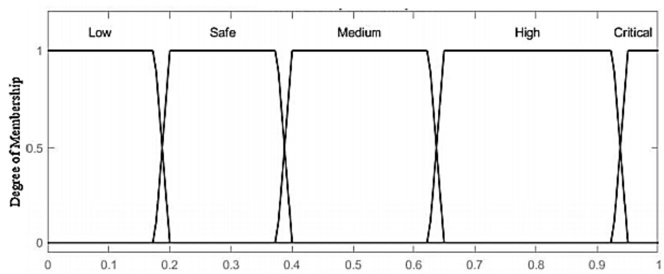

Fig. 8. MF-Kiln Pressure

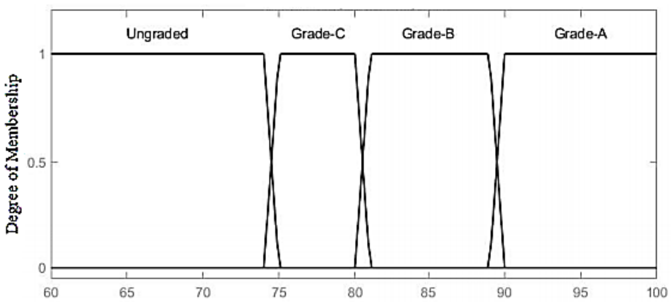

Fig. 9. MF-%Metallization

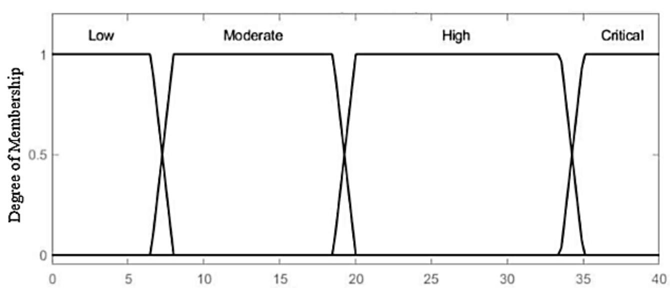

Fig. 10: MF-% Accretion

4. Results and Discussion

In the current study, a fuzzy logic based rotary kiln performance model for sponge iron process is developed. The measured data set for various input parameters from different campaign days of operation of a sponge iron production plant was used for validation of the proposed fuzzy inference system model for estimation of reduction temperature, % metallization and % accretion. Henceforth, the critical input attributes based on industrial practice (80 m kiln length) are varied in the ranges depicted in Table 2, whilst Table 3 outline the vital properties of the materials. However, due to different source of origin, the properties of these materials may vary. In this study data for other raw material properties like Silica-%, Sulphur-%, Phosphorus-%, Lacterite-% in the iron ore was not available. Therefore, an assumption was made that the sponge iron processing plant was utilizing the raw material that possesses the qualities that lie within the recommended values. Currently at the sponge iron plant, Programmable Logic Controllers (PLC) and some stand-alone controllers are used to maintain desired pressure difference between inlet and out let pressure inside the kiln through measurements from Honeywell ST 3000 pressure transmitters and temperature profile measured by K-type thermocouple.

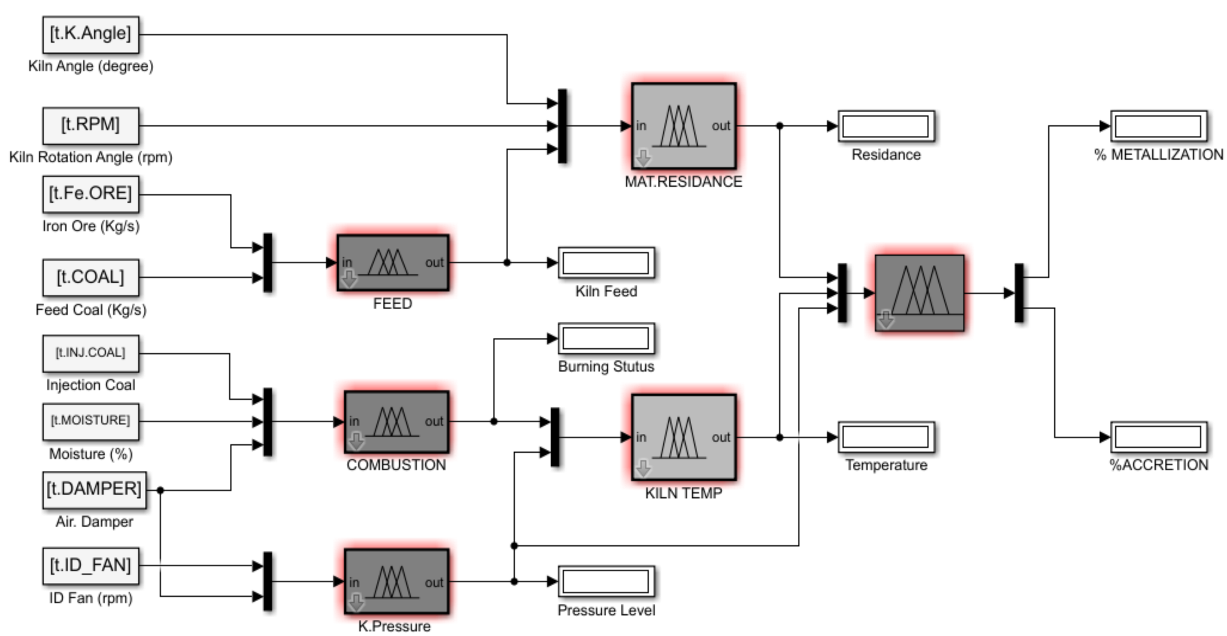

Fig. 11. Fuzzy logic-based Kiln performance model

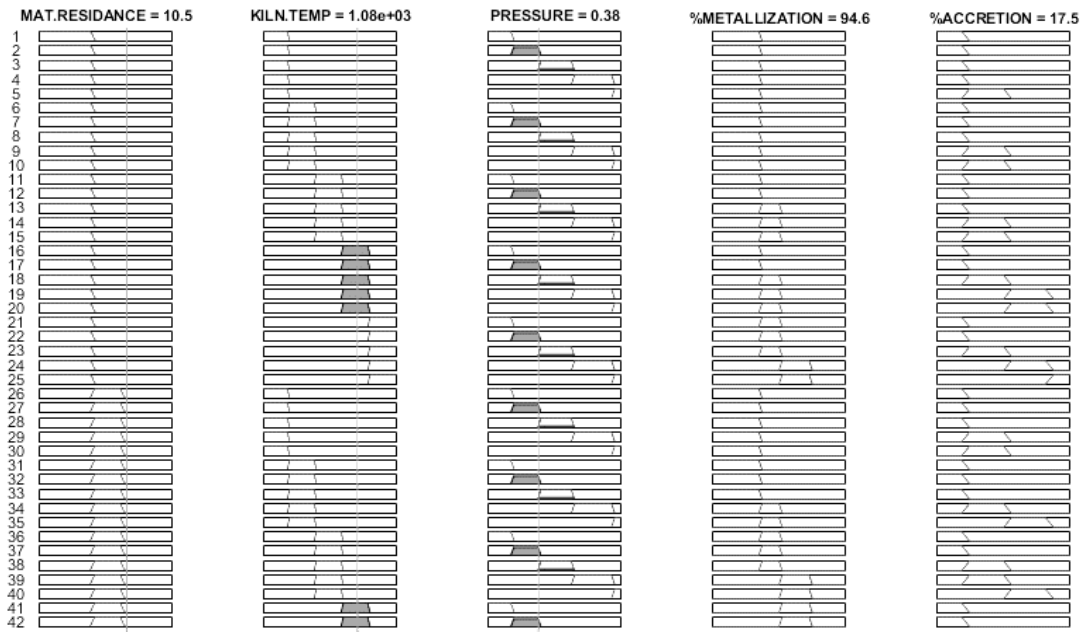

Fig. 12: Rule viewer

For illustration, in Table 4, a 12-hour kiln temperature profile from the sponge iron plant is recorded.

TABLE 2: Variation in control attributes

Attribute	Range	Unit
No. of kiln rotation	4.2-5.8	rpm
Angle of inclination	2.5-3.5	degree
Flow rate of iron ore	1-8	Kg/s
Flow rate of coal	1-2.5	Kg/s
Injection coal	0.5-6	mm
Moisture in injection coal	0-8	%

The designed fuzzy inference system is based on the reduction kiln outlet temperatures of the reduction zone. A sample of the obtained results from the industrial practice and those ones of the model for an 80m long kiln are outlined in Table 5. Changing parameters like kiln angle and speed during kiln operation within the same campaign life results in imbalance of reduction process thus, serial number 1 to 10 results depicted in Table 5 were obtained at a constant kiln angle and rotation of 2.6^o and 4.5 rpm, respectively at a residence time of 10.5 hours from the same campaign life. Additionally, serial number 11 to 20 in Table 5 represents a sample of results obtained during different campaign life whilst utilizing different kiln parameters. It was observed from industrial practice that the optimal residence time of charge inside the kiln for proper metallization is approximately 10.5 hours for raw material of required standard quality. Henceforth, it is articulated in the obtained results for both industrial practice and model simulation results that residence time of above 10 hours and outlet reduction temperatures of above 1050 ^oC and pressure ranging from 0.3 - 0.52 mBar led to % metallization of beyond 90% and also possibilities of accretion less than 15%.

TABLE 3: Materials properties [4], [7], [19]

Properties	Iron Ore	Iron oxide	Iron	Carbon	Dolomite	Air
Density (kg/m^3)	5242	5745	7874	2250	2840	1.292
Molecular weight	159.7	71.84	55.85	12.011	94.7	28.966
Thermal conductivity (W/m-K)	1.3	3.3	80.4	0.33	94.7	0.0242
Enthalpy (J/Kg mol)	-826	-272	13.1	-101.27	92.5	0
Entropy (J/kg mol-K)	87400	60750	34.28	5731.75	92	194336
Specific heat (J/Kg ^{o}C)	960	-	-	890	85	1032.6

TABLE 4: Thermocouple Temperature data along Kiln Profile

No	Thermocouple Kiln Bed Temperatures											
	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8	T_9	T_{10}	T_{11}	T_{12}
1	773	854	902	954	1007	1048	1057	1063	1070	1073	1079	1081
2	770	849	901	951	1004	1051	1048	1060	1065	1064	1068	1076
3	766	851	889	951	1029	1062	1061	1073	1071	1062	1063	1059
4	775	854	906	954	1034	1061	1066	1075	1074	1065	1069	1063
5	784	868	911	958	1028	1063	1070	1070	1072	1069	1073	1078
6	793	874	922	974	1039	1065	1066	1085	1083	1088	1085	1087
7	788	870	922	978	1043	1050	1058	1061	1054	1062	1067	1075
8	786	868	905	953	1037	1058	1056	1062	1052	1066	1054	1059
9	780	856	898	959	1044	1066	1072	1083	1082	1077	1075	1077
10	775	848	899	952	1061	1065	1073	1076	1080	1083	1076	1080
11	772	848	900	956	1055	1062	1066	1069	1070	1072	1071	1074
12	768	846	892	949	1046	1055	1064	1073	1073	1070	1072	1078

Results in [14] also confirmed that accretion of less than 15% can be attained with temperatures in the range of 1050^{o}C and pressure less than 0.5mBar, however, the factor of % metallization was not recorded. Additionally, the kiln characteristics are different from the current work. It can also be noted from Table 5 that the % error for metallization for the industrial practice and the simulated model results are in acceptable range. This confirms, the efficacy of the developed fuzzy inference model for kiln performance improvement.

From industrial operation, kiln % accretion can only be actualized at the end of campaign life; thus, the simulation results are only a projection to highlight the possibilities of accretions build up when the kiln is operated in those working variables. However, it is worth noting that the simulated results from the model may change when the actual implementation of the design is actualized on a real working kiln operation plant. Since rotary kiln is a chaotic dynamical system and also, depending on the experience of the operator, the fuzzy rules may change from time to time resulting in variation of results. Fuzzy rules actually create an expert system and the parameters of one expert system cannot be transported to another system. Henceforth, the limitations of applicability of this system to different sponge iron plants without proper amendments. Nevertheless, the obtained results from the proposed fuzzy inference model outline the feasibility of utilizing soft computing inference in improving sponge iron rotary kiln operation processes.

4.1. Simulated Results on parameter variation

Parameter variation was considered in assessing its effect on product % metallization and accumulative kiln % accretion build up. In Fig. 13, the effect of varying angle of inclination upon ranges noted in Table 2 is highlighted. Consequently, the kiln rotation, iron ore flow rate, feed coal flow rate and injection coal size were maintained fixed at 4.5rpm, 6.8kg/s, 2.4kg/s and 2.5mm, respectively. A maximum % metallization rate of 94.7 % was obtained at an inclination angle of 2.8^{o} as highlighted in Fig. 13. The industrial practice gave an output of 92.1 % for the same parameters. Thus, in both cases, Grade A metallization rate was obtained. It can be observed from the results that as the angle increases from 2.5^{o} to 2.8^{o}, so does the % metallization rate. However, it starts decreasing as the angle continues to rise. It can be argued that, lower kiln inclination improves residence time of charge material in the kiln, but at the expense of appropriate mixing rate, thus low metallization of iron. Henceforth, increase in angle up to an optimal value leads to better mixing of charge material within the kiln, but at the expense of residence time. Thus, % metallization of iron increases up to an optimum inclination angle, then decrease comes into effect as residence time is shortened. These observations are also supported by results obtained in [4], [7], [8]. In this study an inclination angle of 2.8^{o} is considered the optimum angle as it gives the highest % metallization.

In addition, at the best inclination angle and mass flow rate of bed, the kiln rotational speed is varied from 4.2 to

5.8 rpm. Subsequently, for this rotational speed variation, % metallization is projected and depicted in Fig. 14. It signifies that kiln revolution is considered optimal at 4.8 rpm for a % metallization value of 94.8%. This high metallization rate could have been caused by slightly higher rotations leading to proper charge mixture in the rotary kiln. However, higher rotation is not advisable since no effective mixing will materialize in the kiln, thus consequently reduced residence time for reduction leading to low metallization rate.

TABLE 5: Industrial Practice and Proposed Model Simulation Results

No	Material Residence Hrs	Out-let pressure mBar	Plant-Out Let Temperature °C	Model-Out-Let Temperature °C	Plant %Metallization	Model % Metallization	Model % Accretion	% Error Metallization
1	10.5	0.4	1081	1084	92	94.6	24.3	2.83
2	10.5	0.36	1073	1070	90.2	94.6	17.5	4.87
3	10.5	0.34	1052	1048	88.4	91.3	11.8	3.28
4	10.5	0.38	1070	1075	92.2	94.6	14.9	2.6
5	10.5	0.33	1056	1050	88.5	90.2	13.2	1.92
6	10.5	0.52	1083	1088	90.1	94.7	27.2	5.1
7	10.5	0.5	1074	1080	89.6	94.6	27.2	5.58
8	10.5	0.39	1065	1065	90.1	94.5	22.2	4.88
9	10.5	0.44	1058	1055	88.9	92.8	24.9	4.39
10	10.5	0.32	1048	1046	85	87.2	7.5	2.59
11	10.2	0.28	1055	1052	91.6	93.5	13.9	2.07
12	10.8	0.3	1033	1038	85	85	4.3	0
13	10.8	0.35	1050	1053	92.5	94.8	15	2.49
14	10.2	0.32	1051	1053	90.1	93.5	13.9	3.77
15	11	0.34	1032	1030	85	85	4.2	0
16	11	0.31	1025	1026	80.2	83.4	3.88	3.99
17	10.8	0.38	1063	1068	92	94.8	17.8	3.04
18	10	0.42	1076	1074	85.3	87.9	20.6	3.05
19	10	0.51	1045	1040	85.2	81.6	15	-4.23
20	10.8	0.48	1092	1087	87.8	93.2	28.6	6.15

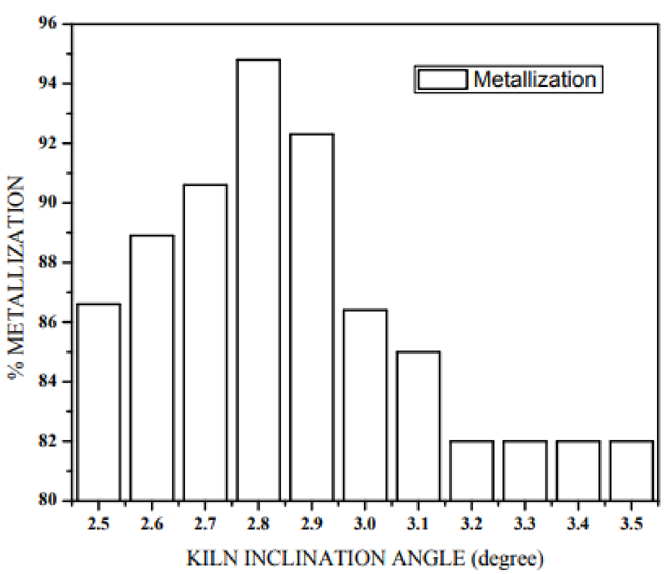

Fig. 13. % Metallization vs Angle of inclination

The critical parameters that influence both % metallization and % accretion are reduction temperature profile and kiln pressure. Fig. 15, illustrates the metallization and accretion profile against the obtained outlet bed reduction temperatures when the residence time is fixed at 10.5 hours. The temperatures used in the graph plotting were as of simulation results from the model. It can be observed that both % accretion and % metallization increases as the temperature increases. However, % metallization remains constant (94.8%) for temperatures beyond 1070°C. Accretion formation is boosted by temperatures beyond 1080°C, thus temperatures around 1100°C and pressure beyond 0.6mBars are not encouraged as they facilitate material melting that can speed up accretion formation inside the rotary kiln.

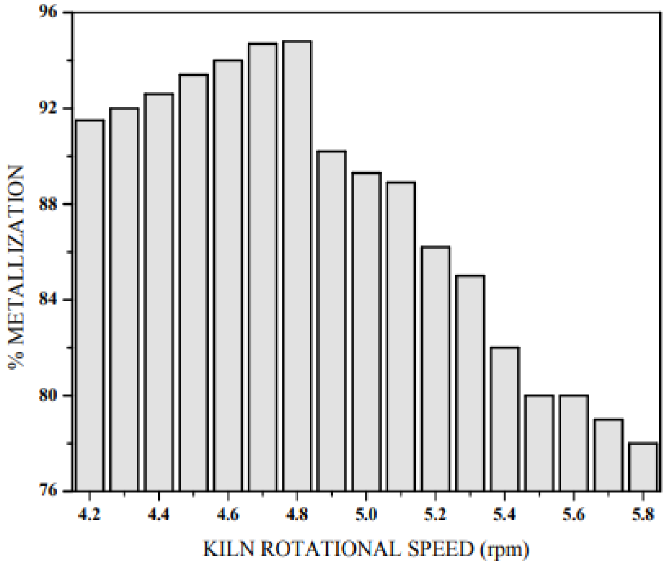

Fig. 14. % Metallization vs Speed of rotation

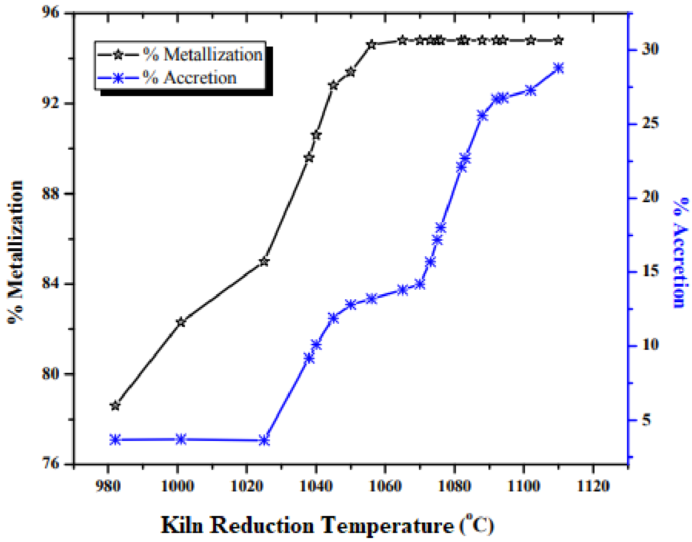

Fig. 15. Temperature vs % Metallization and % Accretion

5. Conclusion

In a sponge iron processing plant, numerous variables need to be manipulated, monitored and controlled. To improve the rotary kiln performance, a soft-computing control system model was established based on process multi-attributes integrated with an inference system which depends on the valuation of a knowledgeable sponge iron expert. In this study, a fuzzy inference system model has been simulated on a kiln process so as to establish the behaviour of % metallization and accretion development as the process parameters were varied. The varied parameters were not limited to kiln rotation speed, kiln inclination angle, material feed flow rate, kiln temperatures and kiln pressure. The results reflect that the best angle of inclination, kiln revolution and feed flow rate of iron ore and coal is 2.8°, 4.8rpm, 6.4kg/s and 2.3kg/s, respectively. Additionally, simulation results indicate that varying the input parameters influence the model output, thus a 94.8% maximum % metallization was realized when inputting optimum values. The simulation results of the design were compared to the experimental results done on an industrial PLC controlled sponge iron plant. The reduction end temperature profiles obtained through industrial practice and simulation results were also found to be comparable. It was also observed that a % accretion value of less than 15% is possible for pressure and temperatures below 0.5mBars and 1060°C, respectively with material residence of 10.5 hours. Henceforth, values beyond these ranges will accelerate accretion formation at the expense of product metallization. However, it can be concluded that the functionality of the established model is acceptable in sponge iron production. Nevertheless, to confirm these simulation results, there is need to pilot experimentation for the proposed fuzzy logic control in the actual kiln-based operation. The reducing gases produced inside the kiln need to be maintained within a desired temperature and pressure composition range to carry out the proper reduction process at minimal accretion formation.

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