2 D Model of Sponge Iron Rotary Kiln Developed Using CFD

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Abstract: The present paper deals with 2D CFD model of rotary kilns employed in sponge iron process. Using this model the effects of variations of input parameters, such as angle of inclination, number of rotation and mass flow rate of iron ore are studied on output parameters like Fe content, and temperature profile. These ranges of input parameters are found from industrial practice. For this purpose different models of CFD such as Species transport model , k-epsilon viscous model , Discrete Ordinates (DO) model, and Finite rate/Eddy dissipation model are used to find Fe content, temperature profiles and velocity. The results of the 2D CFD model show that optimum angle is found as 2.8 degree. The optimum number of rotation and flow rate of iron ore is found as 4.7 and 5.83 kg/s, respectively. At these optimum conditions the Fe content is predicted as 92 %, which is 5 % more in comparison to existing system that is being operated at angle of inclination, number of rotation and mass flow rate of iron ore as 2.5 degree, 4.3 rpm and 5.83 kg/s, respectively. The temperature profiles of gas and bed are also found within acceptable temperature limits. The results are compared well with the published work.

Keywords: CFD, Parameters variation, Rotary kiln, Temperature profile, Fe content.

I. INTRODUCTION

In sponge iron industry rotary kiln is the primary equipment, which is used to reduce iron ore to metallic iron i.e. Fe which is called sponge iron. The performance of rotary kiln significantly affects the production capacities of these industries. The performance of rotary kiln is affected by temperature profile inside the kiln, distributions of gas (air)-solid flow, particle size of raw material, ratio of air to coal, combustion of coal, heat transfer characteristics inside the kiln, etc. Due to complex nature of heat transfer along with chemical reactions, which take place inside the kiln, it is difficult to understand all these parameters individually. Moreover, it is very much difficult to have onsite measurements of parameters such as fluid flow, temperature, pressure, etc. of the process and to know the physical parameters which influence the performance of the process. Kiln inclination and speed, raw material characteristics, etc. are some physical parameters affecting performance of the process.

A few researchers have suggested mathematical expressions to model the temperature profile inside the rotary kiln, heat transfer, fuel combustion and reduction chemistry, etc. Partial differential equations were used by them for solving the energy equation, radiative model equation, viscous model equation etc. of the process [1]. A simplified model was developed by A. Sass for heat transfer occurring inside the kiln, which consists of differential equations. Simultaneous chemical reactions have not been considered in this model. They developed the correlation for predictions of kiln length. Runge - Kutta method was used for solving the model. The data collected from cement kiln and ore heating kiln for U.S steel were verified with this model. The author found that predicted kiln length by simulation close to the actual kiln length [1]. A heat transfer steady-state model was developed by Ghosdastidar and Unni for non-reacting zone of the rotary kiln, which was used for drying and preheating of wet solids. By this model, they simulated the rotary kiln of cement industry. Computer program using finite difference techniques were used to simulate the developed model. They studied the parameters related to better design of rotary kiln such as smaller inclination angle, medium gas flow rate and low rotational speed in the range of 3-5^0, 3-7 kg/s and 1-10 rpm respectively [2]. Present work is to analyze the performance of rotary kiln through CFD, so a few studies related to it are discussed hereunder:

Mujumdar, Arora, and Ranade discussed complexity of rotary kiln which involves the existence of the several processes such as reactions and coal combustion. These processes occur simultaneously in bed as well as freeboard regions. They identified various key issues related to performance of rotary kilns and were simulated based on CFD models. The authors suggested that these key issues are required to be examined whenever a comprehensive model is developed for rotary kilns in cement industry [3]. Furthermore, Mujumdar and Ranade considered bed as well as freeboard regions as separate sections so as to simulate these regions at similar time scales. Through common interface by heat and mass transfer, the developed CFD models were coupled and the transport processes in rotary kiln were captured. The developed approach provided significant information about the burner design along with flame characteristics for improving the kiln performance. They considered that combustion of coal to take place in the freeboard region of the kiln and the clinkerization reactions occur in the bed of the kiln. They found that the computational time for 1D coupling was less as compared to 2D coupling without affecting the accuracy of predicted results [4]. Further, Mastorakos, Massias, and Tsakiroglou considered heat transfer, clinker reactions and flame modeling inside the rotary kiln through CFD. Bed and freeboard models were treated as separate domains and coupled explicitly. Throughout the length of the kiln they assumed axis-symmetric geometry of kiln and coating formation [5]. Wang, Lu, Li, and Hu studied the heat flux for understanding the combustion behavior and thermal effect of the clinker formation based on chemical and physical analyses of the process. They used CFD code to obtain gas temperature, velocity and its components in rotary kiln of cement industry [6]. Kolyfetis and Markatos developed a CFD model for coal combustion in the freeboard region with heat transfer. However, clinker reactions as well as coating inside the kiln were not considered [7]. A CFD based 3D model was developed by Karki, Patankar, and Grant for simulation of combustion and heat transfer simultaneously in the kilns. An effective thermal conductivity was used for defining the degree of mixing in the bed region, which helped in visualizing the process effectively. Their results provided only the qualitative information of the process [8]. Prasad and Ray simulated flow pattern of air using FLUENT software in rotary kiln of a typical 100 tpd sponge iron. For identifying optimum location, CFD analyses were carried out by placing air pipe at different position such as 50 mm, 100 mm, 150 mm, 320 mm above the axis. It disturbed the reducing atmosphere in the solid bed region strongly and obtained a well metalized product for which lowest velocity was required to strike the solid bed. The optimum location of air pipe was found to be at 320 mm above the axis [9]. Majhi modeled the kiln of a typical sponge iron plant having capacity of 500 tpd and carried out the simulation through *ANSYS 13*. He observed that due to the movement of granules these were exposed to freeboard for direct reduction reaction [10].

Above discussion shows that many researchers used CFD to analyze performance of rotary kiln for sponge iron and cement industries. They mainly considered flow pattern of air and bed temperature profile and heat transfer characteristics inside the kiln. However, they did not consider the variation in operating parameters. The present work focuses on optimization of performance of rotary kiln employed in sponge iron process where variation in operating parameters and its effect on temperature profile is studied using CFD analysis. Also, variation in mass fraction of Fe content in kiln outlet stream is observed based on operating parameters.

II. Rotary kiln: Operation and construction details

A schematic diagram of the rotary kiln of sponge iron process considered for the present work is shown in **Fig. 1**. The rotary kiln consists of a rotating cylindrical shell lined inside with refractory material. The kiln is around 80 m long with 4 m internal diameter with nine different ports of secondary air. In general, the variation in length and diameter of the kiln is from 40 to 100 m and 2 to 5 m for different production capacities of the plant respectively. The kiln is inclined with horizontal at 2.5 degree and it rotates with 4.3 rpm. The feed is injected from the feed end of the kiln which consists of iron ore, coal and dolomite. Feed material moves gradually towards the discharge end as kiln rotates, from where sponge iron collects. The reactions involved in two zones are shown in **Table 1**. The reactions such as reduction and combustion occur in bed and freeboard of the kiln, respectively. The temperature range and heat of reaction of these reactions are also maintained in **Table 1**.

For the reduction of iron oxide, the reducing agents are carbon monoxide, carbon and hydrogen which are used. Reactions (1) & (2) take place in the bed region of the kiln towards the discharge end which are exothermic in nature and released heat, as heat of reactions for reaction (1) & (2) are negative. The combustion reaction takes place in the freeboard region of the kiln is considered by reactions (3) - (7), which is exothermic in nature except reaction (3), which is endothermic. The heat released by the combustion reactions is absorbed by Reaction (3) which occurs at high temperature The whole reaction of the process is exothermic in nature.

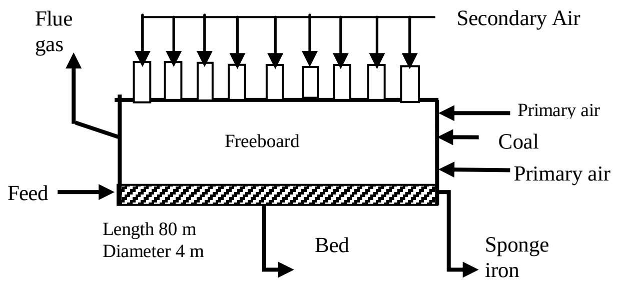

Fig. 1 Schematic of the rotary kiln of sponge iron process

Table 1. Reaction Temperature and its heat of reaction [11]

Rxn No.	Reaction	Heat of formation ΔH_{298} (kCal/kg-mole)	Temperature range (°C)	Heat of Reaction, GCal/kmol	Nature of reaction
1.	$Fe_2O_3 + CO = 2FeO + CO_2$	- 12636	25-1369	-0.003067	Exothermic
2.	$FeO + CO = Fe + CO_2$	-4136	25-1101	-0.002123	Exothermic
3.	$CO_2 + C = 2CO$	+53256.4	25-2227	0.0398375	Endothermic
4.	$2CO + O_2 = 2CO_2$	-135262	25-2227	-0.134017	Exothermic
5.	$C + O_2 = CO_2$	-94050	25-2227	-0.094474	Exothermic
6.	$2C + O_2 = 2CO$	-40884	25-2227	-0.054708	Exothermic
7.	$2H_2 + O_2 = 2H_2O$	-109992.4	25-2227	-0.142466	Exothermic

III. CFD Model: Boundary & Operating conditions

The 2 D geometry of rotary kiln is developed using GAMBIT 2.4.6. The assumptions for the present work are: (1) 2D geometry of the kiln is considered, (2) Feed Consists mixture of iron ore, coal & dolomite which is supplied at inlet stream at 300 K, (3) Sponge iron is considered as outlet stream, (4) Primary air injected from discharge end as shown in **Fig. 1**, (5) Heat transfer through radiation consider in the kiln, (6) No changes in bed height throughout the kiln, (7) Coating and melting are not considered in the freeboard and bed region and (8) combustion and reduction reactions take place in the bed and freeboard regions, respectively. The grid independence test is performed using mesh density for determining the accuracy of the geometry. The different meshes are chosen the present analysis: mesh A is the coarser mesh with 245768 elements whereas mesh B is the finer with 273451 elements and mesh C, the finest mesh with 334578 elements. The variation of temperature along the length of the kiln is shown in **Fig. 2.**

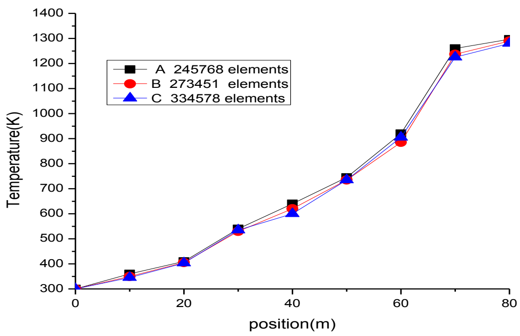

Fig. 2 Effect of mesh size on temperature

The governing equations are solved using CFD software ANSYS CFD-14.5 [12]. The finite volume method is used to solve the governing equations. For observing the temperature flow behavior energy equation is considered. The viscous model k-epsilon with standard k-ε and standard wall function are used in the present model. Discrete Ordinates (DO) model is considered for radiation as it is more accurate. For knowing the reaction behavior of different equation with volumetric equation species transport model is used. At the outlet stream of kiln Fe content is obtained. Under turbulence-chemistry interaction section Finite rate/Eddy dissipation model is used, which shows promising result. For solving the present problem spatial discretization with least squares cell based method is used. The operating parameters such as flow rate , temperature and specific heat capacities of the inlet and outlet streams are shown in **Table 2**.

Table 2. Specific Heat of Streams

Stream	Component	Specific heat (J/kg°C)		Mass flow rate (Kg/s) or mass fraction	Specific heat of mixture (J/kg°C)
		Value	Reference		
Feed	Iron ore	960	(14)	10	1092.7
	Feed coal	1380	(15)	5.1	
	Dolomite	1028.38	(16)	0.29	
Air	-	1032.6	(16)	-	1032.6
Product	Sponge iron	594.93	(17)	3.8	687.9
Water	-	4187	(16)	-	4187
Product	Waste gas	1140	(17)	-	1140

The operating conditions and the dimensions of the kiln are shown in details in **Table 3**. The properties of the materials are given in **Table 4**.

Table 3. Operating conditions and dimensions of the kiln

S. No.	Variables	Values
1.	Speed of rotation (RPM)	4.3
2.	Flow rate (iron ore) (kg/s)	5.83
3.	Flow rate (Feed Coal) kg/s	2.28
4.	Flow rate (Slinger Coal) kg/s	2.042
4.	Flow rate (Dolomite) kg/s	0.32
5.	Height at solid entry (m)	2.5
6.	Burner	2.042 kg/s coal and 1.195 kg/s air
7.	Secondary air	21.205 kg/s
8.	Total air mass flow rate	22.4 kg/s

Table 4. Properties of the materials

Materials & Properties	Iron	Iron ore	Iron oxide	Dolomite	Carbon solid	Air
Density(kg/m^3)	7874	5242	5745	2840	2260	1.29
Molecular weight	55.85	159.7	71.84	184.4	12.011	28.97
Thermal conductivity (W/m-K)	80.4	1.3	3.3	1.75	0.33	0.0242
St. state Enthalpy (J/kg mol)	13.1	-826	-272	-654	-101.27	0
St. State Entropy (J/kg mol-K)	34.287	87400	60750	42365	5731.75	194336

IV. Results and discussion

Here 2D model of rotary kiln is with nine different secondary air ports is simulated using ANSYS 14.5. It is carried out to understand the behavior of operating parameters. These parameters influenced the performance of the rotary kiln. The temperatures of freeboard and bed are observed along with calculation of the mass fraction of Fe present in outlet stream. Also, the effect of variation in input parameters is discussed in the present work. The temperature profiles inside the kiln and final Fe content are optimizing using the variation in input parameters. The oxygen profile in the freeboard section is found out through which it is easier to know the requirement of oxygen in the kiln. The range of the input parameters is shown in **Table 5**. It is also easier where placed air port by which easily supplied oxygen which helped in combustion and saved the wastage of fuel in the kiln.

Table 5. Variation in input parameters

Parameter	Range	Unit
Angle of inclination	2.5-3.0	degree
No. of rotation	4.3-5.3	rpm
Flow rate of iron ore	0.5 – 7	kg/s

A. Impact of input parameters on Fe content

The impact of input parameters on Fe content is also studied here and calculated the maximum possible content of Fe as discussed in previous paper. The variation in angle of inclination and its effect on Fe content are determined by Fig. 2. It is cleared from **Fig. 2** that Fe content is found as 87 % at the inclination 2.5 degree and 4.3 rpm. Now, assuming mass flow rate of iron ore and rotation of the kiln are at the fixed value of 5.83 kg/s and 4.3 rpm respectively. The angle of inclination is varied from 2.5 to 3.0 degree for computing Fe content as condition has been taken similar to first paper. The value of Fe content increases up to 2.8 degree and then decreases which is clear from **Fig. 2**. As angle of inclination increases, filling degree of the material decreases linearly. This is due to decrease of the effective volumes of the kiln, as a result residence time of feed inside the kiln decreased. As value of angle increased up to certain limit the mixing of feed is also increased in the kiln. The accumulation of feed reduced at particular position of the kiln with large angle as a result Fe content increased. Moreover, residence time decreased as angle increased in the kiln simultaneously, which reduced the time required in reduction and thus, the Fe content. Therefore, the maximum fraction of Fe is found as 92 % at the angle of inclination of 2.8 degree which is clearly shown in **Fig. 2**. This angle is considered as optimum angle of inclination. Although, at the optimum inclination and mass flow rate of iron ore as 2.8 degree and 5.83 Kg/s, respectively, and considering rotation of the kiln is varied from 4.3 to 5.3 rpm. Fe content is estimated for each rotation drawn in **Fig. 3**. It denotes that optimum number of rotation is found as 4.7 rpm for which fraction of Fe is 92%. After 4.7 rpm, as ring formation occurs inside the kiln, which imparts obstruction to the flow material and decelerates the forward travels of the materials as a result mass fraction of Fe decreases. Thus, the mixing of feed in the kiln reduced, which decreases the Fe content.

As considered in the earlier paper, different mass flow rate of iron ore from 0.5 to 7 kg/s is assumed to observe its effect on Fe content as indicate in **Fig. 4**. These values are obtained at optimized values of inclination and rotation, which are 2.8 degree and 4.7 rpm, respectively. The Fe content increases with increase in mass flow rate of iron ore up to 5.83 kg/s and then decreases as clearly shown in **Fig. 4**. The maximum value of Fe content is 92%, which is found at 5.83 kg/s of iron ore. Thus, the flow rate of iron ore increases as a result residence time decreases metallization increases due to more amount of iron ore available for reduction inside the kiln. However, Fe content increase up to flow rate of iron ore as 5.83 kg/s. Further, increase in flow rate the residence time reduces significantly. This decrease in conversion is due to improper mixing of feed material and less residence time inside the kiln. Therefore, it fails to achieve the desired degree of metallization. Thus, optimum flow rate of iron ore is found as 5.83 kg/s.

B. Impact of variation of input parameters on temperature profile

The temperature profiles of bed are computed at different values of inclination varying from 2.5 to 3.0 degree along the length of the kiln are shown in **Fig. 5**. For these values the flow rate of iron ore and optimum number of rotations as 5.83 kg/s and 4.8 rpm, respectively, are considered. The minimum and maximum temperatures of these profiles are 27°C and 1052°C, respectively, which are falling within the acceptable limits of temperatures i.e. less than 1100°C.

The temperature profiles of gas at constant value of mass flow rate and rotation i.e. 5.83 kg/s and 4.8 rpm, respectively are found and shown in **Fig. 6**. These first increase then decrease slightly and finally increase up to the discharge end as shown in **Fig. 6**. The temperature of the gas (air) profile observed in the upper zone (freeboard region) vary within temperature range of 327°C -1047°C along the kiln. This range is suitable for combustion reaction in the rotary kiln.

The temperature profiles of both bed and gas are plotted in **Fig. 7** and **Fig. 8**, respectively at different mass flow rate such as 0.5 kg/s, 1.5 kg/s , 2 kg/s, 2.5 kg/s, 3 kg/s, 4 kg/s, 5.83 kg/s, 6 kg/s, and 7 kg/s at optimum condition. Temperature range decreases slightly in the lower section as flow rate increases as shown in **Fig. 7** due to improper mixing inside the kiln. While **Fig. 8** indicates that temperature increases then decreases slightly and further increases in the upper section. It also shows that the temperature of gas decreases as flow rate increases as discussed in details in first paper. The temperature profile of the bed and gas for optimum conditions are shown in **Fig. 9**. These profiles show a smooth rise in bed and gas temperatures, which is due to the heat generated through combustion of coal. Temperature contours of the kiln are shown in **Fig. 10** which is found at optimum conditions. **Fig. 10** shows that the temperature increases from feed end to discharge end along the kiln length, which is an obvious outcome. Temperature of 1050^{o}C is found at the discharge end of the kiln from where sponge iron is collected as a product. Firing helps in projecting the fuel into the kiln through firing pipe (burner pipe) from the discharge end which generates flame. It is carried out for initial charging of kiln. The flame consists of excess oxygen, which helps in combustion reaction. The ignition distance (i.e. distance between end of the firing pipe and start of the flame) and the flame length are controlled by flow rates and temperatures of primary and secondary air.

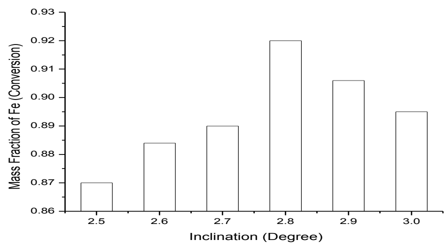

Fig. 2 Mass fraction of Fe with varying angle of inclination

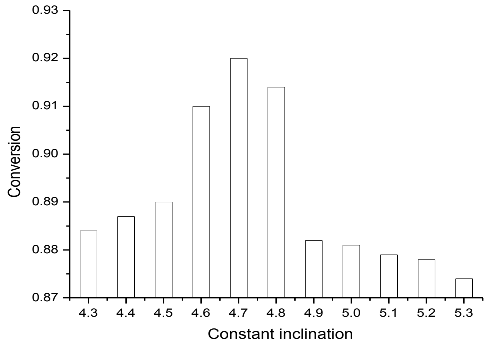

Fig. 3. Mass fraction of Fe with varying rotation of kiln at constant inclination

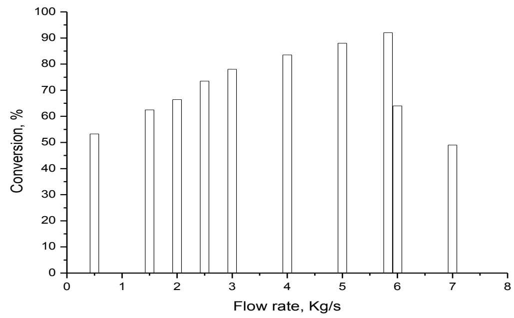

Fig. 4 Mass fraction of Fe with varying mass flow rate of iron ore

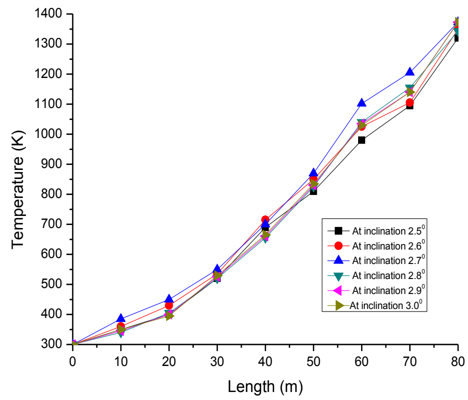

Fig. 5 Bed temperature profile at various inclination

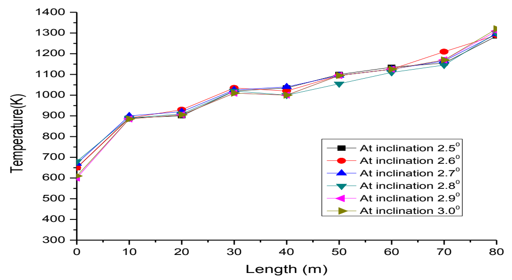

Fig. 6 Gas temperature profile at various inclination

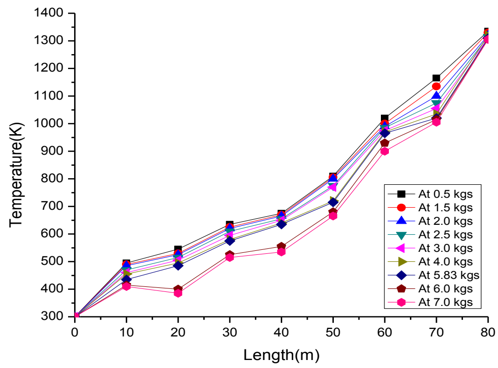

Fig. 7 Bed temperature profile with various mass flow rate of iron ore

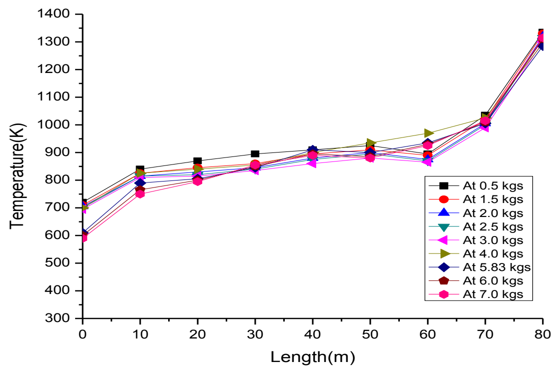

Fig. 8 Gas temperature profile with various mass flow rate of iron ore

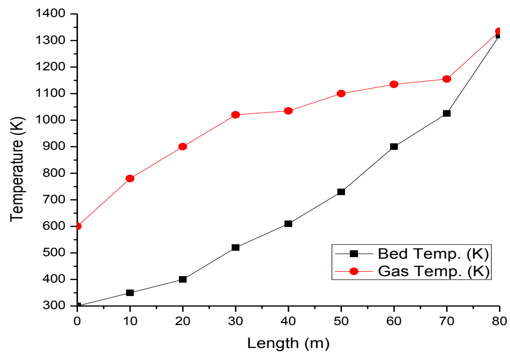

Fig. 9 Bed & Gas Temperature Profile at 2.8 degree and 4.7 inclination at optimum condition

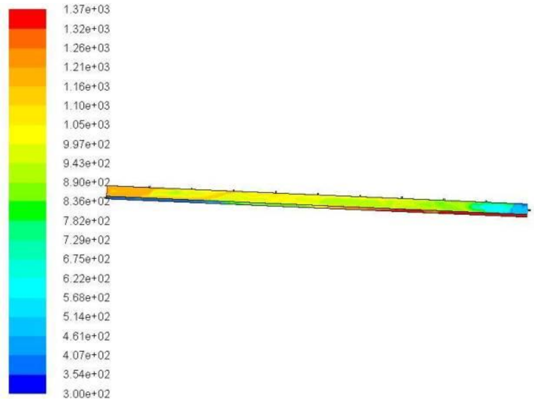

Fig. 10 Temperature contour of the kiln

Conclusions

A 2D CFD model of rotary kiln is developed using ANSYS 14.5 for sponge iron process. The present study discusses the nature of temperature profile of the bed and gas(air) along the length of the kiln, and Fe content. These parameters are studied based on the variation of input parameters such as angle of inclination, number of rotation and mass flow rate of iron ore. The salient conclusions of the study are:

(1) The results indicate that varying the angle of inclination from 2.5 to 3 degree the Fe content increases and then decreased at constant rotation and flow rate of iron ore. The optimum angle is found as 2.8 degree. Similarly, optimum number of rotation and flow rate of iron ore is found as 4.7 and 5.83 kg/s, respectively. At these optimum conditions the Fe content is predicted as 92%.

(2) The bed temperature profile increases from the feed end to discharge end, where as gas (air) temperature profile increases then decreases slightly and further increases with varying mass flow rate of iron ore and rotation at optimum angle of inclination i.e. 2.8 degree.

(3) The temperature profiles of gas and bed zone found in the present at optimum condition are compared well with that predicted in the work of Sarangi [13].

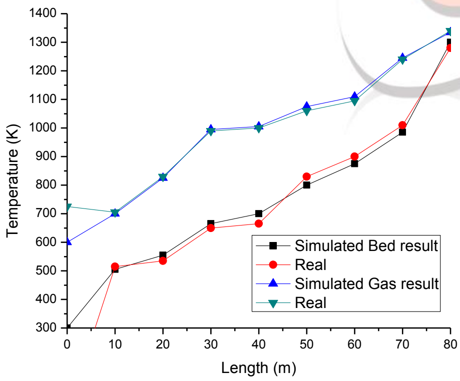

Fig. 11 Comparison of bed and gas temperature profiles

V. References

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