MATHEMATICAL MODEL FOR ENERGY SAVING IN INDURATION OF IRON ORE PELLETS CONTAINING SOLID FUEL

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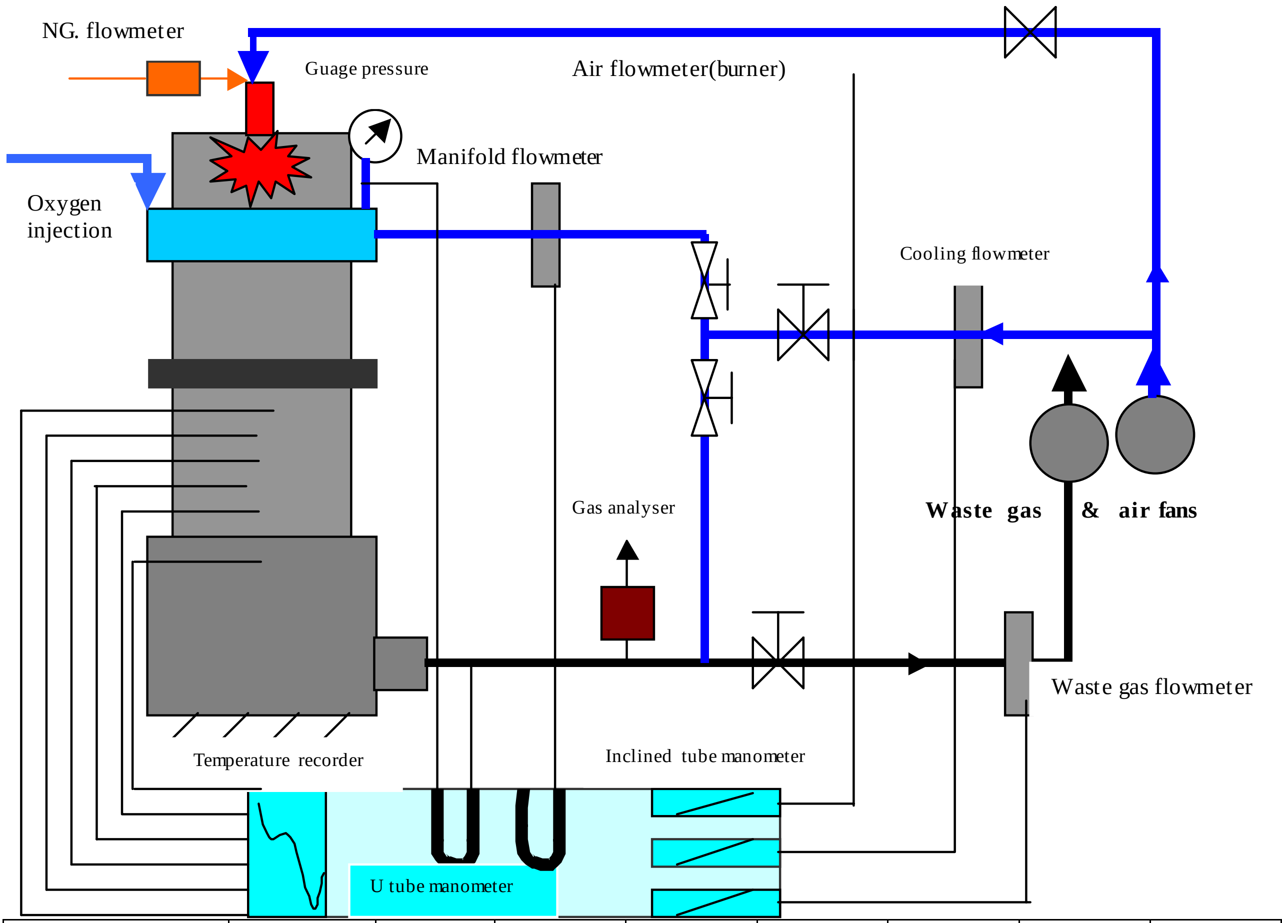
Abstract Mathematical model for a pilot scale iron ore pellet induration furnace has been developed which considers the process of induration including the reactions of limestone, magnetite and coke. The differential equations of energy, mass and momentum are solved simultaneously. The profiles of temperature, pressure and concentration are obtained. Performing separate experiments on sub processes; drying, firing and cooling have checked the validity of the model. At first, a mixture of iron ore is selected and then the percentage of limestone is changed. The maximum metallization and fired pellet strength with minimum sticking vs. basicity is obtained. In the next stage the percentage of coke in iron ore is altered and all of physical and chemical property of the pellets are measured. Finally, the optimum percentage of coke in the iron ore is determined. By using different percentage of coke in the pellet the experiments are performed in three conditions. In the first condition, inlet gas temperature is decreased alone. In the second condition, inlet gas temperature and total indurtion time are decreased together and in the third condition, in addition to above conditions, oxygen injection to the furnace is carried out. Energy savings in all three conditions have been obtained.

Key Words Mathematical Model, Pelletizing, Coke, Iron Ore

چکیده مدل ریاضی در پایلوت پلنت واحد گندله سازی با در نظر گرفتن واکنشهای سنگ آهک، مگنتیت و کربن در گندله ارائه می‌شود. معادلات دیفرانسیل جرم، انرژی و مومنتم بصورت همزمان حل می‌شوند. تغییرات درجه حرارت، فشار و غلظت بر حسب ارتفاع بستر با نتایج تجربی مراحل مختلف شامل خشک شدن، پخت و سرد شدن گندله ها مقایسه می‌شوند. درصد سنگ آهک در گندله تا حصول بازیسیته مناسب (B_4) تغییر داده می شود بطوریکه گندله دارای احیا پذیری مناسب و حداقل چسبندگی باشد. برای افزایش تولید و کاهش مصرف انرژی با استفاده از کک در گندله سه حالت بررسی شده است. در حالت اول با افزودن مقادیر مختلف کک به گندله درجه حرارت گاز ورودی به بستر کاهش داده می‌شود. در حالت دوم علاوه بر کاهش درجه حرارت، زمان گندله سازی نیز کاهش داده می‌شود. در حالت سوم علاوه بر موارد مذکور تزریق اکسیژن به کوره نیز انجام می‌شود و میزان پتانسیل افزایش تولید و کاهش مصرف انرژی معین می‌گردد.

1. INTRODUCTION

Pellet formation in the iron making from the concentrate of raw material is done in rotary disks to form the green pellets. The green pellets, leaving the agglomeration disks, are fed to a traveling grate, where they are dried, fired at elevated temperatures to increase the pellet strength and to oxidize the magnetite and are then cooled. The percentages of additives and coke depend on the composition of the mineral. The aim of this paper is to study, both experimentally and theoretically, the possibility of energy saving in the induration process. Therefore, the additives of iron ore are altered, and the best basicity for the maximum metallization and minimum sticking is obtained. Once this has been determined, the percentage is changed from 0 to 1.5 %. The optimum percent of



Parameter	Waste fan	Air fan	1	2	3	4	5	6
Pressure (mbar)	60	60	-	-	-	-	-	-
Temperature(C)	25-500	25	25	25	25	25-600	25	25
Flow (NM^3/hr)	3720	1620	0-220	0-320	0-20	0-550	0-18	0-700
Density (kg/m^3)	0.52	1.2	-	-	-	-	-	-

Figure 1. Flow diagram and physical property of pilot plant.

coke is found to be 0.75% while the physical and chemical property of pellets remains unchanged. Comparing the results of model with experimental data, the pellets containing 0.75 % coke are selected. The drying stage is affected by passing flue gas through the bed of pellets for 8 minutes in the updraft and down draft directions. Where the temperature is high enough decomposition of limestone and then oxidation of the magnetite and finally combustion of the coke particles take place. The exothermic reactions of magnetite and coke increase the temperature of pellets, at lower energy consumption rate. The pilot scale model of the traveling grate is the pot grate as shown in Figure 1. The pellets within the pot grate undergo the same thermal treatment as in the full size plant. Instead of carrying the pellets on a moving grate from zone to zone, gas temperature at entrance of reactor is affected as a function of time.

The main reason for the present study is energy saving and to demonstrate the effects of parameters such as humidity removal, coke combustion and limestone and magnetite reactions on the performance of the induration process. Within the pellets presence of heat and mass transfer resistances due to conduction and diffusion are considered. A mathematical model

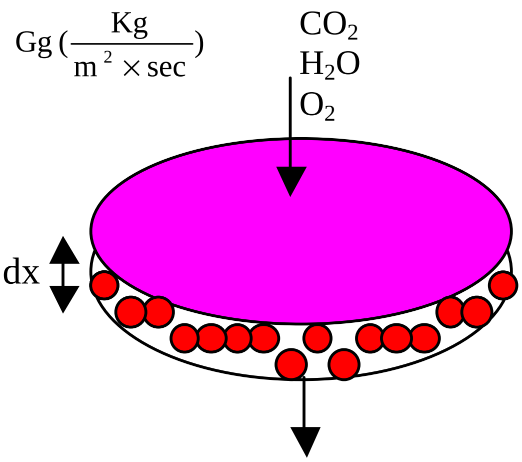


Figure 2. An element of radius R and height dx of the bed.

of this process can help to understand and improve an already existing plant and or design a new plant.

2. MODELING

A number of physical and chemical phenomena must be modeled. Drying and reactions occurring simultaneously with heat and mass transfer between the gas and the pellets as the pellets pass from one zone to another on the traveling grate. The same phenomena take place in the pot grate as drying, firing and cooling zones in the moving grate. A number of models have been proposed in the literature for induration of iron ore pellets. Dianbing Huang [1] only considered the reaction of coke in the pellet. F. Chejne Janna [2] considered the reactions of limestone and coke and drying of humidity in pellets. J. H. Voskamp[3] considered the effects of temperature and concentration gradients within the pellets to be negligible and the coke combustion within the pellets was not mentioned and drying was assumed to take place at the pellet surface. J. R. Wynnyckyj[4], study of iron ore pellet induration considered phenomena such as carbon combustion, magnetite oxidation and drying. This assumption is not valid if the pellet humidity drops below a critical level at which the capillary movement of water to the pellet surface stops. K. Kucukada a mathematical model of the pilot plant scale iron ore pellet induration furnaces is presented. The experiment was performed in such a way that phenomena of heat transfer, drying and coke combustion [8].

K. H. Boss [9] developed a model for straight grate pelletizing process and added higher amounts of coke to iron ore pellets without effecting the quality of fired pellets. Mark Cross [11] developed a mathematical model of straight grate pellet induration processes. They use the induration process model to evaluate whether the first drying zone is best to use on the up draft or down draft gas flow stream and they optimize the gas temperature profile in the hood of P.H., F., and A.F. zones to reduce the burner fuel. R.W. Young [12] developed the model for iron ore kiln-cooler process; they studied the drying phenomena and the reaction of calcination and magnetite oxidation by a shrinking core method. Also mass and heat transfer between the pellets and the gas were seen but the effect of radial temperature and concentration gradients within the pellets were neglect and little attention was paid to the drying of the iron ore pellets and the limestone reaction wasn't considered. The present model consists of the following main elements. It was assumed that the moisture removal takes place at the pellet surface up to some moisture content (critical humidity) below, which the evaporation front propagates within the pellet. Following the drying of pellets reactions of carbon, limestone and magnetite happen and are considered. In all of reactions three main steps for controlling of reaction are considered, film diffusion, diffusion in the porous pellet and the chemical reaction. One-dimensional method is used and the one element from the bed with radius R same as Figure 2 is considered. Ergan equation is used for calculating the pressure drop across the bed. An element same as the shown is considered [5].

$$\frac{dp}{dx} = [\frac{150(1-\varepsilon)^2 \mu_g}{d^2 \varepsilon \rho_g} .G + 1.75 \frac{G^2(1-\varepsilon)}{d\varepsilon^3 \rho_g}] \qquad (1)$$

3. ENERGY BALANCE FOR GAS

The gas is forced through the packed bed and exchanges heat with the pellets. Bed height was given by performing a heat balance for a differential element, dx.

$$C_g G \frac{dT_g}{dx} = -ha(T_g - T_p) \quad (2)$$

4. ENERGY BALANCE FOR THE SOLID

The pellets are exposed to the gas. The temperature gradient within the pellet plays an important role in determining the necessary minimum firing time. By considering the radial temperature gradient in the pellet, It is possible to represent realistically the chemical reactions taking place within the pellet [8].

$$K_p \frac{1}{r^2}\frac{\partial}{\partial r}(r^2 \frac{\partial T_p}{\partial r}) + \Sigma r^o{}_i \Delta H^o{}_i N_1 + \Delta H^o \upsilon (\frac{dw_p}{dt}) = \rho_P C_p \frac{\partial T_p}{\partial t} \quad (3)$$

$$B.C.-1: K_p \frac{\partial T_p}{\partial r}\Big|_{r = d/2} = h(T_g - T_p)$$

$$B.C.-2: \frac{\partial T_p}{\partial r}\Big|_{r = o} = 0$$

5. MASS BALANCE

The reactions of limestone, magnetite and carbon are considered by the shrinking core method and the rate of reactions are written as the following [12]:

$$r^0{}_{Limestone} = \frac{4\pi r_1(t)^2 (C_{CO_2} - C^{eq}{}_{CO_2})}{\frac{K_{eq}}{K_f} + (\frac{r_1(t)}{r_o})^2 \frac{1}{K_d} + \frac{(r_o - r_1(t))}{r_o D_{eff.,CO_2}}}$$

$$r^0{}_{Mag_0} = \frac{16\pi r_m(t)^2 (C_{O_2}{}^{eq} - C_{O_2})}{\frac{1}{K_f} + \frac{r_m{}^2(t)}{r_o{}^2 K_d} + \frac{r_m(t)}{D_{eff.,O_2}}(1 - \frac{r_m(t)}{r_o})}$$

$$r^o{}_{carbon} = \frac{4\pi r_c(t)^2 (C_{O_2}{}^{eq} / K_{eq} - C_{O_2})}{\frac{1}{K_f} + \frac{r_c{}^2(t)}{r_o{}^2 K_d} + \frac{r_c(t)}{D_{eff.,O_2}}(1 - \frac{r_c(t)}{r_o})} \quad (4)$$

6. DRYING OF PELLETS

Drying of free water is a complex process which is generally assumed to take place in two stages (first stage is shown in Figure 3 and second stage is shown in Figure 4), where the moisture movement of saturated water is dominant, and a falling rate period where the moisture level falls below some critical value and heat diffuses into the pellet and evaporates the moisture at a reducing, moving boundary. When the critical moisture content is reached, the pellet is assumed to be formed of two regions: a dry shell and a wet core separated by a front, which moves inward towards the pellet center. The humidity of the wet core remain constant at the critical humidity and the evaporation of water takes place at the outskirts of the moving front, i.e. at a distance r_c from the center (Figure 3).

It was assumed the gas is at its saturation humidity, w_g^e in equilibrium with the liquid water film at the pellet surface and the only driving force for evaporation is the humidity gradient between the evaporation front and the flowing gas

$$-(1-\varepsilon)(\frac{dW_p}{dt}) = K_m a (W_g{}^e - W_g) \quad (5)$$

When the pellet moisture constant is above the critical value, evaporation takes place at the pellet surface. It was further assumed that the gas is at its saturated surface moving towards the pellet center. Based on the approach of the shrinking wet core drying, the drying rate of the pellets bellow the critical humidity was derived. Condensation may occur in the bed at the beginning of the drying cycle when air reaches its saturation humidity and comes into contact with pellets at a temperature lower than the temperature of the saturated air. Finally the law of mass conservation dictates that the water lost by the solid would increase the

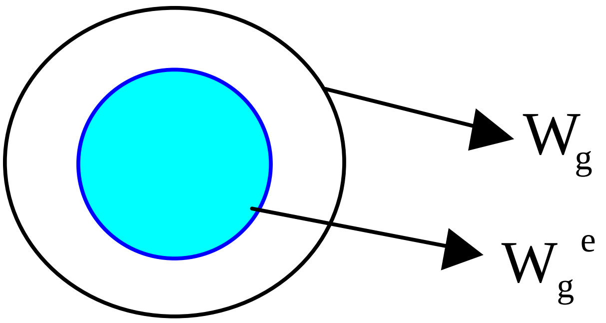


Figure 3. Boundary layer near the pellet.

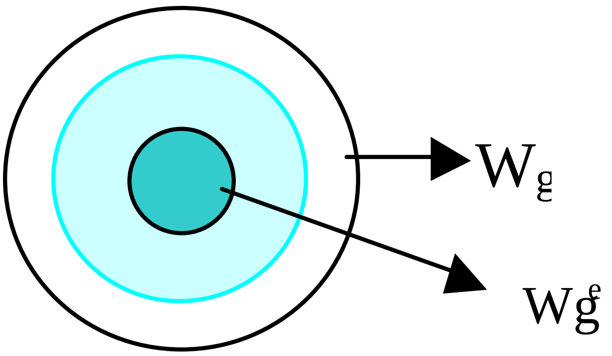


Figure 4. Drying layer is grows to the center of pellet (under the critical humidity condition).

humidity of gas stream. This is given by the following equation [8].

$$\frac{G}{\rho_g}\frac{dW_g}{dx} = -(1-\varepsilon)\frac{dW_p}{dt} \qquad (6)$$

Based on the approach of the shrinking core wet core drying, the drying rate of the pellets below the critical humidity was derived.

$$-(1-\varepsilon).(\frac{dW_p}{dt}) = \frac{a}{(d/2)^2} * \left(\frac{((W_g^{e}(r_c) - W_g))}{\frac{d/2 - r_c}{(d/2)\, r_c D_{H_2O}} + \frac{1}{K_m (d/2)^2}} \right) \qquad (7)$$

If the pellet humidity is greater than critical humidity, then the wet core radius, r_c, is equal to the pellet radius, d/2, and Equation 7 is reduced to Equation 5. The volume of the wet core, V_c pellet humidity and critical humidity if pellets, W_p, can be given by the following water mass balance equation.

$$W_p = W_{pc} (\frac{r_c}{d/2})^3 \qquad (8)$$

7. MASS BALANCE OF O_2

Dissipation of oxygen in the gaseous phase within a differential element of dx is equal to the amount of oxygen consumed by chemical reactions and variation of oxygen concentration in the gas and pellet in comparison to these terms.

$$\frac{G}{\rho_g}\frac{dC_{O_2}}{dx} = \{(r^{o}{}_{mag} N_1 / 4) + r^{o}{}_{carbon}(1-\varepsilon)\} \qquad (9)$$

8. MASS BALANCE OF CO_2

Production of carbon dioxide in the gaseous phase within a differential element of dx is equal to the amount of oxygen consumed by chemical reactions. Variation of carbon dioxide concentration in the gas is also neglected.

$$\frac{G}{\rho_g}\frac{dC_{CO_2}}{dx} = -\{r^{o}{}_{Lime} N_1 + r^{o}{}_{carbon}(1-\varepsilon)\} \qquad (10)$$

Using friendly simulator written in Quick basic, the equations were solved by using explicit finite difference method. Gas temperature difference in the axial direction of the bed vs. time is calculated for time increments of 2 sec and height 1 cm.

9. EXPERIMENTAL SET UP AND PROCEDURE

Experiments were conducted in the pot grate induration furnace installed in the pilot plant of

TABLE 1. The Physical and Chemical Property of Stones Additives.

Analyze (%)	Ferteco	C.V.R.D	Carajas	G.E.G	Chadermalo	Coke	Bentonite	$CaCO_3$
Mixture (total)	20.30	23.70	20.30	3.40	28.10	1.00	0.70	2.50
Fe_{total}	67.5	68	66.2	67.75	68	0	2.48	0
FeO	2.3	0.35	0.5	19.25	13.5	0	Fe_2O_3=3	0
SiO_2	1.35	1.2	0.75	1.5	1.3	8	67.45	1.08
Al_2O_3	0.5	0.33	1.2	0.3	0.76	3.15	12.23	0.04
CaO	0.06	0.02	0.08	0.3	0.39	0.08	4.46	36.49
MgO	0.03	0.05	0.05	1.35	0.19	0.11	1.37	16.71
P	0.022	0.031	0.03	0.04	0.03	0	0	0
S	0.015	0.01	0.029	0.08	0.027	0.53	0	0
K_2O	0	0	0	0	0	0	0.12	0
Na_2O	0	0	0	0	0	0.25	2.22	0
C	0	0	0	0	0	79.5	0	0
Ash	0	0	0	0	0	14.22	0	0
L.O.I.	0	0	0	0	0	85.78	8.9	44.71

TABLE 2. The Physical and Chemical Property of Fired Pellets (Condition I).

Test no.	1	2	3	4	5	6	7	8	9	10	11	12	13
Blaine (cm^2/gr)	2133	1788	1982	1751	2118	2203	1825	1984	2207	2018	1842	1925	2078
Screen-45μ	81.5	81	80	82.3	80.8	79	75.8	77.6	74.3	81	78.4	84	82.4
Lime dolomite (%)	1.8	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Bentonite (%)	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Drop No.	5	3.5	3.6	3.6	3.1	4.1	3.2	3.2	3.3	4	3.3	3.2	3.5
Coke (%)	0	0	0.5	0.5	0.5	0.75	1	1	1	1.15	1.5	1.5	1.5
Firing temperature	1340	1340	1310	1310	1320	1300	1320	1310	1290	1290	1300	1290	1290
Abrasion index (%)	3.3	3.7	4.5	4.5	4.7	4.2	4.4	5.3	5.5	5.1	6.7	7.2	8
Porosity (%)	19.5	21.8	21.9	21.9	22.9	22.6	22.7	23.1	22.5	23.4	25.9	25.6	24.9
C.C.S (Kg/Pellet)	394	385	417	417	376	340	300	303	324	307	262	242	252
Fe_{total}(%)	67	67.03	66.72	66.72	66.8	67.1	67	67	66.8	66.8	66.6	66.4	66.8
FeO (%)	0.11	0.11	0.22	0.22	0.15	0.27	1.25	0.66	0.35	0.6	0.72	0.93	0.54
$SiO_2+Al_2O_3$ (%)	1.8	2.34	2.59	2.59	2.55	2.71	2.52	2.67	2.52	2.64	2.8	3.18	2.9
CaO+MgO (%)	1.7	1.87	1.47	1.47	1.98	1.02	1.71	1.22	1.8	2.02	1.1	1.44	1.73
S (%)	0.03	0.028	0.028	0.03	0.03	0.02	0.03	0.03	0.02	0.03	0.03	0.03	0.03

Khouzestan Steel Company in Iran. This furnace is able to reproduce the gas flow rates and temperatures to which the pellets are exposed in an industrial furnace. The schematic of the pilot is shown in the Figure 1. The pot grate is instrumented in such a way that the temperature and pressure can be controlled. Total height of pellets in the pot grate test pilot is 40cm and 10 cm is hearth layer. The diameter of pot grate is 26 cm. The air is added to the bed to ensure an oxidizing atmosphere at

TABLE 3. The Physical and Chemical Property of Fired Pellets (Conditions II and III).

Condition	Second Condition		Third Condition (Oxygen Injection)	
Test No.	1	2	3	4
Blaine (cm^2/gr)	1958	1972	1930	2016
Screen-45µ	80.5	80	84	80.4
Lime Dolomite (%)	1.5	1.5	1.5	1.5
Bentonite (%)	0.75	0.75	0.75	0.75
Coke (%)	0.5	0.75	0.5	0.75
Firing Temp. (C^o).	1310	1310	1310	1300
Abrasion Index (%)	4.6	5.2	4.6	5
Porosity (%)	21.9	24.1	24.9	24.8
C.C.S. (Kg/Pellet)	334	292	341	373
$Fe_{tot.}$ (%)	67.05	66.8	66.93	66.92
FeO (%)	1.12	0.66	0.26	0.21

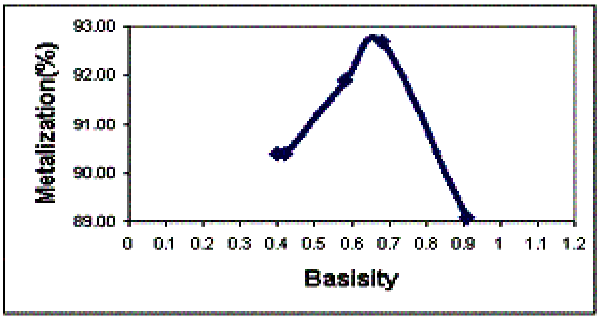


Figure 5. Effect of basisity on the metallization (experimental data of sticking test).

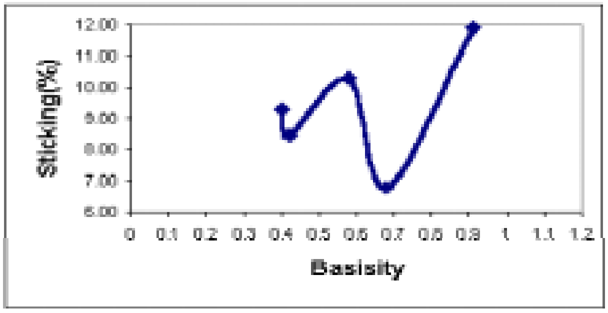


Figure 7. Effect of basicity on the sticking of pellets (exp. Data).

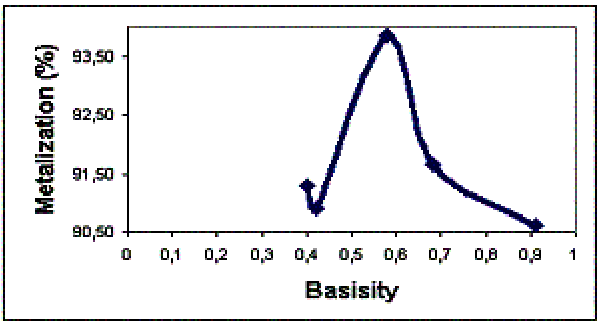


Figure 6. Effect of basisity on the metallization (basket test).

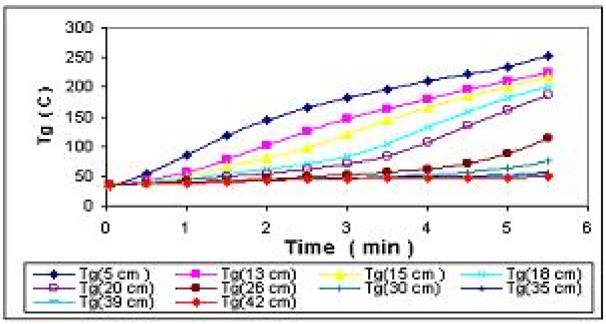


Figure 8. Simulated gas temperature vs. time at different height of the bed.

elevated temperatures. Moving the combustion chamber changes the direction of the inlet gas to the bed.

The analyzer measures the flow rates of air, flue gas by orifice flow meters and natural gas by turbine flow meter are measured and the percentage of components in the waste gas. Carefully designed experiments to analyze the

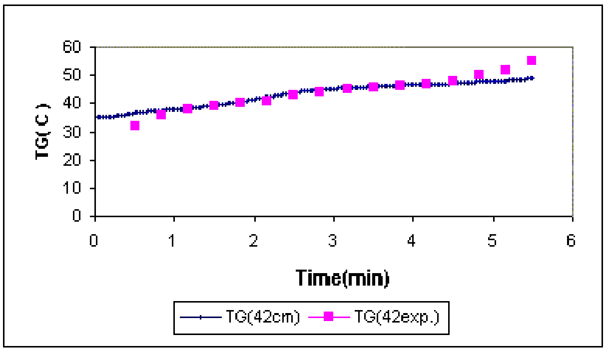


Figure 9. Experimental and simulated outlet gas temperature (up draft condition).

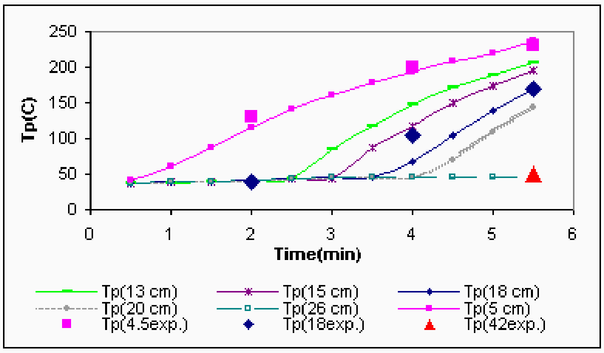


Figure 10. Experimental and simulated pellets temperature in the different height of bed (up draft condition).

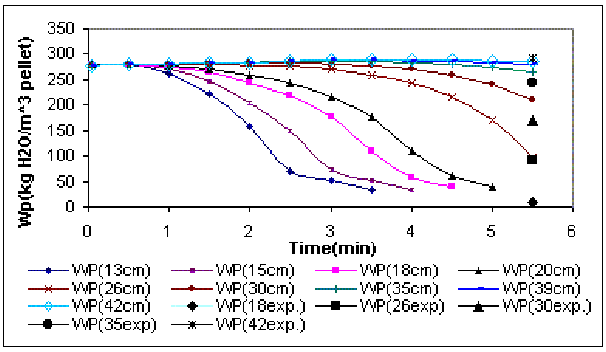


Figure 11. Experimental and simulated pellets humidity in the different height of bed (up draft condition).

drying, firing and cooling periods separately brought a clear understanding of the developed model. For example, after the moisture removal in the updraft condition the test is stopped. Then all pellets take out from the furnace and humidity of pellets are measured. For each condition the experimental results are compared with model.

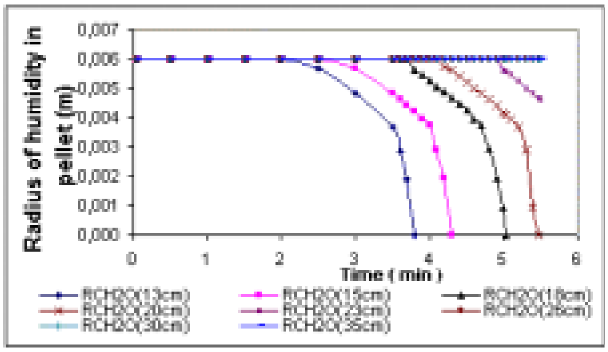


Figure 12. Wet core radius in the pellet at different height of bed (up draft condition).

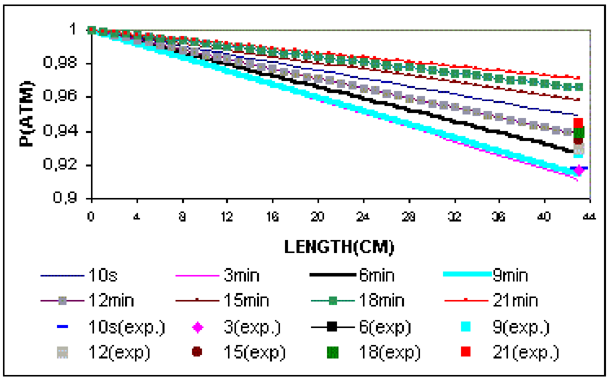


Figure 13. Experimental and simulated pressure of bed at different time.

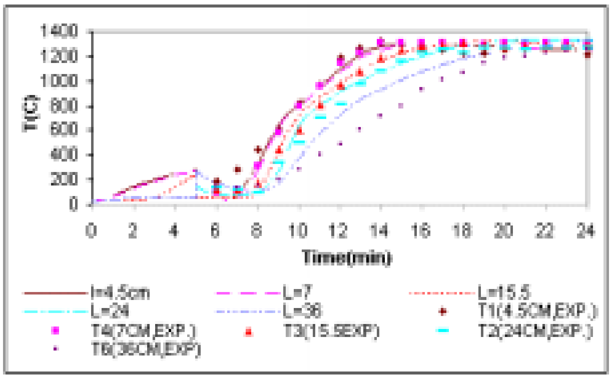


Figure 14. Experimental and simulated pellets temperature at different time.

The pressure and temperature profiles are checked with experimental results. In addition, experiments are done for the selection of the quantity of limestone in the raw material so that the best basicity, lowest sticking with the

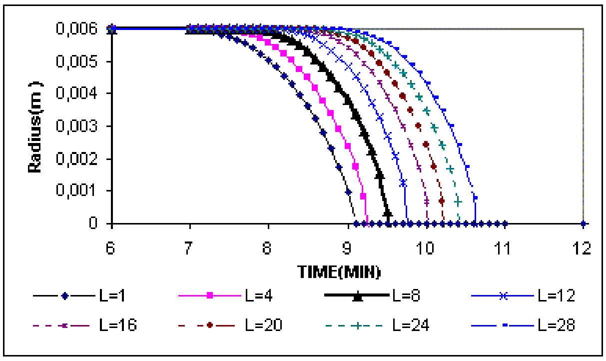


Figure 15. Reaction zone of CaCO3 in pellet at different height of bed (shrinking core method).

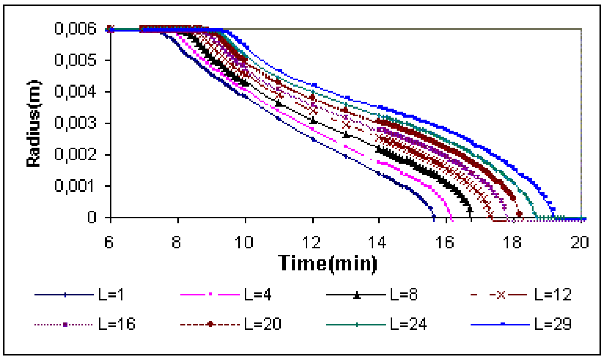


Figure 16. Reaction zone of Fe_3O_4 in pellet at different height of bed (shrinking core method).

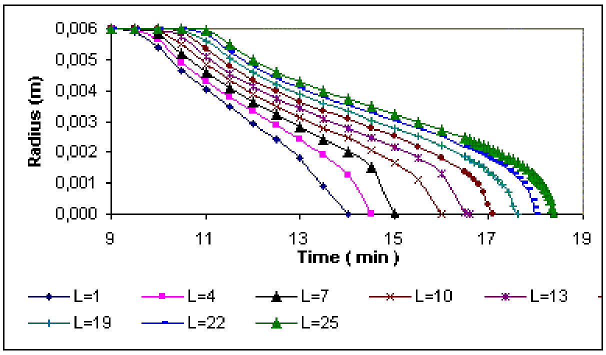


Figure 17. Reaction zone of carbon in pellet at different height of bed (shrinking core method).

maximum metallization and best-fired pellet strength are obtained. In this research mixture of stones are CVRD, Ferteco, Carajas, G.O.G, Chadermalo (G.O.G and Chadermalo are Iranian stones) and additives are bentonite, limestone and Coke. The mixture of iron ore and additives are

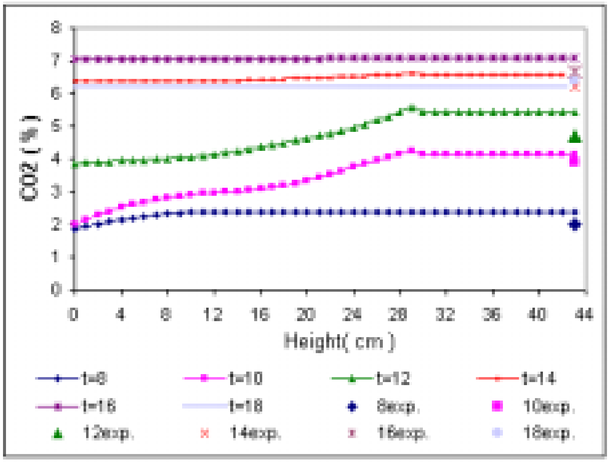


Figure 18. Simulated and experimental CO_2 percent in the waste gas.

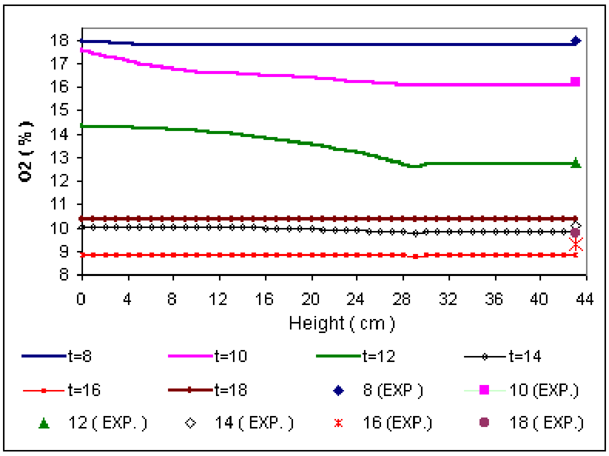


Figure 19. Simulated and experimental O_2 percent in the waste gas.

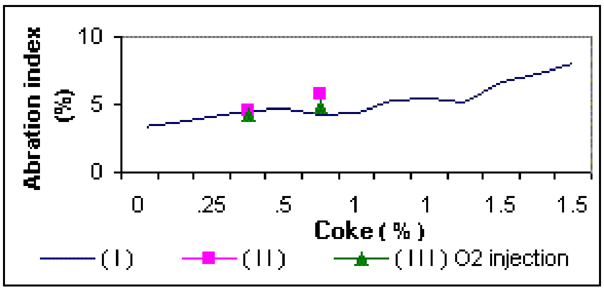


Figure 20. Experimental abrasion index vs. coke percent (for three Conditions I, II, III).

shown in the Table 1. The value of limestone is varied from 0 to 3.5 % and the best basicity

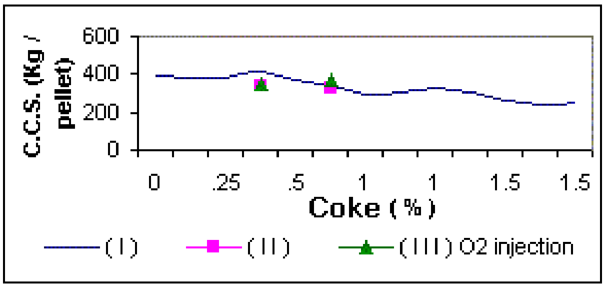


Figure 21. Experimental cold compression strength vs. coke percent (for three Conditions I, II, III).

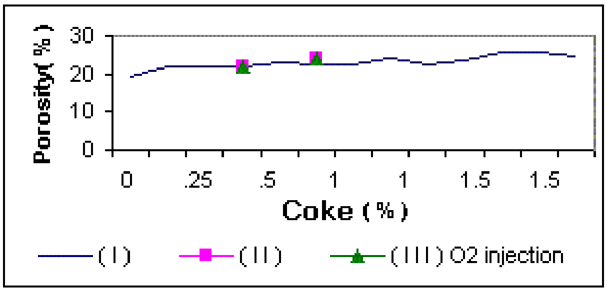


Figure 22. Experimental porosity vs. coke percent (for three Conditions I, II, III).

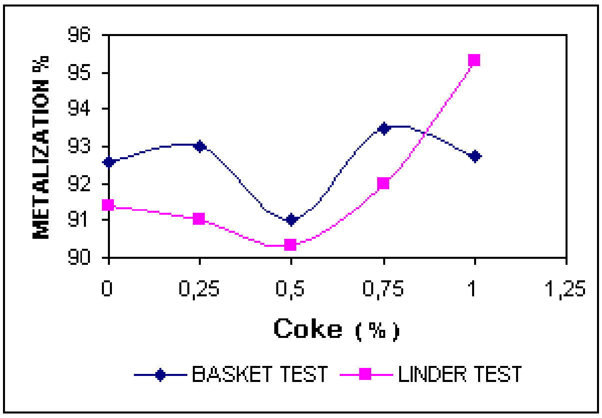


Figure 23. Sponge iron metallization (conditional).

between 0.6 and 0.7 is obtained. Value of Coke from 0 to 1.5 % is altered and then the best value of coke equal 0.75 % is obtained for the mixture of hematite and magnetite stones. The temperature of pellet for the zero percent of coke is varied from ambient temperature to 1340°C. The experiments are performed in three conditions. Experimental results of three conditions are shown in the Tables 2 and 3.

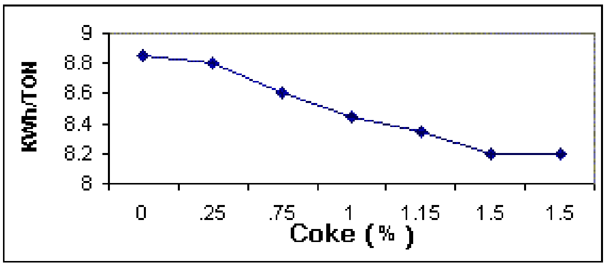


Figure 24. Grinding electrical energy consumption in the pilot plant vs. coke percent.

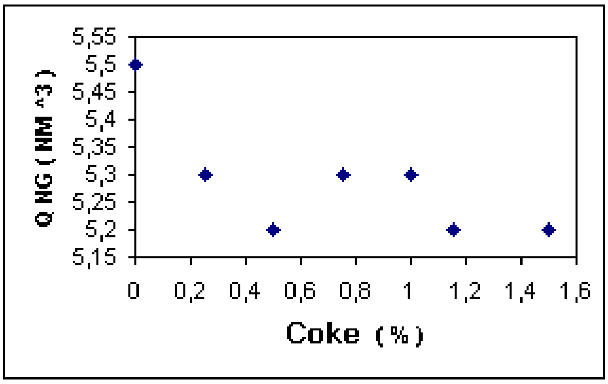


Figure 25. Decrease of NG. Consumption vs. coke percent in the pilot plant (one induration period at Condition I).

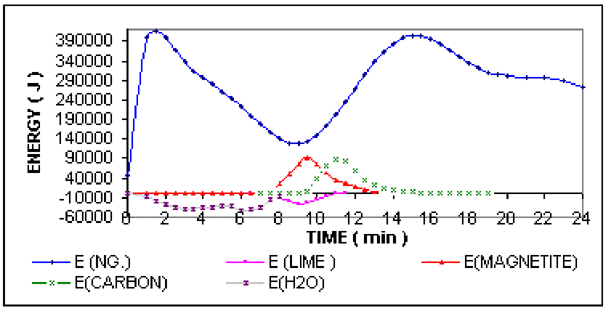


Figure 26. Simulated energy distribution in the pilot plant (Condition I).

10. RESULTS

The reduction, strength and sticking of pellets vs. the basicity (B_4) are checked with increasing the limestone in the pellet. The best Basicity for the maximum reduction of pellets (basket test and sticking test) and minimum sticking of pellets is obtained. Figures 5, 6 and 7 together show the variation of metallization and sticking of the

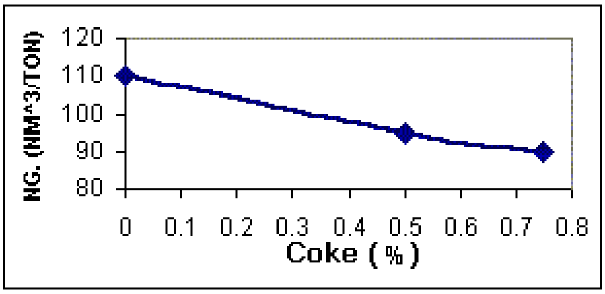


Figure 27. Experimental NG consumption in the pilot plant vs. coke percent (Condition I).

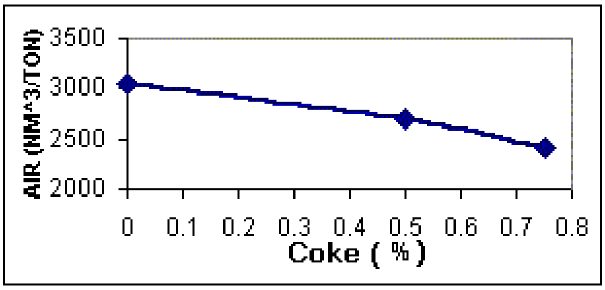


Figure 28. Experimental air consumption in the pilot plant vs. coke percent (Condition II).

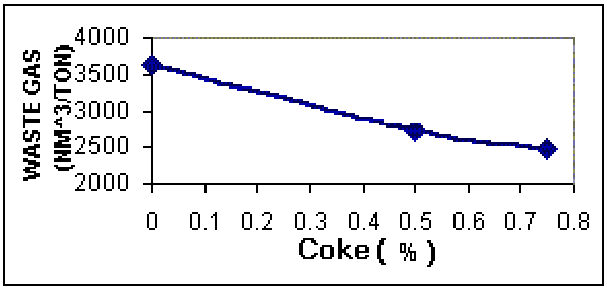


Figure 29. Experimental waste gas consumption in the pilot plant vs. coke percent (Condition II).

pellets vs. basicity.

The results of simulated gas temperature in the height of bed are shown in the Figure 8. The simulated and experimental results show the waste gas temperature in the height of 42 cm from the bottom of the bed, change between 35 to 50^{o}C and the results is shown in Figure 9. Results presented in Figure 10 are given for the thermocouples showing the temperature during updraft heating of the pellet bed, the agreement between the model and experiments is good. After drying time (up draft), the operation is stopped and the pellet humidity is measured at the different levels of bed and the results is shown in the Figure 11. Based on shrinking core method in the critical humidity condition, the wet core radius vs. time is shown in Figure 12. The comparison of experimental and simulated results of pressure drop and pellet temperature are shown in Figures 13 and 14. Also for the reactions of limestone, magnetite and carbon shrinking core are calculated and the results are shown in Figures 14, 15 and 16.

Figures 18 and 19 show the simulated and experimental percentage of carbon dioxide and oxygen in the waste gas. Percentage of carbon dioxide is increased due to limestone reaction and carbon oxidation. Also percentage of O_2 due to magnetite and carbon oxidation is decreased. Percentage of O_2 in the gas is important for oxidizing of magnetite and carbon in the pellet. The percentage of oxygen in the waste gas must be more than 15 %. Therefore oxygen injection in the pot grate test is needed (Condition III). The flow rate of pure oxygen is between 25 to 37 NM^3/hr after preheating condition is injected to the furnace. It would allow to add higher amounts of coke to iron ore pellets, without effecting the quality of the fired pellets. Special attention was given during these tests to the maximum amount of coke to tolerable for product quality and whether a lower heat or NG. Consumption and possible increase of the production rate could be achieved. Variation of abrasion index, cold compression pellet strength (c.c.s.) and porosity vs. coke percentage for three conditions (I, II, III) are shown in Figures 20, 21 and 22. The physical properties of fired pellets after oxygen injection are improved. Porosity is very important in reduction of fired pellets. Variation of metallization vs. coke percent for the basket test (actual Midrex plant) and Linder test (pilot plant scale) is shown in Figure23.

Experimental results indicated a slightly higher reducibility caused by coke addition. The higher reducibility and drop of the cold compression strength with increasing coke addition are most certainly the result of the higher porosity of the fired pellets. For the coke percentage less than one, value of abrasion index is less than 4.6 percent. Experimental results show that if percentage of coke is selected more than 1.15 % then cold compression pellet strength is decreased to 300

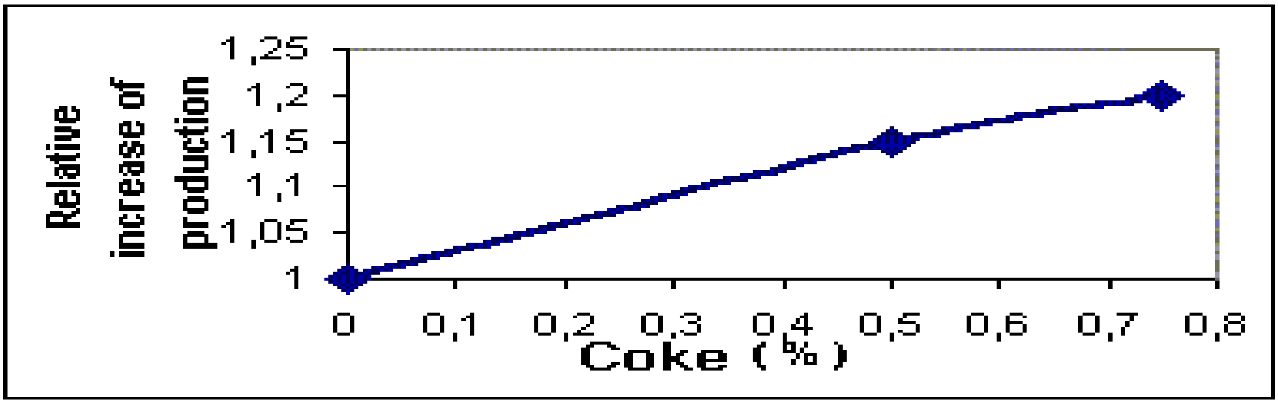


Figure 30. Experimental relative production vs. coke percent in pilot plant (Condition II).

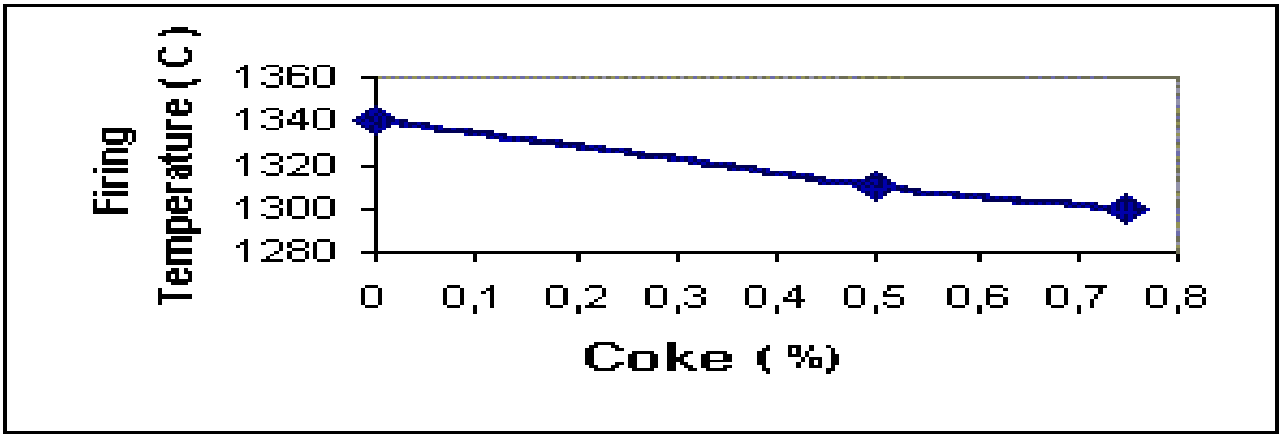


Figure 31. Experimental firing temperature vs. coke in the pilot plant (Condition II).

Kg/pellet. The best condition is seen for coke content of 0.75 %. Therefore model is run based on this percent.

Figure 24 shows electrical energy saving vs. percent of coke in ball mill because coke is soft material and blaine number is increased. Figure 25 shows the potential energy saving or natural gas consumption vs. percent of coke in pot grate test for one induration period in Condition I. Model is run based on 0.75 coke percent and then the result of induration energy distribution is shown in Figure 26 (pilot plant pot grate test). High moisture and limestone contents increase the energy consumption. It shows that the exothermic reaction same as magnetite and coke influences the natural gas consumption and the fans electrical energy consumption is reduced because the flow rates of air and waste gas is reduced. In the second condition; the inlet gas temperature and induration time is decreased. The results of energy saving due to natural gas, air and flue gas rate are shown in Figures 27, 28 and 29. Carbon dioxide intensity trends are closely related to energy intensity trends. Carbon dioxide emissions from pellet production are decreased.

During the past decade, interest in comparing energy use and greenhouse gas emissions trends between countries has grown in response to the many issues raised as a result of the United National Framework Convention Change (UNFCCC). Over 150 countries that to the goal of stabilizing greenhouse gas concentrations at a level that would prevent dangerous anthropogenic interference with the climate system signed the UNFCCC in 1992. In 1997, at the third conference of the parties (COP-3) to the UNFCCC in the Kyoto, Japan, the signatories agreed to the Kyoto Protocol that outlined emissions reduction targets [9]. Use of coke results is increase in production and decrease in firing gas temperature. The results are shown in Figures 30 and 31.

11. CONCLUSIONS

The model developed allows simulation of the heating, burning processes, water evaporation, magnetite oxidation, limestone decomposition and coke combustion in the pellet bed and the calculation of energy balance. The model can be used to simulate the suggested improvements of energy consumption in an industrial plant to predict any possible energy savings. A test pilot plant has been constructed for experiments on the comparison of the simulated and experimental temperature profiles under different operating conditions indicated an overall qualitative agreement.

It has been concluded that using a mixture of hematite and magnetite iron ore and 0.75 % coke in the pellet in comparison to the case of not using any coke would result in the following benefit.

1) Increase in production by 20 %
2) Fuel saving of about 18 %
3) Decrease of firing temperature by 40C^o
4) Air Consumption reduction by 21 %
5) Reduction of waste gas production by 32 %
6) Reduction of electrical energy needed for grinding by 7.3 %
7) The production of sponge iron is increased hence Porosity in the fired pellet is increased.
8) Lower operating temperature for grate system, refractories and insulation results in lower maintenance time and cost.
9) Reduction of flue gas emissions is a more environmental friendly achievement.

12. LIST OF SYMBOLS

a	Specific area (m^2 m^{-3})
C_P	Heat capacity of pellet (kJ)
C_g	Heat capacity of gas (kJ)
C_{O2}^{eq}	Concentration of oxygen at equilibrium (kmol.m^{-3})
C_{O2}	Oxygen concentration (kmol.m^{-3})
C_{CO2}	Carbon dioxide concentration (kmol.m^{-3})
C_{CO2}^{eq}	Carbon dioxide concentration at equilibrium condition (kmol m^{-3})
ΔH^o_i	Enthalpy of reaction i (J.mol^{-1})
ΔH^o_v	Enthalpy of reaction i (J kg^{-1})
d_p	Pellet diameter (m)
D_j	Diffusivity of j component through pellet (m^2/sec)
$D_{eff.,i}$	Effective diffusion i component (m/sec^2)
G	Mass flow density (kg .m^{-2}.sec^{-1})
h	Heat transfer coefficient (kJ $m^{-2}sec^{-1}$ k^{-1})
K_{eq}	Equilibrium constant of limestone (atm)
K_p	Conduction heat transfer (J.$m^{-1}k^{-1}sec^{-1}$)
K_f	Rate constant reaction (m sec^{-1})
k_d	Mass transfer coefficient (m sec^{-1})
k_m	Mass transfer coefficient of humidity (m sec^{-1})
L	Height of pellet bed (m)
N_1	Number of pellets per unit volume (m^{-3})
p	Pressure (atm)
r^o_{Lime}	Rate of limestone (kmol. one $pellet^{-1}sec^{-1}$)
r^o_{mag}	Rate of magnetite (kmol .one pellet $^{-1}sec^{-1}$)
r^o_{carbon}	Rate of carbon (kmol .one $pellet^{-1}$ sec^{-1})
r_0	Outer radius of pellet (m)
r	Radius of pellet (m)
R	Universal gas constant (atm.m^3kmol^{-1}. K^{-1})
$r_m(t)$	Radius of magnetite core in pellet (m)
$r_1(t)$	Radius of limestone core in pellet (m)
$r_c(t)$	Radius of carbon core in pellet (m)
T	Temperature (^{o}C)
T_s	Pellet temperature (^{o}C)
x	Bed axial distance (m)
W_p	Pellet humidity (kg_{H2O}.m^{-3})
W_g	Gas humidity (kg_{H2O}.m^{-3})
W_p^e	Equilibrium pellet humidity (kg_{H2O}.m^{-3})
W_g^e	Equilibrium gas humidity (kg_{H2O}.m^{-3})
ρ_g	Gas density (kg.m^{-3})
ε	Void fraction of bed (m^3 of void m^{-3} bed)
ε_p	Pellet porosity

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