Static Heat Energy Balance Mathematical Model for an Iron Blast Furnace

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Abstract: In this study a static heat energy balance analysis has been carried out for an iron blast furnace. The objective of this work is to provide a mathematical calculation model of the heat distributions for the various components of the blast furnace. The model presented, is also indicative to the amount of excess fuel being charged. To prepare a proper heat balance, the first step is to attain a proper mass balance calculation. To do so, each input and output materials has been analysed, and the respective elemental compositions have been calculated. All major components and reactions of a blast furnace have been included in the study. Each calculation has been done with sufficient details, to allow estimation of heat requirements, according to the working conditions of a blast furnace.

Keywords: Blast Furnace, Heat Energy Balance, Blast Furnace Reactions, Blast Furnace Efficiency

1. Introduction

Heat energy analysis is a very major study for the proper operation of a blast furnace. Heat balance is an account of the input and output of heat in a process, which follows the first law of thermodynamics. A proper heat balance not only helps to predict the efficiency of a furnace, but to also eliminate any excessive fuel wastages. Reduced fuel requirement not only reduces production costs, but more importantly saves a portion of our rapidly depleting natural resources. To get a proper heat balance, a proper material balance is a necessity. A material balance is simply an account of input and output of mass, governed by the law of conservation of mass. A proper material balance will provide accurate quantitative values, thereby simplifying calculations in each step of the heat balance. Besides this, a detailed study of each input and output components of the blast furnace has to be carried out, which includes: 1. Fuel Supplied; 2. Combustion Air or Hot Blast; 3. Blast Furnace Reactions; 4. Hot Metal; 5. Volatile Matter in Input Materials; 6. Moisture in Input Materials; 7. Blast Furnace Gas; 8. Dust Collected; 9. Blast Furnace Slag; 10. Cooling Water Supplied; 11. Other Heat Losses (Heat Loss through the tuyeres, Conduction, Convection, Radiation etc.).

A heat balance analysis for a continuous production blast furnace was presented by [1]. The authors gave a simplified model to calculate heat distributions for various components of the furnace. However, the authors did not provide any insight to the reactions occurring in the furnace. Also, no sub-divisions to the calculations were shown. Taking [1] as reference, the following study has been conducted to calculate exact heat distributions of each input and output component of the furnace, in detail. Various standard textbooks [2-5], and papers [11-14] have been referred to get an in-depth insight into the factors which should be taken into consideration, and the reactions taking place in the different regions of the furnace. The standard enthalpy of formation of compounds data has been taken from [6], the enthalpy data of elements and compounds at high temperatures has been taken from [7] and the heat of solution data has been taken from [8]. Composition analysis of all materials has been carried out using XRF analysis, and BF gas analysis has been carried out using Orsat absorption method.

2. Working of a Blast Furnace

A blast furnace is a huge, steel rack lined with refractory

bricks, which is used to convert iron oxide into pig iron. The blast furnace is an example of a counter current reactor where solids descend and gasses ascend. The fuel (coke, coal, nut coke) and other raw materials (iron ore, sinter, dunite, dolomite, quartzite) are weighed, and charged into the furnace from the top.

Coke is a mixture of coals, crushed and then heated to remove most of the volatile matter. Coke has higher calorific values due to the presence of more carbon content. Nut coke is smaller in size and has a lesser calorific value than coke. Sinter is produced by agglomerating iron ore fines with other plant wastages, having some iron percentages, such as screened sinter fines, flue dust and sludge from the blast furnace, and scales from mills. Limestone and dolomite are added to maintain the required basicity of sinter. Coke fines are used in the coke oven plant, to heat the iron ore fines along with the flux material, to form lumps of sinter. The iron ore is found in mainly two forms, Hematite (Fe_2O_3) and Magnetite (Fe_3O_4).

Air is collected from the atmosphere and heated to 1200°C with the help of giant hot blast stoves. From the stoves the hot combustion air is given sufficient oxygen enrichment, and supplied into the furnace at high pressure, through the tuyeres, as hot blast. The coke descends to the bottom of the furnace and is ignited by the hot combustion air blast. The coke reacts to produce CO_2 and heat, raising temperatures of the combustion region to around 1900°C. The wustite ore, having a high melting point, melts in this region. The CO_2 produced again reacts with excess C, to produce CO gas. This hot gas then moves upwards in the furnace reducing the iron oxides and the other input materials. Other than reduction by CO gas (Indirect Reduction), other reducing processes are reduction by C (Direct Reduction) and reduction by H_2. Dunite, dolomite and quartzite are slag producing agents, which produce slag along with iron ore impurities such as alumina and silica, and help in the removal of elements like sulphur and phosphorus. The raw materials require around 6 to 8 hours to descend to the bottom of the furnace, as the final products: hot metal and slag. The hot metal and slag flow out of the blast furnace through the tapping hole. The hot metal flows through the runner and is collected in the ladles. The slag having a lesser density than that of the hot metal, separates out from the hot metal, as the slag runner is placed in a different direction. The slag is granulated by sprinkling water over it and later sent to cement factories, where it used as a raw material. During reactions, various other gases are produced at various levels inside the furnace. These gases leave the furnace and is known as Blast Furnace Gas (BF Gas). The BF gas carries small particulate matter (dust), which are removed by passing the gas through the Dust Catcher and then the Gas Cleaning Plant (GCP). The BF Gas carries significant amount of energy, and after removal of dust, is reused in various areas of the plant. The dust collected in the Dust Catcher and GCP is used as a raw material for sinter. Figure 1 shows a schematic diagram of a blast furnace plant.
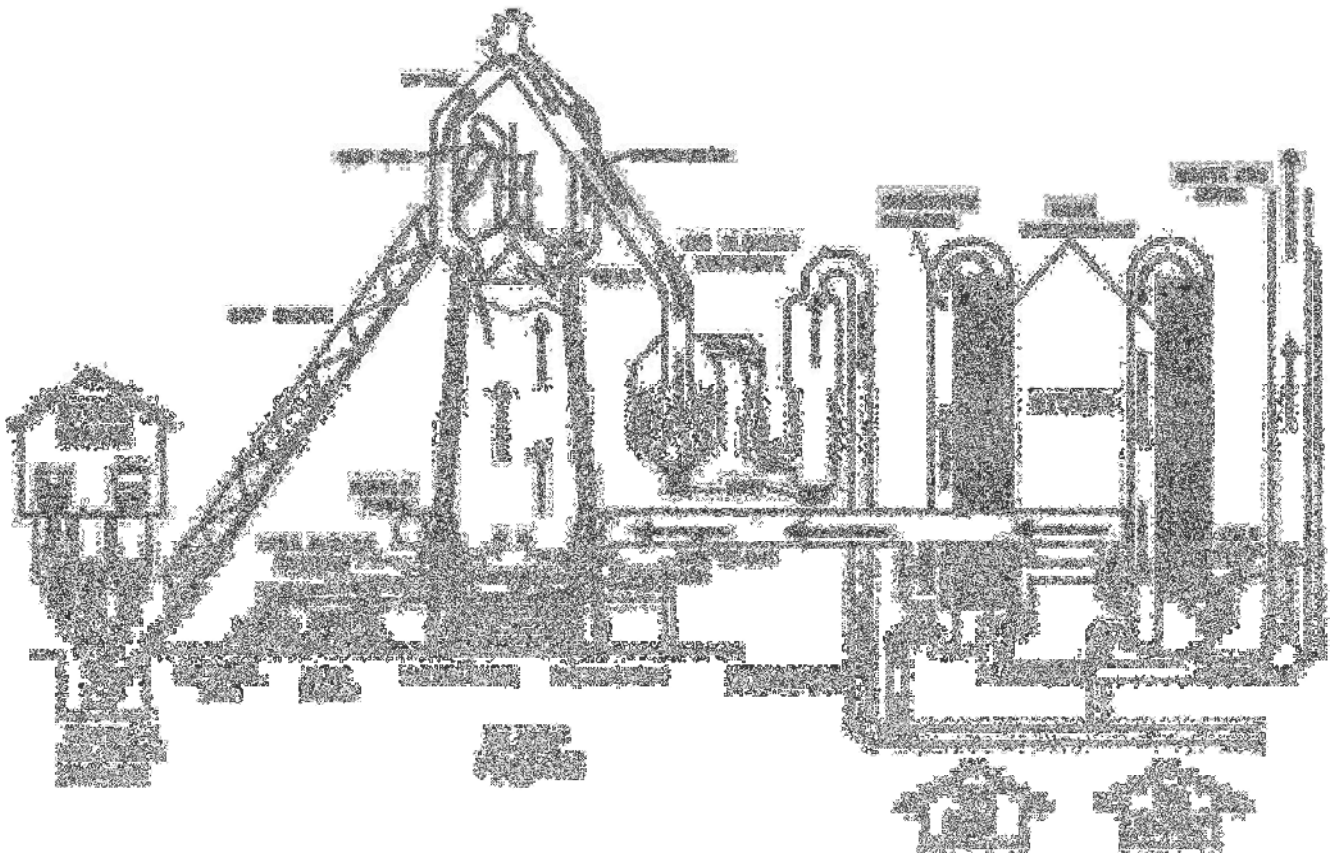

Figure 1. Schematic Diagram of Blast Furnace Plant [2].
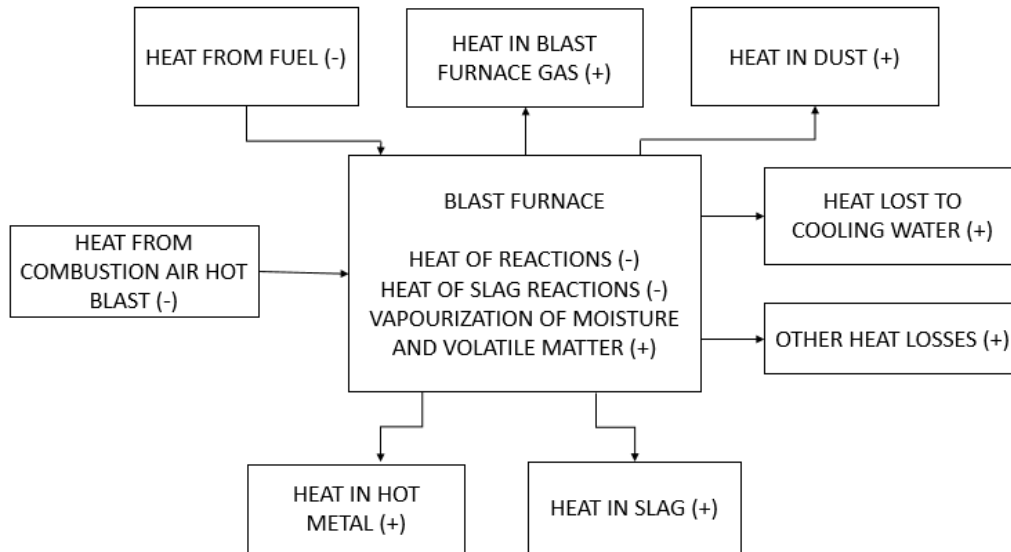
3. Heat Balance Calculations

Figure 2. Heat Energy Flow Diagram.

All data for the study has been taken from the month of April 2017. A heat energy flow diagram is shown in Figure 2 for a demonstration of the calculations. (-) sign indicates components which release heat, whereas (+) sign indicates heat absorbing components.

Hot Metal Production in April 2017= 48411 Tons

3.1. Fuel Analysis

The calorific values of coke, coal and nut coke are tested for

each batch, on arrival. These fuel analysis values have been taken for the fuel used in the month of April, 2017.

Quantity of Coke Consumed= 381 Kg/THM
Calorific Value of Coke= 7020 Kcal/Kg
Quantity of Coal Consumed= 130 Kg/THM
Calorific Value of Coal= 5605 Kcal/Kg
Quantity of Nut Coke Consumed= 19 Kg/THM
Calorific Value of Nut Coke= 6850 Kcal/Kg

Energy Generated from Coke Combustion (A1) = 381 Kg/THM * 7020 Kcal/Kg
= 2674620 Kcal/THM
Energy Generated from Coal Combustion (A2) = 130 Kg/THM * 5605 Kcal/Kg
= 728650 Kcal/THM
Energy Generated from Nut Coke Combustion (A3) = 19 Kg/THM * 6850 Kcal/Kg
= 130150 Kcal/THM
Total Energy Generated from Fuel Input = A1+ A2+ A3
= 3533420 Kcal/THM (-)

3.2. Combustion Air or Hot Blast Analysis

Volume of Moist Blast= 1181 m³/THM

It is taken that atmospheric air contains 21% Oxygen (O_2) and 79% Nitrogen (N_2). Also, 15 gm moisture is considered to be present per m³ of atmospheric air.

Quantity of H_2O in Moist Blast = 15 gm/m³*1181m³/THM
= 17715 gm/THM
= 984 moles/THM
= 21 m³/THM
Volume of Dry Blast= 1181 m³/THM - 21 m³/THM
= 1160 m³/THM
Steam is supplied to the combustion air at 21 gm/m³.
Total Volume of H_2O in combustion air = 21 gm/m³*1181m³/THM + 17715 gm/THM
= 42516 gm/THM
=2362 moles/THM
Oxygen Enrichment of 2.39% is given to the combustion air.

Volume of O_2 Enrichment given= 0.0239 * 1181 m³/THM
$$= 28 \text{ m}^3/\text{THM}$$
Total Volume of O_2 in combustion air= 244 m³/THM + 28 m³/THM
$$= 272 \text{ m}^3/\text{THM}$$
$$= 388576 \text{ gm/THM}$$
$$= 12143 \text{ moles/THM}$$
Total Volume of N_2 in combustion air= 916 Nm³/THM
$$= 1145508 \text{ gm/THM}$$
$$= 40911 \text{ moles/THM}$$
The complete combustion air composition results are shown in Table 1.

Table 1. *Combustion Air Composition Analysis.*

Element	H_2O	O_2	N_2
m³/THM	53	272	916
Moles/THM	2362	12143	40911

Latent Heat of H_2O (Liquid → Gas) (B1) = 42.5 Kg/THM * 540 Kcal/Kg
$$= 22950 \text{ Kcal/THM}$$
Sensible Heat of H_2O (298K → 1473K) (B2) = 2362 moles/THM * 11.14 Kcal/moles
$$= 26313 \text{ Kcal/THM}$$
Sensible Heat of O_2 (B3) = 12143 moles/THM* 9.37 Kcal/moles
$$= 113780 \text{ Kcal/THM}$$
Sensible Heat of N_2 (B4) = 40911 moles/THM * 8.93 Kcal/moles
$$= 365335 \text{ Kcal/THM}$$
Total Heat of all combustion air constituents = B1 + B2 + B3 + B4
$$= 528378 \text{ Kcal/THM (-)}$$

3.3. Composition Analysis

For simplicity in calculations, it has been assumed the input iron ore to be only in the form of Hematite (Fe_2O_3). The percentage compositions of the various input materials are studied using XRF analysis, which is carried out for every batch of input materials, on arrival. The values are of that input materials, used in the month of April 2017. Only the percentage composition of the elements, taken into consideration for this study, has been shown.

3.3.1. Iron Ore
Total Quantity Used= 28118 Tons
Moisture Content= 2.1% = 603 Tons = 12.46 Kg/THM = 692 moles/THM
Dry Weight= 27572 Tons
The iron ore composition analysis results is shown in Table 2.

Table 2. *Iron Ore Composition Analysis.*

Element	C	Fe_2O_3	SiO_2	P_2O_5	MnO	TiO_2	Al_2O_3
%	3.35	89.4	3.57	0.025	0.55	0.16	2.24
Kg/THM	19.45	509.11	14.73	0.66	2.62	0.93	13.01
Moles/THM	1621.45	3182	245.58	4.68	37	11.62	127.55

3.3.2. Sinter
Total Quantity Used= 53101 Tons
The sinter composition analysis results is shown in Table 3.

Table 3. *Sinter Composition Analysis.*

Element	Fe_2O_3	FeO	SiO_2	CaO	MgO	P_2O_5	MnO	TiO_2	Al_2O_3
%	66.28	10.23	3.57	11	2.26	0.037	0.35	0.16	2.65
Kg/THM	707.04	113.11	40.08	112.14	28.8	1.86	3.27	1.76	29.72
Moles/THM	4419	1571	668	2002.5	720	13.09	46	22	291.42

3.3.3. Dunite
Total Quantity Used= 1232 Tons
Moisture Content = 2.5% = 31 Tons = 0.64 Kg/THM =35.35 moles/THM

Dry Weight= 1201 Tons
The dunite composition analysis results is shown in Table 4.

Table 4. Dunite Composition Analysis.

Element	Fe_2O_3	$CaCO_3$	$MgCO_3$	SiO_2	Al_2O_3
%	4.5	0.88	44.36	36.25	0.98
Kg/THM	1.12	0.22	11.34	9	0.24
Moles/THM	7	2.18	135	150	2.38

3.3.4. Dolomite
Total Quantity Used= 324 Tons
Moisture Content= 0%
The dolomite composition analysis results is shown in Table 5.

Table 5. Dolomite Composition Analysis.

Element	$CaCO_3$	$MgCO_3$	SiO_2
%	43.62	33.6	12.4
Kg/THM	2.92	2.25	0.83
Moles/THM	29.2	26.85	13.77

3.3.5. Quartzite
Total Quantity Used= 238 Tons
Moisture Content= 2.5% = 6 Tons = 6.83 Moles/THM
Dry Weight= 232 Tons
The quartzite composition analysis results is shown in Table 6.

Table 6. Quartzite Composition Analysis.

Element	SiO_2	Al_2O_3
%	98	0.3
Kg/THM	4.68	0.01
Moles/THM	78	0.14

3.3.6. Coke
Total Quantity Used= 18445 Tons
Moisture Content= 221 Tons =1.2% =4.57 Kg/THM =254 moles/THM
Dry Weight= 18224 Tons
The coke and coke ash composition analysis results are shown in Table 7 and Table 8 respectively.

Table 7. Coke Composition Analysis.

Substance	Carbon	Ash	Inherent H_2O
%	86.7	12.35	0.95
Quantity (Tons)	15800 = 27198 moles/THM	2251	173 = 199 moles/THM

Table 8. Coke Ash Composition Analysis.

Element	SiO_2	Fe_2O_3	CaO	MgO	MnO	TiO_2	P_2O_5	Al_2O_3
%	53.54	10.21	5.8	1.76	0.23	1.48	1.37	23.13
Kg/THM	24.9	4.8	2.68	1.62	0.11	0.69	0.64	14.79
Moles/THM	415	30	48	40.46	1.5	8.6	4.5	145

3.3.7. Coal
Total Quantity Used= 6301 Tons
Moisture Content= 8% = 504 Tons= 10.41 Kg/THM = 578.38 moles/THM
The coal and coal ash composition analysis results are shown in Table 9 and Table 10 respectively.

Table 9. Coal Composition Analysis.

Substance	Carbon	Volatile Matter	Ash	Inherent H_2O
%	69.22	19.47	10.11	1.2
Quantity (Tons)	4361.55 = 7507.85 moles/THM	1227 = 25.34 Kg/THM	637	75.61 = 86.77 moles/THM

Table 10. Coal Ash Composition Analysis.

Element	SiO$_2$	Fe$_2$O$_3$	CaO	MgO	MnO	TiO$_2$	P$_2$O$_5$	Al$_2$O$_3$
%	43.04	6.69	5.96	1.31	0.04	1.28	1.17	35.89
Kg/THM	48.22	8.71	7.76	2.5	0.05	1.66	0.87	8.8
Moles/THM	803.65	54.42	138.52	62.63	0.73	20.82	6.12	86.29

3.3.8. Nut Coke

Total Quantity Used= 985 Tons
Moisture Content= 8% =83 Tons =1.71 Kg/THM =95.24 moles/THM
Dry Weight= 902 Tons
The nut coke and nut coke ash composition analysis results are shown in Table 11 and Table 12 respectively.

Table 11. Nut Coke Composition Analysis.

Substance	Carbon	Ash	Inherent H$_2$O
%	86.7	12.35	0.95
Quantity (Tons)	782 = 1346.11 moles/THM	111.4=2.3 Kg/THM	8.6 = 9.83 moles/THM

Table 12. Nut Coke Ash Composition Analysis.

Element	SiO$_2$	Fe$_2$O$_3$	CaO	MgO	MnO	TiO$_2$	P$_2$O$_5$	Al$_2$O$_3$
%	53.54	10.21	5.8	1.76	0.23	1.48	1.37	23.13
Kg/THM	1.83	0.23	0.13	0.04	0.05	0.03	0.03	2.36
Moles/THM	30.46	1.47	2.38	1.01	0.7	0.42	0.22	5.21

3.4. Hot Metal Analysis

Temperature of Hot Metal= 1464°C = 1737 K
The hot metal composition analysis results is shown in Table 13.

Table 13. Hot Metal Composition Analysis.

Element	Si	Mn	P	Ti	C
%	0.61	0.42	0.162	0.065	4.42
Kg/THM	6.1	4.2	1.62	0.65	44.2
Moles/THM	218	76.36	52.26	13.54	3684

3.4.1. Silicon

Quantity of Si in Hot Metal= 218 moles/THM
Sensible Heat of Si in Hot Metal (C1) = 218 moles/THM * 21 Kcal/moles
                       = 4578 Kcal/moles
Heat of Solution of Si (C2) = 218 moles/THM * - 28.5 Kcal/mole
                 = - 6213 Kcal/mole

3.4.2. Manganese

Quantity of Mn in Hot Metal = 76.36 moles/THM
Sensible Heat of Mn in Hot Metal (C3) = 76.36 moles/THM * 17.89 Kcal/mole
                     = 1366.08 Kcal/THM
Heat of Solution of Mn (C4) = 76.36 moles/THM * 1.2 Kcal/mole
                 = 91.63 Kcal/THM

3.4.3. Phosphorus

Quantity of P in Hot Metal = 52.26 moles/THM
                = 26.13 moles/THM {2P→P$_2$}
Sensible Heat of P in Hot Metal (C5) = 26.13 moles/THM * 46.266 Kcal/mole
                   = 1209 Kcal/THM
Heat of Solution of P (C6) = 26.13 moles/THM * - 29.2 Kcal/mole
              = - 763 Kcal/mole

3.4.4. Titanium

Quantity of Ti in Hot Metal = 13.54 moles/THM
Sensible Heat of Ti in Hot Metal (C7) = 13.54 moles/THM * 11.38 Kcal/mole
                   = 154.08 Kcal/THM

Heat of Solution of Ti (C8) = 13.54 moles/THM * -13.35 Kcal/mole
$$= - 180.76 \text{ Kcal/THM}$$

3.4.5. Carbon

Quantity of C in Hot Metal = 3684 moles/THM
Sensible Heat of C in Hot Metal (C9) = 3684 moles/THM * 8.84 Kcal/mole
$$= 32566.56 \text{ Kcal/THM}$$
Heat of Solution of C (C10) = 3684 moles/THM * 7.645 Kcal/mole
$$= 28164.18 \text{ Kcal/mole}$$
The carbon entering into the hot metal, enters as elemental carbon. As it is considered all carbon to be undergoing oxidation in the furnace, the reversible reaction is taken to indicate the release back of elemental carbon.
$$CO_2 \rightarrow C + O_2 \qquad \Delta H_{Reaction} = 94.14 \text{ Kcal/mole}$$
Latent Heat of Elemental Carbon (C11) = 3684 moles/THM * 94.14 Kcal/mole
$$= 346811.76 \text{ Kcal/mole}$$

3.4.6. Iron

Quantity of Fe in Hot Metal= 941.752 Kg/THM
$$= 16817 \text{ moles/THM}$$
Sensible Heat of Fe in Hot Metal (C12) = 16817 moles/THM * 17.171 Kcal/mole
$$= 288764.71 \text{ Kcal/THM}$$
Heat of Solution of Fe= 16817 moles/THM * 0 Cal/mole
$$= 0$$
Total Heat of all elements in Hot Metal =C1+C2+C3+C4+C5+C6+C7+C8+C9+C10+C11+C12
$$= 696730 \text{ Kcal/THM (+)}$$

3.5. Volatile Matter

Assuming all volatile matter to be phenol. [4]
Heat Capacity of Phenol= 122 Kcal/Kg
Heat of vaporization of coal volatile matter = 25.34 Kg/THM * 122 Kcal/Kg
$$= 3091.48 \text{ Kcal/THM (+)}$$

3.6. Moisture in Input Materials

Total Moisture content in all input materials = 1662 moles/THM
$$= 30 \text{ Kg/THM}$$
Sensible Heat absorbed by moisture (E1) = 1662 moles/THM * 1.353 Kcal/mole
$$= 2249 \text{ Kcal/THM}$$
Latent Heat of Evaporation of Water = 540 Kcal/Kg
Heat Lost in evaporation of moisture (E2) = 30 Kg/THM * 540 Kcal/Kg
$$= 16200 \text{ Kcal/THM}$$
Total Heat Lost in evaporation of moisture = E1 + E2
$$= 18449 \text{ Kcal/THM (+)}$$

3.7. Blast Furnace Gas (BFG)

Quantity of BFG = 1702 m³/THM
Calorific Value of BFG= 870 Kcal/m³
Temperature of Blast Furnace Gas= 179°C = 452 K
The blast furnace gas composition analysis results is shown in Table 14.

Table 14. Blast Furnace Gas Composition Analysis.

Element	CO	CO_2	O_2	N_2	H_2
%	23.74	20.09	0.71	53.41	2.05
m³/THM	404	342	12	909	35
Moles/THM	18024	15257	536	40580	1564

Latent Heat of BFG = Quantity * Calorific Value
$$= 1702 \text{ Nm}^3/\text{THM} * 870 \text{ Kcal/Nm}^3$$
$$= 1480740 \text{ Kcal/THM (+)}$$

Sensible Heat of CO (F1) = 18024 moles/THM * 1.07 Kcal/moles
= 19285.68 Kcal/THM
Sensible Heat of CO_2 (F2) = 15257 moles/THM * 1.51 Kcal/moles
= 23038.07 Kcal/THM
Sensible Heat of O_2 (F3) = 536 moles/THM * 1.11 Kcal/moles
= 594.96 Kcal/THM
Sensible Heat of N_2 (F4) = 40580 moles/THM * 1.09 Kcal/moles
= 44232.2 Kcal/THM
Sensible Heat of H_2 (F5) = 1564 moles/THM * 1.06 Kcal/moles
= 1657.84 Kcal/THM
Total Sensible Heat of all elements in BFG = F1 + F2 + F3 + F4 + F5
= 88809 Kcal/THM (+)

3.8. Dust Analysis

Dust Formation Temperature= 1400K

The dust formation temperature is taken as 1400 K as the reactants with the dust, undergo reaction only after reaching the desired temperature. Also, dust is produced after a reaction, hence the calculation for sensible heat of dust will take into consideration the temperature in which a reaction takes place. Other than the mentioned compounds, dust also contains nominal amounts of MnO, TiO_2, P_2O_5. The heat effects of these compounds can be neglected. Table 15 shows the composition analysis results for the dust collected in dust catcher, and Table 16 shows the composition dust analysis results for the dust collected in gas cleaning plant.

3.8.1. Dust Catcher
Quantity of Dust Collected in Dust Catcher= 728 Tons

Table 15. Composition of Dust Collected in Dust Catcher.

Element	C	Fe_2O_3	SiO_2	Al_2O_3	CaO	MgO
%	12.1	68.24	6.84	5.84	2.55	1.37
Kg/THM	1.82	10.25	1.04	0.88	0.38	0.23
Moles/THM	151.65	64.12	17.29	8.55	6.71	5.72

Sensible Heat of C (G1) = 151.65 moles/THM * 4.99 Kcal/mole
= 757 Kcal/THM
Sensible Heat of Fe_2O_3 (G2) = 64.12 moles/THM * 37.65 Kcal/mole
= 2414 Kcal/THM
Sensible Heat of SiO_2 (G3) = 17.29 moles/THM * 17.64 Kcal/mole
= 305 Kcal/THM
Sensible Heat of Al_2O_3 (G4) = 8.55 moles/THM * 30.8 Kcal/mole
= 263 Kcal/THM
Sensible Heat of CaO (G5) = 6.71 moles/THM * 13.43 Kcal/mole
= 90 Kcal/THM
Sensible Heat of MgO (G6) = 5.72 moles/THM * 12.57 Kcal/mole
= 72 Kcal/THM
Total Sensible Heat of Dust Collected in Dust Catcher (P8) = G1 + G2 + G3 + G4 + G5 + G6
= 3901 Kcal/THM

3.8.2. Gas Cleaning Plant
Quantity of Dust Collected= 478 Tons

Table 16. Composition of Dust Collected in Gas Cleansing Plant (GCP).

Element	C	Fe_2O_3	SiO_2	Al_2O_3	CaO	MgO
%	23.48	52.66	7.62	6.03	2.5	2.22
Kg/THM	2.32	5.2	0.75	0.95	0.25	0.22
Moles/THM	193.2	32.5	12.51	5.92	4.41	5.48

Sensible Heat of C (G7) = 193.2 moles/THM * 4.99 Kcal/mole
= 964 Kcal/THM
Sensible Heat of Fe_2O_3 (G8) = 32.5 moles/THM * 37.65 Kcal/mole
= 1224 Kcal/THM

Sensible Heat of SiO_2 (G9) = 12.51 moles/THM * 17.64 Kcal/mole
$$= 221 \text{ Kcal/THM}$$
Sensible Heat of Al_2O_3 (G10) = 5.92 moles/THM * 30.8 Kcal/mole
$$= 182 \text{ Kcal/THM}$$
Sensible Heat of CaO (G11) = 4.41 moles/THM * 13.43 Kcal/mole
$$= 59 \text{ Kcal/THM}$$
Sensible Heat of MgO (G12) = 5.48 moles/THM * 12.57 Kcal/mole
$$= 69 \text{ Kcal/THM}$$
Total Sensible Heat of Dust Collected in GCP (P9) = G7 + G8 + G9 + G10 + G11 + G12
$$= 2719 \text{ Kcal/THM}$$

The dust comes out of the furnace in elemental form. As it is considered all carbon to be undergoing oxidation in the furnace, the reversible reaction is taken to indicate the release back of elemental carbon.
$$CO_2(g) \rightarrow C(s) + O_2(g) \qquad \Delta H_{Reaction} = 94.14 \text{ Kcal/mole}$$
Latent Heat of Carbon Dust (P10) = (151.65 + 193.2 = 344.85) moles/THM * 94.14 Kcal/mole
$$= 32464 \text{ Kcal/THM (+)}$$
Total Heat in Dust = P8 + P9 + P10
$$= 39084 \text{ Kcal/THM (+)}$$

3.9. Cooling by Water

Quantity of Water Supplied= 17014.3 Kg/THM
Rise in Temperature of water= 10℃
Heat Capacity of Water= 1 Kcal/Kg℃
Heat carried away by water= Mass * Heat Capacity * Temperature Difference
$$= 170143 \text{ Kcal/THM (+)}$$

3.10. Slag Analysis

Quantity of Slag Produced= 362.2 Kg/THM
The blast furnace slag composition analysis results is shown in Table 17.

Table 17. Slag Composition Analysis.

Element	SiO$_2$	Al$_2$O$_3$	FeO	CaO	MgO	TiO$_2$	MnO
%	33.36	18.57	0.73	34.53	9.32	0.91	0.83
Kg/THM	120.82	67.26	2.64	125.06	33.75	3.30	3
Moles/THM	2014	659	37	2233	844	41	42

The slag calculation is done taking reference from [1]. The values of [1] are selected, as the slag composition data is similar to that produced in the blast furnace, taken in the study.
Heat produced during slag formation= 362.2 Kg/THM * 140 Kcal/Kg-slag
$$= 50708 \text{ Kcal/THM (-)}$$
Sensible Heat of Blast Furnace Slag= 362.2 * [(1561℃ * 0.2741 Kcal/Kg℃) – (25°C * 0.185 Kcal/Kg℃)]
$$= 153299 \text{ Kcal/THM (+)}$$

3.11. Reactions

Table 18 shows the elements entering into the blast furnace for reactions, after excluding dust losses, carbon in hot metal and FeO in slag. The mentioned elements have been excluded in beforehand for more accuracy in results. The amounts excluded are taken from the respective composition sheets.

Table 18. Elements Entering the Blast Furnace for Reactions after Excluding Dust Losses, Carbon in Hot Metal and FeO in Slag.

Elements	Fe$_2$O$_3$	FeO	C	CaCO$_3$	CaO	MgCO$_3$	MgO
Moles/THM	7624	1534	33611	31	2202	162	856
Elements	**SiO$_2$**	**MnO**	**P$_2$O$_5$**	**TiO$_2$**	**H$_2$O**	**O$_2$**	**Al$_2$O$_3$**
Moles/THM	2232	118	31	67	2677	11607	659

The enthalpies of reactions, as shown in Table 19, are calculated according to the temperature in which the reaction takes place, by applying Kirchoff's equation (1).

$$(\Delta H_{Reaction})_{T2} = (\Delta H_{Reaction})_{T1} + [\sum (\Delta H_{T2} - \Delta H_{T1})_{Products} - \sum (\Delta H_{T2} - \Delta H_{T1})_{Reactants}] \qquad (1)$$

where, T2 is the temperature at which the reaction takes place and T1 is the standard temperature of 298K. Figure 3 shows the different temperature zones in a blast furnace.
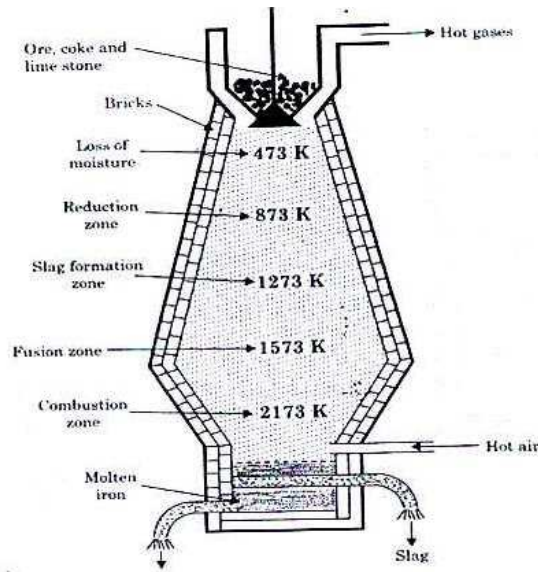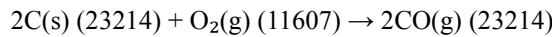

Figure 3. *Temperature Zones in a Blast Furnace.*

The CO produced, for the reduction of ores, is produced by the combustion of fuels at 1700 K.

$$2C(s) (23214) + O_2(g) (11607) \rightarrow 2CO(g) (23214)$$

The values in brackets is the number of moles of the substance undergoing reaction according to the mass balance shown in Table 18.

After performing various calculations, the reduction percentages are taken to be 60% Indirect Type (CO) Reduction, 35% Direct Type (C) and 5% reduction by Hydrogen (H_2), as this yields the most accurate results, as shown in Table 19. These percentages vary according to the operating conditions of the furnace. The percentages can be estimated by taking into consideration the BF Gas analysis.

Table 19. *Blast Furnace Reactions and Enthalpy.*

Reactions (Value in brackets indicate number of moles)	Temperature (K)	ΔH $_{Reaction}$ (Kcal/mole)	Total ΔH (Kcal)
C(s) (2677) + H_2O(g) (2677) → CO(g) (2677) + H_2(g) (2677)	1700	+32.1	+85931.7
$3Fe_2O_3$(s) (4574) + CO(g) (1525) → $2Fe_3O_4$(s) (3049) + CO_2(g) (1525)	1000	-12.47	-19012.59
Fe_3O_4(s) (3049) + CO(g) (3049) → 3FeO(s) (9147) + CO_2(g) (3049)	1200	+4.585	+13979.66
FeO(s) (9147 + 921 = 10068) + CO(g) (10068) → Fe(s) (10068) +CO_2(g) (10068)	1200	-3.85	-38761.8
$3Fe_2O_3$(s) (2668) + C(s) (889) → $2Fe_3O_4$(s) (1179) + CO(g) (889)	1400	+26.95	+23967.53
Fe_3O_4(s) (1179) + C(s) (1179) → 3FeO(s) (3537) + CO(g) (1179)	1400	+44.43	+52383
FeO(s) (3537 + 537 = 4074) + C(s) (4074) → Fe(s) (4074) +CO(g) (4074)	1700	+27.48	+111953.5
$3Fe_2O_3$(s) (381) + H_2(g) (127) → $2Fe_3O_4$(s) (254) + H_2O(g) (127)	1200	-46	-5842
Fe_3O_4(s) (254) + H_2(g) (254) → 3FeO(s) (762) + H_2O(g) (254)	1200	+12.45	+3162.3
FeO(s) (762 + 76 = 838) + H_2(g) (838) → Fe(s) (838) + H_2O(g) (838)	1300	+3.73	+3126
$CaCO_3$(s) (31)→ CaO(s) (31) + CO_2(g) (31)	1200	+39.42	+1222.02
$MgCO_3$(s) (162) → MgO(s) (162) + CO_2(g) (162)	700	+27	+4374
P_2O_5(s) (26) + 5C(s) (130) → 2P(s) (52) + 5CO(g) (130)	1700	+206	+5356
TiO_2(s) (13) + 2C(s) (26) → Ti(s) (13) + 2CO(g) (26)	1700	+129.36	+1681.68
MnO(s) (76) + C(s) (76) → Mn(s) (76) + CO(g) (76)	1700	+69.33	+5269.08
SiO_2(s) (218) +2C(s) (436) → Si(s) (218) + 2CO(g) (436)	1700	+158.89	+34638.02
CO(g) (1219) + H_2O(g) (1219) → CO_2(g) (1219) + H_2(g) (1219)	1000	-8.33	-20350.19
C(s) (910) + CO_2(g) (910) → 2CO(s) (1820) --------------------------------- (X)	**1300**	**+40.05**	**+36445.5**
Fe(s) (16780) → Fe(l) (16780)	1800	+3.56	+59737
∑ Summation of Enthalpies			**+359261**

Reaction X is the mass balancing equation to balance the excess C supplied (excess fuel).

Moles produced in the BF according to calculations:
CO = 18660; CO_2 = 15144

But the moles leaving the furnace in BF Gas:

CO = 18024; CO_2 = 15257

Difference in moles of CO =18660 – 18024 =636 (Excess)

Difference in moles of CO_2=15144 – 15257 =113 (Less)

This difference in the number of moles can be explained due to the other reactions taking place inside the furnace. It can be said that 113 moles of CO are reducing some other oxides (other than those taken in this study) to produce 113 moles of CO_2. Hence CO_2 balance will then be achieved. Excess CO (523) may be due to the following reasons: 1. Furnace having a lesser percentage of direct reduction (<35%). 2. Excess fuel supply (From reaction X)

Reaction X is indicative to the excess fuel supplied inside the furnace. Though some amount of excessive fuel is desirable in order, to maintain the working temperature of the furnace. High amount of excessive fuel would produce negative effects on the efficiency of the furnace. As from above, reaction X, is an endothermic reaction, so adding extra fuel will reduce the efficiency of the furnace and also disturb the CO/CO_2 gas balance, which is undesirable. In general, around 8-10 Kgs of fuel is supplied in excess to prevent cooling down of the furnace. However, any quantity more than this, is wastage of fuel and should be restricted.

4. Heat Energy Balance Sheet

The final heat energy balance sheet is shown in Table 20.

Table 20. *Heat Energy Balance Sheet.*

HEAT INPUTS		
Sources	**ΔH (Kcal/THM)**	**%**
Energy from Fuel	3533420	85.90
Energy from Combustion Air	528378	12.85
Energy from Slag Production	50708	1.25
Total Heat Input	**4112506**	**100**
HEAT OUTPUTS		
Sources	**ΔH (Kcal/THM)**	**%**
Sensible Heat of Hot Metal	696730	16.94
Sensible Heat in Volatile Matter	3091	0.07
Heat needed to vaporize Moisture	18929	0.46
Latent Heat in BF Gas	1480740	36.02
Sensible Heat in BF Gas	88809	2.15
Total Heat in Dust (Dust Catcher + GCP)	39084	0.95
Heat Carried away by Water	170143	4.14
Sensible Heat in Slag	153299	3.73
Summation of BF Reactions	359261	8.73
Calculated Heat Output	**3010086**	**73.19**
Other Heat Losses	**1102420**	**26.81**
Total Heat Output	**4112506**	**100**

5. Conclusion

A static heat energy balance mathematical model has been developed in this study. The model takes into consideration all the factors which play a significant role, in the heat requirements of a blast furnace. The calculations of the balance presented in the study will help to estimate the heat requirements of a furnace, and eradicate any excessive fuel supply. Individual percentage composition of each input and output component, taken in the study, would help to alter the quantity of supply of any component, for improving the efficiency. From the above calculations, one can account for approximately 73% of the heat supplied [Table 20]. This result is in accordance with the literature of heat energy balance for a blast furnace [3-5]. The remaining 27% can be explained as other heat losses taking place in the tuyere region [9-10], conduction, convection, radiation etc.

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