IRON MAKING IN ANCIENT INDIA - A CRITICAL ASSESSMENT

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Introduction

It is a well known fact, that Indian craftsman produced quality iron products much earlier than the developed countries, making use of local reserves of iron ore. Iron produced in ancient India was mostly wrought iron. The metal was obtained in the form of a pasty mass and then shaped under hammer. Today, when India is producing several million tons of iron, primitive iron making is still exists in some parts of India. The primitive iron making furnaces declined in numbers gradually from about 500 in the beginning of 20'h century to about 150 by the middle of the century. Their present number is not known. Such furnaces are in operation deep into the forests and the tribal areas of India. The paper discusses briefly the history of iron making along with the critical assessment of the ancient processes. Some of the important measures absolutely essential to upgrade the processes have also been discussed. Several pertinent modifications have been proposed in the design of these furnaces to make them more energy efficient and economically viable for tribal and rural populace.

History

Iron is an important metal to influence the march of civilisation in India. Early iron encountered by man was meteoritic iron, and it has been used by the man over at least 5000 years. The history of iron making by tribal artisans in various parts of India dates back to 1300 to 1200 BC. These tribal artisans such as *Asur, Charas, Birziya, Agarias* etc., earned their livelihood by steel scrap fabrication in the village and town and cater to local needs, Ancient Indian literature abounds in vivid descriptions of swords, spears and other steel weapons. Iron implements and weapons belonging to the 4'h century BC have been unearthed at Adittanathur in Tamil Nadu comprising of agricultural implements, tools for black smiths etc., Sushruta (3rd century BC), a great authority on medical science in ancient India described in his book a hundred different surgical instruments. The iron pillar of Delhi, a striking evidence of the skill attained by the early iron masters in India, is believed to have been constructed in the 4^{th} century AD. It is 24 feet (7375 mm) in height and estimated to weigh about six tonnes. The Dhar pillar of iron is much larger than the Delhi Pillar. Its length was about forty four feet (13310 mm) and is now laying broken in three pieces. There are several iron beams in the ancient temple of Konark probably built in the 9^{th} century. In the Jagannath temple of Puri in Orissa built in the 12^{th} century numerous iron beams exist. Descriptions of iron guns are available in 16^{th} century literature. Most Mughal guns weighed 30 to 40 tons and maximum length about 31 feet (9449 mm). Until the 13^{th}-14^{th} century AD, India was the only source of ingots of Wootz Steel essential for making the Damascus sword. These iron monuments like pillars at Delhi and Dhar, iron beam at Konark, Damascus sword are the testimonials of ancient metallurgical skill of India. These ancient iron implements, beams, monuments, etc., have drawn attention of metallurgists throughout the world over a long time.

History is a record of rise and fall of civilisations. India is no exception with the passage of time, the art in the manufacture of iron and steel in which Indians had attained such proficiency languished and dried. During the 18^{th} and 19^{th} centuries, some attempts were made to develop an iron and steel industry in India, but these proved a failure. However iron making was practiced widely in many parts of the country, basing on naturally available iron ore and charcoal for reduction. The class of people engaged in iron making came to be known as "*Lohars*". In the interiors, tribal were known to be practicing iron making in traditional furnaces. Thus, in various places in U.P., Bihar, Bengal, Orissa, Maharashtra, Madhya Pradesh, Mysore and Madras, the industry was active. The furnaces were small, up to 3 feet in height, and made of mud, with bellows being used to blow in air. In fact, the profile of a typical furnace used at Salem in the early 19^{th} century resembled the blast furnace in miniature. The indigenous (tribal) communities preserved these methods of iron making into the 20^{th} century in such regions as the hill of Vindhyachal and the Western Ghats. Most of furnaces used by tribal for extracting iron have many features in common. The ancient process of iron making is still in existence in a few interior parts of the country specifically in Bihar, Orissa, M.P., and some places in Southern India. These practices have undergone little change over the centuries and therefore reflect the ancient art of iron extraction.

The ancient industry is still in existence in many parts of the country, but the steadily increasing sales of agricultural implements into bazaars of remote places are gradually driving the smelters to seek employment elsewhere. There was a deadly blow dealt to this traditional industry by the enactment of the laws on the forest resources banning cutting off the trees and exploitation of mineral resources by the first dwellers.

NML's Role

The National Metallurgical Laboratory, a premier research organisation is engaged in documentation and development of iron making furnaces used by the tribals of India. In this context NML scientists recently visited tribal areas of Gumla district and documented in detail the traditional iron making process followed by the smelters there. It is essential to revive the ancient technique as a means to take the place of honour by reducing pollution caused by modern steel plants. It can reinstate the displaced tribals who have been rendered jobless. Being eco-friendly, Indian needs an appropriate technology today.

Ancient Processes of Iron Making

Primitive Furnaces

The ancient processes make use of two distinct types of furnaces in their operation, which differ in their physical form. The basic principle of operation is same for both. The First furnace is a shaft furnace and is fully subterranean while the second is partly subterranean and constructed over a rectangular pit. These furnaces are about 30 inch in height and their bottoms are concave, while the cylindrical furnace shafts rise up as chimneys. These furnaces are built of ordinary clay. The charge comprising of iron ore and charcoal is fed into the shafts. Figure 1 illustrates a primitive iron making furnace made of ordinary clay and bricks, with concave bottom and dome shaped. One clay pipe is inserted through a parabolic opening in the bottom of the furnace which acts as a tuyere. The opening through which the tuyere is introduced is then luted with clay. The dimensions of a typical primitive furnace are given in Table 1.

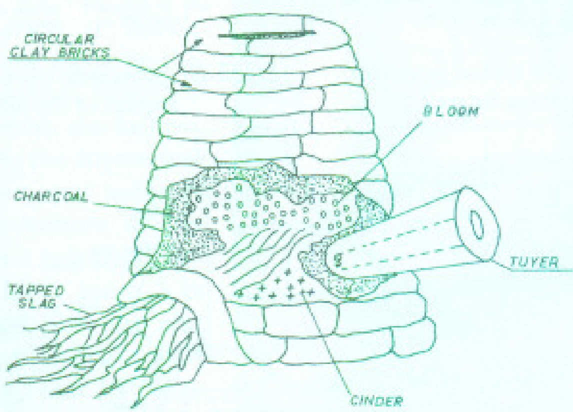

Fig. 3.1: Schematic representation of a primitive iron making furnace

Table 1: Dimensions of a typical primitive iron making furnace

Different parts of the furnace	Inches
Total height, bottom to top of chimney	30
Height of chimney	13
Internal diameter of chimney	5.5
Height of semi-spherical dome from the bottom of the furnace	17
Depth of the basin underground	9
Diameter of the basin on the ground level	12
Width of the wall	3.5
Height of the front parabolic opening from the ground level	12
Width of the opening at the ground level	6
Length of the tuyere	6-8
Internal diameter of the tuyere	1-1.5
Thickness of the tuyere wall	0.25

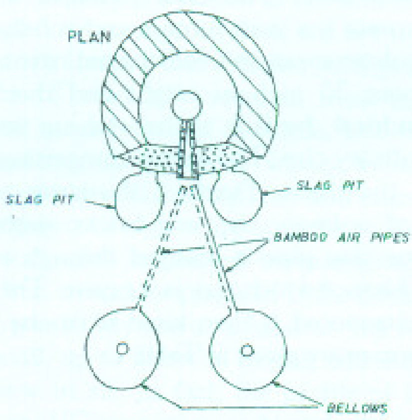

Fig. 3.2a: Plan of a typical primitive iron making furnace

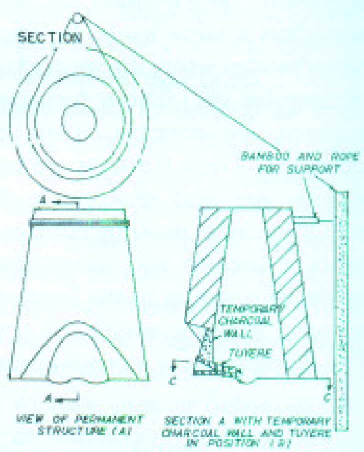

Fig. 3.2b: Schematic representation of section of the furnace

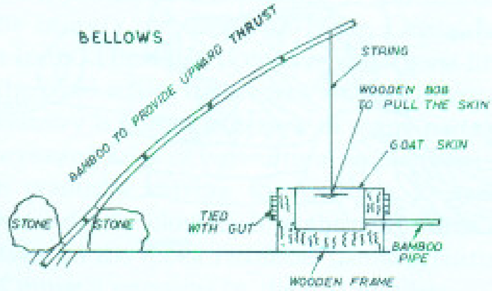

Fig. 3.2c: Schematic representation of the bellows of the furnace

Another primitive iron making furnace comprising of the foot operated bellows is shown in Figure 3.3. The air blast from bamboo pipes enter through the tuyeres. A temporary charcoal wall exists around the tuyeres. The Figures 3.2a, 3.2b and 3.2c represent the plan of the furnace, the section of the furnace and the foot operated bellows respectively. Air is blown into the furnace through a tuyere using a pair of feet operated bellows with a foot on either of these bellows and a stick to serve the dual purpose of support and for maneuvering the solid charge on the top of the furnace, the operator makes a walking action in standing position. Air is let into a wooden chamber during the upward movement and forced through hollow bamboo pipes by pressing the goat skin cover during the downward movement of his feet. The goat skin cover is regularly wetted with water for effective scaling of the air-entry hole by the sole of the foot. The bamboo pipes blow the air into the mouth of the tuyere and a considerable amount of additional air is dragged in, from the surroundings due to the force of the blow.

Operation of Primitive Furnaces

Glowing charcoal are introduced into the hearth before introducing the tuyere. The furnace is then filled up with charcoal. Air is blown through foot bellows. When the furnace gets hot, a mixture of fresh charcoal and iron ore is charged and the blowing continues. Generally a total charge of about 15 kg of iron ore is worked in 5-6 hours and slag is drawn through a hole made by the side of the tuyere. After 5-6 hours operation, the bellows are removed, the tuyere seal is broken out, and lump of iron in the bottom of the Furnace is removed by tongs. This lump is contaminated with slag and charcoal. It is wrought with hammer so that a large portion of the slag is squeezed out. The mass is then used for making imple-

Fig. 3.3: A traditional furnace in operation

ments or utensils. Under these conditions of operation, no liquid metal is found. The temperature obtained in the hearth is rather low. It does not permit melting to rake place. As such molten iron would not serve any purpose as it cannot be wrought. Figure 3.3 shows an ancient iron making furnace in operation. It comprises of the root operated bellows.

Raw Materials Used in Primitive Furnaces

No flux is used by any of the primitive iron makers. The Charge mix mainly comprises of iron ore and charcoal as shown in Figure 3.4.

Fig. 3.4: Charcoal and iron ore lumps

The ore is generally broken into the size of peas for use in the furnaces. The analyses or the iron ores from different places employed in these furnaces are given in Table 2. Hard charcoal, preferably made from sal wood is used. The wood is burnt in open heaps, the fire is quenched and the charcoal is removed. The analyses of the charcoal from Jiragora and Chinglebecha are given in Table 3.

Table 2: Chemical analysis of iron ore

Ironore	Jiragora (Koraput) (%)	Chinglebecha (Koraput) (%)	Pondo Iron Ore (%)	Chawaria Iron Ore (%)	Kamarjoda (near Jamshedpur) (%)
SiO2	2.44	14.32	6.00	13.10	Total Fe=70
A1203	1.66	6.72	5.52	2.68	
TiO2	--	--	0.70	0.10	
Fe2O3	90.57	78.57	79.22	69.22	
CaO	0.50	--	0.30	--	
MgO	0.20	--	0.22	1.15	
MnO	0.90	--	0.49	0.70	
LIO	3.70	0.40	7.52	13.00	

Table 3: Chemical analysis of charcoal

Charcoal	Jiragora (Koraput) (%)	Chinglebecha (Koraput)(%)	Kamarjoda (%)
Ash	3.20	3.60	1.40
V.M.	21.00	13.10	-
F.C.	75.00	83.30	-

Analysis of the Products

The products made in these primitive furnaces are heterogeneous. They vary in carbon content and the quality of entrapped slag. The chemical analyses of iron from the furnace before forging and purification are given in Table 4, and of that purified by repeated forging in Table 5. The chemical analyses of slag are given in Table 6, while the mechanical properties and the details of microstructure of wrought iron are given in Table 7.

Table 4: Chemical analyses of iron from the furnace before forging and purification

Chiglebecha (%)		Kamajoda (%)	
Metallic Fe	44.40	C	3.40
FeO	20.38	Mn	0.03
Fe_2O_3	3.29	S	0.013
SiO_2	20.87	P	0.032
Al_2O_3	8.02	Si	0.19
CaO	1.40	Fe	Balance
MgO	0.72	-	-

Table 5: Chemical analysis of iron purified by repeated forging

	Chinglebecha (%)	Jiragora (%)	Kamarjoda (%)
C	-	0.23	0.59
Mn	-	Not traceable	Trace
S	-	0.006	Trace
P	-	0.015	0.013
Si	-	0.010	0.080
Recovery	10.10	15.50	8.7

Table 6: Chemical Analyses of Slag

Chinglebecha		Jiragora	Kamarjoda
Slag that flowed out (%)	Slag that remained in the furnace (%)	Slag from the furnace (%)	Slag from the furnace (%)
Metallic Fe- 1.00	2.10	SiO_2-27.08	Metallic Fe-16.00
FeO-58.43	12.27	Al_2O_3-6.72	FeO-55.34

Fe_2O_3-8.72	1.86	CaO-5.00	Fe_2O_3-1.14
-	-	MgO-1.16	-
-	-	P_2O_5-1.026	-
-	-	SiO_2-0.075	-
-	-	Total Fe-46.00	-

Table 7: Mechanical properties and microstructure of typical wrought iron produced at Chinglebecha

Mechanical Properties		Microstructure Exhibiting
UTS	456 MPa	Wide variation in the carbon content &
Elongation	17.5%	Considerable amount of non-metallic substances
Reduction in area	40.0%	---

Ancient Iron Making Processes - A Critical Analysis

Inspite of the very disturbing colonial intervention some of our tribal communities such as *Agariya* of Mandala, Rajnadgaon and Bilaspur district of Madhya Pradesh are still practicing the indigenous way of iron making. The *Asur* tribe of Santhal Pargana, Bihar is also practicing indigenous way of iron making. Most of the Indian iron smelting furnaces used wood charcoal at various places in India such as M.P., Bihar, U.P., Rajasthan and Southern regions. The artisans had their own judgment of temperature required in furnace, slap out timing, iron ore reduction, quality of charcoal, ore etc. No doubt the traditional processes are scientific; however the yield and reproducibility are poor. Under identical operating conditions, there is a considerable variation in the yield of the wrought sponge. The ancient processes of iron making are having low productivity since a substantial percentage of iron is lost in the slag. Sufficient amount of air is not blown into the furnace due to inadequate air blast system. The amount of reductant (charcoal) used is much more than the stoichiometric requirement. The fuel/charcoal consumption rate is quite high, about 5 to 6 kg/kg of wrought sponge. The temperature obtained in the hearth of the furnace is rather low. The droplets of metal during falling down to the hearth, came in contact with cold air and are immediately frozen. Since water is being sprinkled on the skin of the bellows to keep them soft, a portion of this water is likely to enter the hearth and reduces the temperature. There is no proper separation of slag and metal and the end product is semi-viscous mass. Since flux is not used, the gangue materials do not fuse at lower temperature and the chance of contamination is more. Due to insufficient availability of reducing gas and lower temperature, the iron ore remains unreduced or partially reduced. Due to lower temperature, fused mass of iron has no fluidity and more slag metal contamination takes place.

These ancient iron making furnaces varied in design in different parts of India and generally had a capacity of 5 to 10 kg per heat. They were repeatedly used after minor repairs. The iron produced in these furnaces was taken out in the form of hot bloom by breaking the front wall and forged to squeeze out the molten slag. No doubt the ancient iron makers had gained high degree of skill and knowledge through ages without the assistance of any modern scientific tools or metallurgical information.

Mechanism of Iron Ore Reduction - Thermodynamic and Kinetic Aspects

The thermodynamics of iron oxide reduction deals primarily with the equilibrium between its oxides and reducing agent (charcoal). The reduction of iron by carbon monoxide beginning with ferric oxide takes place in three stages at temperature above 570^0 C.

$$Fe_2O_3 \xrightarrow{1} Fe_3O_4 \xrightarrow{2} FeO \xrightarrow{3} Fe$$

These three reactions with their heats of reaction at 25^0 C are as follows:

$$3Fe_2O_3 + CO \rightarrow 2Fe_3O_4 + CO, \ \Delta H = -12636 \text{ calories} \quad (I)$$

$$Fe_3O_4 + CO \leftrightarrows 3FeO + CO, \ \Delta H = 8664 \text{ calories} \ (2)$$

$$FeO + CO \leftrightarrows Fe + CO_2 \ \Delta H = -4136 \text{ calories} \quad (3)$$

Reactions 1 and 3 are exothermic whereas reaction 2 is endothermic. Since wustite is metastable below 570^0 C, the iron oxide reduction takes place in two stages at low temperatures. The magnetite produced in first stage is reduced to iron bypassing the wustite stage.

$$\tfrac{1}{4}Fe_3O_4 + C0 = \tfrac{3}{4}Fe + CO_2, \ \Delta H = -936 \text{ calories} \quad (4)$$

This reaction is also exothermic. Generally most direct reduction processes operate at a temperature in excess of 600^0 C and the reduction of metastable wustite is only of minor interest. Figure 5 illustrates the equilibrium gas compositions versus temperature diagram for the iron-carbon-oxygen system. This figure shows four curves, one each for reactions 1. 2. 3 and 4. The figure also contains the curve showing the CO-$C0_2$ composition and temperature equilibrium for the reaction.

$$CO_2 + C = 2CO, \ \Delta H = 41220 \text{ cal/mole carbon} \quad (5)$$

Reaction 5 plays very important role in iron oxide reduction. The oxygen potential of the gas phase can be conveniently represented by $CO/C0_2$ ratio. If a gas phase containing CO and CO_2 is in contact with iron oxide, the possibility and extent of its reduction could be ascertained from the knowledge of its $CO/C0_2$ ratio and the temperature. If the temperature is 800^0 C and the gas phase contains 20% CO and 80% $C0_2$, magnetite is stable phase and reaction 1 will proceed to the right to reduce hematite to magnetite and reactions 2 and 3 will proceed to the left oxidising iron and wustite to magnetite. Likewise, if the temperature is

800°C and the gas composition is 80% CO and 20% CO_2, all types of oxides of iron namely hematite, magnetite and wustite will be reduced to iron.

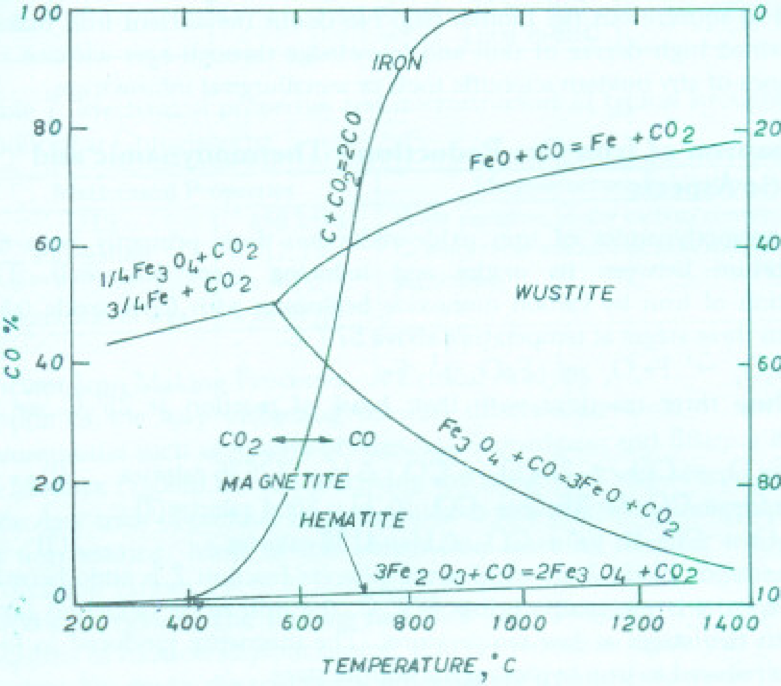

Fig. 3.5: Representation of equilibrium gas composition versus temperature diagram for iron-carbon-oxygen system

The kinetics of iron oxide reduction is equally important because the rate at which the iron ore can be reduced, determines the rate of production of the process. In turn the production rate largely determines its economic feasibility and its competitiveness with other processes. The production rate is not greatly affected by the reduction kinetics if the temperature of furnace operation is well above the melting temperature of iron and slag. On the other hand if the iron is reduced in the solid state and no melting occurs, the maximum temperature is below the melting or even the sintering temperature. Under such conditions, the reaction rates are slower and the production rate of the process is directly proportional to the rate of reduction. The iron oxide reduction mechanism is quite complex because the oxide goes through a series of changes step by step before the conversion is complete. The slowest step in the process determines the overall reaction rate and is referred to as the rate controlling step. The solid state reduction of iron oxides is heterogeneous involving solid and gas phases separated by an interface. The rates of the actual chemical reactions may fully or partly control the rate of reduction. For reactions to occur, the reactants must get to the interface and the products of reactions must get away. The movements of reactants and products in this region are affected by several factors, any one of which might be rate controlling. The porosity of iron ore particles is one of the most important factors controlling reducibility. Some of the rate determining steps in iron ore reduction are associated with the nature of the reaction system and contact between the reacting phases while others are associated with the nature of the ore. The latter determines the ease with which oxygen can be removed from the iron oxides in the ore by the reducing gases. The properties of an ore, which determines its reducibility, are particle size, shape particle size distribution, density, porosity, crystal structure and composition. All of these influence the relative amount of reactive surface area of the iron oxides exposed to the reducing gases. The porosity of the iron particles is one of the most important factors controlling reducibility.

Material and Energy Balance for an Ancient Iron Making Process

Considering the furnace trial results of Jiragora, material and energy balance calculations were carried out. The trial results are given in Table 8. The flow of materials in a primitive iron-making furnace of Jirogora is shown in Fig. 3.6. A comparative picture of the performance of ancient furnace with that of mini blast furnace and blast furnace is shown in Table 9. The ancient furnace has much low productivity and a considerable energy is not properly utilised. Hence there is lot of scope to increase it productivity and make it energy efficient.

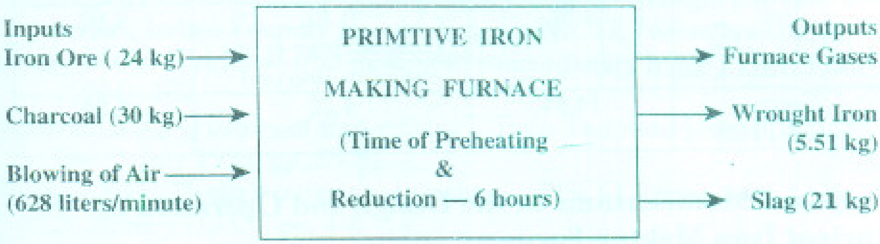

Fig. 3.6: Diagram showing the flow of materials in a primitive iron making furnace of jiragora

Table 8: Furnace trial results from Jiragora

- Time of pre-heating and reduction = 6 hours
- Air blown in six hours = 226 m3
- Air blowing rate = 628 litres/minute
- Heat generated by combustion = 81625.6 Kcal
- Percentage radiation loss = 20.5

Inputs of Materials

Iron ore= 24 kg;		Charcoal= 30 kg	
$Fe[Fe_2O_3]$	63.4%	F.C.	75.8%
SiO_2	2.44%	Ash	3.2%
P_2O_5	0.01%	V.M.	21.0%
Al_2O_3	1.66%		
CaO+MgO	0.70%		
MnO	0.90%		
LOI	3.7%		

Outputs of Materials

Metal= 5.510 kg		Slag= 21 kg	
C	0.4%	SiO_2	27.08%
Si	0.2%	Al_2O_3	6.72%
Fe	Rest	Fe	46%
		MnO	1.026%
		CaO	5.0%
		MgO	1.16%
		SO_2	0.075%
		O_2	12.98%

Table 9: Comparison of the performance of Ancient furnace,

Performance Index	Ancient Furnace (Jiragora)	Mini Blast Furnace	Blast Furnace
Iron Ore Tonnes/THM	4.36 (Fe= 63.4%)	1.45 (Fe= 67%)	1.45 (Fe= 60%)
Reductant Tonnes/THM	5.45 (Charcoal)	0.60	0.70 (Coke)
Slag Tonnes/THM	3.82	0.30 (Low ash coke & low alumina rion ore)	0.60
Energy G Cal/THM	14.84	4.50	3.89

Proposed Modifications in the Design and Operation of Ancient Iron Making Furnaces

In order to improve the productivity of the ancient iron making furnaces and make them energy efficient, the following measures are proposed in the design and operation of such furnaces:

- Present foot driven air blast system should be replaced by a mechanical driven one without using electric power.
- The location of tuyere and its design is to be modified so as to distribute the air blast uniformly.

- In order to increase the ratio of CO/C02, the temperature in the tuyere zone is to be enhanced.
- For better utilisation of CO, the height of the furnace shaft is to be increased by trial and error and optimised.
- The useful volume of furnace is to be increased in order to improve the productivity.
- The shape of the.furnace shell is to be suitably modified.
- One inner lining of fire clay is to be provided in the shell of the furnace so as to withstand higher operating temperature and reduce the heat losses.
- The size of the iron ore and charcoal in the charge mix is to be optimised.
- The quantity of air blown into the furnace is to be optimised.

Conclusion

An attempt has been made to represent the critical analysis of the performance of ancient iron making process. The successful operation of the primitive iron making furnace is directly related to CO/CO2 ratio in the reduction zone and the size and porosity of iron ore lumps. The performance indexes of the ancient iron making furnace in comparison to present day furnaces clearly state that there is a good scope to improve the productivity of the ancient furnace and make it energy efficient.

References

Chakraborty, P.N. and R.H. Khan, "Metal casting through the ages in India", Indian Foundry Journal, Vol. 33, No. 11, November (1987).

Ghosh, Moni, "Primitive iron making in contemporary India", Tisco 1193 (1964), 132.

Nanavati, S.K., "History of iron making", Tisco Technical Journal, Vol. 2, No. 3, July 1955, pp. 89-97.

Percival, F.G., "India's indigenous smelters", TISCO Review, vol. 1, No. 3, January (1933), pp. 4-8.

Rao, K.N.P., "Wootz", Indian Crucible Steel Metal News, Vol. 11, No. 3, June (1989).

Rao, K.N.P., "A brief history of the Indian iron and steel industry special report 78", Journal of Iron & Steel Institute, London(1964).

Srinivasan, N.R., "History of iron making in India", all India seminar on "Extraction of Iron", Metallurgical and Engineering Aspects, Bhilai, 28-29 February, 1984, pp. 66-72.