Technological Aspects of Low Shaft Furnace Process

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WHILE the primary object of the low shaft furnace is to produce commercial grades of pig from iron-ore and fuel unsuitable for smelting in the conventional blast furnace, there is a wide diversity in the design of the furnace, all of which are characterised only by the shortness of the shaft and the smallness of one of the horizontal dimensions. Low shaft furnaces of circular, rectangular and oval hearths and with double rows of tuyeres have been tried. In the construction of the furnace, width is governed by the ability of the blast to penetrate to the centre with minimum dust losses and for this reason a rectangular or oval cross-section is preferred. The height of the charge in the low shaft furnace seldom exceeds 16 ft. This low height widens the choice of raw materials. The burden may, therefore, consist of friable ores and ore fines and fuels like small coke, non-coking coal, carbonised lignite briquettes or similar fuels of an inferior grade both from the point of view of physical strength and heating value, the cost of which compared to blast furnace coke is very low and which are available in abundance. The reduction of height causes the burden in a low shaft furnace to descend in 2 to 4 hours compared to 8 to 12 hours in a conventional blast furnace. With the shorter throughput time, the time of reaction afforded in the low shaft furnace becomes 1/3 to 1/5 of that in a blast furnace. It is, therefore, obvious that a suitable burden prepartion is necessary. Uniform distribution of the burden, reducibility of iron-ore, intimacy of cotact between the oxide and the reductant on which the reaction time depends are to be taken into consideration for deciding the size and shape of the furnace. The height and the cross-section can be adjusted to meet the demands of the raw materials. But once the design has been worked for a particular set of conditions, treatment of raw materials widely varying in analyses, may not be economical. The low shaft furnace differs from the conventional blast furnace not only in design but also in the smelting operation. The raw materials smelted in the blast furnace are somewhat similar in nature but those in the low shaft furnace vary considerably.

The reactions in coke blast furnace producing iron have received much attention from the theoreti-

cal standpoint of thermodynamics and kinetics of these chemical reactions and equilibria, and the practical aspect of economising the coke consumption in the blast furnace. Paranjpe[1] has discussed about these reactions in a lucid way. As low shaft furnace of smelting is a recent development, it is considered that a brief review of its technological aspects will be of interest. The author, however, claims no originality in presenting a critical review from the data collected during his visits to different low shaft furnace plants in Europe and published papers.

Furnace height

The height and diameter of a blast furnace have been progressively increased to increase the daily output and its thermal efficiency. It has been recognised that a considerable part of the height of a blast furnace does not contribute either for exchange of heat between the ascending gases and descending charge or for the reduction of iron oxide by carbon-monoxide which is termed as "indirect reduction" to distinguish it from the reduction by solid carbon known as "direct reduction". Bearing in mind the thermal conductivity and specific heat of the charge, attainment of reaction temperature[2] can be effected by the adjustment of grain size. The influence of grain-size on the heat transference is shown in Fig. 1. It may be observed that with particle size of 50–100 mm the difference in heat-transfer between a 5 m high shaft and 30 m is relatively small and better transfer can be achieved by reducing the grain-size. On decreasing the grain-size to 30 mm and below, the difference in heat transfer becomes conspicuous. The particle size of the charge in a low shaft furnace has to be properly adjusted to assure heating of the charge. It is known that a plot of temperature with height of a blast furnace results in a "S" curve, which means that a more or less constant temperature zone of 850°C prevails in the central part of the shaft. In Calbe Low Shaft Furnace, the temperature of this zone is probably around 800°C and the top gas attains an average temperature of 300°C in a furnace of 4·8 m high with particle of iron ore and limestone of 40–50 mm. Operation of the International Low Shaft Furnace working on 9 to 30 mm particle size of raw materials disclosed that the high temperature zone did not extend for more than 1·6 m above

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Fig. I.
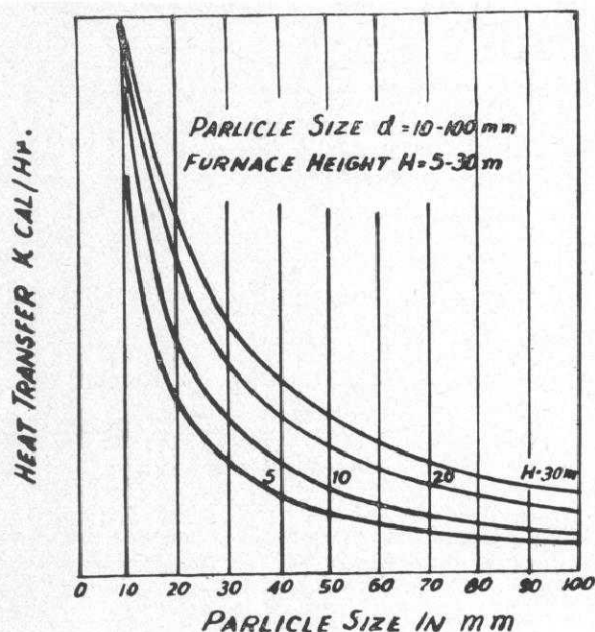
The effect of grain size of the charge on the heat transference.

tuyere level and the top gas temperature of 100 to 200°C was remarkably low for the effective height of the furnace[3]. Therefore with correct particle size of the charge, the top gas temperature can be reduced to minimise the heat carried away by it. Reduction of the particle size will also accelerate the rate of reaction, which bears parallelism with the heat-transference.

Furnace output

Apart from the chemical and physical characteristics of the burden, the output of a blast furnace depends on the rate of combustion of coke per unit hearth area. This depends on the cross-section of hearth, the pressure and the volume of the blast. The Calbe low shaft furnaces normally have a hearth area of 11 m² with a combustion of 550–700 kg coke/m² hr. The International Low Shaft Furnace has been operated with coke combustion of 1,000–1,100 kg/m²h. A coke combustion of over 1,200 kg/m²h is generally attained in blast furnaces. The loss of the burden as dust is, amongst other factors, related to the intensity of coke combustion. The dust loss as percentage of the total input is 2·4% for the Calbe furnace, 4-5% for the DHN Pilot Low Shaft Furnace, and 7% for a normal blast furnace. Fig. 2 illustrates the relation between the loading of the furnace and dust generation from which it is apparent that it increases with higher coke combustion per unit of hearth area, despite the difference in the smelting processes in various low shaft furnaces. It is of interest to observe that although very friable

and fine-grained materials are charged in the low shaft furnace, the dust loss is relatively low which is probably because of the shorter throughput time and lower pressure exerted by the column of the burden[2].

Fuel consumption and reduction equilibrium

The single factor which has received much attention for the economic operation of the blast furnace is the consumption of fuel. The factors influencing the coke-rate are :

(i) Composition of coke-ash,
(ii) Analysis of ore and flux,
(iii) Blast temperature and humidity,
(iv) Weight of slag and its composition,
(v) Iron analyses and
(vi) Radiation and other losses.

Carbon is burnt at the tuyeres producing CO. If the entire amount of CO formed by the combustion of coke at the tuyeres can be utilised in the reduction of iron ore and be converted into CO_2 thereby completely utilising the reductant, the efficiency of fuel utilisation will attain its peak. It has, however, been known that reduction of iron-oxides by CO attains at a certain temperature and pressure an equilibrium when the iron-oxide, $CO + CO_2$ and iron can co-exist. In order, therefore, to understand the thermal efficiency of the smelting operation, a description of the thermodynamics and the mechanism of the reduction of iron-oxide is necessary.

Fig. 2.
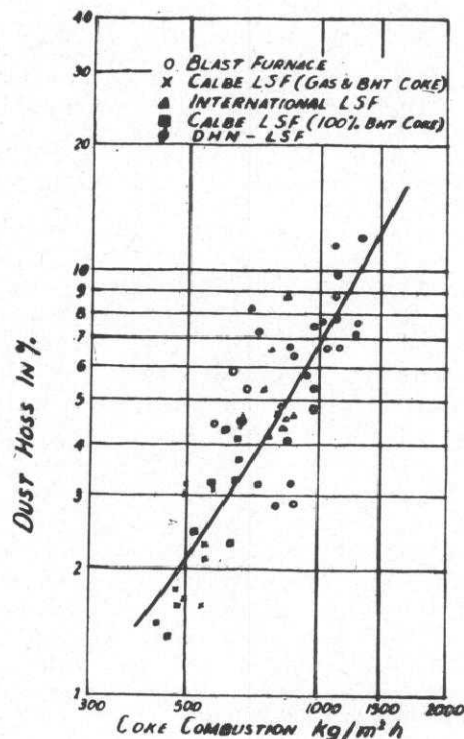
Rate of coke combustion and dust generated.

As the oxides of iron cannot be dissociated thermally, reduction depends on the presence of a reducing agent to combine with oxygen of the ore. The direct reduction reaction is a combination of reactions :

$$MxOy = xM + y/2 \; O_2 \qquad \ldots \qquad \ldots \qquad (1)$$
$$yC + y/2O_2 = yCO \qquad \ldots \qquad \ldots \qquad (2)$$
$$\text{or} \;\; MxOy + yC = xM + yCO \qquad \ldots \qquad (3)$$

where M is a metal, or MxOy is the metallic oxide under consideration. The indirect reduction i.e. reduction effected by the gaseous phase CO can be represented as :

$$MxOy + yCO = xM + yCO_2 \qquad \ldots \qquad (4)$$

It is understandable that the reduction of the iron oxides mainly occurs in the gaseous phase as represented by reaction (4) as the heterogeneous solid-solid reaction of iron-oxide with carbon (reaction 3) is slow. Besides the amount of heat required to reduce a gram-mole of Fe_2O_3 differs with the different reducing agents, as given in Table III.

TABLE III

Thermal requirements of reducing 1 lb of iron from Fe_2O_3 by different reductants.

Reaction	Heat effect, B.Th.U. per lb of Fe	
	70°C	1,650°F
(a) $Fe_2O_3 + 3 \; H_2 = 2 \; Fe + 3 \; H_2O$ ($\triangle H° = +21.8 \; Kcal$). …	502	134
(b) $Fe_2O_3 + 3 \; C = 2 \; Fe + 3 \; CO$ ($\triangle H° = +116 \; Kcal$) …	2,334	2,076
(c) $Fe_2O_3 + 3 \; CO = 2 \; Fe + 3 \; CO_2$ ($\triangle H° = -7.6 \; Kcal$) …	−92	−339

As the redution with CO is exothermic, it is preferred on thermochemical grounds to the other reducing reactions. The temperature dependence of the reduction of iron-oxides by CO and the curve for Boudouard reaction $2 \; CO = CO_2 + C$ is given in Fig 3. Below the lower limit of 0·96 of the ratio of CO/CO_2 reduction of iron-oxide cannot occur. From the equilibrium data it is clear that reduction of FeO by CO cannot be correctly represented by the equation $FeO + CO = Fe + CO_2$. Further, the reduction of FeO determines the total amount of the reductant necessary. At 900°C the reaction can be represented by the equation :

$$FeO + 3.1 \;\; CO = Fe + CO_2 + 2.1 \; CO \ldots \ldots (5)$$
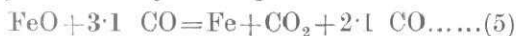
The composition of CO_2 and 2·1 CO forms equilibrium gas mixture, and is ineffective in reducing FeO at 900°C. This mixture can reduce Fe_2O_3 to Fe_3O_4 to FeO. The presence of nitrogen in the furnace gas is without any effect on the equilibrium which depends on the temperature and ratio of CO to CO_2 in the gas. If this ratio differs from that prescribed by the Boudouard curve, (Fig. 3) the reaction :

$$CO_2 + C \rightleftarrows 2 \; CO$$
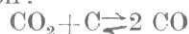
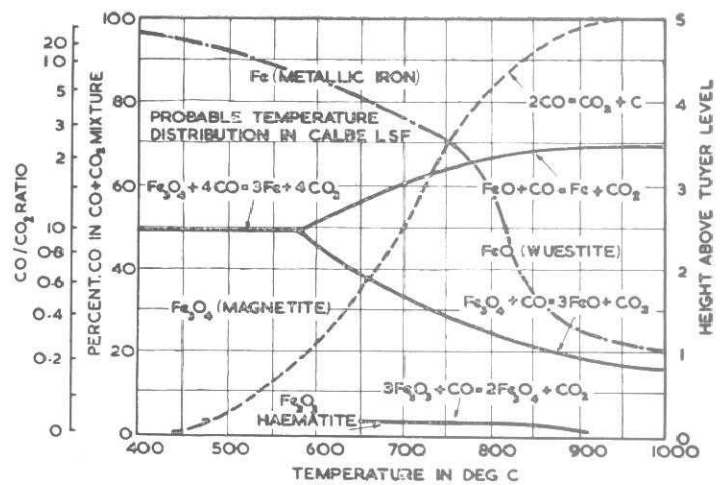occurs in the direction of attaining the equilibrium.

Fig. 3.

Reduction of iron-oxides by carbon-monoxide and temperature distribution in low shaft furnace.

The equilibrium diagram further indicates the reduction of Fe_2O_3 dierctly to iron by CO is possible only at temperatures up to 575°C. Above this temperature, Fe_3O_4 is reduced in two steps. At a given temperature, the gap between the Boudouard curve and the other curves are indicative of the reducing action of the reducing agent CO. But as the equilibrium ratio of CO to CO_2 for the reduction of FeO increases with temperature, more carbon will be needed for indirect reduction at a higher temperature. From the equilibrium conditions it is apparent that low temperatures favour indirect reduction and requirement of carbon is therefore decided by the chemical equilibrium of the reducing reactions particularly of FeO to iron as reduction of Fe_2O_3 and Fe_3O_4 and FeO can take place at lower concentration of CO in the gas mixture of CO_2 and CO. As a matter of fact gas mixture of equation (5) is effective for reducing Fe_2O_3 to Fe_3O_4 to FeO. It is clear that the higher the CO_2 in the top gas, approaching the ratio of CO/CO_2 to 0·96, the lower is the fuel consumption for the reduction. In this connection necessary correction for the CO_2 from the calcination of limestone has to be taken into account.

The temperature distribution of a Calbe low shaft furnace has been superimposed in Fig. 3. The average temperature of the central zone being about 800°C attainment of equilibrium will give a corrected CO/CO_2 ratio of about 2. The higher CO/CO_2 ratio of the top gas indicates that the shortness of the shaft and the quicker rate of descent militates against the gaseous reduction in a low shaft furnace. Coheur[5] accounted for 16% higher fuel consumption due to the higher CO/CO_2 ratio, in the top gas of the International Low Shaft Furnace. It has been reported that the degree of direct and indirect reactions influences the coke-rate. Struve and Ebert[7] mentioned that the mean degree of

indirect reduction in the low shaft furnaces at Cable was 30% in comparison with 50% in a normal blast furnace which is one of the factors for high coke consumption. Danielsson[6] has given an interesting example where the degree of indirect reduction of 47, 44, and 50% and CO/CO_2 ratio of 1·42, 2·55 and 2·48 for a Domnarfvet blast furnace operating on self-fluxing sinter and an U.S. plant and an Indian blast furnace at Hirapur, showed carbon (in coke) consumption of 1015, 1404 and 1586 lb/ton of iron respectively. These differences can be explained by other operating characteristics other than reducibility. The higher coke consumption at Hirapur is primarily due to higher ash content of the coke.

Apart from this factor, it is known that the coke consumption depends on the composition of iron and the volume of slag. Fig. 4 shows the relation between the burden yield and coke consumption[5], in the blast furnace at Maxhutte and the low shaft furnace at Calbe, which depicts that lower burden yield leads to higher coke consumption. This fact has to be borne in mind to avoid false conclusions on the coke consumption in a low shaft furnace in relation to a blast furnace[8]. Malcor[9] mentioned that with a coke rate of 50 tons/day, the ratio of CO_2/CO in top gas was about 0·3 against 0·5 in a normal blast furnace and the reduction of coke-rate to 40 tons per day improved the ratio to 0·44. This was evidently due to lower velocity of the ascending gases allowing more contact with the descending charge and therefore better indirect reduction. However, there was a limit below which the coke consumption could not be decreased by reducing the blast pressure as it would not reach the centre of the charge and the necessary temperature will not be attained. With a top pressure of 1·5–2kg/cm² the indirect reduction was improved with consequent saving in fuel rate and the amount of dust[7] was decreased.
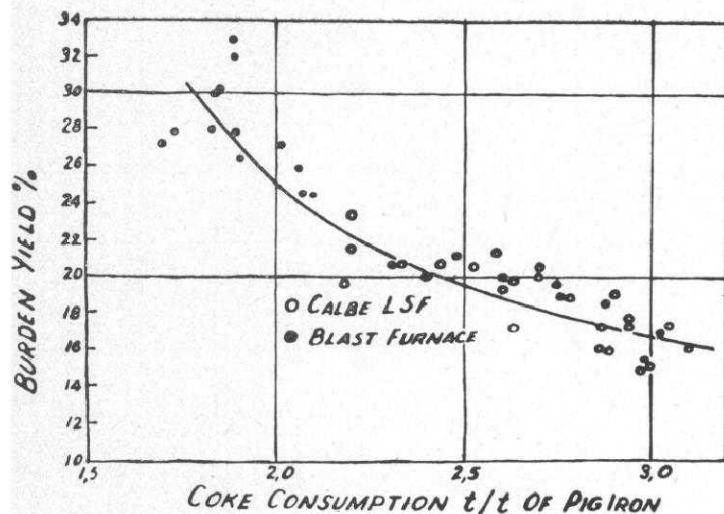

Fig. 4.
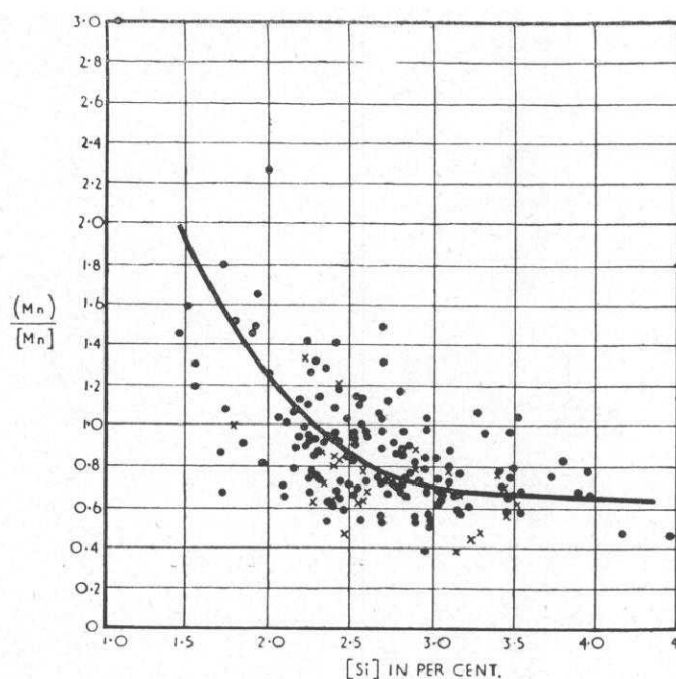Relation between burden yield and coke consumption.

Fig. 5.
Effect of silicon on the partition of manganese.

Reduction characteristics

In the bosh and hearth of the furnace direct reduction of iron-oxide, silica, manganese oxide and phosphorus oxide occurs. The reduction of these oxides occurs by the direct contact of solid carbon with primary slag. The reducing conditions prevalent in these areas can be assessed from a study of manganese reduction index K_{Mn-Si} and desulphurising index K_{S-Si} as has been proposed by Oelsen etal[10]. The relation between silicon contents of pig iron and the partition of manganese between the metal and slag of Calbe low shaft furnaces[7] is depicted in Fig. 5, which indicates that higher silicon reduction results in higher manganese recovery. It also depends on the basicity of slag as acid slag can absorb a large amount of manganese silicate. The recovery of manganese and its dependance on slag basicity are combined by Oelsen and Maetz[10].

The equilibrium constant of the manganese recovery reaction as represented by K_{Mn-Si} against the basicity of slag $\dfrac{CaO}{SiO_2}$ for the Calbe low shaft furnace[7] is shown in Fig. 6. These values are in fair agreement with those of blast furnace operation and the values obtained by Oelsen and Maetz on the basis of laboratory investigations on the equilibrium of manganese reducing reaction. Due to the higher amount of slag, the actual manganese recovery in the Calbe furnace is, however, only about 37% instead of 65% in a blast furnace.
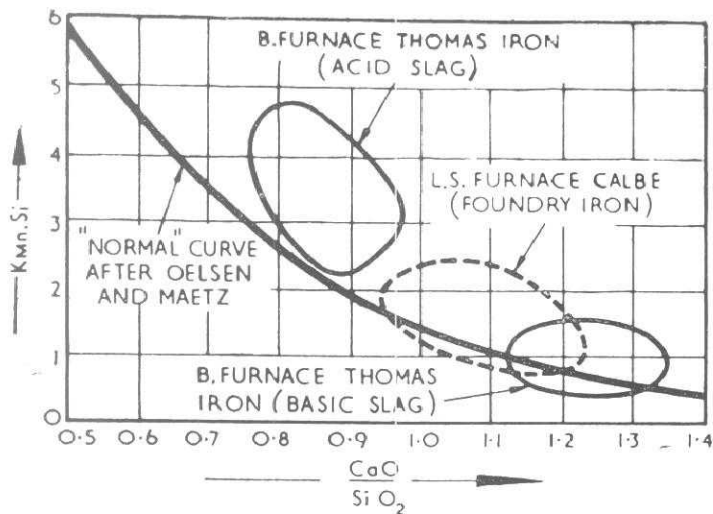
Fig. 6.

Effect of basicity of the slag on manganese partition.

Reinfeld[11] presented the values obtain from the DHN low shaft furnace, for the relation between K_{S-Si} and K_{Mn-Si} to the slag basicity as shown in Fig. 7 and from which it was concluded that equilibrium conditions in the low shaft furnace were similar to blast furnace reactions.
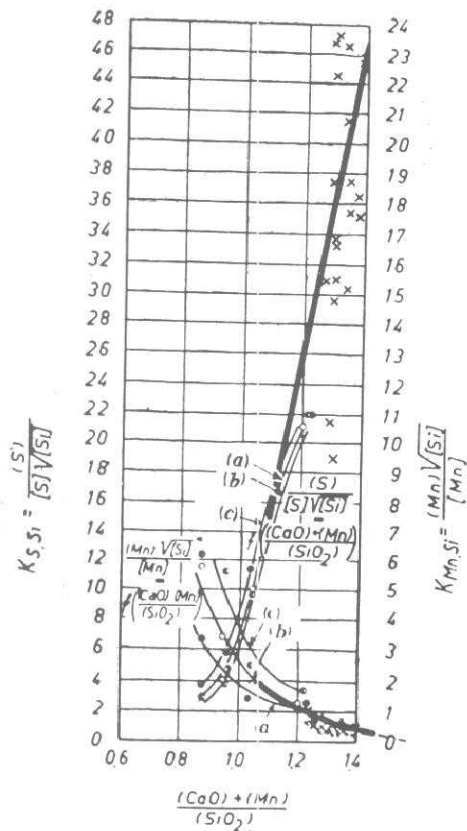
Desulphurisation

The sulphur present in the burden finds its way to the slag and metal and its partition is of much practical importance. The mechanism of the desulphurising reaction has, therefore, received much attention. Oelsen and Maetz[10] considered that the desulphurising occurs according to the reaction,

$$FeS + CaO + \tfrac{1}{2} Si = CaS + Fe + \tfrac{1}{2} SiO_2$$

The equilibrium constant for the reaction may be expressed as :

$$K = \frac{S \text{ in slag}}{S \text{ in metal} \times \sqrt{Si} \text{ in metal}} \times \frac{\sqrt{SiO_2} \text{ in slag}}{CaO \text{ in slag}}$$

The desulphurising index K_{Si-S} expressed by

$$\frac{S \text{ in slag}}{S \text{ in metal} \times \sqrt{Si} \text{ in metal}}$$

will therefore increase with increase in the basicity degree of the slag. The values of K_{S-Si} against the basicity of the slag $\frac{(CaO) + (Mn)}{SiO_2}$ are plotted in Fig. 8 in the standard curve of Oelsen and Maetz in which the values of the DHN and Calbe low shaft furnace[7] are incorporated. Reinfeld[11] observed that in the smelting of the combind ore-coal-limestone

Fig. 7.

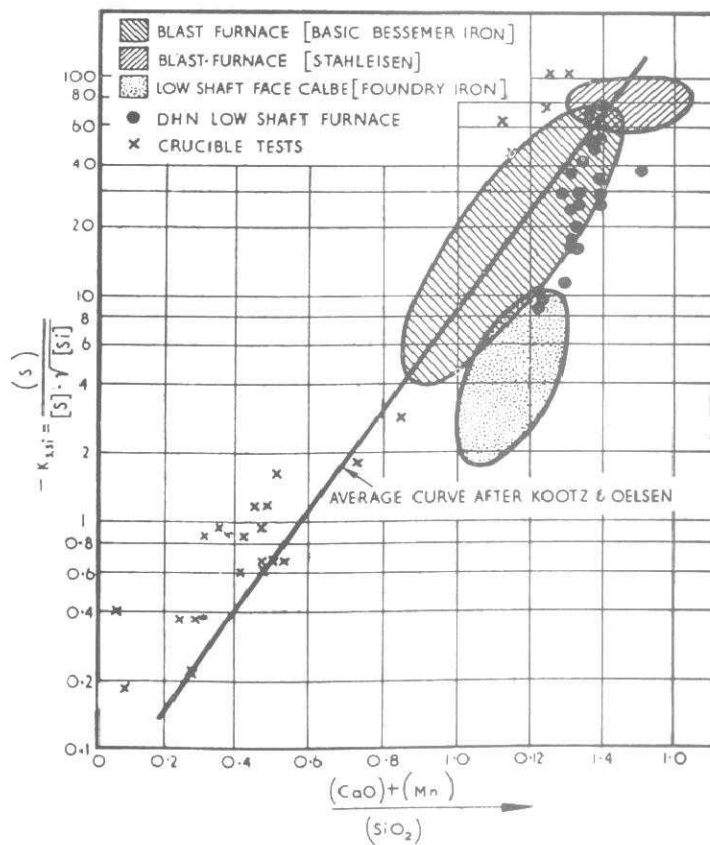Relation between K_{Mn-S}, K_{S-Si} and slag basicity.

Fig. 8.

Dependence of desulphurising index on slag basicity.

briquettes, these values lie below the line thereby representing better desulphurisation of the process. The K_{Si-S} values obtained in the smelting in the Calbe furnaces are comparable with these values for the conventional blast furnace.

Blast temperature and its enrichment with oxygen

In blast furnace operation, preheated air at 800°C is introduced and the waste gases leave the furnace at about 200°C. The sensible heat thus put into the furnace is equivalent to 300–340 lb of coke per ton of iron or about 15 to 20 per cent of the net heat supplied to the furnace. The effect of blast temperature on coke-consumption is shown in Fig. 9 from which it is apparent that greater saving of coke can result in increase in blast temperature at lower temperatures than by an identical rise at high temperatures. A higher combustion temperature is attained by an increase in the temperature of the blast. A similar effect can be had on enriching the blast with oxygen. Fig. 10 shows the equivalence between preheating and oxygen enrichment of the blast[12]. If a similar degree of preheating of the blast be not possible in the low shaft furnace operation, it is obvious that an equivalent heat has to be attained from additional combustion
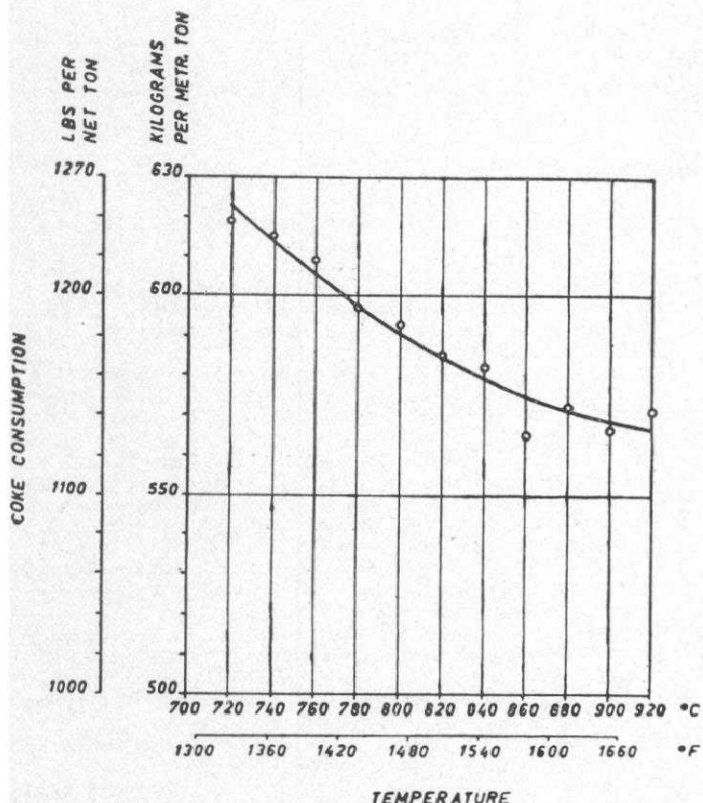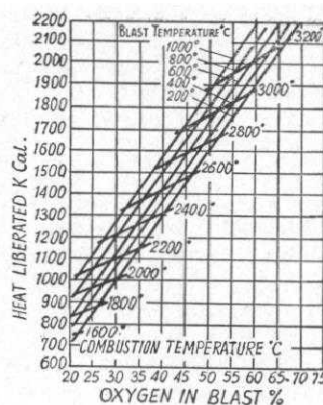
Fig. 10.
Relation between pre-heating and oxygen-enrichment of blast.

of fuel. Oxygen enrichment will be necessary to have optimum hearth temperature and set up a steep temperature gradient in the furnace to avoid wastage of heat as sensible heat of the top gas.

Attempts have been made in the blast furnace to increase the production by oxygen enrichment of the blast but the benefits are of doubtful significance. Investigations were conducted in the low shaft furnace, in East Germany to assess the implications of oxygen enrichment[7,8,12]. The effects of an increase of oxygen in the blast to a total of 22 to 25 per cent is shown in Fig. 11. It resulted in an increase of CO contents of the top gas without conspicuous change in its CO_2 contents. The small increase in oxygen from 21 to 24 per cent decreased the throughput time from 2·2 to 1·9 hr. and the throat gas temperature from 494 to 370°C, manganese recovery from 49·5 to 34·1 per cent, while the output increased from 84·7 to 97·7 tons in 24 hrs. Coheur[5] reported an increase in CO contents from 29·5 per cent with atmospheric air to 39 per cent with a total oxygen of 28 per cent but the CO_2 contents remained unchanged at 10 per cent. Sauberlich[12] has reported the results of the investigations on the production of high manganese iron with oxygen enriched blast having total oxygen contents of 21·0, 23·1 and 24·2 per cent. The results are shown in Figs. 12–14 from

Fig. 9.
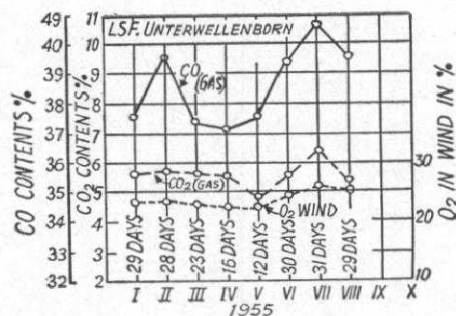Effect of blast temperature on coke consumption.

Fig. 11.
Effect of oxygen enrichment on top gas.

which it is apparent that the throughput time decreased from 2·54 to 2·18 hrs, iron production increased from 84·7 to 97·7 tons/24 hrs. and the coke combustion increased from 670 to 769 kg/m²h. Fig. 13 illustrates that oxygen enrichment decreases the recovery of manganese from 49·5 to 34·2 per cent and promotes direct reduction[12]. The decrease in manganese recovery is attributed to shorter throughput time and lesser indirect reduction. Oxygen enrichment without adequate burden preparation is not beneficial. The improvement on reducing the particle size of the charge below 40 mm coupled with oxygen enrichment of the blast[7, 12] is depicted in Fig. 14. The total oxygen of 24·5 per cent causes a slight decrease in direct reduction, but lowers the manganese recovery from 51 to 47·5 per cent. But with a higher amount of ore particles below 40 mm of the burden, the manganese recovery improved to 52 per cent and improved the indirect reduction. A reduction in the size of the coke further improved the manganese recovery to 55·6 per cent and slightly decreased the CO contents of the gas.

From these results it has been concluded that chemical reactions in a low shaft furnace are somewhat similar to those in a blast furnace and for controlling these similar techniques can be employed.
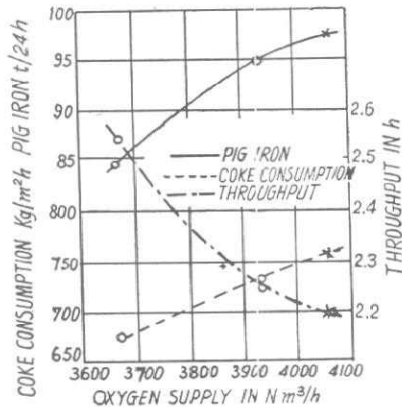
Fig. 12.

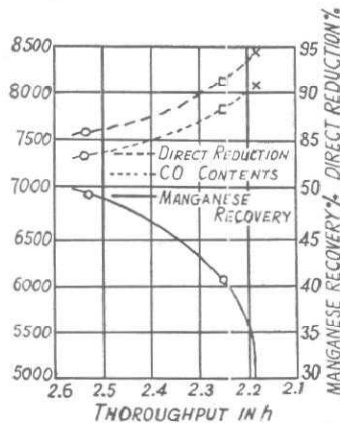Effect of oxygen enrichment on iron production.

Fig. 13.

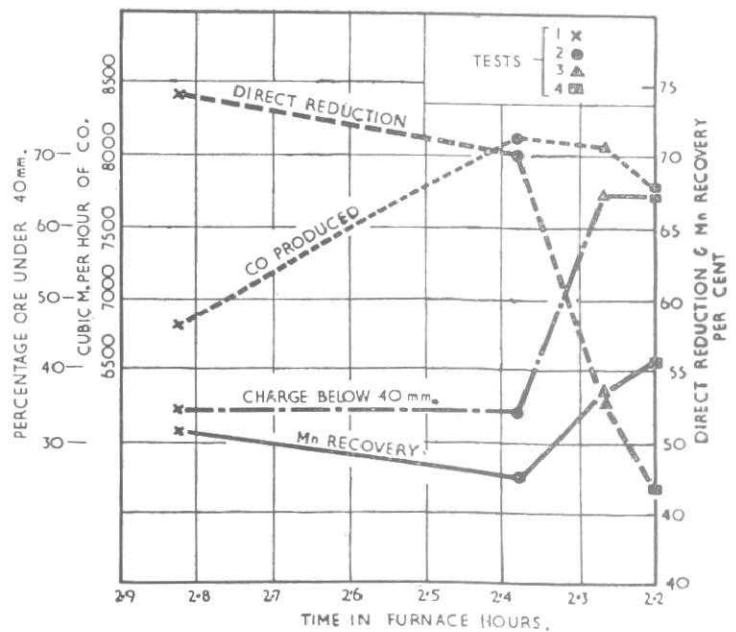Effect of oxygen enrichment on manganese recovery.

Fig. 14.

Effect of oxygen enrichment and reduction of particle-size on manganese recovery.

Acknowledgements

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