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PERFORMANCE ANALYSIS OF A BLAST FURNACE AT BHILAI STEEL PLANT

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ABSTRACT

The present paper reports a statistical analysis of the performance of the blast furnace number X at the Bhilai Steel Plant over a period of sixteen years with the special reference to the quality and consumption of sinter. The variation in basicity and consumption of sinter, for the blast furnace data considered, is wide. The range of data covers high level to almost nil amount of raw limestone in the burden. Equations have been established relating blast furnace performance indices, viz. productivity, carbon rate and slag volume, with independent parameters. The productivity depends largely on the fines content in iron ore lump. The charge weight is the most important parameter for carbon rate, followed by the blast temperature. The findings seem to indicate that priority has to be given for elimination of raw fluxstone and fines from burden for improved furnace performance.

INTRODUCTION

The behaviour of blast furnace has always appeared complex due to large number of inter-influencing variables connected with the design, the operation and the process itself. While the first two are difficult to change, the process parameters are variable. Proper selection of process parameters is possible in day to day operation for improved furnace performance.

Amongst the process parameters, more stringent demands on quality of raw material are being increasingly made by the blast furnace operators. Sinter constitutes a major part in iron bearing burden throughout the world. It is known that significant decrease in coke rate and increase in productivity are achieved on replacing raw lump ore by fluxed or superfluxed sinter [1]. The development of large blast furnace requires that more attention be paid on the quality of raw materials in general and to the production of quality sinter in particular. The sinter should be of superior quality as regards size, strength, reducibility, softening behaviour etc. [2]. During the last decade, there has been considerable improvement in the sintering technology throughout the world and this is so, also, with the Bhilai Steel Plant. The Bhilai Steel Plant has been producing superfluxed sinter since the beginning.

Quality of sinter and the level of sinter consumption in a blast furnace are not easily related to the overall furnace performance. Their role in blast furnace performance, however, can be quantitatively assessed through an analysis of actual plant data so as to establish empirical relationships [3]. Probably this is the only way to provide an assessment of various changes in process parameters [4], although there are some drawbacks and limitations [5,6]. Flint has derived an expression for carbon rate in terms of as many as twenty one variables [5]. While the effects of the variables cannot be calculated on a fundamental basis, his approach succeeded in relating, quantitatively, furnace performance with burden variables and operating practices. Ridgion and Whitehouse also established regression equations for carbon rate and productivity of five furnaces. The burden weight was found to affect the carbon rate significantly in all the cases [6].

The present work adopts a similar approach to establish empirical relationships for productivity, carbon rate and slag volume of a blast furnace (number X of Bhilai Steel Plant) in terms of independent and controllable parameters.

VARIABLES

The blast furnace performance indices Y_1 to Y_3, the process parameters X_1 to X_{18}, their average values, coefficients of variation and ranges studied are listed in Table IA. Monthly and yearly average data for the past sixteen years have been taken for analysis of these variables.

While selecting the variables, major emphasis has been given to the parameters related to sinter. The sinter constitutes about half of the iron bearing burden in Bhilai furnaces and its consumption is likely to increase in the coming years due to higher availability of fines from the mines. It should be noted that under the Indian conditions, the quality of sinter can be regulated more easily than the quality of the other raw materials. For example, variation in coke ash and alumina in iron ore etc. are restricted by natural supply. The day to day fluctuation in the quality of sinter may also affect the blast furnace performance. Depending upon the requirement, the norm of the Fe content and available lime ($CaO-SiO_2$) content in sinter is laid down by the blast furnace operators. The variables X_7 and X_8 show how much percentage of the chemical analysis of the sinter falls within the norm in a particular month.

Considering the limitation of the computer programme for the number of independent variables to be accepted, some of the variables, like manganese ore in burden, alumina content in iron ore lump, burden weight etc. were not taken in the main programme. They were, however, analysed based on yearly average data. These variables with their average values, coefficients of variation and ranges studied are listed in Table IB. Most of these variables taken for the present analysis are without any transformation in order to have first hand information to the blast furnace operators. The variable, humidity in blast, could not be taken, since operational data were not available for the whole period. The variation in micum value of coke, M_{10}, was marginal during the years 1968 to 1978, so it was discarded.

In a complex system, like a blast furnace, it is quite probable that some variables may be left out. Inspite of that, it should be noted that, the equations obtained in the present work remain meaningful in the sense that prediction of maximum and minimum values match excellently with observed values. This has been discussed in detail subsequently.

DATA COLLECTION AND DATA ANALYSIS

The sources of all the data, except that for reducibility of sinter, are compilations of operational statistics of the Bhilai Steel Plant. The reducibility data of sinter have been taken from the quality reports of the sintering plant.

Table I: List of dependent and independent variables, showing their average values ($\bar{X}$), coefficient of variation ($100\ \sigma/\bar{X}$) and approximate operative range studied

Symbol	variables	Unit of measurement	Value: Average ($\bar{X}$)	C.V $\frac{100\ \sigma}{\bar{X}}$	Range (min.- max.)
A. Variables taken into analysis of the monthly & yearly average data:					
Dependent variables:					
Y_1	Productivity	t/m^3 of working volume day	1.24	11.50	0.80-1.56
Y_2	Carbon rate	kg/THM	634.80	6.08	568 - 795
Y_3	Slag volume	kg/THM	620.00	6.08	521 - 704
Independent variables:					
X_1	Sinter consumption	kg/THM	681	36.70	0-1298
X_2	Basicity of sinter $\frac{CaO + MgO}{SiO_2 + Al_2O_3}$	–	1.98	8.49	1.45-2.37
X_3	Reducibility of sinter	%	47.05	3.97	37.5-51.9
X_4	MgO content in sinter	%	5.02	11.51	3.99-6.24
X_5	Fe content in sinter	%	46.2	2.89	42.7-51.6
X_6	FeO content in sinter	%	9.49	7.86	5.51-12.3
X_7	Consistency factor in chemical composition ($CaO-SiO_2$) of sinter	%	71.65	12.38	45.3-90.3
X_8	Consistency factor in chemical composition (Fe) of sinter	%	66.14	19.88	41.4-95.0
X_9	Sinter return in the process of sintering	%	31.2	5.25	26.7-36.8
X_{10}	-10 mm content in sinter	%	42.33	6.29	36.42-46.10
X_{11}	40-60 mm size fraction in sinter	%	2.68	19.24	2.0 - 4.9
X_{12}	-12 mm content in iron ore lump	%	20.19	25.65	12.2-32.0
X_{13}	Weight of raw limestone in burden	kg/THM	220.96	47.41	12-554
X_{14}	Charge weight	kg/THM	2889	4.05	2679-3245
X_{15}	Blast rate	Nm^3/min.	1778	5.56	1495-2140
X_{16}	Avg. top pressure	Atm.	0.71	21.10	0.36-0.95
X_{17}	Avg. blast temp	^oC	777.6	19.24	600-902
X_{18}	Ash content in coke	%	24.96	5.13	22.6-28.0

B. Additional independent variables taken into analysis of the yearly average data

X_{19}	Burden weight	kg/THM	2046	3.84	1947-2251
X_{20}	Mn ore in burden	kg/THM	44.5	21.0	33-65
X_{21}	Alumina in iron ore lump	%	3.36	9.94	2.71-4.15
X_{22}	Moisture in coke	%	2.69	6.58	2.5 -3.0

The reducibility of sinter is determined by passing hydrogen, at the rate of 1 litre per minute for 30 minutes to the 50 grams of sample kept at 800°C in the reduction furnace. This is reported as the percentage loss in sample weight to the total weight of oxygen associated with the sinter samples.

The appendices A_1 and A_2 summarize plant data of some important variables. During the past sixteen years, there has been considerable change in basicity of sinter and consumption of sinter in the blast furnace. This results in high reduction of the amount of raw limestone in the burden. Such a large collection of data covers the said period in order to have more reliable relationships. Besides, the effect of sinter consumption or the effect of raw limestone elimination is more clearly established when the data collection is large.

RESULTS AND DISCUSSION

The important results of multiple linear regression computations are summarized in Table II. The table shows the correlation coefficient (r) of the regression equations which is defined as follows:

$$r = \sqrt{\pm 1 - \frac{\Sigma(y - y')^2}{\Sigma(y - \bar{y})^2}} \quad \text{.............................(1)}$$

where

- y = the observed value of the dependent variable
- y' = the estimated value of the dependent variable using the regression equation, and
- $\bar{y}$ = the average value of the dependent variable.

This also shows the F-ratio of the regression equations which are established through analysis of monthly and yearly average data. The F-ratio is the ratio of the mean sum square of the Y value due to regression to that of residual. The table shows the calculated values of the furnace performance indices against the observed values of yearly data for two situations: one when observed index was minimum and the other for which index was maximum.

The reduced models of the performance indices are listed in the Table II instead of full models consisting of all the independent variables. The goal is to arrive at adequate description of observed phenomena in terms of as few meaningful variables as possible. However, the null hypothesis was tested for each of the

Table II: Effect of process parameters on performance indices

Equation	Index values of the year when observed value is minimum: Obs.	minimum: Calc.	maximum: Obs.	maximum: Calc.
I Productivity (Y_1)				
i. $Y_1 = 1.62 - 0.019\, X_{12}$; $r = 68\%$, $F = 165$	1.01	1.06	1.42	1.33
ii. $Y_1 = 0.815 - 0.018\, X_{12} + 0.0004\, X_{15}$; $r = 74.5\%$, $F = 119$	1.01	0.96	1.42	1.25
iii. $Y_1 = 1.348 - 0.365\, X_{16} - 0.011\, X_{12} + 0.0006\, X_{15} + 0.017\, X_3 - 0.013\, X_{10} - 0.0003\, X_{14}$; $r = 84.6\%$, $F = 78$	1.01	1.11	1.42	1.44
II Carbon rate (Y_2)				
i. $Y_2 = -110 + 0.258\, X_{14}$; $r = 77\%$, $F = 281$	602	612	701	679
ii. $Y_2 = 684.5 - 0.073\, X_1$; $r = 46.6\%$, $F = 53$	602	627	701	653
iii. $Y_2 = 40.3 + 0.242\, X_{14} - 0.133\, X_{17}$; $r = 80\%$, $F = 169$	602	616	701	678
iv. $Y_2 = -389.2 + 0.298\, X_{14} - 0.017\, X_1 - 0.186\, X_{17} + 7.821\, X_5 + 2.066\, X_{12} - 41.463\, X_2$; $r = 84.7\%$	602	602	701	711
v. $Y_2 = 85.6 + 0.268\, X_{19}$; $r = 71.6\%$	602	617	701	658
vi. $Y_2 = 542.3 + 2.06\, X_{20}$; $r = 65.2\%$	602	618	701	654
vii. $Y_2 = -588 + 13.075\, X_{18} + 0.4376\, X_{19}$; $rY_2X_{18}\cdot X_{19} = 44.4\%$; $rY_2X_{19}\cdot X_{18} = 72.7\%$; $r = 78.1\%$	602	624	701	662

viii. $X_{14} = 2725 + 0.741\ X_{13}$ $r = 66.4\%,\ F = 151$				
ix. $X_{13} = 466.8 - 0.39\ X_1$ $r = 93\%,\ F = 1230$				
III <u>Slag volume</u>(Y_3)				
i. $Y_3 = 842.5 - 0.286\ X_{17}$ $r = 48.2\%,\ F = 58$	554	594	666	621
ii. $Y_3 = 520.3 - 0.245\ X_{17} + 0.1\ X_{14}$ $r = 57\%,\ F = 46$	554	592	666	625
iii. $Y_3 = 719 - 12.87\ X_5 + 0.161\ X_1 - 4.204\ X_{12} + 9.366\ X_{18} - 0.156\ X_{17} + 0.277\ X_{13} - 0.095\ X_{14} - 18.279 X_4 + 2.696\ X_{10}$ $r = 81.5\%,\ F = 41$	554	571	666	657
iv. $Y_3 = 492.1 + 38.74\ X_{21}$ $r = 50\%$	554	604	666	653

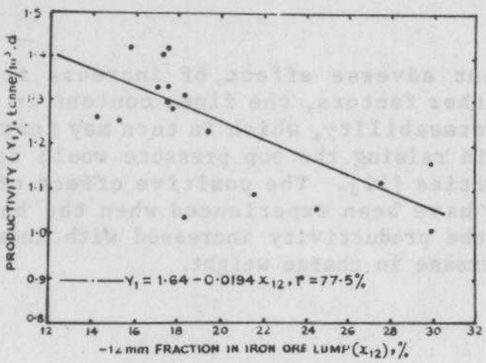
reduced models using the F-statistics. It was found that the null hypothesis was not rejected in all the three cases. This shows that few variables appeared in the reduced model together can explain the variation in dependent variables as adequately as all the independent variables. For example, six independent variables together are adequate for mathematical expression of the furnace productivity. It is said that this economy in description has two advantages:

i. it enables to isolate the most important variables,
ii. it provides with a simpler description of the process studied.

Figs. 1-3 represent graphically the effects of most significant parameters on productivity, carbon rate and slag volume respectively. Only the annual average data points are shown for the sake of clarity. The line drawn through these points represents the regression equation established through an analysis of these data. This equation is somewhat different from the equation listed in the Table II.

Effect of Fines Content on Productivity

Compared to other parameters the fines in the iron ore lump showed the maximum adverse effect on productivity (Fig. 1). Presumably, this was because of the decrease in burden permeability. Earlier reports from Bokaro and Durgapur indicate a linear decrease in permeability with increase in fines content [7]. According to literature, considerable increase in production is achieved on elimination of under size of iron ore and sinter [1,8,9]. The fines in sinter, also, affected the productivity adversely.



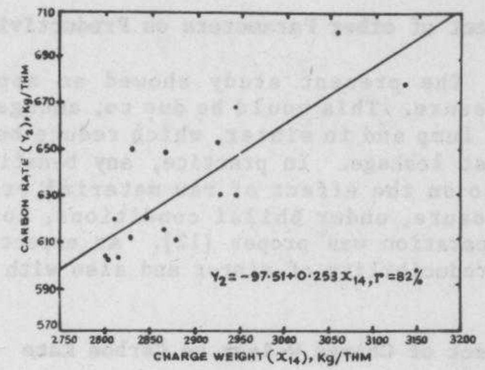


Fig. 1 Dependence of furnace productivity (Y_1) on -12mm fraction in iron ore lump (x_{12}).

Fig. 2 Dependence of carbon rate (Y_2) on charge weight (x_{14}).

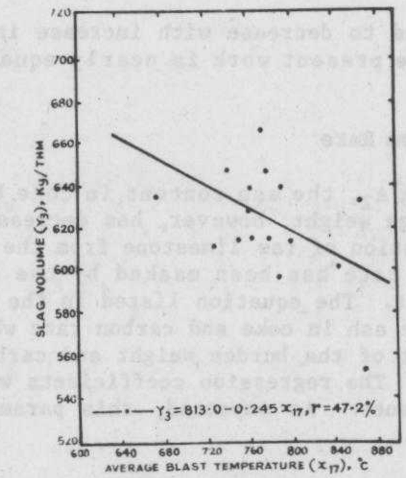


Fig. 3 Dependence of slag volume (Y_3) on average blast temperature (x_{17}).

Effect of Blast Rate on Productivity

As expected, the equations showed that the productivity increased with increase in blast rate. Earlier work has shown that a linear relation exists between productivity and blast rate [7,10].

Effect of other Parameters on Productivity

The present study showed an apparent adverse effect of increase in top pressure. This could be due to, amongst other factors, the fines content in iron ore lump and in sinter, which reduce bed permeability, which in turn may increase blast leakage. In practice, any benefits in raising the top pressure would depend also on the effect of raw material properties [11]. The positive effect of top pressure, under Bhilai conditions, could have been experienced when the burden preparation was proper [12]. As expected the productivity increased with increase in reducibility of sinter and also with decrease in charge weight.

Effect of Charge Weight on Carbon Rate

Carbon rate was found to be highly dependent on the charge weight as expected (Fig. 2). Increase in charge weight in the Bhilai furnace is mainly due to the increase in raw limestone in the burden. Under Indian conditions the raw limestone can be eliminated from the burden and a substantial decrease in charge weight can be attained through the use of higher percentage of fluxed or superfluxed sinter.

Effect of Average Blast Temperature on Carbon Rate

The carbon rate was found to decrease with increase in the blast temperature. The coefficients found in the present work is nearly equal to those reported by others [5,6].

Effect of Ash in Coke on Carbon Rate

As shown in the appendix A_2, the ash content in coke has increased since the year 1967 to 1978. The charge weight, however, has decreased gradually. This was mainly due to gradual elimination of raw limestone from the burden. So, the effect of this parameter on carbon rate has been masked by the charge weight, or more precisely by the burden weight. The equation listed in the table shows the partial correlation coefficient of the ash in coke and carbon rate when the effect of burden weight is eliminated and that of the burden weight and carbon rate when the effect of ash in coke is eliminated. The regression coefficients were calculated from the partial correlation coefficients. As expected, this parameter showed the adverse effect on carbon rate.

Effect of other Parameters on Carbon Rate

In the present study the fines content increased the coke rate. This corre-borates the Flint's finding [5]. The effect of top pressure was found to be insignificant. Similar is the finding of Flint [5]. Iron content of sinter apparently decreased with increase in sinter consumption in the furnace and presumably because of this reason, this parameter has shown a negative effect. The Mn ore in burden increased the carbon rate. Similar is the finding of Flint [5]. A trend in increase in carbon rate was found with increase in alumina content in iron ore lump or moisture in coke. However, the correlation coefficients were low, so the results were not reported in the present paper.

Effect of Various Parameters on Slag Volume

In the present study the slag volume decreased with increase in blast temperature (Fig. 3) and also with decrease in the charge weight. An increase in blast temperature and/or a decrease in charge weight implies less coke consumption and, therefore, less ash input through burden. The slag volume also decreased with increase in iron content of iron ore lump or decrease in ash in coke or decrease in alumina content in iron ore lump, as expected. The reasons for their influence is attributed to gangue input in the burden. The quality of raw materials, which are generally used in the sintering plant, are inferior to that of blast furnace. So, the higher amount of sinter in the burden implies more gangue input. An increase in slag volume was found with increase in sinter consumption. The regression equations pertaining to slag volume had low correlation coefficients compared to carbon rate or productivity. This may be ascribed to uncertainities in measurement of this index.

CONCLUSIONS

Empirical equations for the performance indices of a blast furnace have been established. These equations are reliable in the sense that these are based on analysis of nearly two hundred data points, they have high correlation coefficients and the values of performance indices calculated using equations compare well with the observed values. These findings also corroborate those mentioned in literature. The productivity is basically governed by aerodynamics of the furnace. The burden weight and the blast temperature are found significant for carbon rate and slag volume. These findings indicate that priority should be given for elimination of fines and raw limestone from the burden.

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APPENDIX

Some operational data for the blast furnace under consideration are summarized in Fig. Al and A2.

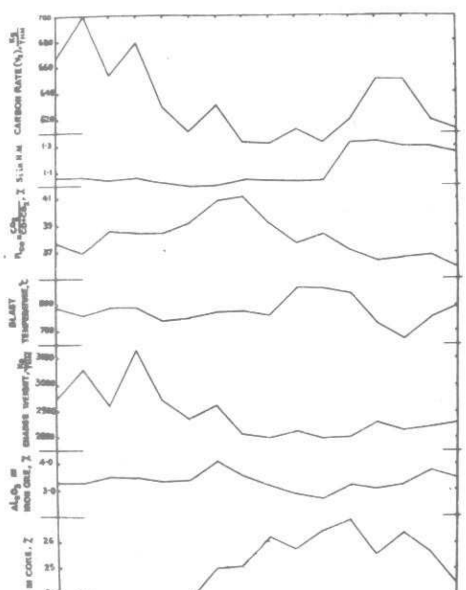

Fig. Al Influence of process papameters on furnace productivity over sixteen years.

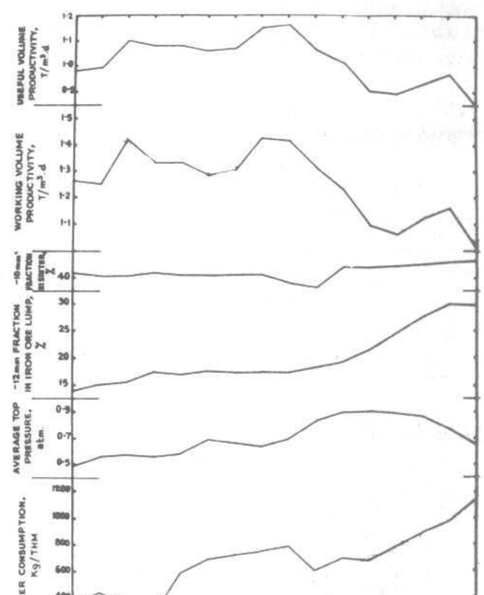

Fig. A2 Influence of process parameters on carbon rate over sixteen years.