Proc. : Inter. Conf. on Energy Efficiency in Steel Industry (EESI-2011), Org. by SAIL-RDCIS Ranchi, Bureau of Energy Efficiency Min. Of Power, Gov. of India New Delhi, Indian Institute of Metals, Ranchi Chapter at Ispat Bhawan, Ranchi December 14-16, 2011, Tech. session IIB (Energy Conservation in Iron Making (ECIM#2) 14th December, 16.00-17.45 PM, Pages: 1-11 (in CD)

INTER-INFLUENCING FACTORS IN AFFECTING BF COKE RATE – STATISTICAL APPROACH

Ram Pravesh Bhagat
Mineral Processing Division
National Metallurgical Laboratory
Council of Scientific & Industrial Research
Jamshedpur 831 007
E-mail : rpb@nmlindia.org

A blast furnace (BF) is a multivariate system which is subjected to a large number of inter-influencing variables affecting its performance: productivity and coke rate. It is important to isolate the inter-influence before drawing any conclusions. It is essential to support the parameters' effect (on the responses) through theoretical consideration. .

The explanatory variables affecting the coke rate have been statistically analysed in case of typical BF at Bhilai Steel Plant, SAIL and discussed in the present paper. The results (sixteen years' monthly average data points) show that some variables are not orthogonal which have been explained in terms of (a) natural cause and effect relationship amongst the variables and (b) apparent inter-relationship amongst the explanatory variables and masking the effect. The inter-influences of the variables have been isolated and their effect on coke rate has been discussed which are substantiated by the theoretical consideration.

The study shows that the variable, burden rate was the most significant one followed by temperature of hot blast. A change in burden rate has been mainly reflected by a change in weight of raw limestone in the burden.. The adverse effect of the variables, ash content of coke was inter-influenced by the variable, limestone consumption. However, analysis shows the variable, ash content in coke affected the coke rate, though marginally when the inter-influence was isolated. The range studied against this variable during the period was quite high: 12 to 554 kg/ THM which indicates that lump ore constituted high proportion in the burden with nearly zero sinter consumption during some period. The empirical equation, established through the analysis of more recent data shows that an increase in ash content of coke (range 21.5- 26.6%) increased the carbon rate and the correlation coefficient was similar to those observed previously.

The study indicates that an equation developed need to be modified when the value of an independent variables deviates from the range of data considered in the analysis.

Key words: blast furnace, coke rate, regression equation, sinter, burden, statistics

Preamble

An blast furnace is a typical case of multivariate system which is subjected to a large number of inter-influencing variables; some of them may act in uncontrolled manner. The performance data of the blast furnace have been analysed in the past using statistical techniques in order to know the functional relationship between the response variables namely, coke rate / productivity and the independent variables[1-3]. The objective was to improve the performance of the Blast Furnace by controlling the independent variables .

Functional Representation of a Blast Furnace

The effect of variables on the response can be well represented to a certain degree of accuracy by a set of regression equation. Data which serve the basis for the regression analysis can be obtained from operating log sheets[4] and/or specifically designed experiments. However, experimentation on a complex system, such as an iron blast furnace, may not be permitted because of cost and time factor and quite often inferences need to be drawn from the operating log data[1,2] physical model [5 6].

In case of blast furnace, for example, operating data is of considerable value in number of ways:

(a) It provides a standard with which to appraise current performance of a blast furnace by taking into account the external conditions,

(b) It helps in estimating the effect of changes in raw materials supplies, burden preparation operation particles etc.. these are perhaps not accountable on purely thermo-chemical treatment, and

(c) Studies of variation in furnace economy and productivity by this techniques may assist in making comparison of different furnace.

With these board observations, the present analysis has been carried out in order to develop the empirical equations relating the coke rate with the process parameters. The anomalies which generally appear with such analysis and the techniques of their handling, are discussed. On the basis of the results arrived at salient considerations towards decrease in the coke rate of the furnace are outlined.

Statistical Analysis of Performance Data

The carbon rate, Y1, as response variable and independent variables X1 to X14 considered in the present work are listed in Table 1. A majority of the independent variables, considered in the present work, are related to the burden. Most of the burden materials are the product of nature with inherent variability in physic-chemical properties. Whereas, sinter is produced in the plant whose quality can be regulated through control of sintering condition and requisite chemistry of sinter. Besides, additional lime in super-fluxed sinter eliminates limestone from the burden. Therefore, while selecting the variables, emphasis has been given to the variables related to sinter.

During the period under consideration the ash content in coke was high, but not varied widely and a considerable amount of limestone was charged directly which could be reduced easily through incorporation of super fluxed sinter at a higher basicity. In the following years ash content in coke was decreased considerably through imported low-ash coking coals while reducing the level of limestone consumption to near- zero level. The above analysis has been substantiated with inclusion of the recent monthly average data for 3 years to cover the period. Table 1 also compares the average values, coefficient of variation, and the ranges of the independent and dependent variables during the recent period with those during previous period.

The variables, auxiliary fuel rate, slag rate, hot metal temperature etc. do affect the coke rate in addition to the burden variables. Injection of the auxiliary fuel through tuyers was not practised during the period of consideration. Besides, a direct correlation between the coke rate and the amount of auxiliary fuel addition could be arrived using thermal balance. The variability in hot metal temperature was not significant. In complex system, such a blast furnace, the variables, which affect the performance, are many and it is possible that some variables may be left out. Nevertheless, while the effects of the theoretical factors are accountable on purely thermo chemical treatment [6], the effects of the burden variables are not, and therefore need statistical analysis. Viewed in this respect, it is logical to understand why in the past, the statistical techniques have been applied to represent the functional representation of the response with the variables related to burden[1,7,8].

In the present work, the data were analysed following the step wise regression technique with forward selection and the linear and multiple linear regression equations were established. In order to explain the effect of some independent variables on the response variable, which is otherwise masked by the other strong explanatory variables, the matrixes of correlation coefficients were analysed. The inter-influences amongst the explanatory variables were isolated and the partial regression equations were established. Additionally, the reliability of data[9] was checked by materials balance. Iron, carbon and oxygen balances were made for the 28 sets of randomly collected monthly average data. It was estimated that the difference between input iron and the output iron was within the range of -5 to +6 percent.

Table1 : List of dependent and independent variables, showing their average vales, coefficient of variations (CV), and the ranges studied.

Variables	High ash & low sinter period (16 year monthly average data)		Low ash & high sinter period (3-year monthly average data)	
	Avg. (CV)	Range	Avg.(CV)	Range
Dependent variables				
Carbon rate (Y1), Kg/T	635 (6.1)	568 - 795	533 (5.9)	503 - 629
Independent variables				
Sinter consumption (X1), kg/T	681 (17)	0 - 1298	1045 (10)	657-1187
Basicity of sinter (X2), ---	1.98 (8)	1.45 - 2.37	1.85 (4)	1.74 1.98
Reducibility of sinter (X3), %	47 (4)	37.5– 51.9	47 0 (2.8)	44 - 49.3
Fe content in sinter (X4), %	46.2 (2.9)	42.7 -51.6	47.6 (3)	45 -50
Consistanc in chemical composition of Fe in sinter, (X5a), %	66.1 (20)	41.4 -95.0	62.1 (13)	39 – 78
Consistanc in chemical composition of (CaO-SiO2) in sinter, (X5b), %	71.6 (12)	45.3 -90.3	83.7 (8)	71 - 95
Return fines re-circulated (X6), %	31.2 (5)	26.7 -36.3	32.1 (2)	28.5 - 35
-10 mm content in sinter (X7), %	42.3 (6)	36.4 -46.1	41.4 (14)	40.5 – 43
-60+40 mm content in sinter (X8),%	2.68 (19)	2.0 - 4.9	2.51 (17)	1.9 - 4.4
-12 mm content in lump ore (X9), %	20.2 (25)	12.2 - 32.0	21.5 (11)	15 – 22.7
Limestone in burden (X10), kg/T	221 (47)	12 -554	55.4 (71)	16 - 169
Burden rate (X11), kg/T	2043 (4)	1851-2351	1963 (4)	1831-2101
Blast rate (X12), m3/min.	1778 (6)	1495-2140	1586 (12)	1244-1872
Avg. Blast temperature (X13), K	1051 (19)	873– 1175	1050 (7)	893-1170
Ash content in coke (X14), %	24.96 (5)	22.6 - 28.0	23.5 (6)	21.5- 26.6

Results and Discussions

Empirical Equations for Carbon Rate

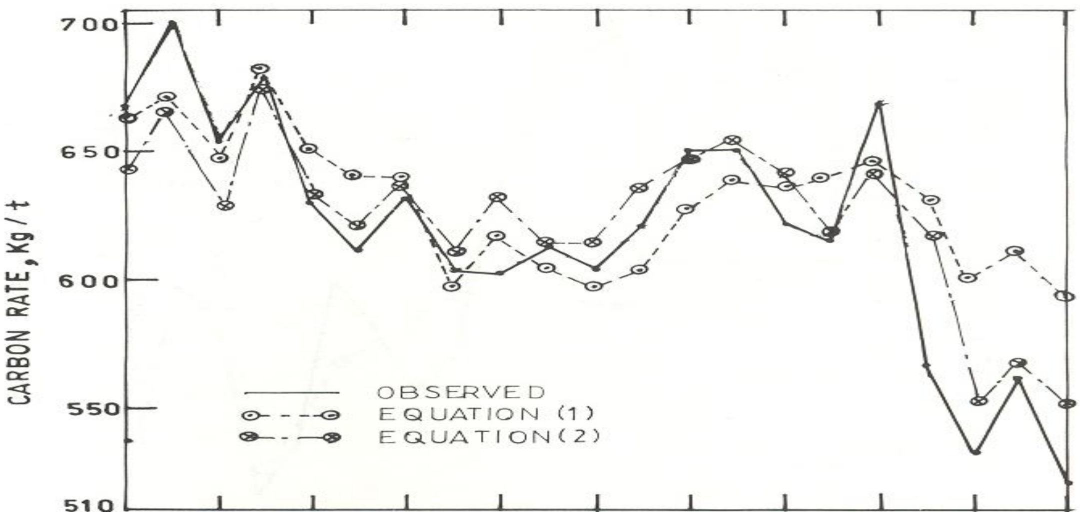
Analysis of the 16-year monthly average data shows that the variables which affect the carbon rate in order of relative significance are :

- Burden rate (X11) kg/ T,
- Avg. Temperature of hot blast (X13), K
- Specific sinter consumption (X1), Kg/T
- Basicity of sinter (X2), ---
- Content of -12 mm size fraction in iron ore lump (X9), %
- Reducibility of sinter (X3), %
- Return fines re-circulated in the process of sintering (X6), %5

The following equation could be established relating the carbon rate (Y1) with the above mentioned variables:

$$Y1\ (kg/T) = 652 + 0.221 * X11 - 0.19 * X13 - 0.029 * X1 - 32.37 * X2 + 1.94 * X9 - 3.11 * X3 - 2.57 * X6 \quad (\text{Correlation coefficient} = 0.84) \quad \text{----------- (i)}$$

Figure 1 shows the predicted value of the carbon rate against the observed value during the first 16 years periods. The carbon rate has been computed using the Eq. (1) substituting the yearly average data of the variables. Fig. 1, however, shows a wider gap between the predicted values and the observed values of the carbon rate during the recent years. This was possibly because of significant reduction in ash content in coke during the recent years as it is evident from a comparison of its average value and the range of variation during the two periods (Table 1). Apparently, Eq. 1 does not include the term for ash content in coke.



Year

Fig. 1 : Prediction of carbon rate , Y1 (kg/T) of the blast furnace

In order to predict the carbon rate, more accurately, during the recent years the equation was modified by the further analysis with incorporation of the 3- year recent data. The following equation could be established expressing the carbon rate in terms of the significant variables:

$$Y1\ (kg/T) = 251 + 0.195 * X11 - 0.182 * X13 + 13.49 * X14 - 0.032 * X1 + 0.07 * X10 + 2.24 * X9 - 4.26 * X3 \quad (\text{Correlation coefficient} = 0.89) \quad \text{----------- (ii)}$$

The predicted values using this equation are also shown in Fig.1. The Figure shows that these values match closely with the observed ones during the recent years when the equation was modified.

Burden Rate and Specific Consumption of Limestone and Sinter

The burden rate has been found to be the most significant variable which affects the carbon rate. The literature reports that considerable saving in coke rate is achieved by decreasing the burden rate[1,7,10]. Salient empirical equations relating the burden rate with the coke rate, reported in the literature, are shown in Fig. 2[11,12]. The present finding is also shown for comparison. Coke in the above equations consists of 85% carbon. For comparison, the coke rate has been computed from the carbon rate in the present analysis considering the same basis.

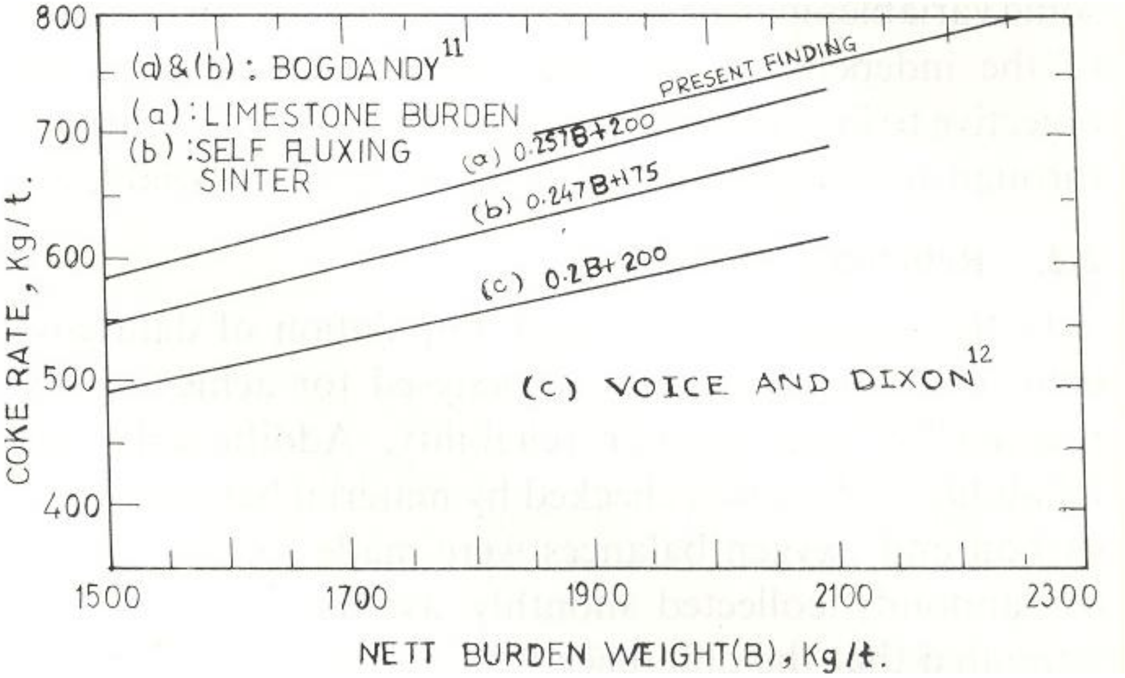


Fig. 2 : Relationship between coke consumption & burden weight according to various investigators. The present finding (Coke Rate = 0.226B+285) is also shown

Addition to the burden is mainly contributed from the following:

- Increase in the gangue constituents in the burden material which results in increased slag formation inside the furnace, and
- Increase in the consumption of limestone directly charged in the furnace (addition of CO_2) which increases the calcinations duty inside the furnace.

Figure 3 shows the schematic representation of increase in the coke rate (85%C) due to the different addition to the burden[10]. The benefits of pre-fluxing the burden is evident from the Figure. Elimination of 100kg of CO_2 from limestone results in the saving of about 75 kg of coke, whereas a reduction of 100 kg of slag results in the saving of about 20 kg of coke. The increase in the coke rate with addition to the burden, established in the present analysis, is also shown in Fig. 3. The dotted line representing the present finding is below the line which represents the average gangue. This is due to the considerably higher proportion of slag constituent in the burden of the furnace resulting from the higher coke rate coupled with the higher ash content in coke.

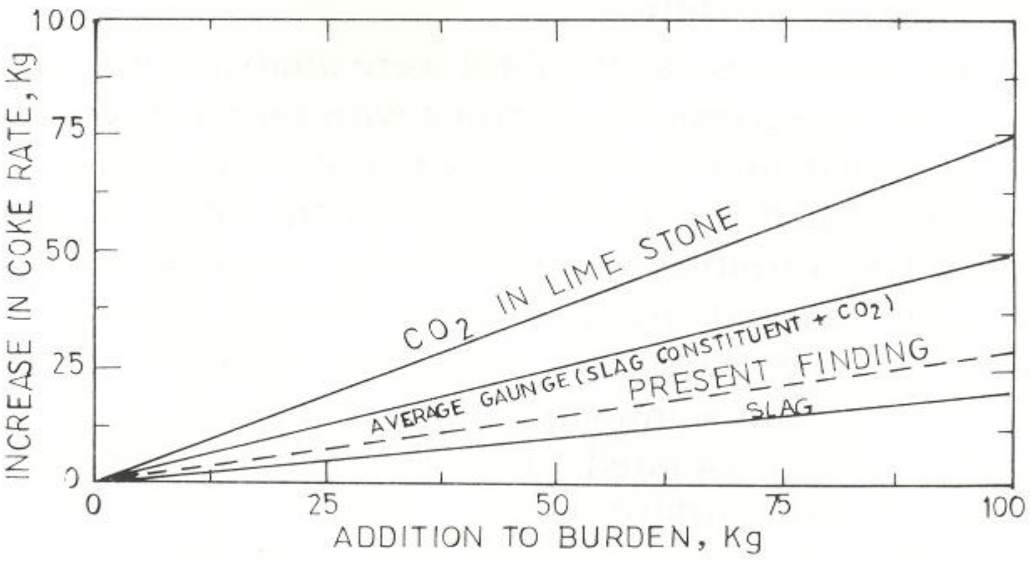
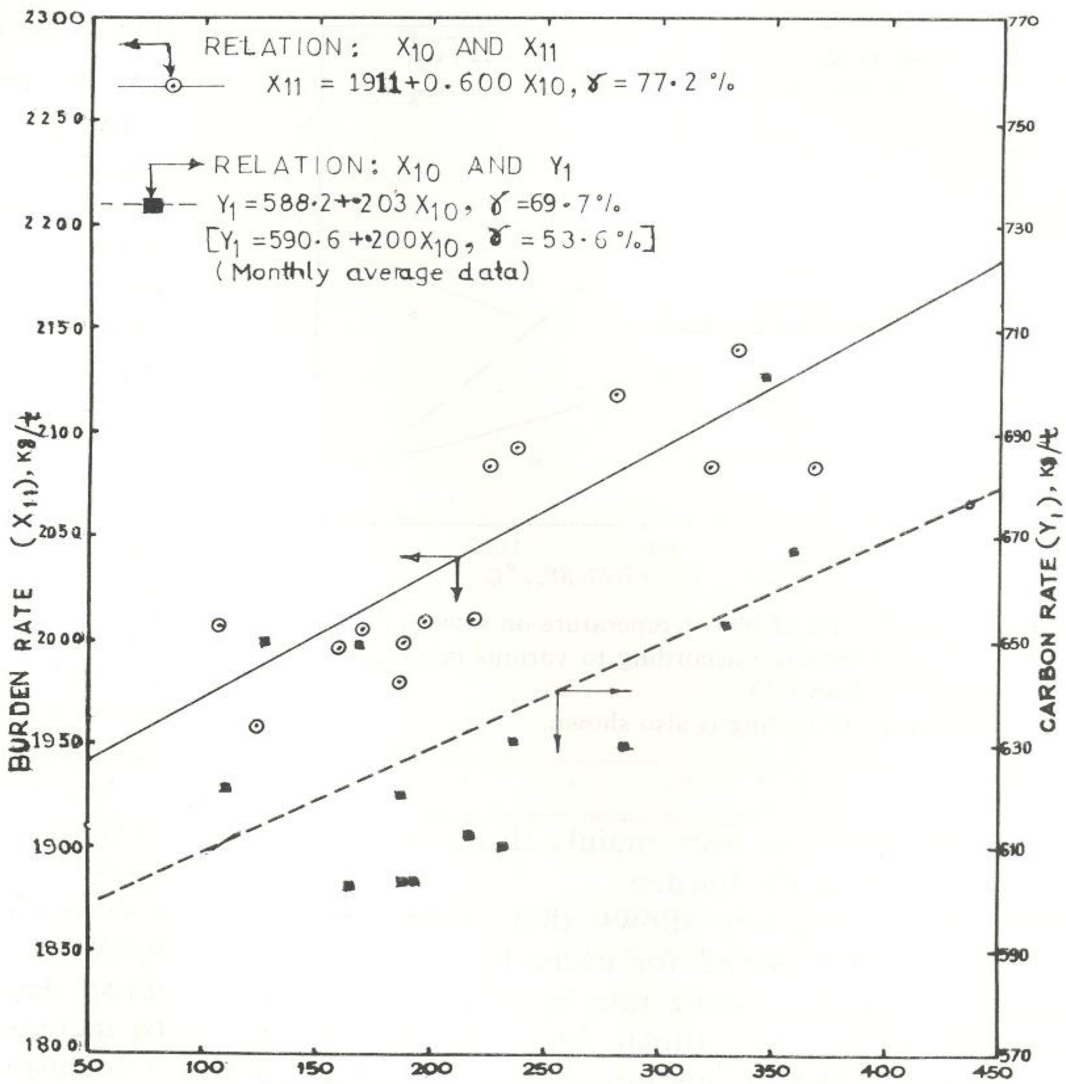


Fig. 3 : Schematic representation of increase in coke rate due to different addition to the burden (Astier et al. [10]). The present finding is also shown

The present analysis has shown the advantage of eliminating raw limestone from the burden through the use of greater percentage of fluxed sinter (Figures 4 and 5). Fig. 4 shows that an increase in the burden rate is primarily due to an increase in the raw limestone in the burden during the initial 16 years period.. Fig. 4 also shows the effect of limestone consumption on carbon rate. Fig. 5 show that the specific sinter consumption and the weight of raw limestone in the burden are closely correlated (r = -.93). Fig. 5 also shows the dependence of carbon rate on the specific consumption of sinter.

The above findings show that under Indian condition a significant saving in coke rate could be achieved by eliminating raw limestone from the burden through us of greater percentage of fluxed/super-fluxed sinter in the burden. A decrease in coke rate with the increase in sinter basicity has also been observed in the present analysis. The effect has been mainly through reducing the raw limestone in the burden.

Theoretical calculation shows that approximately 0.26 kg of carbon is saved for every kg of limestone removed [9]. A saving in coke rate by 96 kg/t has been reported earlier in the Bhilai furnace when approximately 244 kg of raw limestone was eliminated from the burden per tone of hot metal produced[13]. The investigation on the Bhilai furnaces has shown that the coke rate decreased by 4.6 % when 100 kg of raw limestone was eliminated from the burden for every tone of hot metal produced[14]. The present work has shown that the coke rate decreased by approximately 4% with such elimination



Weight of raw limestone in the burden

Fig. 4 : Effect of raw limestone in charge on burden rate and carbon rate

Ash Content in Coke

Apparently. Eq. (i) does not include the variables, ash content in coke in case of older data During this period ash content in coke had increased, while the consumption of raw limestone decreased significantly (with high CV). Therefore, the effect of ash content in coke had been masked, apparently, by the effect of weight of limestone in the burden. However, Eq.(ii), establish through analysis of the recent data, shows that an increase in the ash content in coke increased the carbon rate. Inclusion of the recent data shows considerable effect of this variable. This fact suggested that an equation developed need to be modified when the value of an independent variable deviates from the range of data considered in the analysis. This aspect perhaps has not been adequately pointed in early analysis.

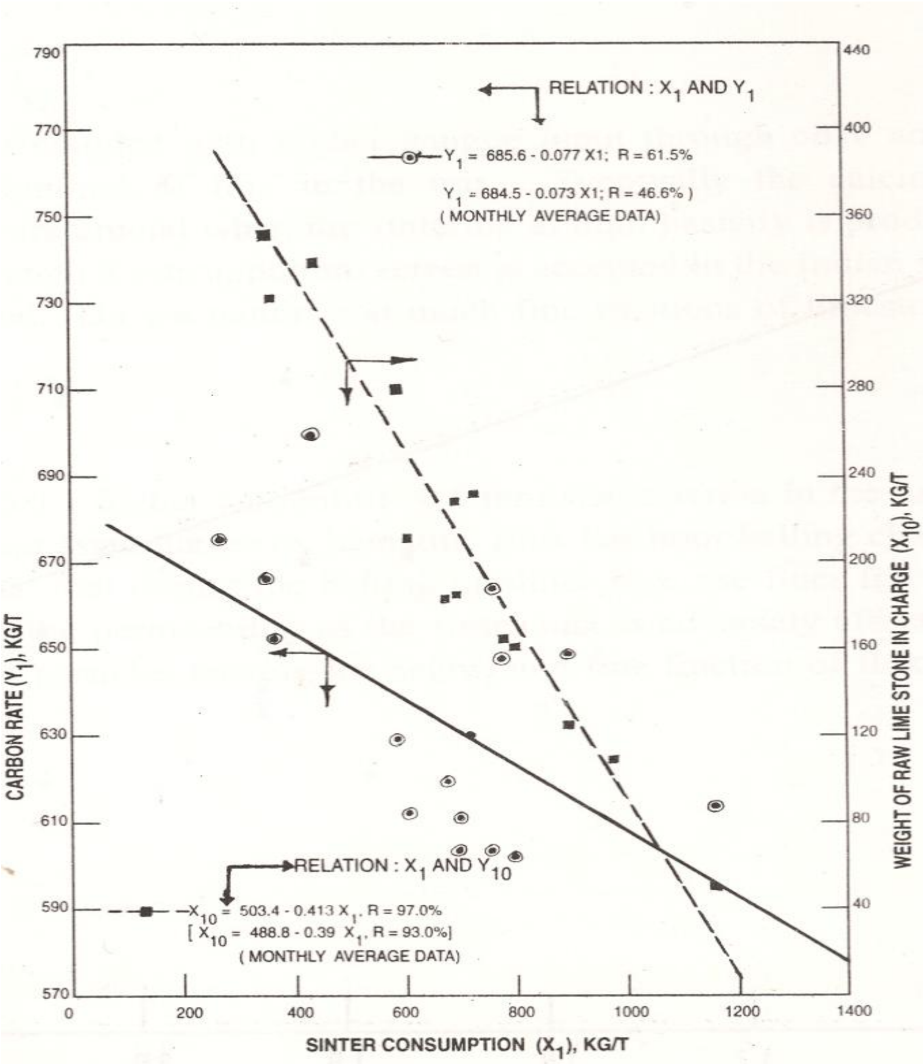


Fig. 5: Effect of sinter consumption on coke rate and limestone in burden

Blast Temperature

The present analysis shown that the carbon rate decreased significantly with an increase in the temperature of the hot blast. The saving is mainly due to the increased supply of sensible heat through the blast (Fig. 6)[9]. It is believed that the saving in coke is more at lower blast temperature than at higher ones. The percentage coke (85% C) saved, according to the present finding, when the blast temperature was raised from 872 to 1172 K is also shown in the Figure.

Reducibility and Fe Content in Sinter

The present analysis, in line with the literature[15,16] shows that the carbon rate decreased with increase in the sinter reducibility. The present analysis shows that the Fe content in sinter apparently decreased with increase in the specific sinter consumption. The reducibility also increased with decreased in the Fe content in sinter[3,17]. So the effect of Fe content in sinter on carbon rate has been masked by these strong variables.

Fines Content in Ferrous Burden

The present study shows that content of -12 mm size fraction in lump ore increased the cake rate [Eqs. (i) & (ii)]. This finding corroborates the Flint's finding[1]. Fines in the burden promote channelling which results in poor heat transfer efficiency. Undesirable size fraction also promote direct reduction.

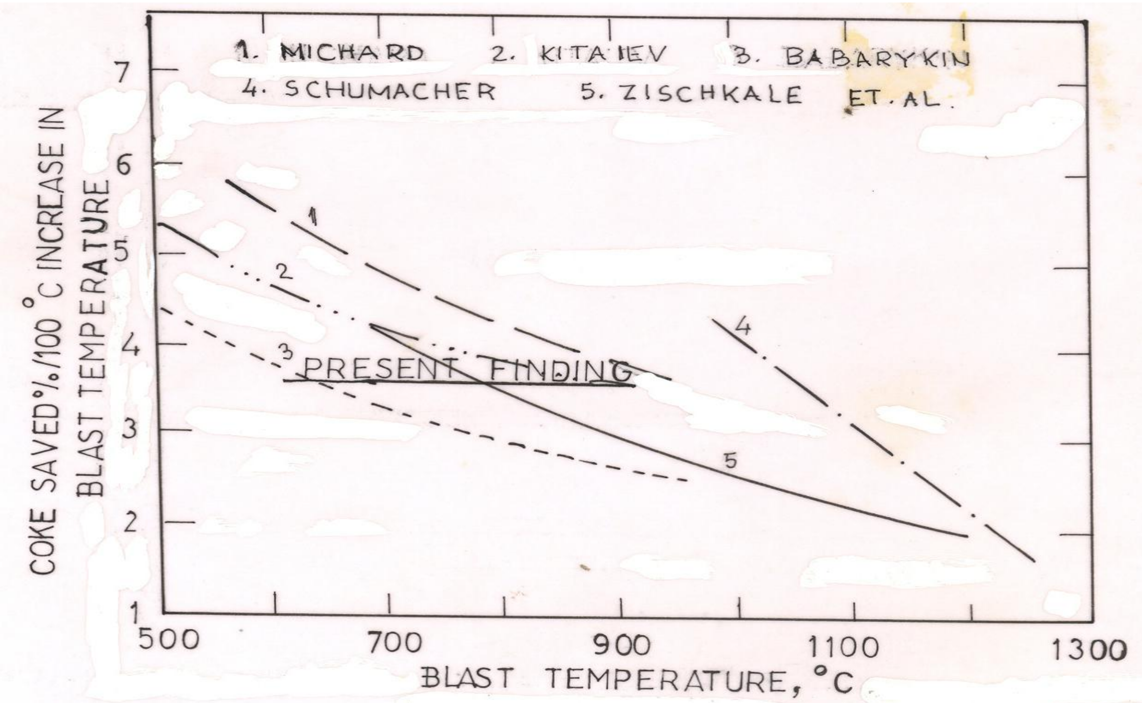


Fig. 6: Influence of blast temperature on saving in coke rate in actual practice according to various investigators. The present finding is also shown

Inter- influence between the Explanatory Variables

Some of the explanatory variables may not be orthogonal in case of blast furnace. Lack of orthogonality, in case of multi-variate system may be due to:

(a) *Natural cause and effect relationship amongst the explanatory variables* **:** In the present case, the specific consumption of limestone has been inter-influenced by the charge rate as well as the specific sinter consumption; both have appeared in equation. Fig. 5 shows that limestone directly charged in the furnace is closely related to the specific sinter consumption (r= -0.93).

When the two independent variables are closely related to each other, it may be essential for better reliability of the partial regression coefficient that one of them is included in the equation. For instance, in the present analysis, the variables, the limestone consumption could be replaced by the variables, the specific consumption of sinter, because they are closely related (r= -0.93). However, in order to avoid anomalies, such replacement should be justified on theoretical considerations.

From the direct correlation (r= 0.664) it seems that the variable charge rate could be replaced by the weight of limestone (and, ultimately by the specific consumption of sinter). However, this may not be permissible because the addition of the burden is not only contributed by the CO_2 associated with limestone, but also by gangue constituents associated with other burden materials.

(b) *Apparent inter–relationship amongst the explanatory variables and masking the effect.* Quite often we come across the explanatory variables which are not theoretically dependent to each other; but, they do influence the response variable and vary inadvertently either in the same direction or opposite direction of increasing magnitude so that the effect of one (on the response) is masked by another. For example, limestone in burden as well as ash content in coke influences coke rate independently. Apparently, Eq. (i) does not include the variables, ash content in coke. This was due to the fact that the effect of this variable has been masked by the specific consumption of limestone which has decreased significantly during this period.

In either of the above cases it becomes essential to isolate the inter-influences before drawing any conclusion which can be done through establishing the partial correlation coefficients amongst the explanatory variables..

Priority Determination through Statistical Inference

For effective and better functioning of a multivariate system, it may be desirable to set priority: short, medium and long term. Philosophy of setting priority lies on the basis that the variables which can be easily controlled and have more influence on the response variable are concentrated first. Gradually the variables, which are difficult to control and have less effect, are tackled later. The obtained regression equation can be applied to formulate the basis for priority determination. For instance, in case of blast furnace the factors which do affect the coke rate can be categorized in to two:

(a) *Factors which are controllable with difficulty.* These factors are guided by the constraints from the nature. For example, it requires elaborate treatment of raw materials to improve upon the chemistry which quite often may not be permissible, of course, under economic compulsion.

(b) *Factor which are easily controllable.* These are mostly within the control of operators, for examples, granulometric composition of burden materials, sinter basicity, reducing limestone etc.

Concluding Remarks

- The established equation could be dynamic as it changes when a newer variable is incorporated or/ and when the variability in an explanatory variable becomes more significant. In order to establish a meaningful regression equation the independent variables should be chosen with extreme carefulness. The objective of the study, in general, could be a deciding factor in this regard. In the present case, the objective was to establish the influence of only those variables on coke rate which are related to burden. Identification of the inter-influence amongst the explanatory variables and its isolation through the examination of partial correlation coefficient matrices of the variables is essential in order to draw a conclusion.
- Coke rate of the blast furnace has been represented by a functional equation through the statistical analysis of operating data. The coke rate is significantly affected by the burden rate which is correlated with the elimination of limestone from the burden through the use of higher percentage of fluxed / super- fluxed sinter. During the recent years it is affected by the variable, ash content in coke.

References

1. Flint R.V., B F & Steel Plant, **50** (1962), 47, 76.
2. Bhagat R. P, Ray H. S and Gupta S. K., ISIJ Inter. 31 (1991), No. 7, 669-676
3. Bhagat R. P, Sintering and Blast Furnace Iron Making: Theoretical and Experimental Investigations , Ph. D. Thesis, IIT Kharagpur (1988), Chap. 5.
4. Chatterjee S. and Price B. , Regression analysis by Example, J. Wiley & Sons , NY, (1977), Chap. 3.
5. Desai B.S., Ramna R. V. Chandra S. & Singh U. Tata Search 1(2006), 163 -167.
6. Desai B., Ramna R. V. and Sathaye J. Tata Search 1 (2007), 141-148.
7. Bogdandy L. V., Lange G. and Heinrich P., Stahl Eisen, **88** (1968), 1177.
8. Ridgion J. M. and Whitehouse A. M. J Iron & Steel Inst. (1956), 249
9. Biswas A. K. Principles of Blast Furnace Iron-Making Theory & Practice , Cootha Publ. House, Australia, (1981), Chap. 10 .
10. Astier J. E., Michard J., Dancoishe P., J Iron & Steel Institute (1961), 143.
11. Bogdandy L. V., Stahl Eisen, **81** (1961), 12.
12. Voice E. M. & Dixon K. G., J. Iron & Steel Inst. **200** (1962), 43.
13. Dastur M. N., Das-Gupta S. and Parthsarthy C. R. Trans. **21** (1968) 92
14. Prasad N. and Aswath H. S. Proc. Silver Jubilee Workshop Research Needs in Mineral Processing & Chemical Metallurgy, IIT Bombay (1983),C1.
15. Vidal S., Leccorte P. and Poos A., Trans. IIM, **26** (1973)
16. Heinrich A., Kortman and Burghart O.P., in Agglomeration (KVS Sastry Ed.), AIME, NY, (1977), 219
17. Bhagat R. P., Gupta S. K., Ray H. S. Trans. IIM 41 (1988) 465.