IMPROVEMENT OF IRON ORE BURDEN COMPONENTS DISTRIBUTION WHEN CHARGING INTO BLAST FURNACE TOP BY PHYSICAL AND MATHEMATICAL MODELING OF FIXED EFFECTS

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ABSTRACT

To provide the blast furnace high productivity and coke low specific consumption, the causes of uneven distribution of burden components during their discharge out of the trough type bell-less charging device (BCD) of the bunker into the furnace top had been found out in the process of laboratory research. A series of experiments on the full two-factor experiment scheme with variation on three levels had been conducted. Sinter and pellets were used as charge materials. The content of the pellets was varied from 10 to 50 %. They were placed in the bunker under the agglomerate in the middle of its bed and above it. Five portions of the material of equal volume were formed in the process of discharging. Then it was dissipated into 9 fractions, the batch components were separated from each other and their mass was weighed. After that the sources of the uneven sinter and pellets distribution in each test had been revealed by the method of the analysis of variance. The material mass distributions according to the groups of lump size and by the number of portions were used as the output variables.

As a result, it had been found that the materials lump size has the most significant effect on its uneven distribution. The average proportion of the influence of the "lump size" factor for the sinter and pellets had been respectively 0.71 and 0.61. The distribution of the agglomerate mass in portions emerging in the process of loading the charge into the furnace top space depended on the location of the sequence of its components in the bunker of the BCD and its contents in the volume of the pellets charge. The maximum share of influence on the unevenness of the factor "weight" equal to 0.27 was observed at 50 % of the pellets content and their location at the bottom of the BCD bunker. With this arrangement, the interaction of the studied traits was of significant importance. The highest proportions of interactions, equal to 0.66; 0.45 and 0.30, was observed in the experiments, when the content of pellets from the iron ore part of the charge was 10, 30 and 50 %, respectively. Possible reduction in specific coke consumption by improving distribution came to 7 %.

Keywords: blast furnace, a compact bell-less charging device, the trough distributor, iron ore materials, charge, fixed effects model, analysis of variance.

FORMULATION OF THE PROBLEM

For operation of the furnace with high efficiency and low specific consumption of coke, it is necessary to ensure the uniform distribution of the materials [1 - 3] and gases [4 - 6] over the furnace circumference and the optimal placement of the charge over the radius of the throat [1]. It is possible to receive reduction value of the coke specific consumption by further improvement of the distribution equal to 7 % [7 - 8]. There are no problems with providing a certain ore load over the furnace top cross-section when working with the compact charging device of the tray type. Designed matrix of charge loading at 11 stations of the angular position of the tray in the blast furnaces of Canada (Hamilton Works Company), Germany (Company ArcelorMittal Eisenhu), Japan, Spain and the Ukraine allow to receive a predetermined uniformity of the charge over the furnace top radius and conduct smelting with high technical and economic parameters [1, 9 - 13]. However it is difficult to provide a uniform charge distribution over the circumference [14 - 16] for various reasons. One of them is that the loaded charge is multi-component[17, 18]. For example, in addition to iron ore materials (burden and pellets) nut coke or coke fraction, quartzite, washing materials, as well as iron or manganese ore are used in its composition at the JSC "MMK". Furthermore the materials loaded into the blast furnace are not uniform in the lump size and different in quality [19].That is why, the trajectories of the charge components movement from the tray to the surface of the previously formed layer are various, so that their uneven arrangement takes place and this impairs the course of the processes and performance indexes of the blast furnace. To eliminate the non-uniformity it is necessary to evaluate the sources of its occurrence.

METHODS

To identify the sources of uneven distribution a physical simulation of various regimes of charge components loading into the furnace top space had been conducted. Trials had been conducted according to the scheme of a full two-factor experiment with variation at three levels (Table 1).

During the experiment, sinter and pellets were loaded into the bunker of the BCD. The pellets were placed under the agglomerate, in its middle layer and above it. Pellets content was varied in the range from 10 to 50 %, leaving unchanged the total amount of the material loaded into the bunker discharged in the furnace top space. In the course of discharge 5 portions of the material equal volume were selected and dissipated into fractions 1 - 3; 3 - 5; 5 - 8; 8 - 10; 10 - 12; 12 - 15; 15 - 17,5; 17,5-25; > 25 mm, and then batch components were separated from each other and were weighed. To receive accurate information, each experiment was repeated. The causes of uneven distribution of agglomerate and pellet were revealed by the analysis of variance in each experiment [20]. The mass distribution of the materials into lump size groups and according to the number of batches were used as output variables (responses).

Thus, for each of the scheduling matrix experiments N = 32 (see Table 1) two-factor dispersion systems with a number of experiments N = q · m · n = 5 · 9 · 2 = 90 were obtained, where q is the level (category) of the factor Q (batch number), m is the category of the factor M (particle lump size), n is the number of repetitions. The number of the freedom degrees required for estimation of the total amount of the dispersion will be: $k_Y = k_Q + k_M + k_{QM} + k_{Er}$ or, which is the same for this complex: $k_y = q \cdot m \cdot n - 1 = 5 \cdot 9 \cdot 2 - 1 = 89$.

The number of degrees of freedom k_{Er}, required for calculating of the intraclass variance is determined by the product of (n - 1) into the number of the plan cells, i.e. $k_{Er} = q \cdot m \cdot (m-1)$.

The data grouping of this two-factor complex can always be represented by two variants in the format of the uni-factor plan. For example, when viewed from the perspective of factor Q, the experimental design will look like it is illustrated in Table 2.

The scheme of grouping presented in Table 2 reproduces the one-factor (for a cumulative factor X) experiment with a number of groups qm. Then the basic identity of the dispersion has a view $SS_Y = SS_x + SS_{Er}$ with the numbers of degrees of freedom $k_Y = q \cdot m \cdot n - 1$, $k_X = q \cdot m - 1$, $k_{Er} = q \cdot m \cdot (m-1)$ where N = q · m ·

Table 1. Experiment planning matrix N = $3^{2.}$

Test number	Factors	
	The proportion of sinter, located under the pellets, %	The pellets content, %
1	0	10
2	50	10
3	100	10
4	0	30
5	50	30
6	100	30
7	0	50
8	50	50
9	100	50

Table 2. A method of data grouping in the two-factor experiment with the position of Q factor.

Factor Q groups	Q_1				…	Q_q			
Factor M subgroups	M_1	M_2	…	M_m	…	M_1	M_2	…	M_m
The results of observations	y_{111} … y_{11n}	y_{121} … y_{12n}	… … …	y_{1m1} … y_{1mn}	… … …	y_{q11} … y_{q1n}	y_{q21} … y_{q2n}	… … …	y_{qm1} … y_{qmn}

n. For this classification, the full amount of the response dispersion squares can be written as:

$$SS_Y = \sum_{i=1}^{q}\sum_{j=1}^{m}\sum_{t=1}^{n}(y_{ijt} - \overline{y}_{000})^2 =$$

$$= \sum_{i=1}^{q}\sum_{j=1}^{m}\sum_{t=1}^{n}(\overline{y}_{ij0} - \overline{y}_{000})^2 +$$

$$+ \sum_{i=1}^{q}\sum_{j=1}^{m}\sum_{t=1}^{n}(y_{ijt} - \overline{y}_{ij0})^2$$

For the two-factor variance complex the factor (for a cumulative factor X) sum of the squares $SS_X = SS_N + SS_K + SS_{NK}$, that is, the sum of the squares between the cells $SS_X = \sum_{i=1}^{q}\sum_{j=1}^{m} n\cdot(\overline{y}_{ij0} - \overline{y}_{000})^2$ can be expanded into the sum of the squares on the factor Q (the columns in the matrix of the experiment), the sum of the squares on the factor M (the lines) and the sum of the squares of the effect of these factors interaction (the intersection of rows and columns) or

$$\sum_{i=1}^{q}\sum_{j=1}^{m} n\cdot(\overline{y}_{ij0} - \overline{y}_{000})^2 =$$

$$= nm\sum_{i=1}^{q}(\overline{y}_{i00} - \overline{y}_{000})^2 + nq\sum_{j=1}^{m}(\overline{y}_{0j0} - \overline{y}_{000})^2 +$$

$$+ \sum_{i=1}^{q}\sum_{j=1}^{m}(\overline{y}_{ij0} - \overline{y}_{i00} - \overline{y}_{0j0} + \overline{y}_{000})^2$$

where: $\overline{y}_{i00} = \frac{1}{nm}\sum_{j=1}^{m}\sum_{t=1}^{n} y_{ijt}$ is the average in the i- column, $i = \overline{1,q}$;

$\overline{y}_{0j0} = \frac{1}{nq}\sum_{i=1}^{q}\sum_{t=1}^{n} y_{ijt}$ is the average in the j-line, $j = \overline{1,m}$

$\overline{y}_{ij0} = \frac{1}{n}\sum_{t=1}^{n} y_{ijt}$ is the average in the ij-cell;

$\overline{y}_{000} = \frac{1}{qmn}\sum_{i=1}^{q}\sum_{j=1}^{m}\sum_{t=1}^{n} y_{ijt}$ is the overall average.

Then the plan of the two-factor dispersion complex will look like in accordance with Table 3.

For the two-factor analysis of variance with n observations for each combination of the factors levels the model has the form:

$$y_{ijt} = M(Y) + \alpha_j + \beta_j + (\alpha\cdot\beta)_j + \varepsilon_{ijt}$$

where M (Y) is the expectation of the results observed for the entire set of observations; αi, βi are the effects of factors Q and M respectively on (i, j levels ($i = \overline{1,q}; j = \overline{1,m}$); (αβ) ij are the interaction effects of Q and M factors; ε_{ijt} are the random errors observed in the (ij) cell of the t result, $t = \overline{1,n}$.

For the sample size of experiments N = qmn the expectation $M(Y) = \overline{y}_{000} + \overline{\varepsilon_{000}}$, where $\overline{\varepsilon_{000}}$ is the average error of the overall average. The sums of the determined effects for all the appropriate levels are:

$$\sum_{i=1}^{q}\alpha_j = \sum_{j=1}^{m}\beta_j = \sum_{i=1}^{q}(\alpha\cdot\beta)_{ij} = \sum_{j=1}^{m}(\alpha\cdot\beta)_{ij} = 0$$

The parameters included into the model to describe the observed results yijt are associated with the corresponding average and the average error as follows:

- the mean amount of lines $\overline{y}_{i00} = M(Y) + \alpha_i + \overline{\varepsilon_{i00}}$;
- the mean amount of columns $\overline{y}_{0j0} = M(Y) + \beta_j + \overline{\varepsilon_{0j0}}$;
- the mean amount of cells $\overline{y}_{ij0} = M(Y) + \alpha_i + \beta_j + (\alpha\cdot\beta)_{ij} + \overline{\varepsilon_{ij0}}$
- the overall average $\overline{y}_{000} = M(Y) + \overline{\varepsilon_{000}}$.

Thus, the analysis of variance in the two-factor complex was performed on the basis of the formulae presented in Table 4.

To assess the findings reliability of the analysis of the two-factor variance complex Fisher dispersion relations

Table 3. The method of grouping the data of the two-factor dispersion complex according to the scheme of a rectangular matrix.

M	Q				The mean quantity of lines
	Q_1	Q_2	…	Q_q	
M_1	$y_{111}, y_{112}, \ldots, y_{11n}$	$y_{211}, y_{212}, \ldots, y_{21n}$	…	$y_{q11}, y_{q12}, \ldots, y_{q1n}$	$\bar{y}_{010}$
M_2	$y_{121}, y_{122}, \ldots, y_{12n}$	$y_{221}, y_{222}, \ldots, y_{22n}$	…	$y_{q21}, y_{q22}, \ldots, y_{q2n}$	$\bar{y}_{020}$
…	…	…	…	…	…
M_m	$y_{1m1}, y_{1m2}, \ldots, y_{1mn}$	$y_{2m1}, y_{2m2}, \ldots, y_{2mn}$	…	$y_{qm1}, y_{qm2}, \ldots, y_{qmn}$	$\bar{y}_{0m0}$
The mean quantity of columns	$\bar{y}_{100}$	$\bar{y}_{200}$	…	$\bar{y}_{q00}$	$\bar{y}_{000}$

[21] were determined respectively for the input variables Q and M and their interaction:

$$F_Q = \frac{S_Q^2}{S_{Er}^2}, F_M = \frac{S_M^2}{S_{Er}^2}, F_{QM} = \frac{S_{QM}^2}{S_{Er}^2}.$$

Finally, the proportion of dispersion sources in their total amount $SS_Y = SS_Q + SS_M + SS_{QM} + SS_{Er}$ was assessed using the corresponding correlation relations of the form:

$$\eta_Q^2 = \frac{SS_Q}{SS_Y}, \eta_M^2 = \frac{SS_M}{SS_Y}, \eta_{QM}^2 = \frac{SS_{QM}}{SS_Y}, \eta_{Er}^2 = \frac{SS_{Er}}{SS_Y}$$

RESULTS AND DISCUSSION

The results of the sinter and pellets distribution into portions and lump size in the process of discharging them from the bunker of the bell-less charging device of the trough type into the furnace top space in the experiment number 1 are given in Tables 5, 6.

The analysis of Tables 5 and 6 shows that sinter and pellets are unevenly distributed by lump size and portions. The agglomerate mass in portions No 1 and No 4 varies by more than twice. Excess pellets weight in portion No 1 over the total mass in portions No 2 - 5 is more

Table 4. The basic formulae of the analysis of variance results of the complete two-factor complex with the same repetition of experiments in each cell of the plan.

Source of variation	Number of degrees of freedom	Sum of squares of deviations	Estimation of variances
Between the columns	$k_Q = q - 1$	$SS_Q = mn\sum_{i=1}^{q}(\bar{y}_{i00} - \bar{y}_{000})^2$	$S_Q^2 = \frac{SS_Q}{k_Q}$
Between the lines	$k_M = m - 1$	$SS_M = qn\sum_{j=1}^{m}(\bar{y}_{0j0} - \bar{y}_{000})^2$	$S_M^2 = \frac{SS_M}{k_M}$
Inter Interaction	$k_{QM} = (q-1)(m-1)$	$SS_{QM} = n\sum_{i=1}^{q}\sum_{j=1}^{m}(\bar{y}_{ij0} - \bar{y}_{i00} - \bar{y}_{0j0} + \bar{y}_{000}$	$S_{QM}^2 = \frac{SS_{QM}}{k_{QM}}$
Inside the cells	$k_{Er} = qm \cdot (n-1)$	$SS_{Er} = \sum_{i=1}^{q}\sum_{j=1}^{m}\sum_{t=1}^{n}(y_{ijt} - \bar{y}_{ij0})^2$	$S_{Er}^2 = \frac{SS_{Er}}{k_{Er}}$
Total amount	$k_Y = qm \cdot (n-1)$	$SS_Y = \sum_{i=1}^{q}\sum_{j=1}^{m}\sum_{t=1}^{n}(y_{ijt} - \bar{y}_{000})^2$	–

than 5 times. Fisher dispersion relations at significance level of $p \leq 0.05$ and (Tables 7 and 8) show significant effects of input variables that characterize the distribution of material on the number of portion (Q) and lump size (M), including their interaction (QM).

The overall results of the analysis of variance for the whole range of researches are summarized in Table 9. The particle lump size of the material (M feature) exerts the most significant influence upon the uneven distribution of the charge components. The average share for the characteristic M for sinter and pellets is 0.71 and 0.61, respectively (Table 9).

Varying the material mass fractions of the characteristic Q in experiments 1 - 9 for sinter and pellets ranged from 0.01 to 0.27 and from 0.02 to 0.15, respectively. The distribution of materials into portions depended on the content of pellets in the iron ore part of the sinter and on the sequence of their loading into the bunker of the BCD. The highest share of the variable Q as a source of dissipation caused an increase in the proportion of pellets (tests number 7 - 9) and their location at the bottom of the bunker of the BCD (experiments No 1, 4, 7). In the conditions of their interaction the share value of the variable Q for the sinter had a maximum and was 0.27.

A great significance for pellets was the interaction between characteristics Q and M with an average share of impact 0.29. The maximum proportion of the impact of interactions, equal to 0.66; 0.45 and 0.30 was observed for the conditions of placing the pellets in the bottom part of the bunker of the BCD according to their content from the iron ore part of sinter equal to 10, 30 and 50%.

Thus, the sources of disturbances have been identified by the method of analysis of variance to explain the total variance of the observed non-uniformity at different modes of loading of iron ore materials (sinter and pellets) in the furnace top space of the blast furnace. The

Table 5. The distribution results of conventional mass units of sinter into portions and fractions in experiment number 1.

Levels of factors	1	2	3	4	5	Sum of lines
>25, mm	984	1382	1077	1295	1236	5973
17.5 – 25, mm	2654	4686	3542	3740	3501	18122
15 – 17.5, mm	1616	2796	2550	2659	2567	12189
12 – 15, mm	2381	3350	5226	5553	3756	20266
10 – 12, mm	1093	5427	3018	3363	2937	15837
8 – 10, mm	829	2947	3628	3214	3569	14186
5 – 8, mm	271	754	542	1090	1113	3770
3 – 5, mm	39	97	100	141	123	498
1 – 3, mm	18	45	45	56	129	293
Sum of columns	9884	21483	19728	21109	18929	91134

Table 6. The results of distribution of arbitrary mass units of pellets into portions and fractions in the experiment number 1.

Levels of factors	1	2	3	4	5	Sum of lines
>25, mm	28	0	0	0	0	28
17.5 – 25, mm	565	24	32	0	0	621
15 – 17.5, mm	1079	19	125	85	214	1522
12 – 15, mm	8017	107	50	28	248	8451
10 – 12, mm	803	339	0	36	316	1493
8 – 10, mm	3	0	0	0	0	3
5 – 8, mm	0	0	0	0	0	0
3 – 5, mm	0	0	0	0	0	0
1 – 3, mm	0	0	0	0	0	0
Sum of columns	10495	489	207	149	778	12118

Table 7. The analysis of variance results of agglomerate distribution into portions and lump size in experiment No 1.

No	Dissipation source	SS	F	p	η^2	General SS	General variance	Experimental error
1	Q	468	16.3	0.00	0.09	5164	58	2.679
	M	3983	69.5	0.00	0.77			
	QM	390	1.7	0.05	0.08			
	Error	323	-	-	0.06			

Table 8. The analysis of variance results of the pellets distribution into portions and lump size in experiment No 1.

No	Dissipation source	SS	F	p	η^2	General SS	General variance	Experimental error
1	Q	468	225.7	0.00	0.13	3454	39	1.155
	M	649	156.6	0.00	0.19			
	QM	2276	139.4	0.00	0.66			
	Error	60	-	-	0.02			

Table 9. Evaluation of dispersion sources of shares for the results of the experiment.

Experiment Number	Shares of dispersion sources on the features of relatively total SS accepted as 1									
	For the features of sinter					For the features of pellets				
	SS	Q	M	QM	Er	SS	Q	M	QM	Er
1	5164	0.09	0.77	0.08	0.06	3454	0.13	0.19	0.66	0.02
2	4597	0.00	0.87	0.06	0.07	487	0.04	0.79	0.13	0.04
3	4401	0.01	0.90	0.03	0.06	572	0.08	0.57	0.27	0.08
4	5081	0.25	0.52	0.18	0.05	8569	0.15	0.38	0.45	0.02
5	3376	0.02	0.86	0.06	0.06	4115	0.02	0.69	0.22	0.07
6	3284	0.08	0.83	0.07	0.02	5005	0.05	0.74	0.19	0.02
7	3282	0.27	0.45	0.19	0.09	12750	0.07	0.61	0.30	0.02
8	2303	0.13	0.62	0.11	0.14	10229	0.03	0.79	0.16	0.02
9	3062	0.20	0.59	0.15	0.06	11652	0.05	0.74	0.18	0.03
Average	3839	0.12	0.71	0.10	0.07	6315	0.07	0.61	0.28	0.04

share of experimental error in the reproducibility of the total dispersion of the effective characteristic was ranged from 2 to 14 % in the experiments with the agglomerate and between 2 and 8 % in the experiments with the pellets. The minimum and maximum non-uniformities determined on the basis of decomposition SSy to explain the components are shown in Figs. 1 and 2, respectively.

CONCLUSIONS

The analysis of variance revealed the sources of the non-uniform distribution of the iron ore charge loaded into the blast furnace. The lump size of materials exerts the most significant influence. The average shares of influence for sinter and pellets were respectively 0.71 and 0.62. The rest was accounted for by the distribution of the mass in portions and the effect of interaction between the two variables.

2. The distribution of the sinter mass into portions formed in the process of loading the charge into the furnace top space depends on the sequence of arrangement of its components in the bunker of the bell-less charging device and the content of the pellets. The maximum share of influence equal to 0.27 was observed when the content of pellets from the iron ore part of the sinter was 50 % and they were located on the bottom of the bunker of the BCD.

3. The factor interaction features are of great importance for the pellets in the condition of their placement at the lower part of the bunker of the BCD. The highest proportion of interactions, equal to 0.66; 0.45 and 0.30, was observed in the experiments, when the content of

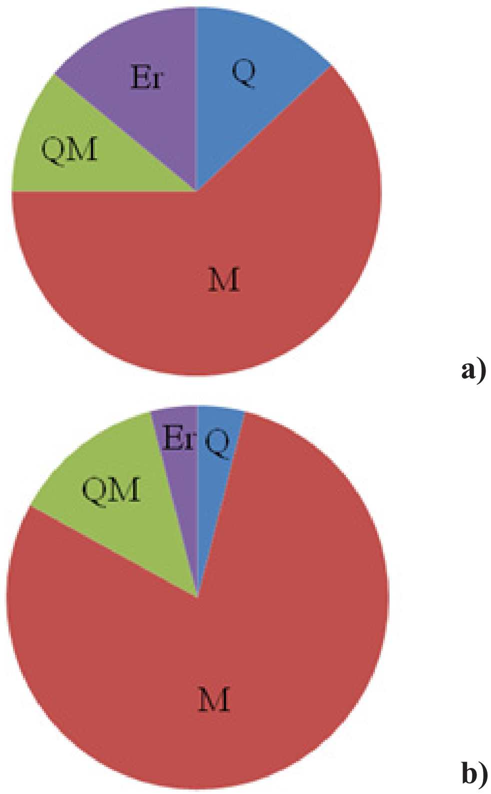

Fig. 1. Minimum quantities SSy and their decomposition to explain the components of the sinter (a - SSy (min) = 2303) and pellets; b - SSy (min) = 487.

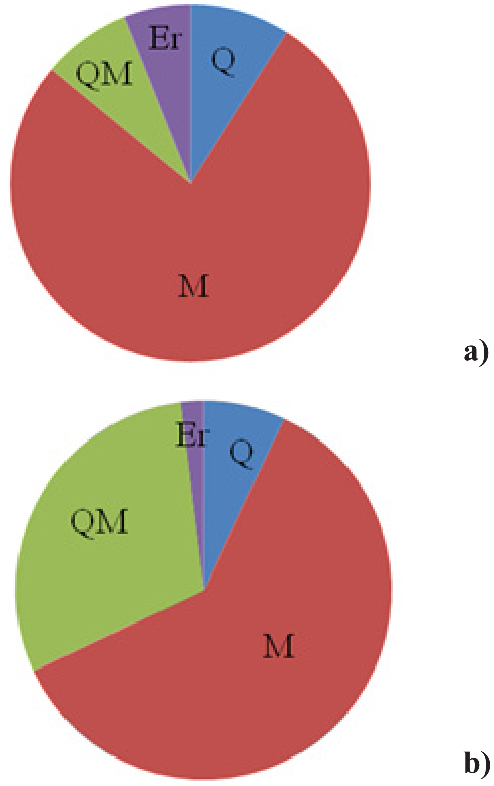

Fig. 2. Maximum quantities SSy and their decomposition to explain the components for the sinter (a - SSy (max) = 5164 and pellets; b - SSy (max) = 12750.

pellets from the iron ore part of the sinter was 10, 30 and 50 %, respectively.

4. The total share of disturbances in the total variance of the distribution factors of the mass and the lump size of the sinter material, including the effect of their interaction, which is 86 - 98 % for sinter and 92 - 98 % for pellets.

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