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BLAST FURNACE PERFORMANCE IMPROVED THROUGH OPTIMUM RADIAL DISTRIBUTION OF MATERIALS AT THE TOP WHILE CHANGING THE CHARGING PATTERN*

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Key words:

Blast furnace, charging matrix, coke, pellets, radial distribution, natural gas.

ABSTRACT

This research looked at the performance of a 1,370 m^3 blast furnace in operation at the MMK site after the percent of pellets in the iron ore charge and the ore burden radial distribution at the furnace top were simultaneously changed. In the periods studied, the percent of pellets was within 28–40%. Through changing the charging matrix, one built a burden layer at the furnace top which had different concentrations of iron ore coming from a hopper of the bell-less top (BLT) charging system through sloping chute stations, where stations No. 9–11, 6–8 and 3–5 are characterized by the following iron ore concentration (%): 85–94, 54–58 and 25–40 respectively. As a result, the authors determined what coke and iron ore distribution pattern would be optimal for a blast furnace with a compact BLT charging system depending on the amount of pellets in the burden.

When pellets account for 28–30%, the amount of iron ore materials charged in the peripheral zone of the furnace with the sloping chute positioned to Stations 9–11 that proved to be optimal was 85–90%. When the amount of iron ore charged at the above stations was reduced from 94 to 90% while Stations 3-5 saw an increase from 25 to 29% and Station 2 saw a decrease from 45 to 22%, it became possible to cut the consumption of coke by raising the amount of natural gas consumed from 13.1 to 13.9 th m^3/h. The natural gas hydrogen utilization rose from 32.2 to 35.4% delivering a 4.6 kg/t of iron reduction in the specific consumption of coke.

A 30 to 40% rise in the amount of pellets justified the increased concentration of iron ore in the peripheral zone (from 85–90 to 93–94%). An increase from 85 to 93% made it possible to raise the consumption of natural gas by 1.2 th m^3/h reaching a substitution rate of 0.85 kg/m^3.

Problem Statement

The distribution of burden at the furnace top has a significant effect of the furnace performance. Maximum performance can be achieved through an even circumferential distribution of the burden materials by type and size [1–8] and a balanced radial distribution at the furnace top [9–17]. Such optimal process of burden formation at the furnace top makes it possible to raise the allowable flow rates of natural gas and blast air [18, 19] while achieving maximum utilization of the chemical and thermal power of the gas flow [20–22]. This charging optimization could result in a total 3% reduction in the specific consumption of coke [13]. Various factors dictate how the burden is formed at the furnace top, including such parameters as chute slope angle, stock line, stock size, burden characteristics (size of materials, coke, etc.), path of the materials moving from the chute to the existing layer, behaviour of the materials on the burden top upon charging [23–28]. The effect produced by the above factors on the counter flow of the materials and gases manifest itself as a burden resistance coefficient and an airflow counteraction [29, 30]. The key component that enables control over the burden distribution in a bell-less top furnace equipped with a chute is a charging matrix. There are optimum radial charging regimes that equate to maximum coke saving. But they can vary depending on the blast furnace process in place. Using the case study of MMK's Blast Furnace 4 equipped with a compact bell-less top charging chute, this study focused on understanding how the charging matrix can influence the furnace performance.

Methods Applied

Five periods were studied using MMK's Blast Furnace 4. The difference between the periods was in the percent of pellets in the iron ore charge and in the ore burden radial distribution at the furnace top (**Table 1**).

The percent of pellets was raised for Period II compared with Period I from 28 to 40% (**Table 2**). As pellets are coarser (based on surface equivalent size) than sinter, the size of the iron ore charge increased during Period II compared with Period I by 3.8% (**Table 3**). According to the findings of a previously conducted study, a greater number of pellets in the charge is associated with their higher concentration in the near-wall zone of a blast furnace, which is indicated by an increased peripheral concentration of CO_2, as well as by increased temperatures of the stack, belly, and bosh cooling staves [31].

Higher concentration of pellets in the near-wall zone leads to higher permeability of the peripheral zone. To

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Table 1. **Concentrations of materials fed from all the stations of the sloping chute,%**

	Coke									
Station No.	11	10	9	8	7	6	5	4	3	2
Period I	0	0	6	10	12	19	11	14	0	28
Period II	0	0	3	10	11	17	10	13	9	26
Period III	0	0	5	5	12	7	17	10	14	31
Period IV	0	0	4	5	11	6	12	10	7	45
Period V	0	0	5	11	13	7	9	11	22	22
	Iron ore charge									
Station No.	11	10	9	8	7	6	5	4	3	2
Period I	0	21	14	10	18	21	17	0	0	0
Period II	4	17	18	12	18	14	17	0	0	0
Period III	16	22	10	6	13	15	18	0	0	0
Period IV	18	29	16	12	7	8	10	0	0	0
Period V	8	17	19	11	12	15	17	0	0	0

Table 2. **Blast furnace 4 charge parameters**

Parameters	Concentration of iron ore in the burden of the peripheral zone (corresponding to Stations 9–11), %			
	85	93	91	94
Periods	I	II	III	IV
Period length, days	7	7	8	7
Pellets in iron ore charge, %	28	40	31	31
Burden-weight ratio, t/t	3.54	3.51	3.37	3.29
Actual stock line, m	1.1	1.0	1.0	1.3
Concentration of iron ore in the peripheral zone burden coming from stations,%:				
9–11 (α_{periph}) — peripheral zone	85	93	91	94
6–8 ($\alpha_{V\text{-}cont}$) — V-shaped contour zone	54	54	58	55
3–5 (α_{inter}) — in between the centre and the V-shaped contour zone	40	34	30	25
Iron ore concentration ratio in circular zones:				
$\alpha_{periph} / \alpha_{V\text{-}cont}$	1.56	1.74	1.57	1.70
$\alpha_{periph} / \alpha_{inter}$	2.13	2.70	2.98	3.72
$\alpha_{V\text{-}cont} / \alpha_{inter}$	1.37	1.55	1.90	2.19

Table 3. **Burden materials sizes**

Parameters	Concentration of iron ore in the burden of the peripheral zone (corresponding to Stations 9–11),%			
	85	93	91	94
Surface equivalent size of, mm:				
sinter	9.6	9.9	9.7	9.7
pellets	12.7	12.3	12.3	12.3
iron ore concentrate	10.4	10.9	10.5	10.5
coke	69.6	69.5	72.2	69.3
Weighted average size, mm:				
sinter	17.4	17.3	16.8	17.0
pellets	14.4	14.3	14.2	14.2
iron ore concentrate	16.5	16.1	16.0	16.1
coke	59.5	57.4	60.5	56.3
Uniformity of size:				
sinter	0.55	0.57	0.58	0.57
pellets	0.88	0.86	0.87	0.87
iron ore concentrate	0.64	0.69	0.67	0.66
coke	1.17	1.21	1.19	1.23

prevent excessive peripheral drive, the iron ore concentration in the zone corresponding to Stations 9–11 was increased from 85 to 93% (Table 1) during Period II compared with Period I.

During Periods III–V, the iron ore concentration in the peripheral zone corresponding to Stations 9-11 was changed from 90 to 94% due to changes in Stations 6–8 (from 58 to 55%), Stations 3–5 (from 30 to 25%) and Station 2 (from 55 to 78%). In those periods pellets accounted for 31–32% of the iron ore charge.

Results

A greater size (surface equivalent size) of the iron ore charge due to a greater number of pellets in Period II versus Period I made it possible to raise the natural gas flow from 15.1 to 16.3 th m³/h. At the same time, the output of the tuyere gas rose by 1.1% (Table 3). An increased burden-weight ratio in the peripheral zone was associated with a more efficient use of natural gas. This is indicated by a 1% (abs.) rise in the hydrogen utilization during Period II versus Period I (**Table 4**) and a decrease in the specific consumption of coke by 2.5 kg/t of iron (Table 3). This became the result of the furnace gases moving predominantly through the V-shaped contour zone and partially through the near-wall zone, which was indicated by a change in the radial concentration of CO_2 (**Fig. 1**) and a greater difference between the average gas temperature in the peripheral zone and the average offtake temperature – 361 versus 343 °C (**Table 5**).

The burden resistance coefficient rose from the middle stack to the top by 2.56% (see Table 5). The biggest rise was observed in the annular zone corresponding to Stations 7, 8 (**Table 6**), which provides another indication of the gas flowing predominantly through the V-shaped contour zone.

Due to the increased amount of iron ore in the peripheral zone (corresponding to Stations 9–11) — from 85 to 93% — and with the percent of pellets raised from 28 to 40%, it was possible to reduce coke consumption by consuming 1.2 th m³/h more of natural gas with the substitution rate of 0.85 kg/m³.

During Period III (**Table 7**), the iron ore concentration in the peripheral zone corresponding to Stations 9–11 was 91%. Increasing the iron ore concentration to 94% during

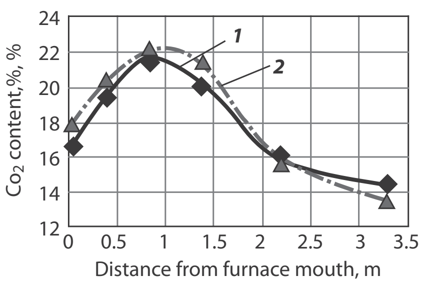

Fig. 1. CO_2 radial concentration in the upper stack of blast furnace 4 during Period I (*1*) and Period II (*2*)

Table 4. **Blast furnace 4 key process parameters**

Parameters	Concentration of iron ore in the burden of the peripheral zone (corresponding to Stations 9–11), %			
	85	93	91	94
Period length, days	7	7	8	7
Specific consumption of coke (dry coke, skip coke), kg/t of iron:				
actual ($K_{sp/act}$)	479.9	489.3	501.3	514.6
corrected ($K_{sp.corr}$)	479.9	477.4	501.3	502.9
Tuyere flow:				
Blast, m³/min.	3062	3069	2642	2603
Natural gas, th m³/h	15.1	16.3	13.7	13.1
Air blast temperature, °C	1151	1156	1169	1157
Water steam flow, g/m³ of air blast	1.3	0.6	4.1	7.0
Oxygen in air blast,%	27.0	27.4	27.9	28.2
Capacity, t/day:				
Based on actual amount of fed charges	3491	3659	3222	3124
As corrected	3491	3658	3222	3135
Consumption of burden materials, kg/t of iron:				
Iron ore	1697	1717	1690	1694
Manganese ore	10.8	57.6	12.7	14.7
Driving rate:				
By air blast, m³/(m³ minute)	2.24	2.24	1.93	1.90
By total carbon, t/m³ days:	1.03	1.10	1.0	0.97
Theoretical flame temperature, °C	2158	2183	2213	2223
Fe concentration in the burden,%	57.2	56.6	57.5	57.3
Utilization,%:				
CO	42.3	42.7	42.2	40.6
H^2	32.2	33.2	32.6	32.2

Period IV while bringing it down at Stations 6–8 – from 58 to 55%, Stations 3–5 — from 30 to 25% and Station 2 — from 69 to 55%, resulted in a smaller difference between the average gas temperature in the peripheral zone and the average offtake temperature — 298 versus 323 °C (see Table 5). This indicates that the gas travels predominantly through the centre of the furnace. Apart from changing the charging matrix by increasing the burden-weight ratio in the peripheral zone, the contributing factors included a decreased weighted average size of coke (from 60.5 to 56.3 mm) (Table 3) and an increased weighted average size of iron ore materials (from 16 to 16.1 mm) (Table 3). This led to an excessive exposure of the peripheral zone of the furnace and made it relevant to reduce the natural gas flow rate from 13.7 to 13.1 th m³/h (Table 4). The utilization of H_2 and CO dropped by 0.4% (abs.) and 1.6% (abs.) correspondingly (Table 4). During Period IV, the specific consumption of coke, that was set per the basic Period III, was raised by 1.6 kg/t of iron (Table 4), and the furnace output dropped from 3,222 to 3,135 t/day.

To enhance performance, during Period V the concentration of iron ore was reduced in the burden of Stations 9-11 from 94 to 90% while being raised in the burden of Stations 3–5 from 25 to 29% and Station 2 from 55 to 78%. Changing the charging matrix improved the natural gas utilization. This enabled to bring the gas consumption from 13.1 up to 13.9 th m³/h for coke saving and, secondly, increase the utilization of the natural gas hydrogen from 32.2 to 35.4% (Table 4), which resulted in a 4.6 kg/t of iron reduction in the specific consumption of coke. The coke-to-natural gas substitution rate was 0.91 kg/m³.

Table 6. **Blast furnace 4: gas dynamics parameters**

Parameters	Concentration of iron ore in the burden of the peripheral zone (corresponding to Stations 9-11),%			
	85	93	91	94
Burden resistance coefficient:				
Upper stack	0.39	0.40	0.41	0.41
Bosh	6.27	6.73	6.86	7.02
Tuyere gas output, m³/min	4006	4049	3518	3489
Top gas output m³/min	4364	4441	3887	3829
Gas pressure loss in the upper section, kPa/m	2.26	2.36	1.89	1.90
Airflow counteraction from the middle stack to the top,%	14.9	15.23	12.46	12.63

Table 5. **Gas temperature in blast furnace 4 upper section**

Parameters	Concentration of iron ore in the burden of the peripheral zone (corresponding to Stations 9–11), %			
	85	93	91	94
Gas temperature in the peripheral zone of the stack, °C	566	550	541	515
Circular gas temperature gradient in the peripheral zone of the stack, °C	107	125	432	394
Gas temperature by top of burden zone, °C:				
Peripheral zone (T_{periph})	372	313	289	286
V-shaped contour zone ($T_{V\text{-}cont}$)	160	133	272	290
Furnace centre (T_c)	428	390	355	370
Temperature ratios:				
$T_{periph}/T_{V\text{-}cont}$	2.33	2.35	1.06	0.99
T_{periph}/T_c	0.87	0.81	0.82	0.78
T_c/T_c	2.68	2.93	1.30	1.28
Differential temperature $T_{periph} - T_{offtake}$, °C	343	361	323	298

Conclusions

The authors determined what coke and iron ore distribution pattern would be optimal for a blast furnace with a compact BLT charging system depending on the amount of pellets in the burden.

When pellets account for 28–30%, the amount of iron ore materials charged in the peripheral zone of the fur-

Table 7. **Radial gas dynamics parameters**

Airflow counteraction from the middle stack to the top by station,%:										
Station No.	11	10	9	8	7	6	5	4	3	2
Period I	12.5	12.5	14.1	16.0	14.9	15.6	14.9	48.0	48.0	48.0
Period II	12.7	12.7	13.4	16.0	15.2	17.4	15.2	50.3	50.3	50.3
Period III	10.3	10.3	12.2	13.8	13.8	12.2	13.8	40.1	40.1	40.1
Period IV	10.4	10.4	11.7	12.3	16.8	14.0	15.7	40.5	40.5	40.5
Period V	7.9	7.9	8.7	10.6	10.6	9.4	9.4	30.9	30.9	30.9
Burden resistance coefficient by station:										
Station No.	11	10	9	8	7	6	5	4	3	2
Period I	1.14	1.14	0.90	0.71	0.81	0.74	0.81	0.09	0.09	0.09
Period II	1.19	1.19	1.07	0.77	0.84	0.65	0.84	0.09	0.09	0.09
Period III	1.20	1.20	0.88	0.70	0.70	0.88	0.70	0.09	0.09	0.09
Period IV	1.22	1.22	0.98	0.89	0.50	0.70	0.57	0.09	0.09	0.09
Period V	0.91	0.91	0.77	0.52	0.52	0.66	0.66	0.07	0.07	0.07

nace with the sloping chute positioned to Stations 9–11 that proved to be optimal was 85–90%. When the amount of iron ore charged at the above stations was reduced from 94 to 90% while Stations 3–5 saw an increase from 25 to 29% and Station 2 saw a decrease from 45 to 22%, it became possible to cut the consumption of coke by raising the amount of natural gas consumed from 13.1 to 13.9 th m^3/h. The natural gas hydrogen utilization rose from 32.2 to 35.4% delivering a 4.6 kg/t of iron reduction in the specific consumption of coke.

A 30 to 40% rise in the amount of pellets justified the increased concentration of iron ore in the peripheral zone (from 85–90 to 93–94%). An increase from 85 to 93% made it possible to raise the consumption of natural gas by 1.2 th m^3/h reaching a substitution rate of 0.85 kg/m^3.

REFERENCES

1. Huatao Zhao, Minghua Zhu, Ping Du, Seiji Tagucchi, Hongchao Wei. Uneven Distribution of Burden Materials at Blast Furnace Top in Bell-less Top with Parallel Bunkers. *ISIJ*. 2012. Vol. 52. No. 12. pp. 2177–2185.
2. Pykhteeva K. B., Zagainov S. A., Tleugabulov B. S., Filippov V. V., Nikolaev F. P., Belov V. V. Stabilizing the composition of blast-furnace products from titanomagnetites with a nonconical loading trough. *Steel in Translation*. 2009. Vol. 39. pp. 45–49.
3. Sibagatullin S. K., Kharchenko A. S., Devyatchenko L. D., Steblyanko V. L. Improvement of iron ore burden components distribution when charging into blast furnace top by physical and mathematical modeling of fixed effects. *Journal of Chemical Technology and Metallurgy*. 2017. No. 4 (52). pp. 11–18.
4. Sibagatullin S. K., Kharchenko A. S., Logachev G. N. The rational mode of nut coke charging into the blast furnace by compact trough-type charging device. *International Journal of Advanced Manufacturing Technology*, 2016. 86. pp. 531–537.
5. Vorontsov V. V., Stepanov A. T. On circumferential distribution of burden materials at the blast furnace top. *Vestnik Cherepovetskogo gosudarstvennogo universiteta*. 2010. No. 1. pp. 127–130.
6. Lyalyuk V. P., Tovarovsky I. G., Kassim D. A. On circumferential distribution of blast furnace smelting parameters. *Stal*. 2018. No. 3. pp. 8–13.
7. Vaisberg L. A., Korovnikov A. N., Podgorodetskiy G. S. Improvement of charge preparation systems in blast furnace practice. *Chernye Metally*. 2017. No. 8. pp. 24–27.
8. Stumper J.-F., Viktor K., Mirkovic T., Josupeit Th., Pethke J. Investigation of distribution of charge material in a blast furnace using 3D section gauge. *Chernye Metally*. 2017. No. 6. pp. 25–30.
9. Buchwalder J., Dobroskok V. A., Lonardi E., Goffin R., Tillen G., Kuehler S. Advanced blast furnace charging technologies. *Chernye Metally*. 2008. No. 9. pp. 21–25.
10. Yongfu Zhao, Jerry C. Capo, Steven J. McKnight et al. Development of burden distribution technology at U.S. Steel Canada's. Hamilton Works 'E' blast furnace. *Iron & Steel Technology*. 2011. No. 1. pp. 52–61.
11. Michinori Hattor, Bungo Iino, Akio Shimomura, Hideaki Tsukiji, Tatsuro Ariyama. Development of Burden Distribution Simulation Model for Bell-less Top in a Large Blast Furnace and Its Application. *ISIJ International*. 1993. Vol. 33 (1993). No. 10. pp. 1070–1077.
12. Juan Jiménez, Javier Mochón, Jesús Sainz de Ayala. Mathematical Model of Gas Flow Distribution in a Scale Model of a Blast Furnace Shaft. *ISIJ International*. 2004. Vol. 44. No. 3. pp. 518–526.
13. Tovarovsky I. G. Predictive estimate of the effect produced by the circumferential distribution of burden materials at the top on smelting processes and parameters. *Metallurg*. 2014. No. 8. pp. 46–52.
14. Tovarovsky I. G., Bolshakov V. I., Togobitsskaya D. N., Khamkhotko A. F. Optimisation of ore burden distribution following a comprehensive analysis of blast furnace processes. *Chernaya metallurgiya. Byulleten nauchno-tekhnicheskoi i ekonomicheskoi informatsii*. 2008. No. 7. pp. 10–15.
15. Tovarovsky I. G. Analysis of the criteria for evaluation of the circumferential distribution of burden materials and gases in a blast furnace. *Chernaya metallurgiya. Byulleten nauchno-tekhnicheskoi i ekonomicheskoi informatsii*. 2012. No. 12. pp. 33–38
16. Bolshakov V. I., Gladkov N. A., Shutylev F. M. Optimised distribution of pellets in the cross section of a blast furnace. *Metallurgicheskaya i gornorudnaya promyshlennost*. 2003. No. 1. pp. 12–15.
17. Semenov Yu. S. Identifying rational charging regimes for a blast furnace with the BLT charging system for the conditions of light charges and inconsistent burden materials. *Chernaya metallurgiya. Byulleten nauchno-tekhnicheskoi i ekonomicheskoi informatsii*. 2013. No. 12. pp. 14–19.
18. Sibagatullin S. K., Kharchenko A. S., Beginyuk V. A., Selivanov V. N., Chernov V. P. Improving the blast furnace process by raising the natural gas flow rate in the upper heat exchange stage. *Vestnik of Nosov Magnitogorsk State Technical University*. 2017. Vol. 15. No. 1. pp. 37–44.
19. Chukin M. V., Sibagatullin S. K., Kharchenko A. S., Chernov V. P., Logachev G. N. Influence of coke nut introduction in blast furnace charge on melting parameters. *CIS Iron and Steel Review*. 2016. Vol. 12. pp. 9–13.
20. Marder B. F., Shvets L. N., Volovik G. A., Tripolets Yu. I., Kalashnyuk P. G. Distribution of burden and gases in a blast furnace and utilization of natural gas during smelting. *Metallurgicheskaya i gornorudnaya promyshlennost*. 1998. No. 1. pp. 11–15.
21. Bolshakov V. I., Arzamastsev A. N., Lebed V. V., Zherebetsky A. A. Optimisation of burden distribution in Blast Furnace 6 of NLMK. *Stal*. 2013. No. 1. pp. 2–5.
22. Bolshakov V. I., Roslik N. A., Shutylev F. M., Shuliko S. T., Loginov V. N. Control over gas distribution in a blast furnace with a bell-less top charging system. *Stal*. 1995. No. 7. pp. 15–19.
23. Kaoru Nakano, Kohei Sunahara, Takanobu Inada. Advanced Supporting System for Burden Distribution Control at Blast Furnace Top. *ISIJ International* 2010. Vol. 50. No. 7. pp. 994–999.
24. Zhao-Jie Teng, Shu-Sen Cheng, Peng-Yu Du, Xi-Bin Guo. Mathematical model of burden distribution for the bell-less top of a blast furnace. *International Journal of Minerals, Metallurgy, and Materials*. 2013, Volume 20, Issue 7, pp. 620–626.
25. Bolshakov V. I. Evaluating the efficiency of using bell-less charging apparatuses on blast furnaces. *Metallurgist*. 2010, Volume 54, Issue 3-4, pp. 153–157.
26. Sibagatullin S. K., Kharchenko A. S. Identification of an efficient sequence of charging components of raw materials into the hopper of the bell-less charging device of a chute type by physical modeling. *Vestnik of Nosov Magnitogorsk State Technical University*. 2015. No. 3 (51). pp. 28–34.
27. Sibagatullin S. K., Kharchenko A. S., Devyatchenko L. D., Steblyanko V. L. Improvement of iron ore burden components distribution when charging into blast furnace top by physical and mathematical modeling of fixed effects. *Journal of Chemical Technology and Metallurgy*. 2017. Vol. 52. No. 4. pp. 694–701.
28. Sibagatullin S. K., Kharchenko A. S., Teplykh E. O. Quality comparison of coke nuts. *Koks i khimiya*. 2012. Vol. 55. Issue 2. pp. 62–65.
29. Tarasov V. P., Tarasov P. V. Theory and technology of blast furnace smelting. Moscow : Intermet Inzhiniring, 2007. 384 p.
30. Sibagatullin S. K., Kharchenko A. S., Chernov V. P., Beginyuk V. A. Improvement of blast furnace practice due to creation of the conditions for elevation of natural gas consumption via usage of raw materials with increased strength. *Chernye Metally*. 2017. No. 8. pp. 27–33.
31. Sibagatullin S. K., Kharchenko A. S., Kashapov M. M., Tyapkin S. S., Semenyuk M. A. Identifying rational regimes of iron ore charging in the furnace top with high percent of pellets in the burden. *Teoriya i tekhnologiya metallurgicheskogo proizvodstva*. 2017. No. 3 (22). pp. 4–9.