CSCanada
Energy Science and Technology
Vol. 6, No. 1, 2013, pp. 14-19
DOI:10.3968/j.est.1923847920130601.2675

ISSN 1923-8460[PRINT]
ISSN 1923-8479[ONLINE]
www.cscanada.net
www.cscanada.org

Substitution of Coke and Energy Saving in Blast Furnaces

Part 2. Study of influence on the Processes of Individual Charge Parameters

I. G. Tovarovskiy[a],*

[a]Iron and Steel Institute of the Ukraine National Academy of Science, Academician Starodubov Sqv., Dnepropetrovsk, Ukraine.
*Corresponding auhtor.

Received 1 August 2012; accepted 14 September 2013

Abstract

The system of discrete material and thermal balances in the radial annular cross-sections for 12 vertical and 10 radial ring zones is used to describe the heat and mass transfer processes of iron ore reduction and melting in blast furnace with respect to the various degree of preliminary metallization of the metallic burden. It was found that with increase in preliminary metallization degree the heat demand on direct reduction and the ratio between material and gas flow heat capacities are reduced which leads to the decrease in intensity of a heat transfer in the bottom zones of the furnace. As a result, the height of the bottom zones of blast furnace is increased, while the height of the upper zones is decreased. The gas isotherms move upwards, increasing heat losses through the furnace top. The cohesive zone also moves up and increases in size. The influence of material distribution at the furnace top on parameters of blast furnace operation becomes weaker. Because of decrease in extend of direct reduction the effect of natural gas injection on coke rate is also reduced. As a result the reduction in coke rate associated with the preliminary metallization of the metallic burden could not be fully realized if the burden metallization degree is grater than 20%.

The model makes it possible to determine the relationships that exist between processes which take place in the furnace and which affect the character of the smelting regimes and the final results.

Key words: Metallization; Burden; Blast furnace; Modeling; Ring radial zones; Vertical temperature zones; Overall balance; Coke rate; Productivity

I. G. Tovarovskiy (2013). Substitution of Coke and Energy Saving in Blast Furnaces.Part 2. Study of influence On the Processes of Individual Charge Parameters. *Energy Science and Technology*, *6*(1), 14-19. Available from: URL: http://www.cscanada.net/index.php/est/article/view/10.3968/j.est.1923847920130601.2675
DOI: http://dx.doi.org/10.3968/j.est.1923847920130601.2675

INTRODUCTION

The aim of this research is to study the influence of the parameters of the charge on the main indicators of the blast-furnace smelting, as well as on the processes in the volume of blast furnace (BF). During the study of quantitative relationships parameters with the consumption of coke, performance unit and other characteristics of the heat, and also revealed the influence of each parameter on the status and progress of the processes in the volume of BF. The researches revealed a different nature of parameters influence on the processes in the BF. Among all charge parameters the strongest influence on the processes in the BF has the using of pre-metallized burden (PMB). The results of the analysis for specified parameter are given below. Analysis of other parameters is shown in the works (Ramm, 1980, p.304; Tovarovski, 1987, p.192; Tovarovskiy, Bolshakov, & Gordon, 2007; Tovarovskiy, 2009, p.768).

1. USE IN BF OF PRELIMINARY-METALLIZATION BURDEN

1.1 Initial Conditions and Method of Analysis

The system of discrete material and thermal balances in the 10 radial ring zones of equivalent area (RRZ) and 12 vertical temperature zones (VTZ) is used to describe the heat and mass transfer processes of iron ore reduction in blast furnace (See Part 1 of the article). The height of the individual zone and the residence time of material in this zone are estimated based on the assumed parameters of kinetics and heat transfer. Heights of individual zones are numbered from top to down with "1" as the number for the top VTZ and '12" for the bottom one. The numbering of the ring zones RRZ is going from "1" at the center of the furnace to "10" at the periphery.

The heat and mass transfer processes and transformation of the material from solid to fused and finally to liquid phases are specific for each VTZ. Each RRZ represents also the position of the Paul Wurth spout. Charging of these zones differs from each other by ore load and coke consumption, set by the charging program and estimated by charging model. The charging model allows assigning the distribution of each component of the metallic burden and coke for various RRZ. Because of this the isotherms of material softening, fusion, melting and liquation and composition of slag estimated also separately for each RRZ.

The operating parameters of blast furnace #9 of Arselor-Mittal, Krivoi Rog with useful volume 5,000 м^3 and #5 blast furnace of Cherepovets I & S Works (Severstal) with useful volume 5500 м^3 were used as the base case for the study. The non-compliance of the gas balance and gas composition was used as a tuning parameter of the model and was minimized for the base case by adjusting the top gas composition for BF 9 and oxygen enrichment for BF 5 (the parameters which cause the greatest errors). After that the turned model was used for evaluation of the influence of burden metallization on the furnace performance for two scenarios: actual distribution of metallic burden (MBL_{actual}) on the furnace top and uniform distribution of metallic burden (RUMBL). The distribution of metallic burden load is presented in Figure 1.

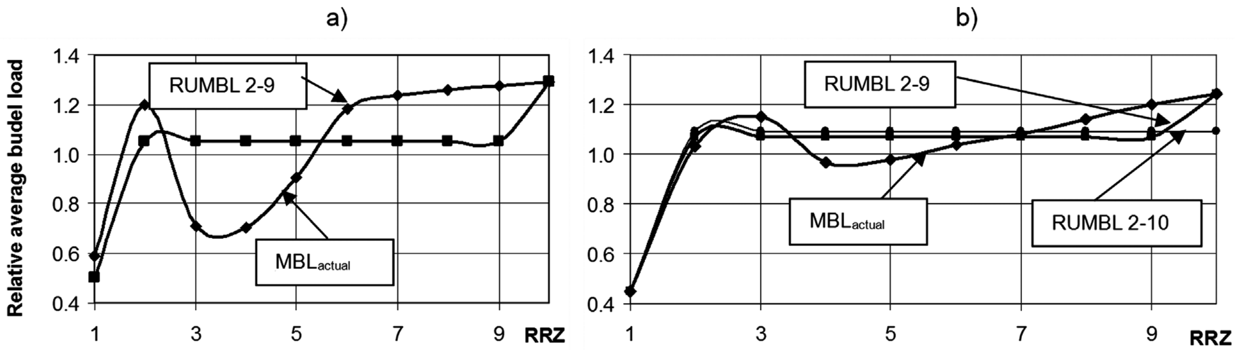

Figure 1
Distribution of Metallic Burden Load for BF #9 (a) and BF #5 (b)
[MBL_{actual}—actual metallic burden load; RUMBL 2-9—radial metallic burden load for RRZ 2-9; RUMBL 2-10—radial metallic burden load for RRZ 2-10]

1.2 Analysis of Results

The usage of the developed mathematical model requires the assignment of distribution of total iron F_{total}, metallic iron Fe_{metal}, Fe_2O_3 and FeO on the furnace top for the overall burden. It was assumed that Fe_{metal} changes in all burden components by the same value. The percentage of Fe_{total} was adjusted taking into account the amount of reduced oxygen during metallization outside blast furnace. The metallization degree $M = Fe_{metal}/Fe_{total}*100$, % was also assumed as a boundary condition for the blast furnace top.

Influence of burden metallization on blast furnace performance for actual metallic burden load MBL_{actual} is presented in Table 1 and Table 2 for BF 9 (Krivoi Rog) and BF 5 (Severstal), respectively. Changes in value of all parameters are attributed to 1% change in metallization degree M. Here ΔT_{top}—change in temperature of the top gas, ^{0}C/1% M; Δr_d—change in extend of direct reduction, %/1 %M; ΔK—change in coke rate, %/1 %M; ΔP—change in productivity, %/1% M.

Table 1
Influence of Burden Metallization on BF 9 (Krivoi Rog) Performance

M, %	0	8,9	17,3	33,1	47,8	78,2
Fe_{total}, %	55,2	56,4	57,7	60,4	62,7	70,3
$Fe_{мetal}$,%	0	5	10	20	30	55
ΔT_{top}, ^{o}C		0	0	+ 0,4	+ 3,5	+ 1,0
Δr_d, %		− 0,05	− 0,2	0	+0,08	+ 0,53
ΔK, %		− 0,48	− 0,55	− 0,27	− 0,05	− 0,14
ΔP, %		+ 0,43	+ 0,43	+ 0,22	0,00	+ 0,13

Table 2
Influence of Burden Metallization on BF 5 (Severstal) Performance

M, %	0	16,0	30,6	43,8
Fe_{total}, %	59,7	62,4	65,3	68,5
$Fe_{мetal}$,%	0	10	20	30
ΔT_{top}, ^{o}C		+ 4,0	+ 3,2	+ 2,4
Δr_d, %		− 0,23	− 0,05	+ 0,05
ΔK, %		− 0,25	− 0,15	− 0,11
ΔP, %		+ 0,05	+ 0,05	+ 0,09

The main reason for the overall coke rate reduction with increase in burden metallization is the decrease in heat demand for iron oxides direct reduction. When metallization of metallic burden is below 20% the values of ΔK и ΔP are very close to well-know experimental and calculated with the usage of heat and mass balance values (Ramm, 1980, p.304; Tovarovski, 1987, p.192) and depend on degree of preliminary metallization M (Tovarovski, 1987, p.192). Further increase in metallization degree is less effective. At metallization M = 30% the reduction in coke rate is almost half as much as compared to M equal to 16 or 17%.

The top gas temperature for both furnaces increases with increase in metallization of the metallic burden. The greater extend of this for BF 5 of Severstal is a consequence of change in heat transfer along the furnace height (see below) which limits the benefits of this technology.

Extend of direct reduction r_d decreases with increase of burden metallization up to M = 30 % for both furnaces because of the gas reduction potential increase stipulated by lower amount of oxygen of iron oxides. With M > 30% the influence of metallization becomes weaker while the retarding influence of reduced concentration of iron oxides in a furnace burden increases. As a result, extend of direct reduction r_d slightly increases.

These phenomena are valid for all variants of metallic burden load—MBL_{actual}, RUMBL 2-9 and RUMBL 2-10. The transition from actual metallic burden distribution MBL_{actual} to uniform one RUMBL 2-9 for BF 9 or RUMBL 2-10 for BF 5 unusually does not bring any essential changes in blast furnaces performance. For BF 5, however, it leads to increase in gas utilization and reduction in coke rate, which is usually observed in such cases. Table 3 and Table 4 present the blast furnace parameters at base case, actual metallic burden load MBL_{actual} and uniform metallic burden load distribution amongst the ring zones RUMBL 2-9 and RUMBL 2-10.

Apparently, the weaker influence of material distribution at the furnace top on blast furnace performance with increase of material burden metallization is a specific feature of blast furnace process. The operation of BF 5 with uniform metallic burden load RUMBL 2-10 (Table 4) should be considered as an exception from the rules since RRZ10 is a critical zone at MBL_{actual} and metallic burden load in this zone is much greater than for other RRZ. Presence of such micro zone in blast furnace reduces the possibility in coke reduction in other micro zones of the furnace volume (Tovarovskiy, Bolshakov, & Gordon, 2007). For the scenario of RUMBL 2-9 the maximum coke reduction is 6 kg/thm with increase in M from 16% to 48%. Scenario RUMBL 2-10 allows avoiding this limitation, metallic burden load decreases at the RRZ10 and the coke savings increases to 12 kg/thm with increase in M from 16% to 48%.

Table 3
Major Parameters of BF 9 Operation

Parameter	Base case	NG=0	MBL_{actual}					RUMBL2-9		
M, %	0	33,1	8,9	17,3	33,1	47,8	78,2	17,3	33,1	47,8
Fe_{metal}, %	0	20	5	10	20	30	55	10	20	30
Specific productivity, thm/м^3 24 h (UW)	1,71	1,82	1,77	1,84	1,91	1,91	1,98	1,84	1,89	1,93
Coke rate (including ~ 46 kg anthracite), kg/thm/т	513	467	491	468	448	445	429	468	451	441
NG rate, Nm3/thm	80.8		80.8	80.8	80.8	80.8	80.8	80.8	80.8	80.8
Wind, м^3/min.	6694	7821	6715	6754	6829	6882	7054	6748	6823	6885
Oxygen rate, м^3/thm	147,2	0	142,3	137,5	134,3	135,1	133,5	137,7	135,5	134,1
Blast temperature, ^{o}C	1042	1042	1042	1042	1042	1042	1042	1042	1042	1042
Metallic burden: Sinter+Pellets+Ore, kg/thm	1629	1491	1595	1560	1491	1433	1275	1560	1491	1433
Fe_{total} in metallic burden, %	56,06	61,32	57,29	58,57	61,32	64,33	72,80	58,57	61,32	64,33
Metallic burden load, t/t coke	3,48	3,5	3,56	3,65	3,64	3,54	3,28	3,65	3,62	3,56
Top gas temperature, ^{o}C	242	216	242	234	248	286	318	242	266	277
Top gas composition										
CO %	28,42	26,88	29,24	29,81	32,27	34,42	39,32	29,75	32,20	34,31
CO_2, %	19,55	13,68	18,28	17,16	13,82	11,04	4,86	17,20	13,83	11,13
H_2, %	6,06	0,59	6,5	6,93	7,81	8,41	9,94	6,92	7,76	8,44
$\eta_{CO} = CO_2/(CO+CO_2)$, %	40,75	33,73	38,46	36,54	29,98	24,29	11,0	36,63	30,04	24,50
$\eta_{H2} = H_2O/(H_2+H_2O)$, %	40,50	33,41	38,19	36,26	29,67	23,95	10,54	36,36	29,73	24,15
$\eta_{total} = (CO_2+H_2O)/(CO_2+H_2O+CO+H_2)$, %	40,71	33,73	38,41	36,48	29,92	24,22	10,91	36,58	29,98	24,43
RAFT, ^{o}C	2236	2262	2223	2209	2200	2202	2198	2210	2203	2199
Material residence time, h	7,85	8,05	7,83	7,82	7,89	8,03	8,26	7,83	7,94	8,00
Top gas volume, м^3/thm (dry)	1721	1648	1663	1603	1566	1574	1564	1604	1576	1563
Extend of direct reduction, r_d, %	30,99	45,35	30,51	28,95	29,39	30,62	46,35	28,65	28,65	30,33
Total carbon rate, kg/thm	436,1	397,1	417,5	398,0	381,5	378,2	364,7	398,0	383,6	375,5
Coke' carbon burned at tuyeres, kg/thm	319,4	282,6	307,2	295,4	287,4	289,4	285,5	295,8	290,4	287,0
Carbon for direct reduction, kg/thm	59,5	57,5	53,3	45,7	37,3	31,9	22,1	45,2	36,3	31,6
Total heat input, kJ/kg	4848	4576	4672	4503	4385	4409	4345	4509	4427	4375
Heat demand, kJ/kg	3707	3645	3617	3511	3390	3318	3187	3505	3379	3313
Top gas enthalpy, kJ/kg	735	567	704	651	660	752	791	673	713	722
Heat losses, kJ/kg	407	364	352	341	335	338	366	331	335	339

Two stage heat exchange along the blast furnace height is an important and an inner feature of blast furnace operation with conventional metallic burden, which divides blast furnace for three distinct zones. The upper heat exchange zone is characterized by intensive heat exchange between gas and burden material. The heat capacity of gas flow W_g in this zone is higher than heat capacity of material flow W_b: $m_{upper} = W_b/W_g < 1$. This zone is associated with material preheating and indirect reduction. The middle zone is a reserve zone where $m_{reserve} = W_b/W_g = 1$. This is a mix reduction zone. At the bottom zone the heat capacity of gas flow is lower than heat capacity of material flow $m_{bottom} = W_b/W_g > 1$. The direct reduction plays the major role in heat demand in a bottom zone. The increase in extend of direct reduction also intensifies the heat transfer in the bottom zone. However, with increase in preliminary metallization of the blast furnace burden extend of direct reduction is reduced as well as intensity of heat transfer. Because of this the heat exchange regularities in blast furnace are transformed towards two stage heat exchange schematics, which are typical for pig iron cupolas (Chapligin & Erinov, 1976, p.239, c.161). Calculated ratio of material (W_b) and gas (W_g) heat capacities for upper heat transfer zone—m_{upper} and bottom heat transfer zone—m_{bottom} for different VTZ are presented in Table 5 for various degrees M of metallic burden preliminary metallization.

Table 4
Major Parameters of BF 5 Operation

Parameter	Base case	MBL_{actual}			RUMBL2-9			RUMBL2-10		
M, %	0	16,0	30,6	43,8	16,0	30,6	43,8	16,0	30,6	43,8
Fe_{metal}, %	0	10	20	30	10	20	30	10	20	30
Specific productivity, thm/м^3 24 h (UW)	1,765	1,78	1,793	1,815	1,78	1,79	1,791	1,85	1,861	1,873
Coke rate, kg/thm	421	404	395	389	402	395	394	389	380	377
Natural gas rate, Nm3/thm	106	106	106	106	106	106	106	106	106	106
Wind, м^3/min.	7838	7899	7977	8063	7897	7975	8068	7897	7970	8058
Oxygen rate, м^3/thm	57,16	57,11	57,25	57,17	57,0	57,2	58,0	54,9	55,1	55,4
Blast temperature, ^oC	1184	1184	1184	1184	1184	1184	1184	1184	1184	1184
Metallic burden: Sinter+Pellets+Ore, kg/thm	1585	1517	1449	1381	1517	1449	1381	1517	1449	1381
Fe_{total} in metallic burden, %	59,84	62,52	65,45	68,67	62,52	65,45	68,67	62,52	65,45	68,67
Metallic burden load, t/t coke	3,78	3,77	3,68	3,56	3,78	3,68	3,52	3,91	3,82	3,68
Top gas temperature, ^oC	252	317	364	396	316	364	411	270	322	360
Top gas composition										
CO %	21,39	22,85	25,03	27,20	22,77	24,99	27,31	22,27	24,39	26,82
CO_2, %	19,73	16,97	13,89	11,01	17,04	13,92	10,90	17,54	14,43	11,32
H_2, %	6,94	7,73	8,64	9,54	7,73	8,64	9,47	7,81	8,75	9,70
$\eta_{CO} = CO_2/(CO+CO_2)$, %	47,98	42,62	35,70	28,80	42,80	35,78	28,53	44,06	37,17	29,67
$\eta_{H2} = H_2O/(H_2+H_2O)$, %	47,95	42,60	35,69	28,80	42,79	35,77	28,52	44,06	37,18	29,69
η_{total} = CO_2+H_2O) /($CO_2+H_2O+CO+H_2$), %	47,97	42,61	35,69	28,80	42,80	35,78	28,52	44,06	37,17	29,68
RAFT, ^oC	1998	1998	1999	1998	1997	1999	2005	1980	1981	1983
Material residence time, h	8,86	9,17	9,39	9,55	9,17	9,39	9,60	9,03	9,28	9,44
Top gas volume, м^3/thm (dry)	1700	1682	1686	1690	1677	1684	1711	1620	1623	1640
Extend of direct reduction, r_d, %	26,62	22,95	22,18	22,88	22,71	22,04	22,90	22,31	20,88	22,14
Total carbon rate, kg/thm	362,5	347,3	340,1	334,6	346,1	339,6	339,0	334,3	326,6	324,0
Coke' carbon burned at tuyeres, kg/thm	251,4	251,2	251,9	251,5	250,4	251,6	255,8	239,4	240,3	241,7
Carbon for direct reduction, kg/thm	53,66	38,85	31,04	25,95	38,5	30,8	26,0	37,8	29,2	25,1
Total heat input, kJ/kg	4433	4426	4435	4427	4414	4430	4495	4240	4252	4272
Heat demand, kJ/kg	3200	3009	2908	2843	3003	2905	2844	2989	2879	2827
Top gas enthalpy, kJ/kg	744	914	1028	1093	908	1026	1151	751	878	964
Heat losses, kJ/kg	489	503	499	491	503	499	500	500	495	481

In a base case (M = 0) for VTZ 7 (900-1000^oC) m_{bottom} = 4.34 and 3.96 for BF 9 and BF 5, respectively. With increase of metallization degree M for the VTZ 7 m_{bottom} decreases and reaches 1.58 at M = 78.2 % for BF 9 and 2.32 at M = 43.8% for BF 5. Such reduction in m_{bottom} and heat transfer efficiency moves the high gas temperatures isotherms to the upper levels of blast furnace and increases the top gas temperature. Figure 2 illustrates these phenomena for operation of BF 9.

Analysis of temperature distribution in a furnace volume shows that the minimum difference in material and gas temperature along the furnace height in RRZ 2-9 increases from 15 ÷ 97 ^oC (average 66 ^oC) to 98 ÷ 167 ^oC (average 132 ^oC) for BF 5 and from 70 ÷ 140 ^oC (average 105 ^oC) to 80 ÷ 180 ^oC (average 130 ^oC) for BF 9 with movement of the correspondence points to the upper levels of blast furnace by 1-5 meters. This means that the height of the bottom heat transfer zone required for metal and slag heating increases, while the height of the upper heat transfer zone decreases.

Similar to the gas and material isotherms cohesive zone moves upwards with increase of metallization degree M and thickness of cohesive zone increases (Figure 3).

Table 5
Ratio of Material and Gas Heat Capacities as a Function of Burden Preliminary Metallization at Mbl_{actual} Distribution

VTZ		BF 9					BF 5			
		M (%)					M (%)			
		0	17,3	33,1	47,8	78,2	0	16,0	30,6	43,8
Tcharge−400 °C	m_{upper}	0,838	0,842	0,828	0,807	0,783	0,693	0,667	0,644	0,631
400−500 °C		0,974	0,971	0,925	0,888	0,856	0,893	0,880	0,838	0,797
500−600 °C		0,879	0,915	0,902	0,901	0,895	0,786	0,733	0,741	0,755
600−700 °C		1,087	1,108	1,071	1,010	0,938	0,989	0,947	0,922	0,892
700−800 °C		0,970	0,971	0,950	0,916	0,898	0,912	0,876	0,884	0,864
800−900 °C		1,055	1,075	1,049	1,018	0,981	1,040	1,009	0,965	0,927
900−1000 °C	m_{bottom}	4,340	3,699	3,032	2,625	1,578	3,957	3,090	2,628	2,319
1000−1100 °C		0,984	1,145	1,194	1,210	1,416	0,833	0,819	0,823	0,828
1100−1200 °C		1,373	1,522	1,541	1,559	1,848	1,181	1,161	1,142	1,136
1200−1300 °C		1,902	2,082	2,098	2,091	2,336	1,765	1,742	1,725	1,719
1300−1400 °C		1,384	1,482	1,501	1,462	1,485	1,258	1,246	1,238	1,237
1400− $T_{melting}$		1,132	1,208	1,216	1,161	1,185	0,846	0,828	0,818	0,815

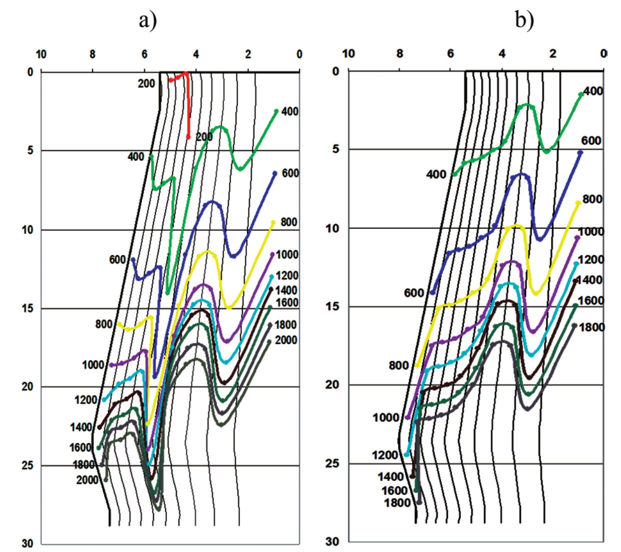

Figure 2
Temperature Distribution in BF 9 Krovoi Rog as Function of Burden Metallization
(a) Base Case, M = 0; MBL_{actual} (b) M = 30%; MBL_{actual}

Results of blast furnace performance modeling show that the highest reduction in coke rate is achieved with metallization degree of metallic burden M below 20%. At M above 20% the efficiency of metallic burden preliminary metallization reduces because of inversed affect of the heat transfer, phase transformation and gasdynamics processes.

The efficiency of natural gas injection with increase of burden preliminary metallization also decreases. The comparison of furnace operation with M = 33.1 % with and without natural gas injection is presented in Table 3 for BF 9, Krovoi Rog. With increase in burden preliminary metallization extend of direct reduction is reduced and less hydrogen is required for indirect reduction. Because of these the replacement coefficient of coke by natural gas dramatically decreases and injection of natural gas becomes non profitable.

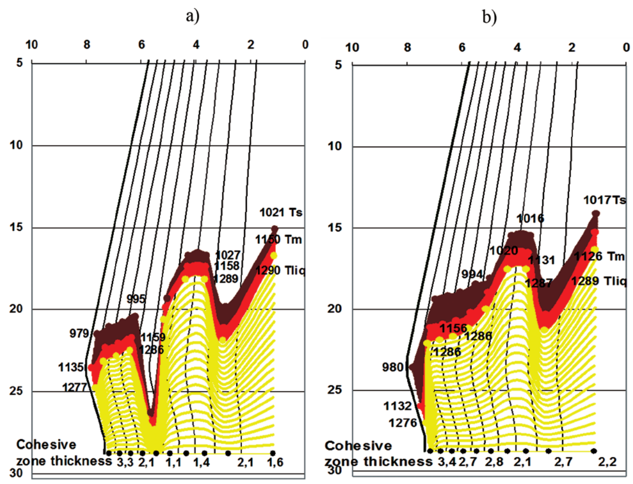

Figure 3
Location and Thickness of Cohesive Zone as a Function of Burden Metallization (BF 9, Krivoi Rog)
(a) Base Case, M=0; MBL_{actual} (b) M=30%; MBL_{actual}
[Ts—softening temperature, ^{0}C; Tm—melting temperature, ^{0}C; Tliq—liquefaction temperature, ^{0}C]

CONCLUSIONS

To analyze the influence of preliminary metallization of metallic burden on regularities of blast furnace process was used the multi-zone mathematical model of ISI NASU. It allowed to find the numerical relationship between degree of preliminary metallization and coke rate, furnace productivity, top gas temperature etc. and also to reveal the influence of internal processes such as heat transfer, phase transformation, gasdynamics, material distribution etc. on blast furnace performance parameters.

Preliminary metallization of the metallic burden reduces extend of direct reduction and required for direct reduction amount of heat. As a result the ratio between material and gas flow heat capacities at the bottom zone decreases as well as intensity of heat transfer in a bottom zone of blast furnace. All of these increases the height of the bottom heat transfer zone required for metal and slag heating and decreases the height of the upper heat transfer zone. The minimal difference between material and gas temperature along the furnace height increases, gas isotherms move upwards increasing the top gas temperature and heat losses with top gas. The cohesive zone also is moving up and increases in thickness.

Results of the modeling of blast furnace performance show that the highest reduction in coke rate is achieved with metallization degree of metallic burden M below 20%. At M above 20% the efficiency of metallic burden preliminary metallization reduces because of inversed affect of the heat transfer, phase transformation and gasdynamics processes.

The efficiency of natural gas injection with increase in burden preliminary metallization also decreases. With increase in M extend of direct reduction is reduced and less hydrogen is required for indirect reduction. Because of these the replacement coefficient of coke by natural gas dramatically decreases and injection of natural gas becomes non profitable.

The weaker influence of material distribution at the furnace top on blast furnace performance with increase of material burden metallization was revealed, numerically estimated and was considered as a specific feature of blast furnace process.

ACKNOWLEDGEMENTS

With special thanks to my colleagues from Iron and Steel Institute of Ukrainian National Academy of Science and professor Gordon I.M. from Hatch, Canada, also to authors given in the references.

REFERENCES

Chapligin, Y. V., & Erinov, A. E. (1976). *Natural gas usage in hot metal production*. Kiev: Naukova Dumka.

Ramm, A. N. (1980). *The modern blast furnace process*. Moscow, Metallurgy.

Tovarovski, I. G. (1987) *Modernization and optimization of blast furnace process*. Moscow, Metallurgy.

Tovarovskiy, I. G. (2009). *Blast furnace process*. Dnepropetrovsk, Porogi.

Tovarovskiy, I. G., Bolshakov, V. I., & Gordon, Y. M. (2007). Method and results of numerical modeling of physico-chemical processes in radial annular cross-sections along the blast furnace height. *Metec Proceedings* (pp.39-46). Dusseldorf.

