CSCanada
Energy Science and Technology
Vol. 6, No. 1, 2013, pp. 20-43
DOI:10.3968/j.est.1923847920130601.2683

ISSN 1923-8460[PRINT]
ISSN 1923-8479[ONLINE]
www.cscanada.net
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Substitution of Coke and Energy Saving in Blast Furnaces

Part 3. Study of Influence on the Processes of Individual Blast Parameters

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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 degrees of blast parameters.

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. The study is performed for a wide range of blast temperatures, different oxygen contents in the blast, by variation in the flow rates of natural gas, coke-oven gas, pulverized coal and different distributions of the charge materials over the furnace radius. New scientific results are obtained along with conclusions that can be put to practical use.

Key words: Blast furnace; Modeling; Ring radial zones (RRZ); Vertical temperature zones; Overall balance; Coke rate; Productivity; Natural gas; Coke-oven gas; Blast temperatures; Oxygen contents; Pulverized coal

I. G. Tovarovskiy (2013). Substitution of Coke and Energy Saving in Blast Furnaces. Part 3. Study of Influence on the Processes of Individual Blast Parameters. *Energy Science and Technology*, *6*(1), 20-43. Available from: URL: http://www.cscanada.net/index.php/est/article/view/10.3968/j.est.1923847920130601.2683
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INTRODUCTION

The aim of this research is to study the influence of the parameters of the charge and the blast 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 blast melting, 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. The strong influence on the processes in the BF have changing the temperature of the blast, the injection of natural gas (NG), coke-oven gas (COG) and oxygen (OX). Injection of pulverized coal injection (PCI) is not so significantly alters the course of the processes of heat-mass exchange, but more strongly reduces the share of coke in a pillar of charge, which complicates the progress of all processes. The results of the analysis are given below for specified parameters.

1. INJECTION OF NATURAL GAS (NG) AND COKE-OVEN GAS (COG)

To assess the influence of the gas consumption on the blast furnace parameters, we use data for 5000 m^3 blast furnace 9 at OAO ArcelorMittal Krivoi Rog and 5500 m^3 blast furnace 5 at OAO Severstal’, in characteristic (basic) operating periods. The discrepancy in the balance of the gasified components during the basic periods is minimized by correcting the composition of the blast furnace gas in furnace 9 and the oxygen content in the blast in furnace 5. These are the parameters most likely to introduce major errors in the results. The gas composition is as follows:

Gas	Carbon, kg/m^3	Hydrogen, m^3/m^3	Nitrogen, m^3/m^3	Oxygen, m^3/m^3	Heat of combustion at tuyeres, kJ/m^3
NG	0,55	2,0	0,01	0,002	1700
COG	0,22	1,2	0,03	0,007	340

The natural gas consists mainly of hydrocarbons (up to 99%, including 90-95% methane); the coke oven gas contains 25-30% coke oven gas and 55-60% free hydrogen. Specifying the consumption of natural gas (0, 50, 100, 150, and 200 m^3/t) and coke oven gas (0, 100, 200, and 300 m^3/t), we may predict the blast furnace parameters for two different distributions of the relative ore loads in the charge hole (Figure 1).

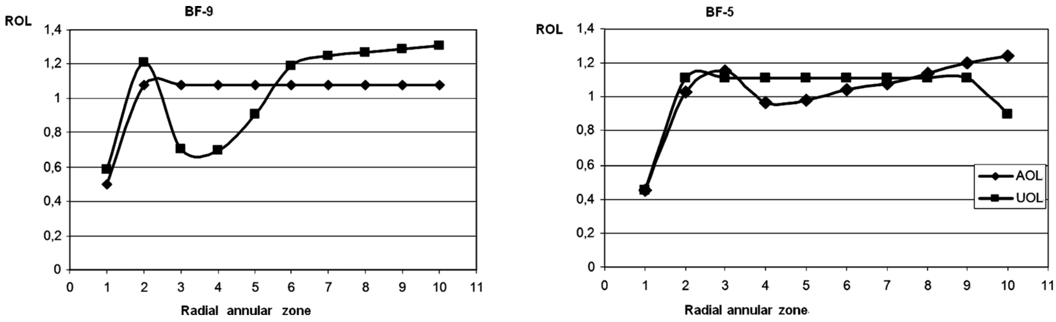


Figure 1
Distribution of the Relative Ore Loads (ROL) over the Radial Annular Zones of the Charge Hole in Blast Furnaces 9 and 5 in the Actual Conditions (AOL) and with a Uniform Distribution in Radial Annular Zones 2-9 (UOL)

Tables 1-3 present the basic numerical results. The results for the processes within the blast furnaces are shown in Figures 2-8.

Table 1
Basic Characteristics for Blast Furnace 9 with Different Blast Parameters, for the Actual and Uniform Ore Load Distribution over the Charge Hole

Characteristic	Actual ore load distribution						Uniform ore load distribution					
	O_2 = 21%			O_2=30%			O_2 = 21%			O_2=30%		
Natural gas consumption: m^3/t	50	100	200	50	100	200	50	100	200	50	100	200
% of blast	3,66	7,21	11,79	4,55	8,98	15,33	3,87	7,68	12,66	4,89	9,69	16,70
Productivity, t/(m^3 day)	1,606	1,572	1,307	1,747	1,717	1,484	1,679	1,652	1,384	1,847	1,823	1,588
Solid fuel consumption, kg/t	483	441	437	532	489	471	465	420	402	504	457	427
Anthracite consumption, kg/t	47	43	42	52	47	46	45	41	39	49	44	41
Blast flow rate, m^3/min	7670	7626	7750	6719	6685	6767	7574	7520	7644	6601	6574	6647
Blast temperature , °C	1042	1042	1042	1042	1042	1042	1042	1042	1042	1042	1042	1042
BF top-gas: temperature, °C	199	200	371	247	250	386	110	103	297	137	140	288
Content, %: CO	21,73	21,02	21,56	28,82	27,59	27,26	21,45	20,70	20,72	28,10	26,70	26,13
CO_2	17,43	16,10	12,09	20,34	19,03	15,02	18,06	16,70	12,80	21,41	20,08	15,95
H_2	4,10	6,90	11,55	4,91	8,17	13,64	4,16	7,06	11,85	4,99	8,35	14,11
Sinter + pellet + ore consumption, kg/t	1630	1631	1631	1629	1630	1630	1630	1632	1632	1629	1631	1631
Limestone consumption, kg/t	41	37	37	43	41	40	39	36	34	43	39	36
Iron in batch, %	55,20	55,27	55,27	55,16	55,19	55,22	55,23	55,30	55,33	55,17	55,24	55,29
Ore load, t/t	3,694	4,045	4,076	3,354	3,652	3,789	3,838	4,244	4,429	3,541	3,899	4,170
Quantity of slag, kg/t	409	407	407	410	409	408	408	406	406	410	408	407
Theoretical combustion temperature, °C	2046	1853	1627	2388	2155	1856	2034	1829	1586	2369	2119	1797
Residence time in furnace, h	8,65	9,34	11,28	7,48	8,03	9,50	8,47	9,14	11,19	7,32	7,87	9,41
Quantity of tuyere gas, m^3/t	1782	1909	2490	1553	1672	2126	1688	1804	2348	1450	1564	1985
Quantity of dry blast furnace gas, m^3/t	1905	1963	2454	1680	1730	2081	1812	1857	2293	1576	1615	1923
Direct reduction of Fe oxide, %	34,72	27,80	17,92	33,29	25,87	14,20	35,72	28,79	16,31	33,99	26,09	13,20
Degree of gas utilization, %:	44,46	43,31	35,84	41,33	40,76	35,45	45,68	44,59	38,10	43,21	42,87	37,83
Carbon consumption, kg/t: total	411	375	372	453	416	400	395	357	342	429	389	363
Combustion of coke at tuyere	287	265	281	332	309	316	270	245	254	307	282	281
Indirect reduction of iron	67	53	34	64	50	27	69	55	31	65	50	25

To be continued

Continued

Characteristic	Actual ore load distribution						Uniform ore load distribution					
	O_2 = 21%			O_2=30%			O_2 = 21%			O_2=30%		
Total heat input, kJ/kg	4847	4676	5305	4925	4741	5121	4571	4365	4881	4567	4362	4629
Heat consumption, kJ/kg	3779	3609	3392	3738	3564	3299	3794	3623	3339	3750	3556	3259
Enthalpy of BF top-gas, kJ/t	624	652	1513	725	763	1419	324	315	1138	374	398	982
Heat losses, kJ/t	444	416	401	462	414	403	453	426	404	443	408	388
Proportion of useful heat, %	78	77	64	76	75	64	83	83	68	82	82	70
Ratio of water equivalents	0,738	0,674	0,531	0,874	0,798	0,641	0,759	0,694	0,545	0,905	0,824	0,658
Heat of combustion of blast furnace top-gas, kJ/m^3	3193	3406	3977	4178	4374	4924	3164	3383	3902	4095	4282	4831
Gas intensity, m^3/(m^3 min)	2,21	2,27	2,38	2,13	2,20	2,32	2,20	2,27	2,38	2,12	2,19	2,32
Differential equivalent of coke replacement, kg/m^3	1,08	0,85	0,16	0,90	0,88	0,05	0,92	0,90	0,56	0,94	0,94	0,25
ΔΠ, %/ м^3 (everywhere (-))	0,017	0,042	0,194	0,030	0,034	0,154	0,03	0,03	0,288	0,024	0,026	0,136

Table 2
Basic Characteristics for Blast Furnace 5 with Different Blast Parameters, for the Actual And Uniform Ore Load Distribution over the Charge Hole

Characteristic	Actual ore load distribution						Uniform ore load distribution					
	O_2 = 21%			O_2=30%			O_2 = 21%			O_2=30%		
Natural gas consumption:m^3/t	50	100	150	50	100	200	50	100	150	50	100	200
% of blast	4,13	7,96	11,42	5,09	9,74	18,02	4,46	8,88	12,68	5,41	10,43	18,62
Productivity, t/(m^3 day)	1,779	1,702	1,614	1,946	1,867	1,686	1,886	1,846	1,739	2,034	1,966	1,724
Solid fuel consumption, kg/t	448	408	376	488	443	393	420	372	341	466	413	382
Anthracite consumption, kg/t	8220	8168	8094	7303	7324	7148	8075	7937	7856	7184	7201	7070
Blast flow rate, m^3/min	1184	1184	1184	1184	1184	1184	1184	1184	1184	1184	1184	1184
Blast temperature, °C	151	198	233	214	309	311	48	48	83	118	232	256
BF top-gas: temperature, °C	199	200	371	247	250	386	110	103	297	137	140	288
Content, %: CO	20,39	19,48	19,20	26,23	23,94	24,48	18,94	18,23	18,31	25,30	22,28	24,37
CO_2	19,70	18,08	16,23	23,52	22,50	17,58	21,34	19,67	17,37	24,70	24,15	17,74
H_2	3,97	6,74	9,50	4,63	7,59	14,05	3,88	6,83	9,80	4,63	7,51	14,30
Sinter + pellet + ore consumption, kg/t	1584	1585	1585	1584	1584	1585	1585	1585	1583	1584	1584	1584
Iron in batch, %	59,59	59,68	59,75	59,50	59,60	59,71	59,65	59,76	59,83	59,55	59,64	59,74
Ore load, t/t	3,559	3,898	4,224	3,275	3,597	4,046	3,789	4,272	4,649	3,427	3,860	4,162
Quantity of slag, kg/t	271	269	267	274	271	268	270	267	265	272	270	267
Theoretical combustion temperature, °C	2117	1910	1737	2446	2202	1821	2099	1862	1677	2428	2168	1796
Residence time in furnace, h	8,46	9,36	10,36	7,32	8,12	9,67	8,30	9,12	10,16	7,22	8,05	9,62
Quantity of tuyere gas, m^3/t	1592	1751	1921	1400	1560	1872	1482	1589	1760	1324	1470	1/824
Quantity of dry last furnace gas, m^3/t	1710	1787	1889	1510	1569	1780	1588	1613	1719	1430	1463	1735
Direct reduction of Fe Oxide, %	37,77	29,07	22,62	33,75	21,09	13,63	36,10	28,63	22,73	33,71	19,13	14,73
Degree of gas utilization, %:	49,13	48,13	45,82	47,27	48,44	41,80	52,98	51,90	48,68	49,40	52,01	42,13
Carbon consumption, kg/t: total	386	351	323	420	381	338	362	320	294	401	355	328
Combustion of coke at tuyere	252	235	221	294	281	253	231	205	191	275	259	242
Indirect reduction of iron	76	59	46	68	43	27	73	58	46	68	39	30
Total heat input, kJ/kg	4486	4418	4387	4546	4513	4413	4142	3911	3882	4267	4185	4240
Heat consumption, kJ/kg	3474	3250	3084	3374	3048	2858	3420	3224	3082	3363	2993	2883
Enthalpy of BF top-gas, kJ/t	422	591	743	567	881	998	124	130	241	293	619	797
Heat losses, kJ/t	590	578	561	605	583	558	598	556	559	611	573	561
Proportion of useful heat, %	77	74	70	74	68	65	83	82	79	79	72	68
Ratio of water equivalents	0,831	0,735	0,650	0,994	0,881	0,694	0,857	0,761	0,666	1,015	0,899	0,696
Heat of combustion of blast furnace top-gas, kJ/m^3	3009	3194	3455	3819	3850	4616	2816	3045	3376	3702	3631	4630
Gas intensity, m^3/(m^3 min)	2,20	2,25	2,29	2,13	2,19	2,30	2,18	2,23	2,28	2,12	2,17	2,30
Differential equivalent of coke Replacement, kg/m^3	0,78	0,8	0,64	0,86	0,9	0,66	0,84	0,96	0,62	1,08	1,06	0,28
ΔΠ, %/ м^3 (everywhere (-))	0,074	0,087	0,103	0,062	0,082	0,09	0,078	0,042	0,116	0,027	0,067	0,154

Table 3
Basic Characteristics for Blast Furnaces 9 and 5 with Different Consumption of Coke-Oven Gas, for the Actual and Uniform Ore-Load Distribution Over the Charge Hole

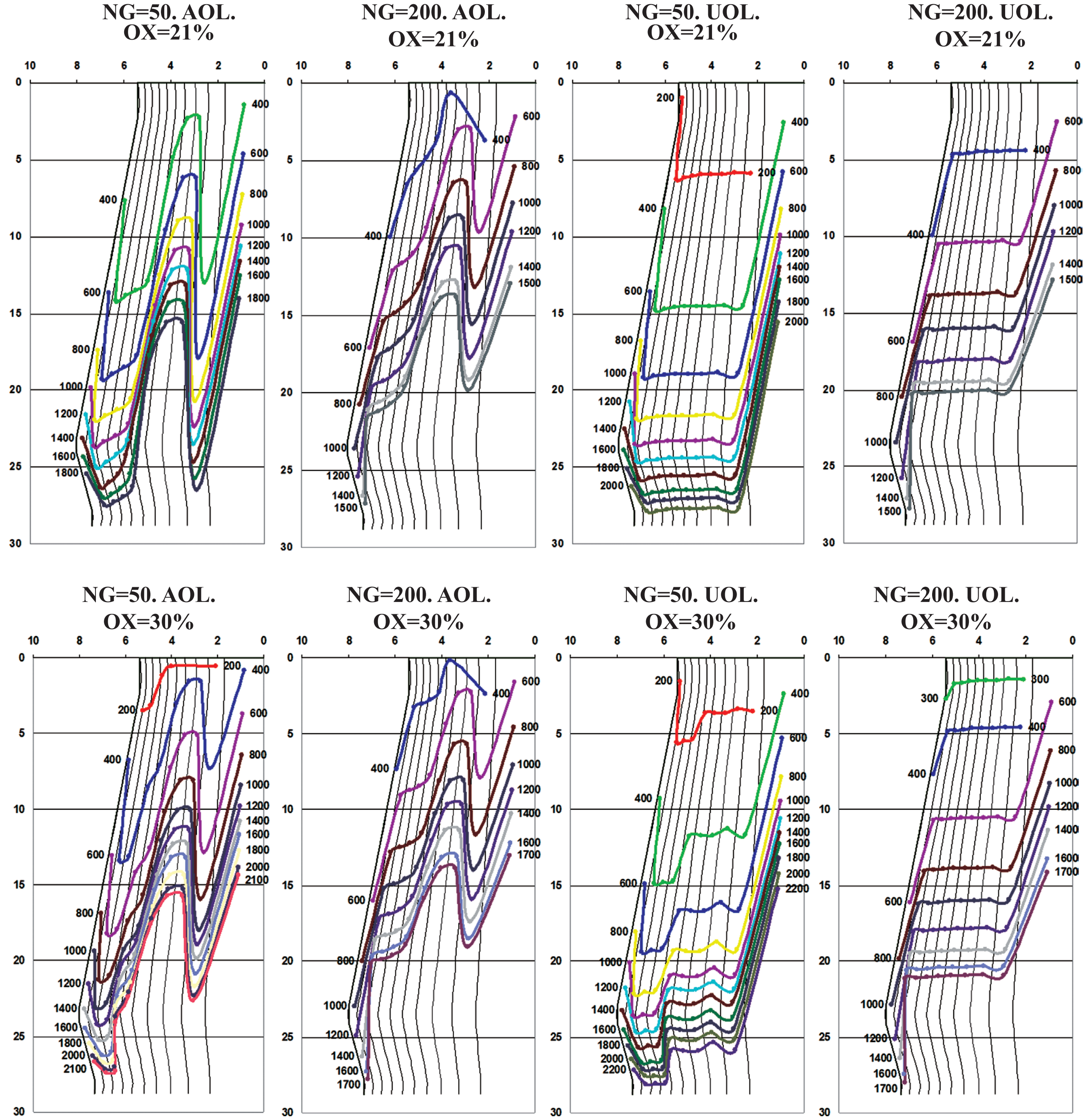
Characteristic	BLAST FURNACE-9						BLAST FURNACE-5					
	AOL			UOL			AOL			UOL		
Coke-oven gas consumption: m^3/t	100	200	300	100	200	300	100	200	300	100	200	300
% of blast	7,3	14,7	20,1	7,8	15,7	22,3	8,4	16,2	23,4	9,2	17,0	25,8
Productivity, t/(m^3 day)	1,595	1,573	1,439	1,677	1,658	1,555	1,781	1,705	1,61	1,915	1,769	1,721
Solid fuel consumption, kg/t	489	445	439	468	423	400	450	410	385	415	389	357
Anthracite consumption, kg/t	47	43	43	45	41	39	0	0	0	0	0	0
Blast flow rate, m^3/min	7607	7482	7498	7498	7361	7328	8139	8023	7878	7959	7930	7647
Blast temperature , °C	1042	1042	1042	1042	1042	1042	1184	1184	1184	1184	1184	1184
BF Top-gas: temperature, °C	212	209	308	116	107	190	159	223	248	48	180	102
Content, %: CO	21,90	20,96	20,82	21,51	20,66	20,05	20,32	19,08	19,15	18,47	18,06	18,77
CO_2	16,98	15,6	13,48	17,72	16,18	14,32	19,43	17,73	15,42	21,48	18,68	16,07
H_2	4,73	8,18	11,17	4,82	8,42	11,64	4,6	7,95	11,46	4348	7,88	11,99
Sinter + pellet + ore consumption, kg/t	1630	1631	1631	1630	1631	1632	1584	1585	1584	1585	1585	1583
Limestone consumption, kg/t	41	38	37	40	36	34	0	0	0	0	0	0
Iron in batch, %	55,19	55,26	55,27	55,22	56,06	55,33	59,58	59,67	59,73	59,66	59,72	59,91
Ore load, t/t	3,649	4,003	4,061	3,813	4,21	4,448	3,548	3,886	4,131	3,837	4,083	4,446
Quantity of slag, kg/t	409	407	407	408	407	406	271	269	267	269	268	266
Theor. Combustion temperature, °C	2045	1849	1718	2031	1823	1669	2113	1904	1733	2090	1884	1680
Residence time in furnace, h	8,64	9,27	10,22	8,44	9,06	9,98	8,43	9,33	10,24	8,24	9,27	10,01
Quantity of tuyere gas, m^3/t	1802	1923	2206	1698	1811	2031	1599	1767	1952	1466	1695	1807
Quantity of dry blast furnace gas, m^3/t	1917	1957	2176	1812	1844	1989	1704	1774	1892	1553	1686	1746
Direct reduction of Fe oxide, %	34,38	26,55	19,31	35,2	27,71	19,38	36,78	26,25	20,72	34,44	24,34	22,34
Degree of gas utilization, %:	43,62	42,59	39,21	45,11	43,84	41,58	48,87	18,16	44,6	53,77	50,84	46,12
Carbon consumption, kg/t: total	416	379	373	398	360	340	387	352	331	357	335	307
Combustion of coke at tuyere	293	271	279	273	250	247	255	242	232	230	229	205
Indirect reduction of iron	66	51	37	68	53	37	74	53	42	69	49	45
Total heat input, kJ/kg	4890	4680	4952	4579	4347	4433	4484	4425	4415	4067	4199	3961
Heat consumption, kJ/kg	3772	3580	3416	3783	3598	3402	3450	3179	3044	3375	3122	3075
Enthalpy of BF top-gas, kJ/t	672	687	1134	345	327	640	446	674	805	123	519	303
Heat losses, kJ/t	446	413	403	452	422	391	588	572	566	568	558	583
Proportion of useful heat, %	77	77	69	83	83	77	77	72	69	83	74	78
Ratio of water equivalents	0,734	0,673	0,595	0,758	0,693	0,618	0,83	0,733	0,646	0,861	0,744	0,659
Heat of combustion of BF top-gas, kJ/m^3	3283	3537	3842	3243	3525	3795	3069	3274	3662	2821	3137	3671
Gas intensity, m^3/(m^3 min)	2,22	2,28	2,35	2,21	2,28	2,34	2,21	2,26	2,32	2,18	2,25	2,31
Differential equivalent of coke replacement, kg/m^3	0,48	0,44	0,06	0,43	0,45	0,23	0,37	0,26	0,25	0,47	0,26	0,32
ΔΠ, %/ м^3 everywhere (-)	0,015	0,014	0,085	0,016	0,011	0,062	0,036	0,021	0,055	0,023	0,021	0,021

2. ANALYSIS OF RESULTS

With increase in the natural gas consumption, the coke consumption declines. This implies decrease in direct reduction with increase in temperature of the blast furnace gas, as in the balance calculations (Ramm, 1980, p.304; Tovarovski, 1987, p.192; Tovarovskiy, Bolshakov, Gordon, 2007, p.39-46; Tovarovskiy, 2009, p.768). However, in contrast to the balance calculations, the decline in coke consumption and direct reduction is not so smooth according to the model calculations. The differential equivalent of coke replacement (the equivalent in the range of natural gas consumption from the previous value to the current value) is 1.0-0.9 kg/ m^3 with natural gas consumption of 50 m^3/t of hot metal (range 0-50 m^3/t) and 0.9-0.8 kg/m^3 with natural gas consumption of 100 m^3/t (range 50-100 m^3/t). At higher natural gas consumption, the differential equivalent of coke replacement declines considerably more rapidly, to 0.2-0.6 kg/m^3. The gradient of the degree of direct reduction declines more smoothly from 0.16-0.20%/m^3 to 0.12-0.16 and 0.12-0.14%/m^3 respectively, while the sharp drop in differential equivalent of coke replacement at natural gas consumption above 100 m^3/t is due to the corresponding temperature rise of the coke-oven gas. With continuous rise in gas intensity, the furnace productivity falls by 1-3% at blast furnace 9 and twice as much at blast furnace 5, with natural gas consumption no greater than 100 m^3/t. Above 100 m^3/t, the productivity falls markedly.

This is clearly apparent in the actual distribution of ore loads at the charge hole. On approaching a uniform distribution in the radial annular zones 2-9 of the charge hole, this effect is less pronounced on account of the increase in the differential equivalent of coke replacement when the natural gas consumption is more than 100 m^3/t (Tables 1-3). The overall variation in the differential equivalent of coke replacement is as follows. With increase in natural gas consumption to 100 m^3/t, the differential equivalent of coke replacement declines sharply, by 0.1%/m^3 from the initial value of 1.0-0.9 kg/m^3. With further increase in natural gas consumption as the degree of direct reduction falls to *r*d < 20%, there is sharp temperature rise of the blast furnace gas, and the differential equivalent falls by a factor of 1.5-4. On establishing a more uniform distribution in radial annular zones 2-9, the drop in the differential equivalent is somewhat less at natural gas consumption above 100 m^3/t.

The explanation for this behavior may be derived from the data in Figures 2-8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NG=200. AOL. OX=21%
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NG=200. AOL. OX=30%
NG=50. UOL. OX=30%
NG=200. UOL. OX=30%

Figure 2
Gas Temperature Distribution in Blast Furnace 9 with Different Distributions of the Relative Ore Loads at the Charge Hole, Different Natural Gas Consumption, and Different Oxygen Content in the Blast. The distance (m) from the furnace axis is plotted horizontally, and the distance (m) from the top of the furnace (the zero point) is plotted vertically

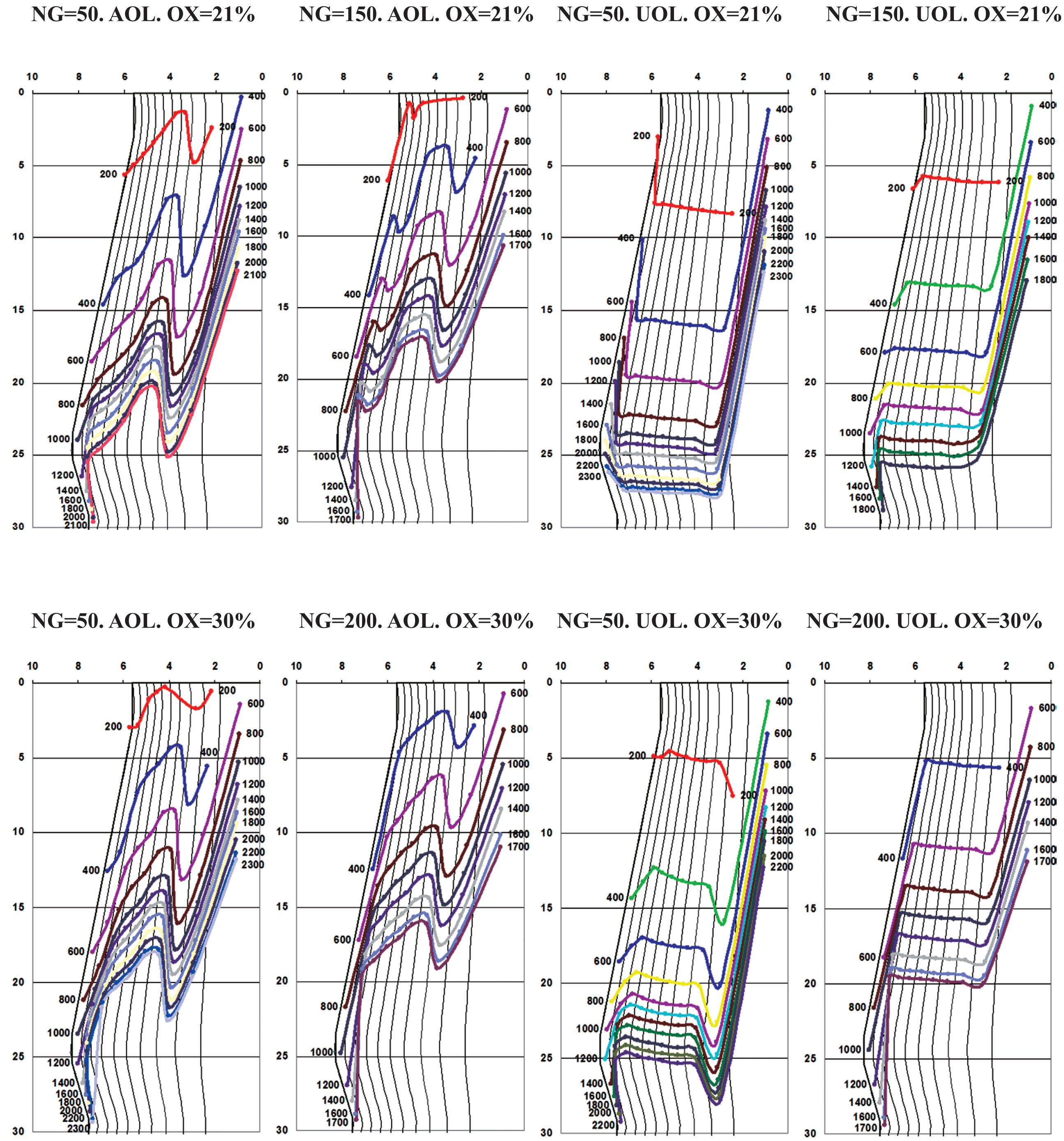


Figure 3
Gas Temperature Distribution in Blast Furnace 5 with Different Distributions of the Relative Ore Loads at the Charge Hole, Different Natural Gas Consumption, and Different Oxygen Content in the Blast. The distance (m) from the furnace axis is plotted horizontally, and the distance (m) from the top of the furnace (the zero point) is plotted vertically

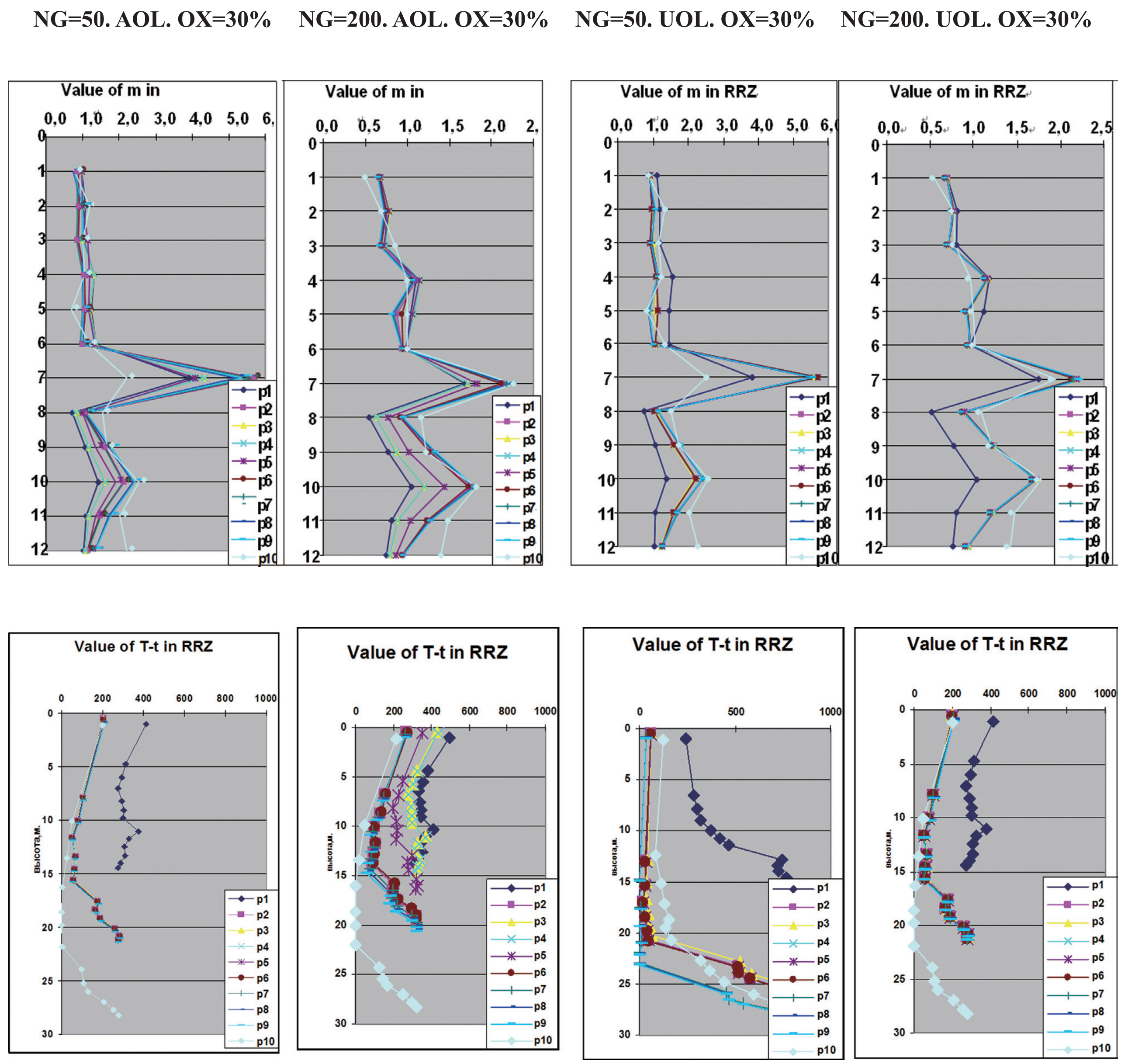
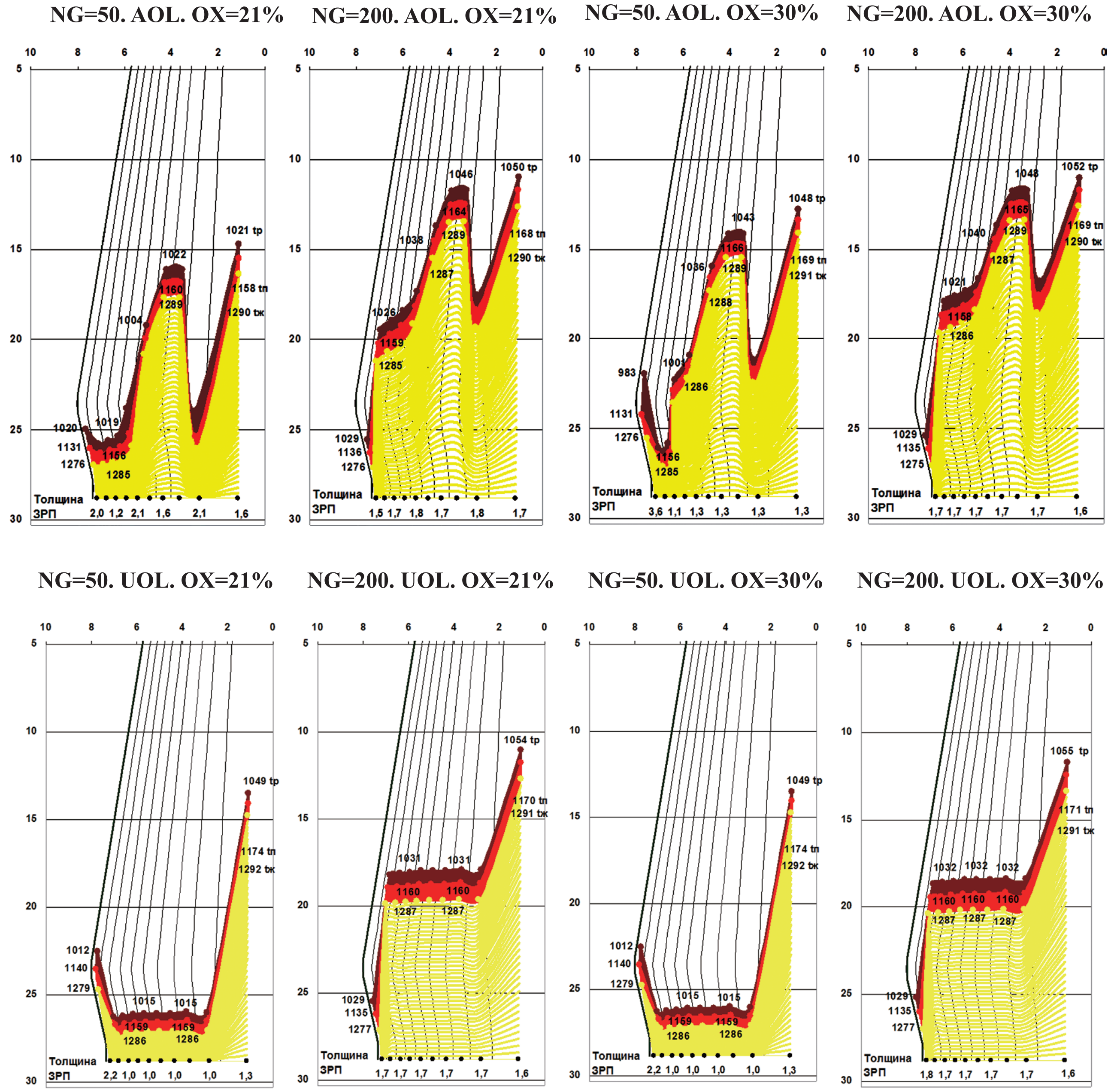


Figure 4

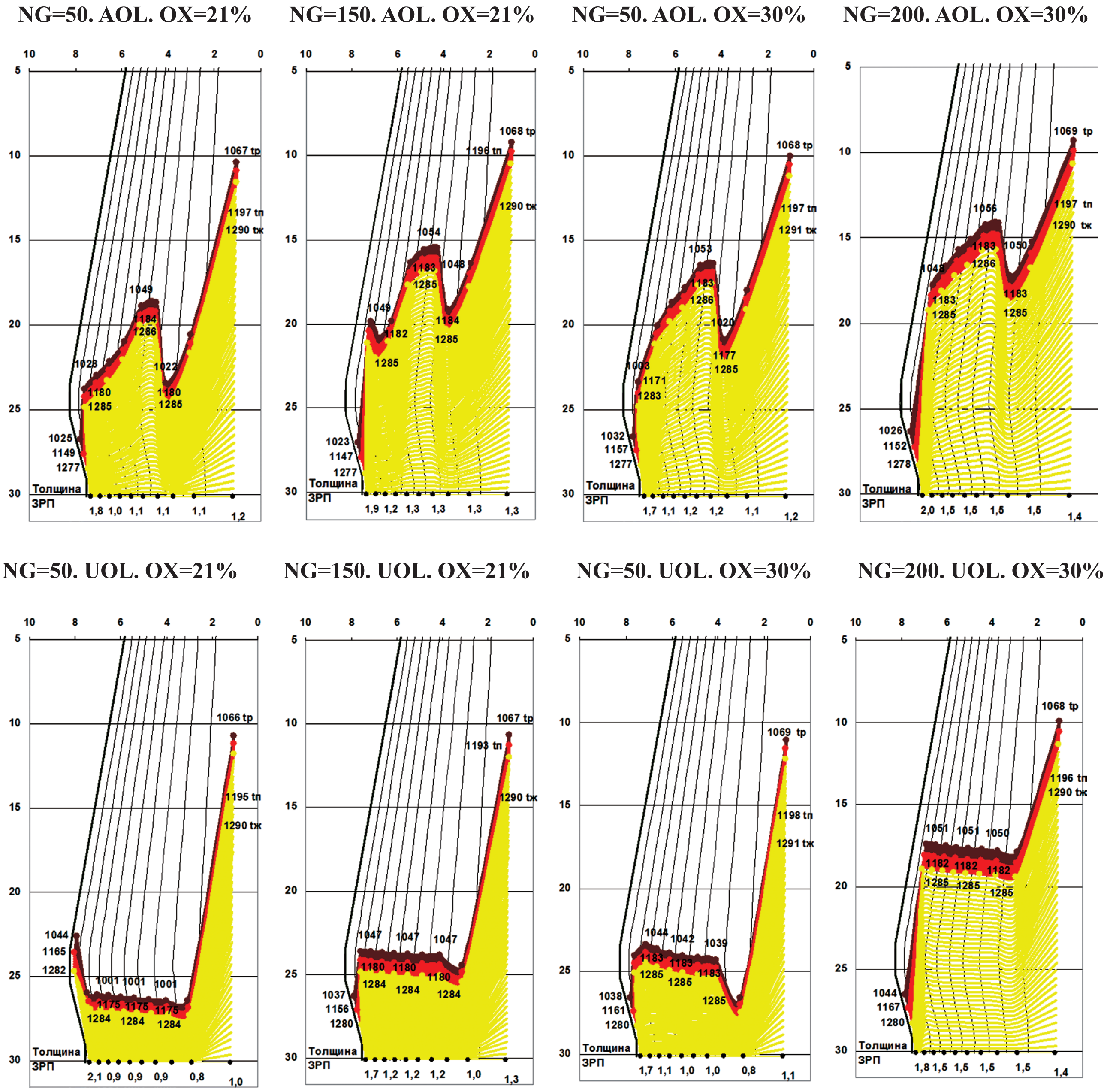
Distribution of the Specific Heat Ratio *m* of the Batch and Gas Fluxes in Radial Annular (Ring) Zones (RAZ or RRZ) p1-p10 (Upper Row) and Distribution of the Temperature Difference *T-t* (Lower Row) over the Height of Blast Furnace 9, with Different Distributions of the Relative Ore Loads, Different Natural Gas Consumption (50 and 200 m^3/t), and 30% Oxygen Content in the Blast


NG=50. AOL. OX=21% NG=200. AOL. OX=21% NG=50. AOL. OX=30% NG=200. AOL. OX=30%

NG=50. UOL. OX=21% NG=200. UOL. OX=21% NG=50. UOL. OX=30% NG=200. UOL. OX=30%

Figure 5

Position of softening and melting zones in furnace 9, with different distributions of the relative ore loads, different natural gas consumption (50 and 200 m^3/t), and different oxygen content in the blast: *ts, tm, tli* (t_p, t_n, $t_{ж}$), initial temperatures of softening, melting, and liquefaction, °C. The distance (m) from the furnace axis is plotted horizontally, and the distance (m) from the top of the furnace is plotted vertically. Thickness of SMZ, m-Толщина ЗРП, м.



NG=50. AOL. OX=21%   NG=150. AOL. OX=21%   NG=50. AOL. OX=30%   NG=200. AOL. OX=30%

NG=50. UOL. OX=21%   NG=150. UOL. OX=21%   NG=50. UOL. OX=30%   NG=200. UOL. OX=30%

Figure 6
Position of Softening and Melting Zones in Furnace 5, with Different Distributions of the Relative Ore Loads, Different Natural Gas Consumption (50 and 200 m^3/t), and Different Oxygen Content in the Blast: *ts, tm, tli* (t_p, $t_{п}$, $t_{жс}$), Initial Temperatures of Softening, Melting and Liquefaction, °C. The distance (m) from the furnace axis is plotted horizontally, and the distance (m) from the top of the furnace is plotted vertically. Thickness of SMZ, m-Толщина ЗРП, м.

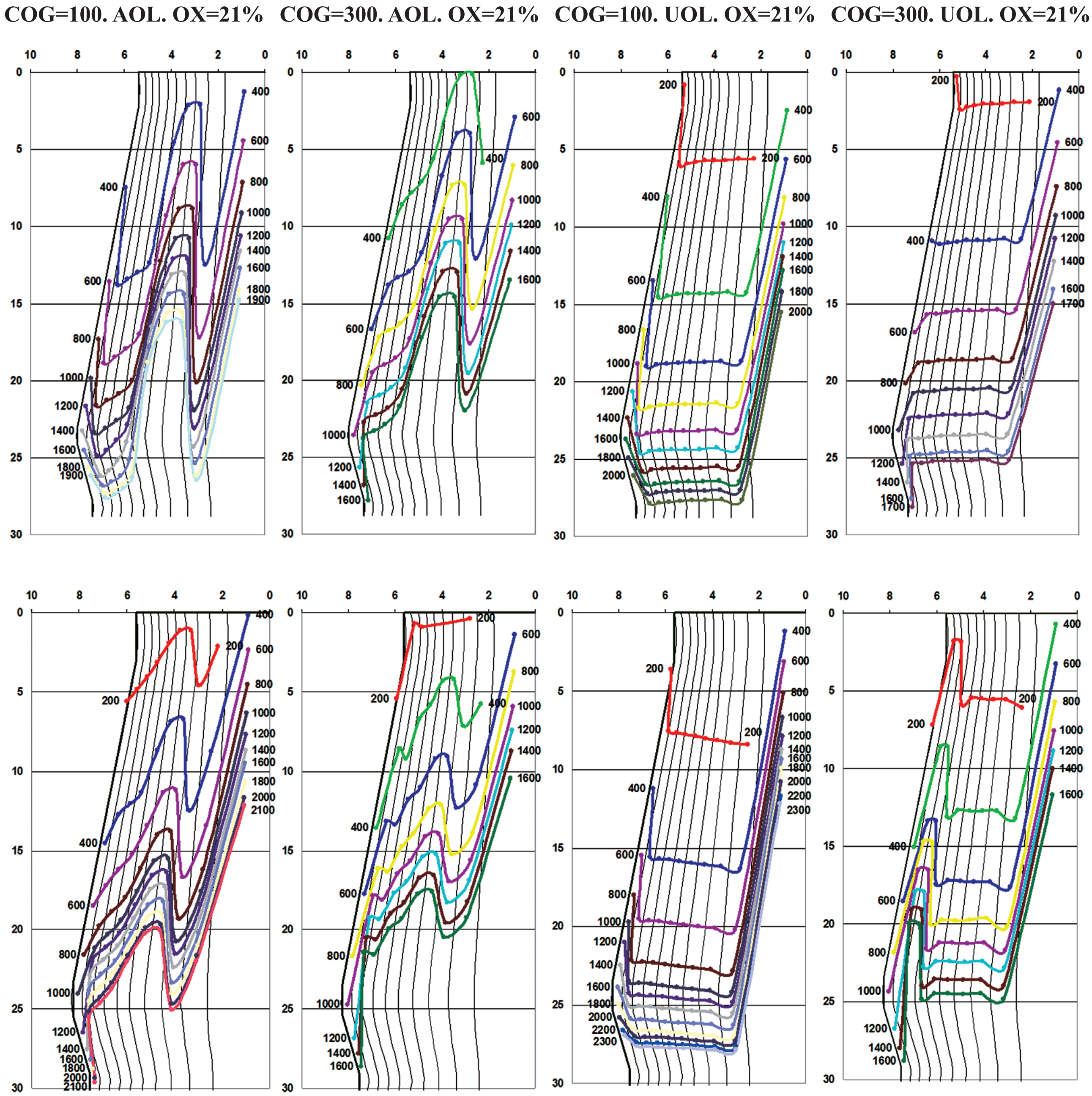


Figure 7

Gas Temperature Distribution in Blast Furnaces 9 (a) and 5 (b) with Different Distributions of the Relative Ore Loads at the Charge Hole, Different Consumption of Coke Oven Gas (100 and 300 m^3/t), and Atmospheric Oxygen Content in the Blast. The distance (m) from the furnace axis is plotted horizontally, and the distance (m) from the top of the furnace (the zero point) is plotted vertically.

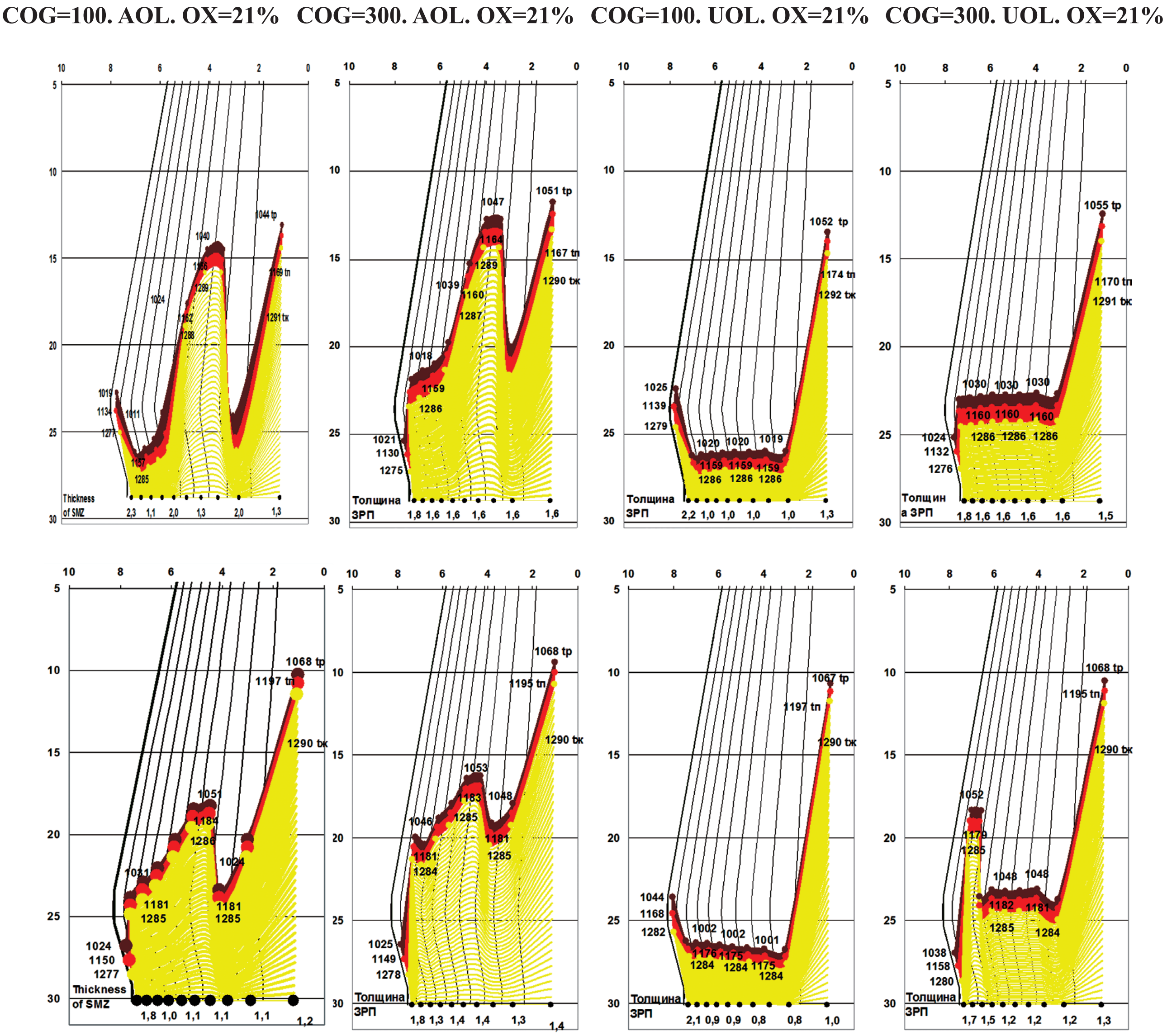


Figure 8

Position of Softening and Melting Zones in Furnaces 9 (a) and 5 (b), for Different Distributions of the Relative Ore Loads and Different Consumption of Coke Oven Gas (100 and 300 m^3/t): *ts, tm, tli* (t_p, t_n, $t_ж$), Initial Temperatures of Softening, Melting, and Liquefaction, °C. The distance (m) from the furnace axis is plotted horizontally, and the distance (m) from the top of the furnace is plotted vertically. Thickness of SMZ, m-Толщина ЗРП, м.

With increase in natural gas consumption, the temperature field of the gas flux within the furnace is deformed: the temperature *T* of the lower zones declines, while the temperature of the upper zones increases (Figs. 4 and 5). In all the radial annular zones, the temperature difference *T-t* between the gas and the batch declines in the lower zone (>900°C) and rises to an analogous value over the height of the upper zone (>900°C). At the same time, the specific heat ratio *m* of the batch and gas fluxes in the direct reduction zone falls from 3-5 to 1.5-2, on account of the drop in the mean degree of direct reduction (from *r*d = 35-40 to <20%). In the peripheral zone and some radial annular zones with a small ore load, *m* reaches very low values. The decline in *T-t* and *m* in the lower zones reduces the heat transfer rate in this zone, while the rise in *T-t* in the upper zone increases the heat transfer there. As a result, the height of the lower heat transfer stages increases in most radial annular zones, while the height of the upper heat transfer stages is reduced. The total height over which the materials are heated to the specified temperatures is reduced. Such variation in *m* and *T-t* is illustrated in Figure 6 for blast furnace 9 with 30% O2 and is confirmed in other furnaces.

In accordance with the motion of the isotherms, the softening and melting zones are shifted upward (Figs. 5 and 6) and their thickness increases, with specified properties of the material. The initial temperatures *t*s and *t*m of softening and melting increase somewhat on account of the reduced quantity of ferrous oxide in the primary slags, with corresponding downward motion of the softening and melting zones. However, this shift is considerable less than the upward motion of the isotherms. The decline in gas temperature in the lower zone leads to a reduction in the heat losses much greater than their increase in the upper zone, where the gas temperature rises. As a result, the overall heat losses decline significantly (Tables 1-3). Thus, the deformation of the gas flux's temperature field with increase in natural gas consumption is analogous to its deformation when using preliminarily reduced batch. In that case, the heat transfer pattern in the blast furnace comes to resemble that in a cupola furnace (Chapligin & Erinov, 1976, p.239). This pattern is seen in all conditions, but natural gas consumption does not always vary smoothly. Different behavior is seen in different smelting conditions and indifferent blast furnaces, on account of the different ore load distribution in the radial annular zones—especially in peripheral radial annular zone 10, with various heat losses through the wall—and also the possible change in the limiting radial annular zones with variation in individual parameters (including the natural gas consumption). These effects, which are seen in the results obtained by means of the multizone model, are not observed in the balance calculations.

Such effects are also seen in comparing the results for blast furnaces 5 and 9. However, despite the difference in the conditions, the differential equivalent of coke replacement, and the gradient of direct reduction, there is little overall difference in the behavior. This may be attributed to mutual compensation of two factors: (1) greater utilization of the reducing and thermal energy of the gases in the initial conditions at OAO Severstal' furnace 5, with little scope for further increase in efficiency; (2) rate constants of reduction and heat transfer derived from the model that considerably exceed the corresponding values for furnace 9 at OAO ArcelorMittal Krivoi Rog, on account of the more favorable kinetic characteristics of the iron ore at OAO Severstal', which permits increased efficiency.

In calculating the influence of coke-oven gas on the blast-furnace process (Table 3; Figs. 7 and 8), the results are qualitatively the same as for natural gas, when the supply ratio of the coke oven gas and natural gas is 1:2. If we take account of the different distribution of material over the charge hole, we find that the calculation results are consistent with experimental results for blast furnaces at Krivorozhstal' metallurgical works (Nekrasov, Pokryshkin, & Buzoverya, 1968):

> …The upper boundary of the slag formation zone is near the lower level of the batch … over the furnace radius, the reduction of iron oxides is greatest at the periphery and in the center of the furnace … and least in the intermediate zone; at slag formation, more than 50% of the oxygen is removed from the iron oxides, and only 30% of the initial oxygen content is present at the level of the bosh extension…

3. COAL-DUST INJECTION (PULVERIZED COAL INJECTION—PCI)

To assess the influence of the coal-dust consumption on the smelting process, we use data regarding the operation of blast furnace 9 at OAO ArcelorMittal Krivoi Rog (useful volume 5000 m^3) and blast furnace 5 at OAO Severstal' (useful volume 5500 m^3) in characteristic operating periods (the baseline periods). Discrepancies in the balance of gasified elements in the baseline periods are minimized by correcting the composition of the furnace gas at blast furnace 9 and the oxygen content in the blast at blast furnace 5; these are the parameters most likely to introduce large errors in the results of the analysis. We consider conditions in which the ash and sulfur concentrations in the coal-dust fuel do not exceed the corresponding concentrations in the coke, while the oxygen content in the blast is 25%. For such conditions, by specifying different coal-dust consumption, we may predict the smelting characteristics for two distributions of the ore load over the charge hole: the actual ore load (AOL); and the uniform ore load (UOL) in radial annular zone RAZ-2-9. Tables 4-7 present the basic numerical results.

Table 4
Smelting Characteristics for Blast Furnace 9 at OAO Arcelor Mittal Krivoi Rog, with Different Blast Parameters and the Actual Ore-load Distribution at the Charge Hole

Characteristic	Actual ore load distribution, O2 = 25%							
Coal dust consumption: m^3/t	0	50	100	150	200	250	150	250
g/m^3 (blast)	0,0	41,6	84,6	130,1	175,1	220,6	128,1	220,3
Output, t/m^3 day	1,698	1,708	1,723	1,746	1,743	1,735	1,692	1,714
Consumption of chunk fuel, kg/t	554	504	452	398	352	305	362	283
Anthracite consumption, kg/t	54	49	44	39	34	30	35	27
Blast: flow rate, m^3/min	7221	7181	7119	7036	6959	6874	6925	6799
Temperature, °C	1042	1042	1042	1042	1042	1042	1042	1042
Consumption of coke oven gas, m^3/t	0	0	0	0	0	0	100	50

To be continued

Continued

Characteristic	Actual ore load distribution, O2 = 25%							
Blast furnace top-gas: temperature, °C	209	215	212	199	204	213	220	220
Content, %: CO	26,44	25,68	25,00	24,22	23,88	23,41	23,67	23,03
CO_2	19,92	20,33	20,74	21,27	21,37	21,53	19,05	20,50
H_2	1,39	1,67	1,95	2,22	2,51	2,79	6,04	4,69
Consumption of sinter + pellets + ore, kg/t	1628	1625	1621	1618	1615	1611	1619	1612
Limestone consumption, kg/t	47	42	38	34	30	25	31	24
Iron in batch, %	55,09	55,17	55,25	55,33	55,41	55,48	55,39	55,51
Ore load, t/t	3,226	3,533	3,917	4,428	4,994	5,740	4,868	6,169
Slag, kg/t	412	410	409	407	406	405	406	404
Theoretical combustion temperature, °C	2444	2396	2346	2295	2244	2194	2057	2071
Residence time in furnace, h	7,50	7,93	8,40	8,94	9,61	10,42	9,73	10,94
Tuyere gas, m^3/t	1545	1540	1527	1503	1503	1505	1650	1569
Dry blast furnace gas, m^3/t	1747	1725	1696	1656	1643	1630	1722	1650
Direct reduction of iron oxide, %	42,54	40,38	38,65	36,94	35,84	34,35	29,43	30,28
Gas utilization, %:	42,96	44,17	45,32	46,74	47,21	47,88	44,56	47,07
Carbon consumption, kg/t: $\sum$	471	429	385	339	299	259	308	241
Burned from coke at tuyeres	332	294	254	212	174	137	195	127
In direct reduction of iron	82	78	74	71	69	66	57	58
Total heat input, kJ/kg	5066	5012	4932	4818	4779	4747	4693	4654
Heat consumption, kJ/kg	3970	3916	3870	3823	3794	3753	3641	3654
Enthalpy of blast furnace gas, kJ/t	611	617	595	541	546	563	633	595
Heat losses, kJ/t	485	479	467	454	439	431	418	405
Useful heat, %	78	78	78	79	79	79	78	79
Water equivalent ratio	0,878	0,863	0,850	0,840	0,822	0,804	0,756	0,764
Heat of combustion of blast furnace gas, kJ/m^3	3496	3431	3374	3305	3293	3265	3648	3422
Gas intensity, m^3/m^3 min	2,10	2,09	2,08	2,06	2,05	2,03	2,14	2,06
Differential equivalent of coke substitution, kg/m^3	-	1,0	1,04	1,08	0,92	0,96	1,28*	1,084*
$\Delta\Pi$, $\%/m^3$	-	+0,012	+0,018	+0,026	-0,004	-0,007	-0,002	+0,004

Note: These values correspond to substitution by both coal dust fuel and coke oven gas.

Table 5
Smelting Characteristics for Blast Furnace 9 at OAO Arcelor Mittal Krivoi Rog, with Different Blast Parameters and Uniform Ore-load Distribution at the Charge Hole

Characteristic	Uniform ore-load distribution, O2 = 25%							
Coal dust consumption: m^3/t	0	50	100	150	200	250	150	250
g/m^3 (blast)	0,0	44,4	89,9	138,2	186,6	235,7	136,7	236,2
Output, t/m^3 day	1,773	1,794	1,805	1,825	1,826	1,820	1,776	1,802
Consumption of chunk fuel, kg/t	535	482	433	380	332	286	342	262
Anthracite consumption, kg/t	52	47	42	37	32	28	33	25
Blast: flow rate, m^3/min	7117	7068	7014	6926	6843	6748	6812	6667
Temperature, °C	1042	1042	1042	1042	1042	1042	1042	1042
Consumption of coke oven gas,m^3/t	0	0	0	0	0	0	100	50
Blast furnace top-gas: temperature, °C	115	125	116	93	90	86	110	95
Content, %: CO	26,26	25,29	24,60	23,93	23,53	23,26	23,38	22,69
CO_2	20,60	21,22	21,59	22,05	22,20	22,24	19,70	21,30
H_2	1,38	1,66	1,94	2,23	2,53	2,83	6,18	4,79
Consumption of sinter + pellets + ore, kg/t	1629	1625	1622	1618	1615	1612	1620	1612
Limestone consumption, kg/t	45	41	36	33	28	24	28	23
Iron in batch, %	55,13	55,19	55,28	55,35	55,43	55,52	55,44	55,54
Ore load, t/t	3,337	3,689	4,095	4,640	5,283	6,112	5,152	6,659
Slag, kg/t	411	410	408	407	405	404	404	403
Theoretical combustion temperature, °C	2444	2393	2340	2285	2231	2177	2033	2046
Residence time in furnace, h	7,34	7,75	8,24	8,79	9,45	10,25	9,57	10,79
Tuyere gas, m^3/t	1458	1444	1438	1418	1413	1413	1557	1472
Dry blast furnace gas, m^3/t	1664	1632	1610	1574	1556	1543	1630	1556

To be continued

Continued

Characteristic	Uniform ore-load distribution, O2 = 25%							
Direct reduction of iron oxide, %	44,10	41,64	39,82	38,37	37,30	36,44	30,96	31,86
Gas utilization, %:	43,94	45,61	46,72	47,94	48,52	48,87	45,69	48,40
Carbon consumption, kg/t: ∑	456	410	368	323	283	243	291	223
Burned from coke at tuyeres	314	273	235	193	155	117	175	106
In direct reduction of iron	85	80	76	74	72	70	59	61
Total heat input, kJ/kg	4786	4705	4647	4545	4492	4451	4393	4343
Heat consumption, kJ/kg	3998	3938	3889	3852	3820	3794	3663	3684
Enthalpy of blast furnace gas, kJ/t	316	335	305	236	225	210	296	237
Heat losses, kJ/t	473	432	453	457	448	447	435	422
Useful heat, %	84	84	84	85	85	85	83	85
Water equivalent ratio	0,905	0,893	0,877	0,866	0,848	0,830	0,778	0,788
Heat of combustion of blast furnace gas, kJ/m^3	3472	3379	3323	3269	3251	3249	3627	3388
Gas intensity, m^3/m^3 min	2,09	2,08	2,07	2,05	2,04	2,02	2,13	2,05
Differential equivalent of coke substitution, kg/m3	-	1,06	0,98	1,06	0,96	0,92	1,29*	1,092*
$\Delta\Pi$, %/m^3	-	+0,02	+0,012	+0,022	+0,002	-0,007	+0,001	+0,006

Note: These values correspond to substitution by both coal dust fuel and coke oven gas.

Table 6
Smelting Characteristics for Blast Furnace 5 at OAO Severstal', with Different Blast Parameters and the Actual Ore Load Distribution at the Charge Hole

Characteristic	Actual ore_load distribution, O2 = 25%							
Coal dust consumption: m^3/t	0	50	100	150	200	250	150	250
g/m^3 (blast)	0,0	47,9	96,6	146,8	198,7	249,5	143,7	245,7
Output, t/m^3 day	1,942	1,926	1,909	1,892	1,872	1,835	1,818	1,787
Consumption of chunk fuel, kg/t	503	460	414	368	321	276	323	257
Blast: flow rate, m^3/min	7809	7680	7549	7386	7198	7021	7246	6945
temperature, °C	1184	1184	1184	1184	1184	1184	1184	1184
Consumption of coke oven gas, m^3/t	0	0	0	0	0	0	100	50
Blast furnace top-gas: temperature, °C	145	142	150	143	134	146	213	184
content, %: CO	23,43	23,41	23,03	22,79	22,50	22,16	21,18	21,66
CO_2	23,90	23,73	23,81	23,86	24,00	24,06	22,01	22,84
H_2	1,10	1,43	1,74	2,06	2,38	2,68	5,76	4,58
Consumption of sinter + pellets + ore, kg/t	1584	1584	1585	1584	1581	1579	1584	1579
Iron in batch, %	59,46	59,56	59,66	59,77	59,88	59,98	59,87	60,03
Ore load, t/t	3,181	3,474	3,847	4,320	4,942	5,731	4,905	6,156
Slag, kg/t	275	272	269	266	264	261	264	260
Theoretical combustion temperature, °C	2541	2489	2437	2383	2329	2277	2116	2143
Residence time in furnace, h	7,20	7,69	8,28	8,95	9,75	10,75	10,02	11,45
Tuyere gas, m^3/t	1339	1341	1343	1340	1333	1340	1492	1422
Dry blast furnace gas, m^3/t	1531	1523	1512	1497	1480	1474	1542	1505
Direct reduction of iron oxide, %	43,00	42,78	41,71	41,06	40,30	39,01	29,67	33,92
Gas utilization, %:	50,50	50,34	50,83	51,15	51,60	52,06	50,97	51,32
Carbon consumption, kg/t: ∑	433	395	356	316	276	238	278	221
Burned from coke at tuyeres	288	251	215	176	138	102	161	96
In direct reduction of iron	87	86	84	83	81	79	60	68
Total heat input, kJ/kg	4575	4550	4526	4481	4428	4421	4376	4389
Heat consumption, kJ/kg	3609	3595	3558	3536	3517	3484	3242	3351
Enthalpy of blast furnace gas, kJ/t	368	355	370	348	319	346	556	453
Heat losses, kJ/t	598	600	597	597	593	592	579	586
Useful heat, %	79	79	79	79	79	79	74	76
Water equivalent ratio	1,032	1,007	0,982	0,958	0,935	0,909	0,840	0,847
Heat of combustion of blast furnace gas, kJ/m^3	3083	3116	3102	3107	3104	3094	3303	3236
Gas intensity, m^3/m^3 min	2,10	2,08	2,05	2,02	1,98	1,94	2,07	1,96
Differential equivalent of coke substitution, kg/m^3	-	0,86	0,92	0,92	0,94	0,9	1,2*	0,98*
$\Delta\Pi$, %/m^3	-	0,017	0,018	0,017	0,021	0,04	0,043	0,03

Note: These values correspond to substitution by both coal dust fuel and coke oven gas.

Table 7
Smelting Characteristics for Blast Furnace 5 at OAO Severstal', with Different Blast Parameters and Uniform Ore Load Distribution at the Charge Hole

Characteristic	Uniform ore load distribution, O2 = 25%							
Coal dust consumption: m^3/t	0	50	100	150	200	250	150	250
g/m^3 (blast)	0,0	50,8	100,9	152,9	208,6	262,9	148,8	264,5
Output, t/m^3 day	2,005	2,006	1,969	1,950	1,943	1,901	1,857	1,873
Consumption of chunk fuel, kg/t	482	444	401	355	302	257	318	236
Blast: flow rate, m^3/min	7752	7540	7452	7308	7114	6906	7151	6762
Temperature, °C	1184	1184	1184	1184	1184	1184	1184	1184
Consumption of coke oven gas,m^3/t	0	0	0	0	0	0	100	50
Blast furnace top-gas: temperature, °C	103	48	48	56	49	50	129	51
Content, %: CO	21,32	23,21	22,56	22,23	21,15	20,82	21,74	21,07
CO_2	25,88	24,49	24,60	24,63	25,38	25,57	21,88	23,94
H_2	1,00	1,42	1,72	2,04	2,30	2,59	5,97	4,63
Consumption of sinter + pellets + ore, kg/t	1583	1584	1585	1586	1586	1577	1586	1578
Iron in batch, %	59,37	59,59	59,69	59,86	59,92	60,02	59,85	60,07
Ore load, t/t	3,328	3,591	3,971	4,464	5,236	6,161	4,978	6,694
Slag, kg/t	277	271	268	264	263	260	264	259
Theoretical combustion temperature, °C	2541	2486	2432	2377	2319	2263	2102	2115
Residence time in furnace, h	7,16	7,55	8,19	8,87	9,72	10,75	9,89	11,36
Tuyere gas, m^3/t	1288	1266	1287	1288	1272	1276	1447	1330
Dry blast furnace gas, m^3/t	1467	1452	1456	1442	1408	1402	1508	1415
Direct reduction of iron oxide, %	39,34	44,37	42,13	41,29	38,98	37,61	32,53	34,88
Gas utilization, %:	54,83	51,34	52,16	52,57	54,55	55,13	50,18	53,19
Carbon consumption, kg/t: ∑	415	382	345	305	260	221	274	203
Burned from coke at tuyeres	277	235	202	165	125	88	151	76
In direct reduction of iron	79	89	85	83	79	76	66	70
Total heat input, kJ/kg	4403	4294	4336	4305	4223	4203	4224	4079
Heat consumption, kJ/kg	3531	3628	3563	3522	3460	3447	3311	3374
Enthalpy of blast furnace gas, kJ/t	251	112	113	129	111	111	323	115
Heat losses, kJ/t	622	554	660	655	652	645	591	590
Useful heat, %	80	84	82	82	82	82	78	83
Water equivalent ratio	1,055	1,031	1,000	0,973	0,954	0,928	0,848	0,867
Heat of combustion of blast furnace gas, kJ/m^3	2806	3091	3041	3033	2925	2915	3396	3168
Gas intensity, m^3/m^3 min	2,08	2,06	2,04	2,00	1,96	1,92	2,07	1,94
Differential equivalent of coke substitution, kg/m^3	-	0,76	0,86	0,92	1,06	0,9	1,09*	0,98*
$\Delta\Pi$, $\%/m^3$	-	0,001	-0,036	-0,019	-0,008	-0,043	-0,049	-0,026

Note: These values correspond to substitution by both coal dust fuel and coke oven gas.

With increase in coal dust consumption, the coke consumption declines. Some of the heat from the coke is replaced by heat from the coal-dust fuel, while the degree of direct reduction is somewhat less, with slight charge in furnace gas temperature, as in the balance calculations (Ramm, 1980, p.304; Tovarovski, 1987, p.192). The first component is responsible for more than 80% of the coke savings and does not greatly depend on the smelting conditions. The second component is different for the two furnaces considered and depends on the reduction conditions. In blast furnace 5 at OAO Severstal', these conditions are closer to limiting (with higher gas utilization), and the diminution in direct reduction is only half as much. Accordingly, the equivalent of coke substitution is somewhat lower at blast furnace 5.

The heat losses through the walls decline smoothly with increase in coal dust consumption for blast furnace 9 at ArcelorMittal Krivoi Rog (0.05%/ m^3), with slight change for blast furnace 5 at Severstal'.

For all values of the coal-dust consumption, the differential equivalent of coke substitution (the equivalent in the range of coal-dust consumption from the previous to the current value) is close to the mean in the range 0-250 kg/t of hot metal: 1.0 and 0.9 kg/kg for blast furnaces 9 and 5, respectively. These values are typical with increase in the coal-dust consumption for both the actual and uniform ore-load distributions. With some lowering of gas intensity, the furnace productivity increases, on average, by 0.01%/m^3 for furnace 9 and 0.02%/ m^3 for furnace 5.

The thermo-physicochemical principles underlying the observed blast furnace behavior are illustrated by the results in Figures 9-12.

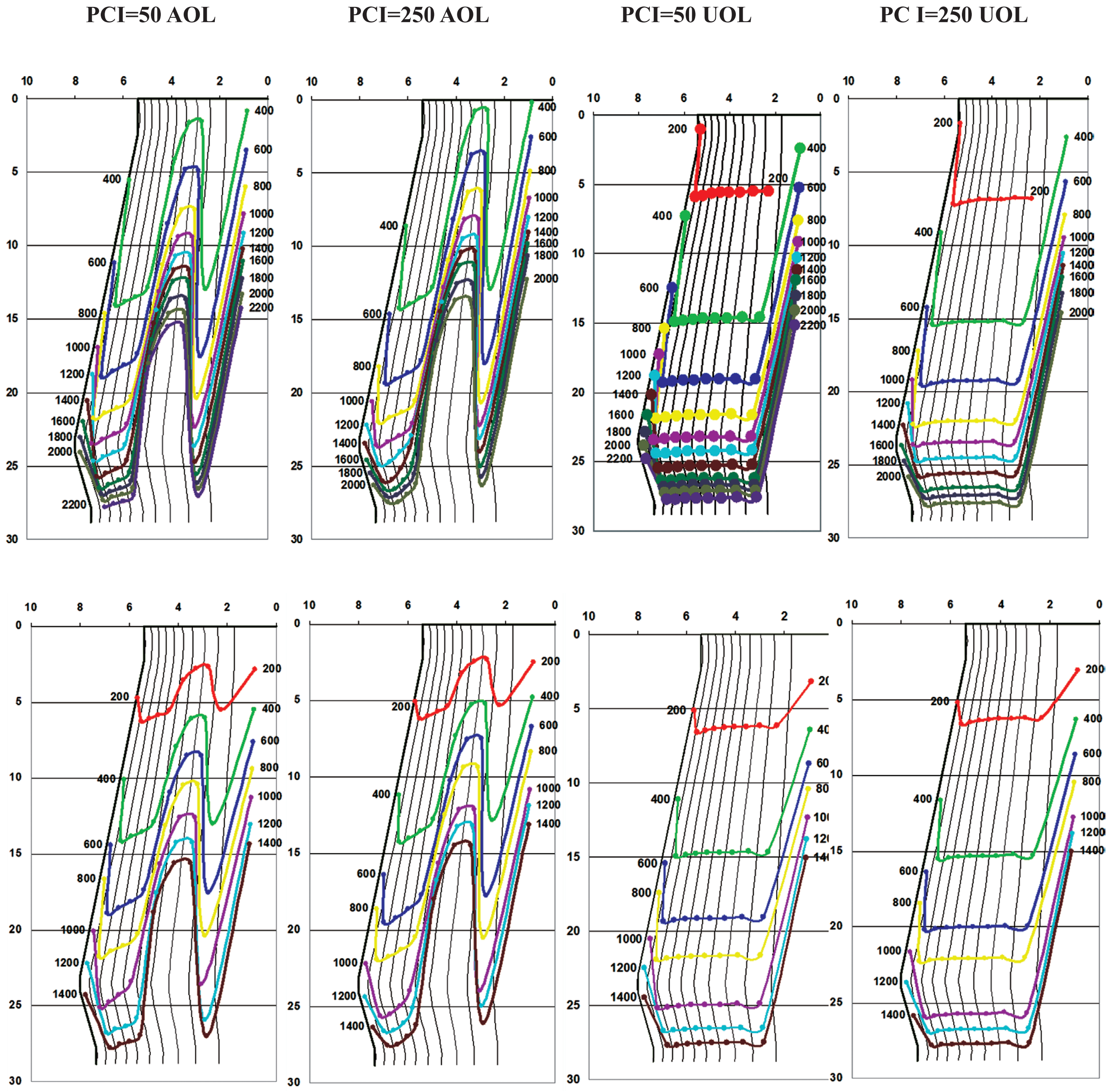


Figure 9
Temperature Distributions of Gas (Upper Row) and Batch (Lower Row) within Blast Furnace 9 at OAO Arcelor Mittal Krivoi Rog, with Actual and Uniform Ore Load Distributions in the Change Hole, Different Coal Dust Consumption (50 or 250 kg/t), and 25% Oxygen in the Blast. The distance from the furnace axis is plotted horizontally, while the distance from the top of the furnace (the technological zero level), m, is plotted vertically.

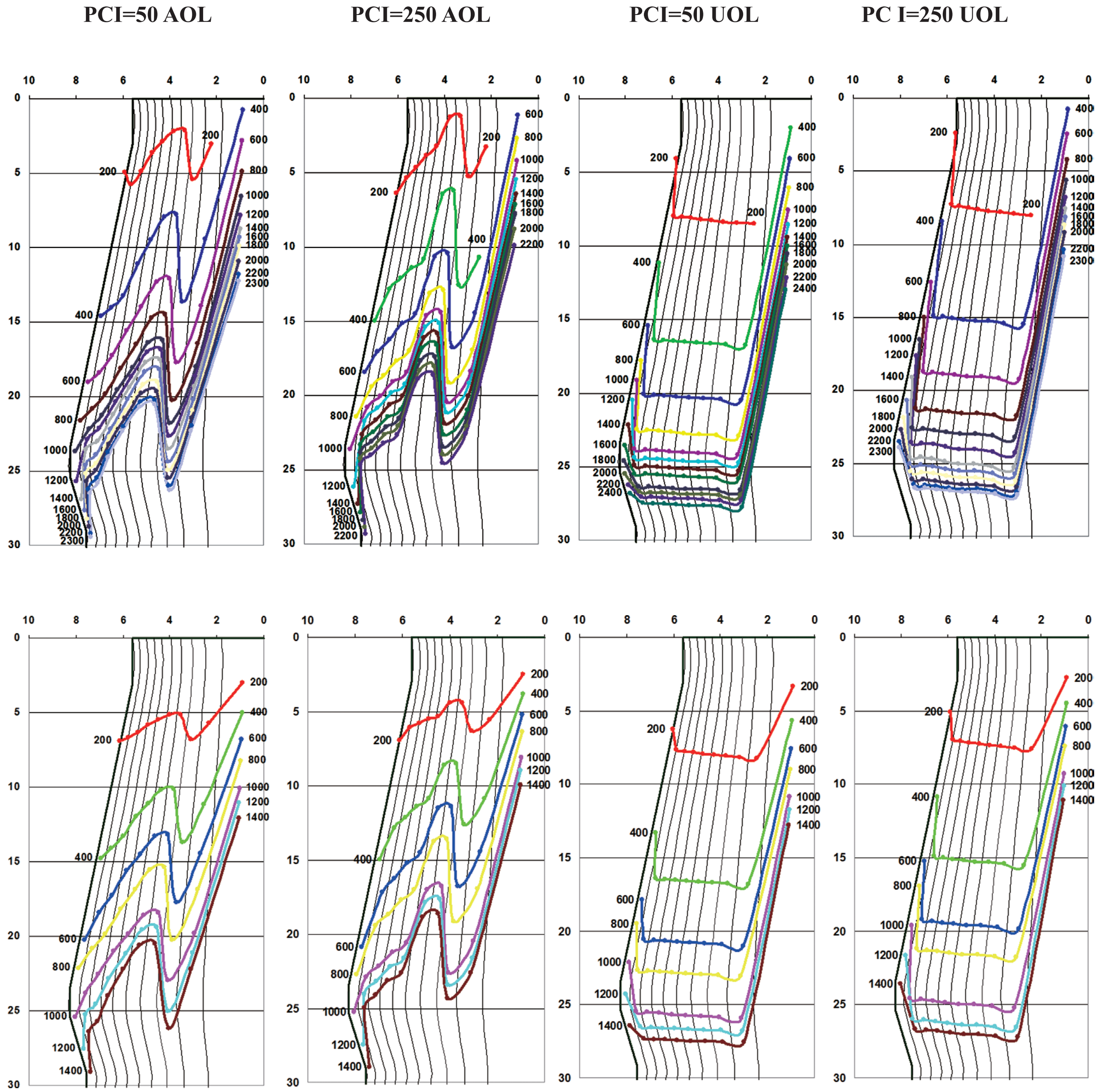


Figure 10
Temperature Distributions of Gas (Upper row) and Batch (Lower Row) Within Blast Furnace 5 at OAO Severstal’, with Actual and Uniform Ore Load Distributions in the Change Hole, Different Coal Dust Consumption (50 or 250 kg/t), and 25% Oxygen in the Blast. The distance from the furnace axis is plotted horizontally, while the distance from the top of the furnace (the technological zero level), m, is plotted vertically.

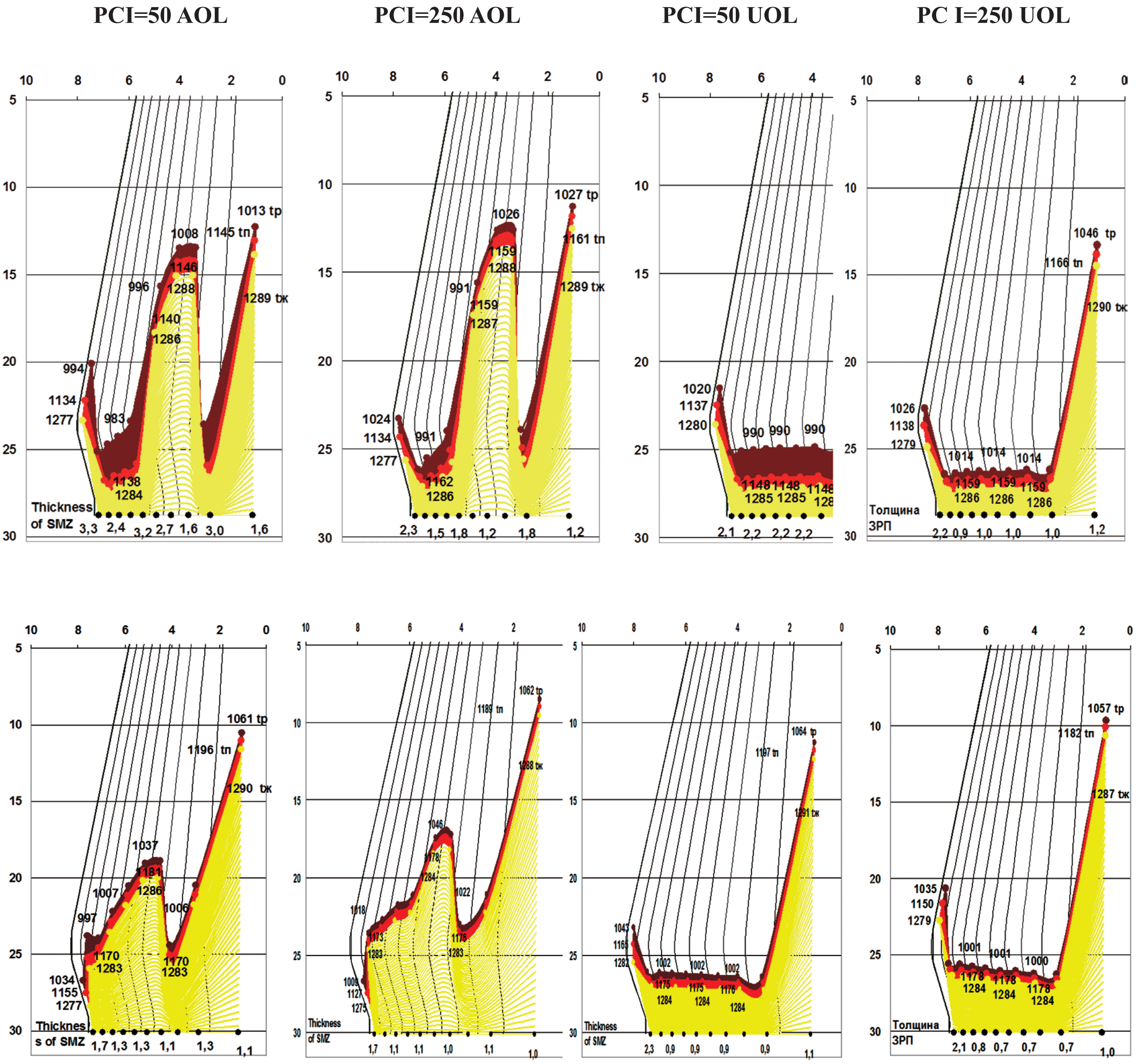


Figure 11

Position of Softening and Melting Zone (SMZ) for Batch Within the Furnace 9 at OAO Arcelor Mittal Krivoi Rog (Upper Row) and Blast Furnace 5 at OAO Severstal' (Lower Row) with Actual and Uniform Ore-load Distributions in the Change Hole, Different Coal-Dust Consumption (50 or 250 kg/t), and 25% Oxygen in the Blast: *ts, tm, tli* (t_p , t_n , $t_{жс}$), Temperatures of the Onset of Softening, Melting, and Complete Liquefaction, °C. The distance from the furnace axis is plotted horizontally, while the distance from the top of the furnace, m, is plotted vertically. Thickness of SMZ, m—Толщина ЗРП, м.

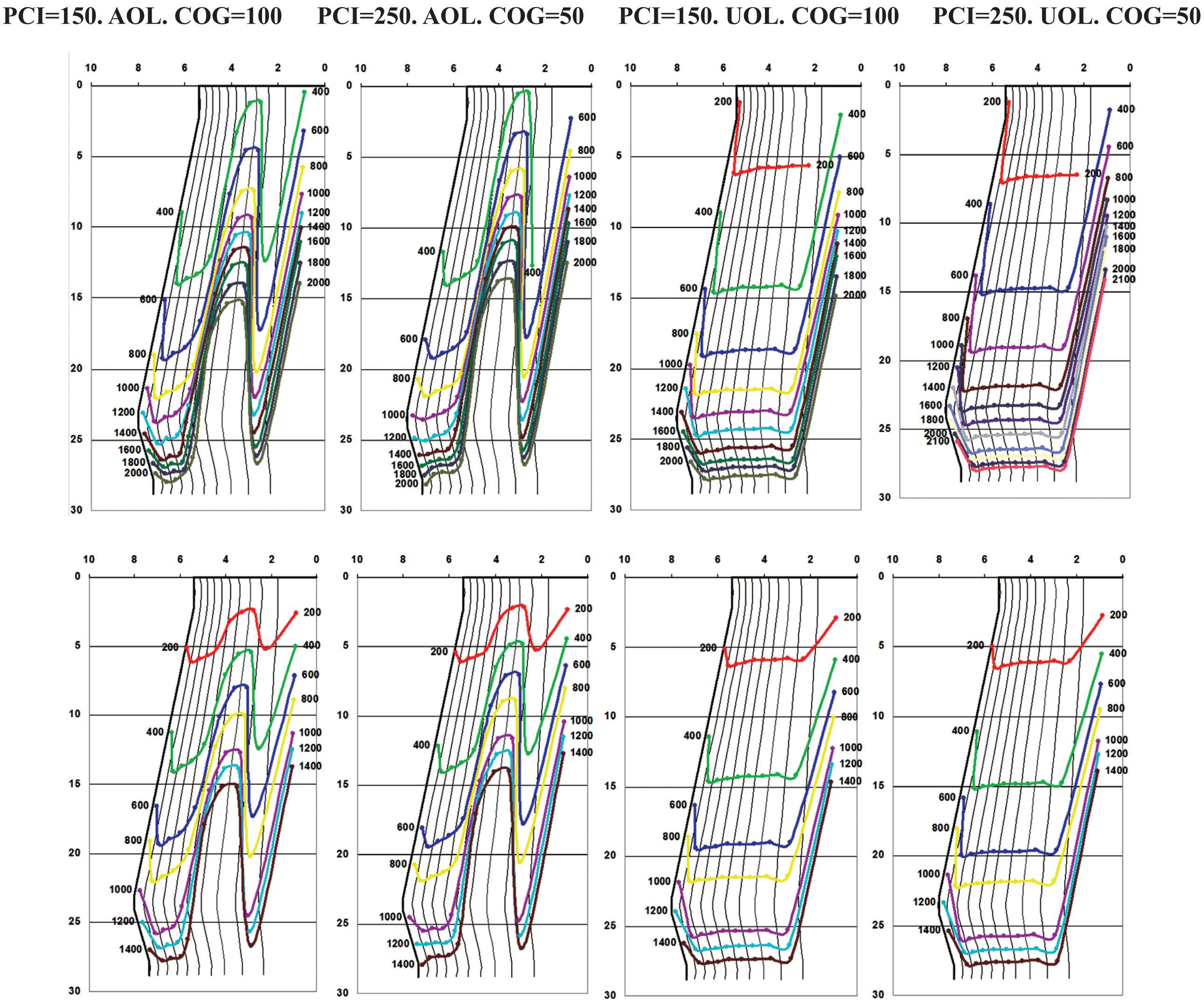


Figure 12
Temperature Distributions of Gas (Upper Row) and Batch (Lower Row) Within Blast Furnace 9 at OAO Arcelor Mittal Krivoi Rog, with Actual and Uniform Ore Load Distributions in the Change Hole, Different Coal Dust Consumption (150 or 250 kg/t), Different Consumption of Coke Oven Gas (150 or 100 m^3/t), and 25% Oxygen in the Blast. The distance from the furnace axis is plotted horizontally, while the distance from the top of the furnace (the technological zero level), m, is plotted vertically.

The temperature field of the batch and the gas flux within the furnaces changes with increase in coal-dust consumption, as in the injection of natural gas and coke-oven gas. However, in the present case, the changes are less pronounced and they do not depend in a simple manner on the furnace conditions and the batch distribution. Thus, with increase in coal-dust consumption, the batch is heated to the specified temperature at lower levels within the furnace (Figure 12). As a result, the softening and melting zone descends somewhat, primarily on account of the softening level. That leads to significant decrease in thickness of the softening and melting zone. At furnace 5, the opposite shift in the temperature field is observed. However, some decrease in thickness of the softening and melting zone is seen. The difference is explained by the different properties of the ore and coke in the blast furnaces. In particular, the kinetic constants of heat transfer and reduction are higher in furnace 5 than in furnace 9; the batch density is also different.

Our analysis shows the possibility of ensuring low coke consumption—286–304 kg/t for furnace 9 and 257-276 kg/t for furnace 5—on account of coal-dust injection at rates up to 250 kg/t and improvement in the ore-load distribution. However, such blast furnace operating conditions cannot be regarded as rational—in particular, in terms of the temperature field, on account of the high theoretical combustion temperature (>2200°C). Especially unfavorable conditions are observed when the coal dust consumption is less than 250 kg/t (theoretical temperature >2300°C).

This problem may best be addressed by the injection of coke-oven gas already produced at the enterprise. Correspondingly, the coke-oven gas used in coke production and in heaters is replaced by blast furnace gas and products of coal gasification (Tovarovski, 1987, p.192).

Calculation results for smelting with the injection of coal-dust fuel and coke-oven gas, as well as experience with coke-oven gas (Tovarovski, 1987, p.192), indicate that this technology is highly efficient and is characterized by an organic relation between the injection of coal dust and coke-oven gas (or another reducing gas). Key considerations here include the following:

- the possibility of organizing a rational temperature field in the furnace, ensuring improved stability of the processes and better heat and mass transfer within the batch column;
- further diminution of the degree of direct reduction, beyond the levels attained in the injection solely of coal dust fuel;
- the presence of 70-75% reducing agents within the coke-oven gas, without the need to organize close contact with the oxidant on introduction in the tuyeres;
- further coke savings due to the injection of coke oven gas (0.38-0.45 kg/ m^3), without limiting the basic savings due to coal dust injection (0.9-1.0 kg/kg).

With coal dust consumption at a rate of 250 kg/t and the addition of coke oven gas at a rate of 50 m^3/t, the coke consumption is lowered by another 20-22 kg/t: to 283-262 kg/t for blast furnace 9 and 257-236 kg/t for blast furnace 5.

This technology is particularly useful in circumstances where coal-dust consumption is constrained for any reason (the lack of the required coal, shortcomings of the equipment, etc.). Thus, when the coal-dust consumption is 150 kg/t, the addition of 100 m^3/t coke-oven gas is expedient in order to optimize the temperature field (Tables 4-7, Figs. 9-12). The coke consumption is lowered to 362–342 kg/t at blast furnace 9 and 323-318 kg/t at blast furnace 5. These values are similar to those for coal dust consumption of 200 kg/t.

To attain the expected results of coal-dust injection in practice, we must improve the metallurgical properties of the coke and the iron ore, as discussed in (Ryzhenkov, Minaev, & Yaroshevskii, et al., 2011; Starovoit, 2010; Yaroshevskii, Afanas'eva, Kuzin, & Mishin, 2010). Solutions exist (Starovoit, 2010). However, whereas there have been successes on a limited scale, large-scale introduction encounters serious constraints—in particular, on account of the shortage of coking coal and coal suitable for the preparation of coal-dust fuel (Starovoit, 2010; Yaroshevskii, et al., 2010). These constraints, which were not noted in the initial expansion of coal-dust injection in Europe and Asia, now affect not only Ukraine and Russia but, as resources are exhausted, metallurgical industries around the globe.

In view of the foregoing, the development of coal-dust injection must be accompanied by the development of alternative coke replacement technologies. Note, in this context, that the idea of coal-dust injection as the only choice for blast furnace production in Ukraine must be regarded as the short sighted perspective of a few enterprises, in the light of growing coal shortages (Ryzhenkov, et al., 2011). This development strategy for blast furnace production requires profound reevaluation, not least because of the following flaws in the arguments against alternative technologies (Ryzhenkov, et al., 2011).

(1) The injection of coke-oven gas was rejected (Ryzhenkov, et al., 2011) on account of lack of supplies (and shortage of the corresponding coal (Starovoit, 2010; Yaroshevskii, et al., 2010)). However, what is relevant here is not the availability of additional reserves of coke-oven gas but rational allotment of the available reserves. In particular, the coke-oven gas required for blast-furnace production may be found if some of the coke-oven gas used in coke production and in the heaters is replaced by blast furnace gas and products of coal gasification (Tovarovskiy, et al., 2007). The production of widely applicable products of coal gasification may be regarded as adequate to cover any emerging fuel shortage.

(2) The replacement of some of the coke by chunk anthracite was rejected in view of the historical switch from anthracite to coke as a blast furnace fuel (Ryzhenkov, et al., 2011). However, this argument ignores the specifics of the proposed technology, in terms of the preparation and charging of anthracite to replace only 10–20% of the coke in the blast furnace, as well as years of successful use of this technology in blast furnaces of size 1143-5000 m^3 at OAO ArcelorMittal Krivoi Rog, OAO Alchevskii Metallurgicheskii Kombinat, ZAO Makeevskii Metallurgicheskii Zavod, and elsewhere (Tovarovskii, Lyalyuk, & Demchuk, et al., 2008).

(3) The effectiveness of the injection of hot reducing gases and products of coal gasification was questioned on the basis of the unfounded assumption of 30-50% losses and the emotional declaration that such losses would diminish the effectiveness of this method by an order of magnitude in relation to coal-dust injection (Ryzhenkov, et al., 2011). The assertion that there are no such losses in coal-dust injection contradicts the finding that considerable losses are implicit in the incomplete gasification of carbon and liquefaction of the coal-dust ash at the tuyeres, as well as the limit on the permissible ash and sulfur content in the coal (Ryzhenkov, et al., 2011).

Thus, if, in today's global marketplace, with growing resource shortages, we were to confine progress in blast furnace production to the expansion of coal-dust injection, we would be leaving many enterprises unprotected in the face of unexpected market changes. In practice, the expansion of coal-dust injection, with corresponding improvement in the metallurgical properties of the coke and the iron ore, must be accompanied by complementary and alternative technologies. This approach is being embraced by a growing circle of specialists, including former opponents (Yaroshevskii, et al., 2010).

One alternative to coal-dust injection is the flexible combination of coal-dust fuel and coke-oven gas (or another reducing gas). Then, in response to a shortage of the coal required for the preparation of coal-dust fuel (for example, in terms of ash content), the rate of coal-dust injection may be lowered from 200-250 kg/t to 100-150 kg/t. To maintain the optimal temperature at the tuyeres and temperature field in the furnace, we must then inject coke-oven gas at rates of 100-150 m^3/t (or equivalent quantities of another reducing gas, such as general purpose products of coal gasification (Tovarovski, 1987, p.192)), so as to obtain coke consumption corresponding to the injection of coal dust fuel at 200 kg/t . Where it is impossible to obtain the required metallurgical properties of coke (for any reason), it is expedient to lower the coal-dust consumption to zero, and to increase the consumption of coke oven gas to 200-250 m^3/t. That approach permits coke savings without loss of blast furnace stability. Some of the coke (50-80 kg/t) may also be replaced by specially prepared chunk anthracite (Tovarovskii, et al., 2008).

The coke consumption may be lowered to 180-200 kg/t of hot metal as a result of replacement by low grade coal, on the basis of a new blast furnace technology with the injection of hot reducing gases and products of coal gasification obtained in special gasification units—either units attached to the tuyeres (within the blast furnace) or separate units close to the blast furnace (Tovarovski, 1987, p.192).

The development of this technology began in 1980-1982 (Tovarovskii, Khomich, & Boyarovskaya, 1982); it continued until 2000. Theoretical interest in this topic is undiminished. However, practical considerations have dampened further progress. Nevertheless, we remain hopeful that development work will intensify as coal resources are steadily depleted, especially in view of the periodic resurgences of research interest and the conversion of former opponents to supporters (Yaroshevskii, et al., 2010). The means to a solution has long been known (Tovarovski, 1987, p.192).

4. WORKING WITH DIFFERENT TEMPERATURE AND THE OXYGEN CONTENT IN THE BLAST

The basic terms are adopted for BF-5 "Severstal". Methodology and initial data of the calculations do not differ from the previous draft of this section.

The objective of this article is to use a systems approach to evaluate how the temperature and oxygen content (%) of the blast affect the smelting indices for a given fixed consumption of natural gas (NG). Previous estimates made on the basis of empirical data and balance calculations (Ramm, 1980, p.304; Tovarovski, 1987, p.192) have mainly connected the initial parameters with the final results (coke consumption, productivity) by using separate intermediate parameters. These investigations did not fully examine all the interrelationships that are intrinsic to the smelting operation and that affect the character of the smelting regimes and the final results.

Based on the analysis of a full complex of the received results the calculation made additional tables that reflect the influence of the processes and indicators of melting temperature changes blast and oxygen content.

Table 8
Gradients of the Decrease in Coke Consumption (ΔC, %/10°), Increase in Productivity (ΔP, %/10°C), and Increase in Direct Reduction (Δ r_d, %/10°) and Certain Influential Factors for an Air Blast and a Blast Containing up to 30% O_2

Indices at 21% O_2	**AOB**					**UOB**				
Temperature, °C:										
Blast	600	800	1000	1200	1400	600	800	1000	1200	1400
Top gas	265	242	217	204	212	84	90	60	75	49
Theoretical combustion temperature, °C	1619	1722	1819	1923	2032	1575	1677	1784	1887	1982
Heat losses, kJ/kg	601	595	583	589	597	599	551	645	592	583
ΔC. %/10°	0.33*	0.40	0.46	0.34	0.28	0.31*	0.38	0.28	0.32	0.38
ΔP, %/10^c	0.28*	0.31	0.33	0.23	0.17	0.24*	0.25	0.18	0.19	0.26
$\Delta r_{\&}$ %/10°	0.10*	0.20	0.07	0.09	0.05	0.06*	0.06	0.14	0.03	0.02
Indices at 30% O_2	AOB					UOB				
Temperature, °C:										
Blast	600	800	1000	1200	1400	600	800	1000	1200	1400
Top gas	312	290	279	260	260	179	163	131	135	133
Theoretical combustion temperature, °C	1950	2034	2123	2210	2304	1905	1993	2081	2170	2259
Heat losses, kJ/kg	591	601	604	607	611	584	591	616	590	583
ΔC, %/10°	0.30*	0.42	0.31	0.31	0.25	0.25*	0.29	0.26	0.28	0.26
ΔP. %/10°	0.22*	0.28	0.20	0.20	0.14	0.17*	0.18	0.17	0.18	0.16
Δr_d, %/10°	0.07*	0.04	0.09	0.07	0.07	0.08*	0.12	0.14	0.03	0.04

Note: Average values in the range 600-1400°C; in the other cases, the results shown are for the range from the previous blast temperature to the current blast temperature.

In each variant, the values of ΔC and ΔP decrease by a factor of 1.5-2 when T_b increases; the higher values of AC are for the air-blast variant with NG = 100 m^3/ton (average of 0.33%/10°), while the lower values are for the blast variant with $[O_2]$ = 30% and NG = 100 m^3/ton (average of 0.25%/10°). The factors responsible for the increases in coke consumption and furnace productivity that accompany an increase in T_b are a rise in the amount of direct reduction r_d (average of 0.10-0.07%/10°). slowing of the drop in top-gas temperature t_t , and a decrease in smelting rate based on the gas flow. The region of minimal top-gas temperatures (, typically corresponds to the range of theoretical combustion temperatures T_c from 2000 to 2200°C for different variants.

Introduction of the charge in such a way as to obtain a uniform ore burden (UOB) results in a lower average coke consumption and greater use of the thermal and chemical energy of the gases. However, since the heat approaches the limiting thermo-chemical conditions in this case, the average decrease in coke consumption and average increase in productivity due to heating of the blast are 10-20% smaller (in relative terms) than for the AOB (see Table 8).

Comparison of the efficiency with which the blast is heated for different variants of the technology shows that heating efficiency invariably declines in the absence of natural gas. This decrease is due not only to the factors mentioned above, but also to the fact that some of the variants exceed the operating range of the equipment as a result of distortions of the temperature field of the furnace caused by the high temperatures of the gases near the tuyeres. In this case, the most effective variant is to inject coke-oven gas (Tovarovskiy, 2009, p.768).

The below data sample shows the effect of enriching the blast with oxygen on coke consumption and furnace productivity for different blast temperatures (AOB variant):

Blast temperature, °C	**600**		**800**		**1000**		**1200**		**1400**	
Oxygen in the blast, %	21	30	21	30	21	30	21	30	21	30
Unit productivity, tons/(m^3 ·day)	1.429	1.629	1.517	1.720	1.618	1.788	1.692	1.859	1.749	1.912
Consumption of lump fuel, kg/ton	529	563	486	516	441	484	412	453	389	430
Top-gas temperature, °C	265	312	242	290	217	279	204	260	212	260
Theoretical combustion temperature, °C	1619	1950	1722	2034	1819	2123	1923	2210	2032	2304
Direct reduction of Fe, %	22.8	22.0	26.8	22.8	28.1	24.6	29.9	25.9	30.9	27.2
Heat losses, kJ/kg	601	591	595	601	583	604	589	607	597	611
Gas-based smelting rate, m^3/(m^3-min)	2.488	2.387	2.404	2.31	2.319	2.254	2.249	2.2	2.185	2.14
Excess coke consumption, %/%	-	0.73	-	0.69		1.07	-	1.11		1.12
Increase in productivity, %/%	-	1.56	-	1.49	-	1.17	-	1.10	-	1.04

Coke consumption increases 0.7-1.1%/% when oxygen is added to the blast; it was shown previously (Tovarovskii, Lyalyuk, Merkulov, & Kassim, 2011) that coke composition increases here because of the decrease wind rate and the associated decrease in the amount of heat introduced into the furnace by the blast, there also being a small decrease in direct reduction and a moderate rise in top-gas temperature. The amount of excess coke consumed increases as blast temperature increases and helps slow the increase in furnace productivity. The increase in productivity is 1.5-2%/% at low blast temperatures, but it decreases by a factor of 1.5-2 with a rise in the temperature and oxygen content of the blast.

To analyze the course of processes taking place inside the furnace, we have determined the numerical values of the heat-transfer rate (deg/m height): heating of the charge materials (RHM) and the rate of cooling of the gases (RCG) in vertical temperature zones VTZ 1-6 and VTZ 7-12.

Variants			**RHM., deg/m height**		**RCG., deg/m height**	
T_b, °c	**$[O_2]$, %**	**OB**	**VTZ 1-6**	**VTZ 7-12**	**VTZ 1-6**	**VTZ 7-12**
600	21	AOB	79.2	188.3	64.5	167.4
1400	21	AOB	79.1	241.0	75.7	268.1
600	30	AOB	83.0	160.8	69.6	171.9
1400	30	AOB	86.9	233.9	89.5	312.3
1400	30	UOB	73.3	275.6	79.9	399.1

It follows from the above data that for the AOB variant the average RHM remains basically unchanged in VTZ 1-6 as the value of 7”$_b$ increases. The average RHM remains roughly the same in this case despite the fact that the RCG in the same zones increases by 10-15% rel.%. In lower vertical temperature zones 7-12, RHM increases appreciably (by 30-45 rel.%) while RCG increases by 60-80%. With a changeover to UOB, RHM decreases in higher VTZ 1-6 but increases by -20 rel.% in lower VTZ 7-12. Here, RCG increases by -28 rel.% in the lower VTZ.

The above features of heat transfer are in large part due to the gas distribution over the radius of the furnace and changes in the direction of the gas flow at different levels. Studies performed for blast furnace No. 9 at the Arselor-Mittal Krivoy Rog plant (Tovarovskii, et al., 2011) showed that within the lower VTZ 8-12 more gas (by mass) passes through the more permeable radial annular zones (RAZ) with a low ore burden than through the less permeable RAZ with a high burden. During heat transfer inside the stock, the gas in the more permeable and less heavily loaded RAZ undergoes less cooling than in the RAZ with a high ore burden and ends up with a higher teniperature than in the latter zones. Accordingly, the volume of the gas in the lightly loaded RAZ is also greater than in the heavily loaded RAZ, and this difference stimulates the flow of gas from the former into the latter through layers of coke—which are more permeable than layers of ore (by a factor of 5-6, and sometimes by an order of magnitude). As a result, inside the higher VTZ 1-6 the mass of gas increases in the heavily loaded RAZ and decreases in the lightly loaded RAZ. This “make-up” with gas moving out of the low-permeability RAZ through layers of coke helps improve heat transfer in the higher VTZ as a whole and partially compensates for the poor heat transfer caused by the nonuniform distribution of the charge materials.

The pattern described above is characteristic of all furnace operating regimes but is manifest to different extents. In the case of an oxygen-enriched blast, the rate of movement of gas as described above decreases with an increase in the oxygen content of the blast (Tovarovskiy, 2009, p.768) but does not decrease with an increase in T_b. This helps keep heat-transfer rate in the low-temperature and medium-temperature zones at a level sufficient to keep top-gas temperature slightly higher than the lowest value it reaches when blast temperatures correspond to the temperature field that exists in the furnace (as a whole) with theoretical combustion temperatures of 2000-2200°C in the tuyere region.

It is shown that with increasing temperature of the blast in the lower part of the furnace appear an additional high-temperature isotherms of gas, and moving isotherms occurs in dependence on the permeability: isotherms burden and gas heavily loaded low-permeability the RAZ moved down, enlarging the area of moderate temperatures in the shaft and isotherms low-loaded high permeability RAZ move up to that contributes slowed to reduce the temperature of the furnace gas. The temperature difference between the gas and the charge rises the bottom in all RAZ and top—low-loaded RAZ, and reduced—heavily-loaded RAZ top. Application of UOB leads to the displacement of all isotherms burden-and-gas down with the increase of moderate temperature in the shaft. The specified character move isotherms is inherent in both the considered variants (on the atmospheric and enrichment-щенном oxygen blast), but in the variant of enriched with oxygen up to 30% of blast the high temperature isotherms are higher than in the case of atmospheric blast, and most of the values of differences of temperatures of gas and charge increase and move up the higher temperature furnace gas in the first case.

The results reported here and the relationships that were discovered can be used to select efficient regimes for smelting in blast furnaces.

CONCLUSIONS

By using the mathematical model to study the influence of blast-furnace parameters on the final results (coke consumption, productivity) we may not only refine the quantitative relations between the parameters and the results, but also identify the internal relations between the furnace processes that affect the smelting conditions and the final results.

The main factor responsible for the decrease in coke consumption with increase in the consumption of natural gas and coke oven gas is that much less heat is consumed in the direct reduction of iron. We also find that the coke consumption is significantly influenced by the heat and mass transfer, the phase transformations, the gas mechanics, and the distribution of materials and gases in the furnace, thanks to various direct and inverse relationships with the coke consumption.

Thus, with increase in natural-gas consumption, the heat consumption in the direct reduction of iron falls, and the specific heat ratio of the batch and gas declines; likewise, the heat transfer rate in the lower zone declines, with increase in the rate in the upper zone. Consequently, the height of the lower stage of heat transfer is increased, while the height of the upper stage shrinks. As a result, the gas and batch isotherms move upward, the losses through the charge hole increase, and the softening and melting zones lie above the basic level and are thicker. The overall heat losses are less with lower gas temperature in the lower zone.

Under the action of these factors, which are disregarded in balance calculations, the variation in the differential equivalent of coke replacement with increase in natural gas consumption is not so smooth. Up to 100 m^3/t, the decline is uniform: by 0.1%/m^3 from the initial value of 1.0–0.9 kg/m^3. With further increase in the natural gas consumption, the temperature of the blast-furnace gas rises sharply in the zone where rd < 20%. Correspondingly, the differential equivalent of coke replacement falls by a factor of 1.5–4. With a more uniform ore-load distribution in radial annular zones 2–9, the drop in the differential equivalent of coke replacement at natural gas consumption above 100 m^3/t is less severe, with corresponding increase in the efficiency.

The influence of coke-oven gas is analogous when the supply ratio of the coke-oven gas and natural gas is 1 : 2. We recommend the use of these findings to optimize blast furnace smelting, with the determination of the rational consumption of natural gas and coke-oven gas.

By simulating the influence of coal-dust consumption on the blast furnace process we find that the main factor responsible for coke conservation with increase in coal-dust consumption is replacement of the heat of combustion of coke by the heat of combustion of coal-dust. This factor is responsible for more than 80% of the drop in coke consumption and does not greatly depend on the smelting conditions, including the coal-dust consumption. The second factor in coke conservation is the minimization of direct reduction. This factor is different for the two furnaces considered and depends on the reduction conditions. For all values of the coal-dust consumption, the differential equivalent of coke substitution is close to the mean in the range 0–250 kg/t of hot metal: 1.0 and 0.9 kg/kg for blast furnace 9 at OAO ArcelorMittal Krivoi Rog and blast furnace 5 at OAO Severstal', respectively.

The temperature field of the batch and the gas flux within the furnaces changes with increase in coal-dust consumption, as in the injection of natural gas and coke-oven gas. However, in the present case, the changes are less pronounced and they do not depend in a simple manner on the furnace conditions and the batch distribution. The thickness of the softening and melting zone is diminished, along with the heat losses.

Our analysis shows that the expansion of coal-dust injection, with corresponding improvement in the metallurgical properties of the coke and the iron ore, must be accompanied by complementary and alternative technologies. One alternative to coal-dust injection is to use a flexible combination of coal-dust fuel and coke-oven gas. Then, in response to a shortage of the coal required for the preparation of coal-dust fuel, it is expedient to lower the coal-dust consumption to zero, with consequent drop in coke consumption. Some part of coke (50–80 kg/t) may also be replaced by specially prepared chunk anthracite.

Study the effect of blast temperature (T_b) on smelting indices has established that for the actual distribution of the ore-burden (AOB) an increase in T_b is accompanied by a decrease in coke consumption ΔC and an increase in furnace productivity ΔP. The values of ΔC and ΔP uniformly decrease by a factor of 1.5-2 with an increase in T_b: larger values of ΔC are seen in the air-blast variant with NG = 100 m^3/ton (0.46-0.28%/10°), while smaller values are obtained in the variant having a blast with 30% O_2 and NG = 100 m^3 /ton (0.42-0.25%/10°). Coke consumption increases 0.7-1.1%/% with oxygen enrichment of the blast because of the decrease in wind rate and the associated decrease in the amount of heat introduced into the furnace by the blast, also some increase in temperature of furnace gas.

The value of the over consumption of coke from the enrichment of blast oxygen who melts increase of the temperature of air and helps to reduce the growth of productivity are concerned furnace from 1.5 to 2%/% at low temperatures blast up to 1%/% increase in pace temperature up to 1200-1400 C and concentration of oxygen in the blast 30%.

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.

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