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IMPROVING THE TECHNOLOGY OF PREPARING COAL FOR THE PRODUCTION OF BLAST-FURNACE COKE UNDER THE CONDITIONS OF MULTI-BASIN RAW MATERIAL BASE. MESSAGE 3. INFLUENCE OF THE MOISTURE CONTENT OF COAL BATCH ON THE PHYSICOMECHANICAL CHARACTERISTICS OF THE COKE

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Abstract

The packing density of the coal batch influence on the physicomechanical characteristics of the coke produced: the strength M_{25} and wear resistance M_{10}. In the absence of mechanical methods (such as ramming or partial briquetting), the packing density depends on the ash and moisture content and the degree of crushing of the coal batch. Since improvement in coke quality entails decreasing the moisture content of the coal batch, we developed a method for decreasing the moisture content directly in the silo, on the basis of osmosis and vacuum. That permits a decrease in the coal's moisture content to the optimal value, thereby boosting coke quality and improving blast-furnace performance.

Keywords*: ramming technology; bed coking; coal batch; packing density; coke quality; moisture removal.*

1. Introduction

The most important means of improving blast-furnace performance is to supply high-quality batch—in particular, high-quality coke.

In the blast furnace, coke plays a complex role. Its transformation at the tuyeres provides most of the heat required for smelting and also forms most of the reducing gas, to which gas from direct reduction is added at higher levels. Besides these functions, the coke serves as solid packing in the zone characterized by softening and melting of the iron-bearing materials: in so doing, it ensures a counterflow of batch and gas in the furnace. The coke also regulates the gas distribution over the furnace cross-section. Accordingly, coke must satisfy strict requirements.

Coke quality may be assessed in terms of physical characteristics, (strength, susceptibility to wear, and granulometric composition), chemical composition, reactivity, and post reactive strength. In terms of chemical composition, we require coke with maximum carbon content and minimum ash and sulfur content. In terms of granulometric (fractional) composition, the coke must be of uniform size, with a minimum content of the smallest (<25 mm) and largest (>80 mm) classes. High hot and cold strength is necessary.

Typical requirements were laid out at the Fifth International Congress of Blast-Furnace Specialists [1]: strength M_{25} no less than 90%; susceptibility to wear M_{10} no more than 6%; content of the >80 mm class no more than 5%; content of the <25 mm class no more than 5%; fluctuations of the moisture content no more than ±0.5%; reactivity CRI = 23—26%; and post reactive strength CSR = 70%.

Under specific conditions, classical bed coking may produce blast-furnace coke of strength M_{25} = 90% and wear susceptibility M_{10} = 6.0%. Ukrainian coke plants with M_{25} > 88.0% between 2009 and 2011 included ChAO Makeevkoks (with annual figures of 89.6, 89.1, and 88.4%), which supplies premium coke, and PAT Avdeevskii KKhZ (with annual figures of 88.5, 88.1, and 88.7%). All the other coke plants met this standard in some years but produced coke with M_{25} < 88% in other years. The coke of lowest strength was produced by PAT ArcelorMittal Krivoi Rog (with annual figures of 84.4, 83.4, and 86.6%).

In the same period, coke with M_{10} < 7% was produced at ChAO Makeevkoks (with annual figures of 7.0, 6.6, and 6.8%) and ChAO Enakievskii KKhZ (with annual figures of 7.0, 7.0, and 6.8%). These figures are considerably lower for coke from PAT Alchevskkoks (6.3, 6.4, and 5.4%); the lowest values (5.5, 5.8, and 4.1%) are observed for coke from battery 10A, which employs ramming of the coal batch and dry slaking of the coke [2].

Coke is supplied to the batch-supply bunker for blast-furnace shop 1 from coke batteries 1-4 at PAO ArcelorMittal Krivoy Rog (Table 1). This coke is produced by classical bed coking, with batch supply through charging hatches. Therefore, it remains to improve batch preparation for those blast furnaces.

Table 1. Weighted-mean characteristics of coke supplied to the blast furnaces of shop 1

Year	Characteristic, %							Content of class (mm), %	
	W	A	S	M_{25}	M_{10}	CSR	CRI	>80	<25
2015	3,9	12,0	0,72	86,8	7,4	50,3	36,1	8,9	5,2
2016	3,8	11,5	0,60	86,5	7,8	52,4	35,2	7,4	6,4
2017	3,9	11,5	0,54	85,3	7,6	48,9	38,0	6,5	7,0

In classical coking, the rank composition and properties of the coal batch mainly determine the physico-mechanical characteristics of the coke produced, while the key factor in batch preparation for coking is the packing density of the batch. In the absence of mechanical methods (such as ramming or partial briquetting), the packing density mainly depends on the ash and moisture content and the degree of crushing of the batch. These factors, in turn, affect the thermal conditions of coking, the physico-mechanical characteristics of the coke produced, and the yield and quality of the coking products [3].

One means of improving coke quality is to increase the packing density of the coal batch before supply to the coke oven.

2. Results and discussions

The factors responsible for the poor quality of the coke produced in batteries 1-4 at PAO ArcelorMittal Krivoy Rog were analyzed in detail in [4]. Primary factors include the high moisture content of the coal batch; insufficient mixing after crushing when numerous coal concentrates are employed; and excessive crushing of batch with a high content (70-80%) of bituminous coal [5].

To investigate the influence of the granulometric composition, ash content, and moisture content of the coal batch on its packing density in the coal-preparation shop for coke production at PAO ArcelorMittal Krivoy Rog, we select samples of coal concentrates for technical analysis and also for the determination of the packing density and granulometric composition.

Table 2 presents the characteristics of these concentrates.

In Fig. 1, we plot the packing density of the coal batch supplied to coke batteries 1—4 as a function of its moisture content. The curve is parabolic, with a minimum at a moisture content of 10.3%. However, the increase in packing density is not due to a decrease in the moisture content of the batch but rather to increase in moisture content. In other words, the packing density increases as a result of an increase in the mass of water in the coal batch.

In physical terms, the influence of the moisture content on the packing density of the coal was analyzed in [6]. In the wetting of coal, the water absorbed by its particles is uniformly distributed over their surfaces, with an increase in the distance between coal particles by the thickness of the water film. That changes the packing density of the coal. With further wetting, corresponding to the minimum of the parabola, the packing density increases more sharply. This may be explained in that the free water in the batch tends to occupy the volu-me with the minimum surface under the action of capillary forces and is concentrated in narrower intervals between the coal particles, predominantly at points of particle contact.

Table 2. Characteristics of the coal concentrates used in the batch

Supplier	Rank of coal	Moisture content W^r_t, %	Content (%) in class (mm)					Packing density, t/m³
			>6	3-6	0.5-3.0	<0.5	<3	
T34, Poland	G	9.1	38.29	15.99	32.69	13.03	45.72	0.859
Coking Coal Pardee, United States	GZh	11.0	42.65	13.76	22.24	21.35	43.59	0.870
Ukrkoks. Ukraine	Zh	14.4	12.48	13.33	41.05	33.14	74.19	0.859
Kievskaya enrichment facility, Ukraine	Zh	12.0	2.86	5.98	49.81	41.35	91.16	0.832
Krasnolimanskaya enrichment facility, Ukraine	Zh	10.5	40.56	19.74	23.10	16.60	39.70	0.871
Pechorskaya enrichment facility, Russia	2Zh	10.5	29.48	14.56	25.10	30.86	55.96	0.841
Vostochnaya enrichment facility, Kazakhstan	K + KZh	12.6	6.68	9.52	40.40	43.40	83.80	0.801
Severnaya enrichment facility, Russia	K	12.7	19.95	15.24	32.32	32.49	64.81	0.847
Ukrkoks, Ukraine	K	19.8	12.15	18.60	40.08	29.17	69.25	0.914
Alpha, United States	K	14.4	6.25	14.70	44.95	34.10	79.10	0.890
Eagle, Canada	K	12.1	14.05	12.81	34.62	38.52	73.14	0.831
Severnaya enrichment facility, Russia	K + KO + PS	17.2	14.08	12.93	34.37	38.62	72.99	0.927

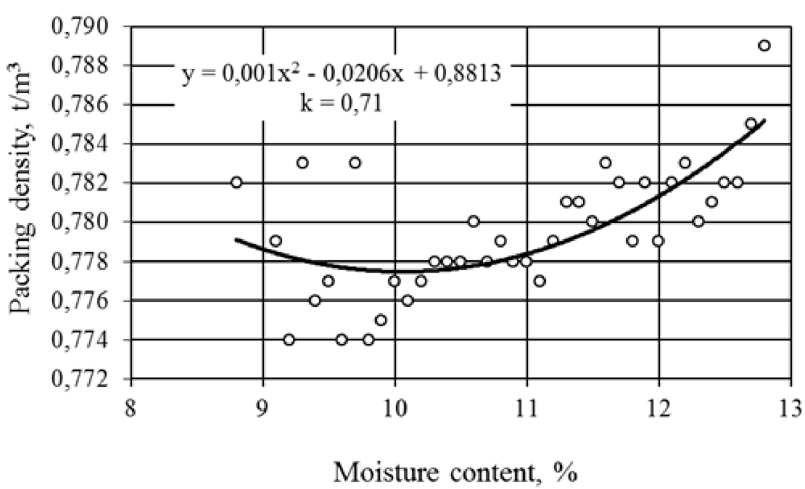


Fig. 1. Influence of the moisture content on the packing density of the coal batch (coke batteries 1—4)

The surface tension of the water around those points tends to retain the particles in place, preventing their free motion and results in denser packing on charging in the furnace chamber. This behavior is observed with an increase in the moisture content to 6— 10%. With the further increase, the capillary forces cannot retain the moisture at the contact points. Under the action of the gravitational forces, the water breaks away from the meniscus and moves into the gaps between the particles. From that point onward, the packing density of the coal batch increases on account of an increase in the water mass [6].

The moisture content of the coal batch also considerable affects the expansion pressure and the shrinkage of the coke cake. The final shrinkage of the coke cake is between 230 and 165% for a batch of moisture content between 8.1 and 14.5%.

The variation in packing density in the given period when water evaporates in the coke oven is also of interest. Recalculated for dry mass, the packing density of the coal batch (Fig. 1) is considerably less than the initial value, as indicated by Fig. 2. With an increase in the initial moisture content, we note a greater decrease in the packing density of the coal batch when the moisture evaporates in the coke oven of the battery. This will necessarily affect coke quality.

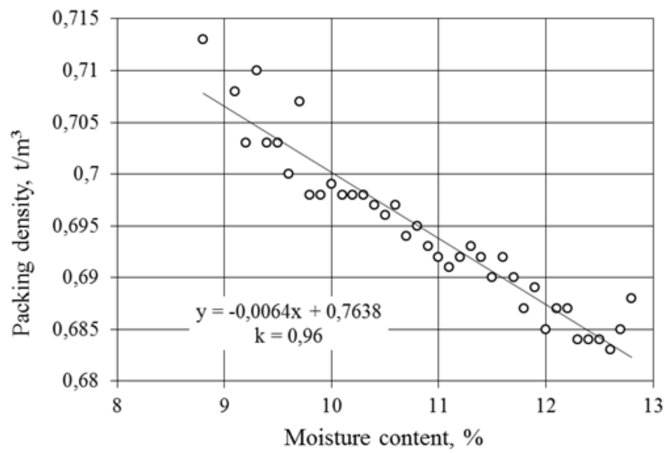


Fig.2. Influence of the moisture content on the packing density of coal batch (coke batteries 1–4), after recalculation for dry mass

It is evident from Figs. 1 and 2 that, when the mean moisture content of the coal batch is 11.2%, its mean packing density is 0.780 t/m^3. In the coke oven after evaporation of the moisture, it falls to 0.690 t/m^3 (by 11.5%).

To determine the packing density of the batch on drying (with determination of the moisture content on the basis of State Standard GOST 11041—81), we use batch of the following rank composition: 28% Zh, 41 % K, 8% K + KO+ OS, and 23% K + KO + KZh.

The granulometric composition of the batch (after crushing) is as follows (%):

>6 mm	6—3 mm	3—0.5 mm	<0.5 mm	<3 mm
1.9	8.1	42.9	47.1	90

Note that, in a batch sample containing 90% of the <3 mm class, the content of the <0.5 mm class, which impairs clinkering, is 47.1%.

In Fig. 3, we plot the dependence of the batch's packing density on its moisture content in a drying chamber. As we see, on drying coal batch with initial moisture content 11.43% and packing density 0.760 t/m^3, with a decrease in moisture content to 7.33%, its packing density increases to 0.819 t/m^3 (by 7.8%). Further drying to 5% increases the packing density of the coal batch to 0.847 t/m^3.

We also are interested in the dynamics of drying (by the method in State Standard GOST 11014—81). We find that 1g of a batch of initial moisture content 14% may be dried to 6% in 2 min; to 4% in 4 min; and to 2.4% in 8 min.

According to extensive literature data, the drying of coal batch decreases the heat consumption in coking by 15—20%; increases coke-oven productivity by 30—40%; permits increase in the content of poorly clinkering coal in the batch to 70%, without loss of coke quality (according to tests in the United States, Japan, Britain, France, Germany, and elsewhere); increases coke-plant profits by 50%; improves coke quality without change in batch composition (2.2— 2.27% increase in M_{25} and 0.8—1.4% decrease in M_{10}).

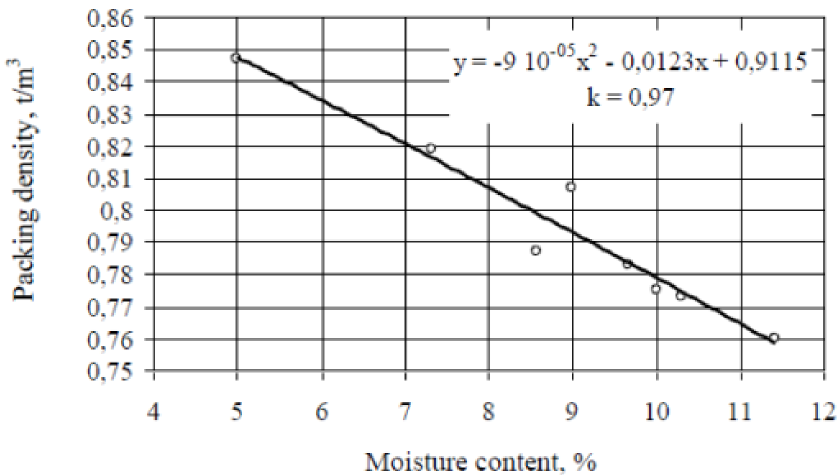


Fig. 3. Influence of the moisture content on the packing density of coal batch in a drying chamber

We also studied the influence of the content of the 0-3 mm and 0-0.5 mm classes on the packing density of the coal batch. Analyses of the results show that with a mean moisture content of 11.2%, greater crushing results in lower packing density; note the high content of 0-0.5 mm class in the batch (44—50%) and the decrease in packing density of the batch with an increase in its content.

In Fig. 4, we show the influence of the ash content on the packing density of the coal batch supplied to coke batteries 1—4 at PAO ArcelorMittal Krivoy Rog. With the increase in ash content, the packing density of the coal batch increases, because the actual density of the coal's mineral component is considerably greater than that of its organic mass. For example, the actual density of the organic mass of Donetsk Basin coal is1.16—1.39 t/m^3, depending on its metamorphic stage, while the actual density of the mineral component is more than 1.8 t/m^3 [7]. Note also that the mineral inclusions are centers of internal stress: they weaken the coke structure.

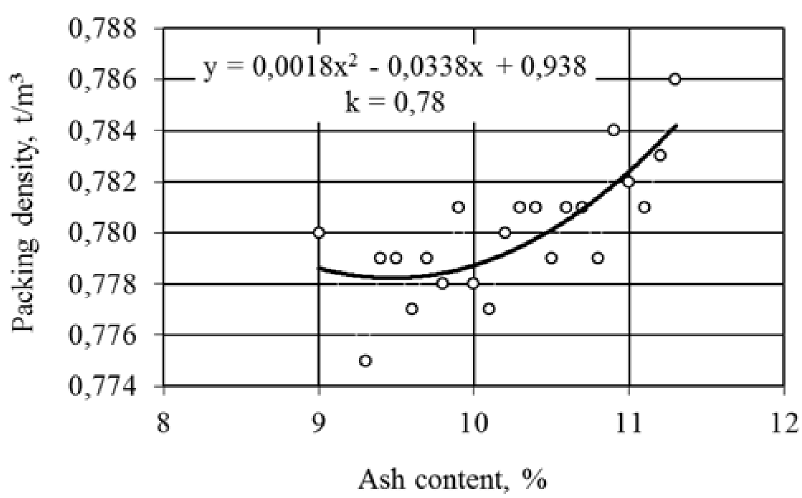


Fig. 4. Influence of the ash content on the packing density of coal batch

Analysis of the characteristics of the coal concentrates used in coking batch shows that, for the foreseeable future, the batch will contain 25—30% Karaganda Basin coal, as well as concentrates from Ukraine and Russia and other imported coal. That results in 1% increase in the mean ash content of the batch and at least 12% increase in the ash content of the coke produced [8].

To assess the aggregate effect of the moisture content, ash content, and granulometric composition (the content of the 0-3 mm and 0-0.5 mm classes) on the packing density of the coal batch, we select batch samples of the following rank composition: 10.8% G, 67.1% Zh, 14% K, 5.5% OS, and 2.6% of other ranks. Table 3 presents the characteristics of the batch samples.

Table 3. Characteristics of coal-batch samples

Sample	Packing density BD^r, t/m^3	Moisture content W^r, %	Ash content A^d, %	Content (%) of class <3 mm	Content (%) of class <0,5 mm
1	0,779	10,3	9,4	87,6	46,9
2	0,779	9,5	9,4	87,56	46,5
3	0,782	9,1	9,3	87,2	45,9
4	0,783	9	9,5	87,3	46
5	0,786	8,3	9,7	86,9	45,6
6	0,788	7,5	9,5	87,0	45,5
7	0,787	7,8	9,6	87,5	46,1
8	0,79	7,7	9,5	85,6	42,9
9	0,795	7,7	9,8	83,0	40,6
10	0,797	8,2	9,8	82,4	40,6
11	0,812	7,8	9,2	80,6	39,0
12	0,805	7,3	9,2	82,5	39,3
13	0,803	7,3	9,6	82,1	39,0
14	0,804	7,9	9,7	82,2	39,7
15	0,803	7,2	10	82,9	41,5
16	0,798	7,5	9,4	84,0	43,2
17	0,798	7,7	9,7	84,3	44
18	0,796	9	9,4	84,7	43,4
19	0,794	9,3	9,8	84,8	42,7
20	0,797	9,3	9,6	84,7	42,6

On the basis of correlation analysis, we obtain the pair correlation coefficients in Table 4. Their values indicate a close relation of the moisture content and granulometric composition of the batch with its packing density. The corresponding regression equation is as follows

$$BD^r = 1.16 - 0.00174W_t^r + 0.000553\gamma(< 0{,}5mm) - 0.00423\gamma(< 3mm) - 0.00274A^d \qquad (1)$$

Table 4. Pair-correlation coefficients

Parameter	Pair-correlation coefficients			
	W_t^r	A^d	$< 3\ mm$	$< 0.5\ mm$
Packing density BD^r of batch, t/m^3	-0,63	0,098	-0,95	-0,914

For this equation, the determination coefficient D = 92% and the correlation coefficient r = 0.96. That indicates its statistical significance.

In Figs. 5 and 6, we show the influence of the packing density on the physicomechanical characteristics of the coke produced: the strength M_{25} and wear resistance M_{10}.

On the basis of industrial tests and multifactorial correlation analysis, we may write the following regression equations for M_{25} and M_{10} as a function of the batch's packing density BD^r

$M_{25} = -32.9939 + 149.4599 \cdot BD^r$ with D = 72.4 %, r = 0.85; (2)

$M_{10} = 44.46453 - 46.067 \cdot BD^r$ with D = 65 %, r = 0.81. (3)

The moisture content of the coal batch significantly affects the processes in the coking chamber and the coke quality, according to research at OAO Zapadno-Sibirskii Metallkurgciheskii Kombinat [9]. The influence of the initial moisture content on the physicomechanical properties of the coke may be attributed both to change in the heat-transfer conditions within the batch over the height of the coke cake at different stages of coking and to some impairment of coke quality on account of the temperature drop due to the heat consumption in removing the extra moisture. Experimental coking of coal batch with different rank composition and moisture content reveals significant changes in the cake conditions and hence in coke strength. Increasing the moisture content from 7.3 to 12.6% increases M_{10} from 8.6 to 10.2% and increases the content of the >80 mm class from 29.9 to 49.9%.

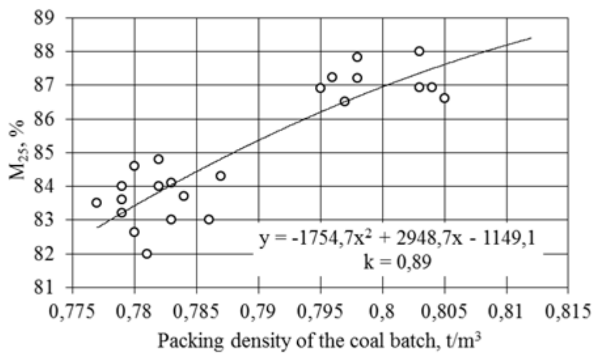


Fig. 5. Dependence of the coke strength M_{25} on the packing density of the coal batch

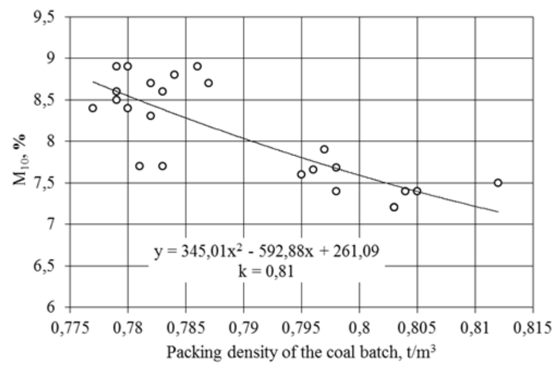
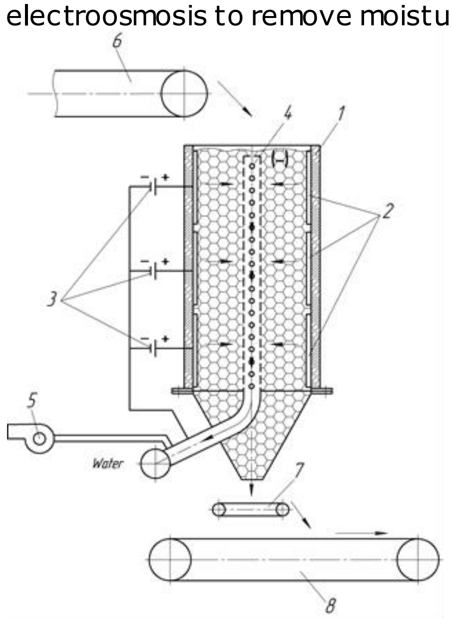


Fig. 6. Dependence of the wear resistance M_{10} on the packing density of the coal batch

Experiments at Yasinovsk coke plant with six different moisture contents of the batch also show that the coke quality declines with an increase in moisture content. Increase in moisture content from 8.1 to 14.7% reduces M_{40} from 75.8 to 73.5% and increases M_{10} from 6.7 to 8.9%. Even a small change in moisture content of the batch considerably changes the physicomechanical properties of the coke [10].

In improving the physicomechanical characteristics of coke, it is important to decrease the moisture content of the coal batch. Therefore, we need to develop a method of decreasing the moisture content directly in the silos of the coal-preparation shop.

Electroosmosis—the process in which liquid moves through capillaries or porous media under the action of an external electric field—is widely used to remove excess moisture from the soil in road and dam building, to dry peat, and also to purify water and industrial fluids. The use of electroosmosis to remove moisture from coal in storage silos is of interest [11].



To that end (Fig. 7), a row of electrodes 2 (annular plates) connected to the positive pole of current sources 3 is positioned at the internal surface of silo wall l. In the central part of the silo, the water drain is perforated pipe 4 connected to the negative pole of sources 3. The voltage applied to annular plates 2 from sources 3 increases from the upper to the lower plates—for example, from 12 to 24 V. The number of current sources is equal to the number of annular plates.

Fig. 7. Silo in enclosed coal store:
1) silo wall; 2) electrodes (annular plates); 3) current sources; 4) perforated pipe; 5) vacuum pump; 6) conveyer belt; 7) dosing feeder; 8) output conveyer

The vacuum pump 5 creates a low-pressure zone so as to accelerate the motion of the moisture from the coal at the silo wall 1 to the center and its extraction through perforated pipe 4. Coal is charged in the silo by means of conveyor 6. Coal is discharged from the silo onto conveyor 8 by means of dosing feeder 7 in accordance with its rank composition, so as to obtain batch for coking.

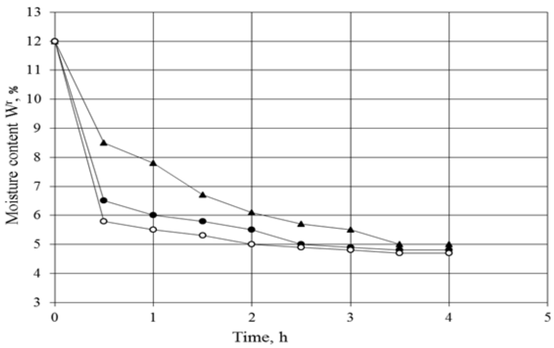


Fig. 8. Variation in coal's moisture content at pressures of 3.5 (∆), 5 (•), and 7.5 (o) mm Hg

In Fig. 8, we show the experimental time dependence of the coal's moisture content when using osmosis in a laboratory system (height 1 m, diameter 4 m), with a voltage of1.5 V at the plates, at an internal pressure of 3.5-7.5 mm Hg. We see that, at any pressure, the loss of moisture is greatest within the first hour: after 0.5 h at 7.5 mm Hg. Thus, the laboratory tests show that electroosmosis permits a decrease in moisture content of the coal to the optimal value for coking batch. That will increase the strength of the coke and decrease its consumption in the blast furnace while improving blast-furnace performance. Thus, we have established that in the blast-furnace shops at PAO ArcelorMittal Krivoy Rog, 1% decrease in M_{10} lowers the mean coke consumption by 5.5%. With the increase in M_{25} by 1%, the mean coke consumption falls by 2.1%, on average.

3. Conclusions

Thus, the high moisture content of the batch and its significant variability has the primary influence on coke quality. The moisture content of the batch supplied to coal-preparation shops at coke plants must be no more than 6—7%. Otherwise, the plant must take measures to dry the coal. At present, in accordance with the relevant technical specifications, PAT ArcelorMittal Krivoi Rog accepts coal concentrates whose moisture content is up to 13%, with consequent loss of coke quality.

Symbols

W^r_t	*water content of the coal batch (or coke), %;*
A^d	*ash content of the coal batch (or coke) in the dry state, %;*
S_t^d	*sulphur of the coal batch (or coke) in the dry state, %;*
BD^r	*packing density of the coal batch, t/m³*
M_{10}, M_{25}	*indices of resistance of coke abrasion and crushability, respectively, %;*
>80, <25	*content of particles more and less 80 and 25 mm in coke accordingly, %;*
CRI, CSR	*coke reactivity index and coke strength after reaction, %*

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