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NUMERICAL ANALYSIS AND DESIGN OF AN EFFICIENT SYSTEM OF UNLOADING OF LIME FROM A SHAFT BURNING FURNACE

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We consider principle of operation and a procedure of evaluation of the constructive, energy, and force parameters of the drive of a new system of unloading of a shaft lime-gas furnace. The proposed method enables us to determine the power of the electromechanical drive of the system with the rational number of knives-scrapers required to guarantee the desired productivity of a vertical-type furnace with the maximum possible uniformity of the unloading of burnt lime over the perimeter of a moving hearth with regard for the mechanical characteristics of the loose material and the design parameters of the unit.

Keywords: shaft furnace, unloading unit, lime, loose material, torque, drive.

Lime is extensively used as a flux in the metallurgical production to remove sulfur and phosphorus from cast irons and steels. At present, it is produced by burning limestone in drum rotating and shaft-type furnaces. At present, the shaft burning furnaces are regarded as preferable because they have numerous advantages. The normal daily productivity of shaft furnaces is equal to 145–160 tons of lime (more than 90% of CaO) for a fraction 0–80 mm in size with a bulk density of 1.0 $tonx/m^3$. The indicated productivity should be regulated within the range 40–160 tons due to the possibility of variation of the intensity of output of the lump material. The operation of the aggregate in a given technological mode is mainly determined by the reliability and technical possibilities of its unloading system, which operates in a dusty zone under the conditions of high pressure (up to 700 $mm H_2O$) at a temperature of the ambient air that can be as high as + 60°C. As the principal criteria of efficiency of the operation of units aimed at unloading burnt lime from the shaft-type furnaces, one can use the degree of uniformity of unloading and the limits of regulation of the volume of the material coming from the aggregate unit time.

As important criteria for the evaluation of the efficiency of operation of the unloading system, one can also consider its reliability and maintainability. In this connection, the design of the system must guarantee the possibility of free access to all elements subjected to the action of high in-service loads and requiring periodic replacements. The indicated characteristics strongly depend on the specific features of design and the principle of operation of the unloading system used in the furnace.

The indicated units can be conventionally split into three main groups by the type of motion realized in them and by the shape of the working organ. The first group includes unloading systems with reciprocating motion of elements transporting the material from the center of the lower part of the furnace shaft to its periphery.

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The second group of units forms a system with rotating hearth equipped with special combs in the form of spiral or curvilinear blades forcing back the burnt material in the course of rotation relative to the lower part of the furnace shaft in the radial direction from its central axis to the outer edge of the hearth. As a distinctive feature of units from the third group, we can mention the discharge of the material by a special drum or a set of rolls rotating with the help of an individual drive or a group of electromechanical drives [1–9]. As shown by the results of the performed comparative analysis of the advantages and disadvantages of all available systems for unloading lime from the burning shaft furnaces, their subsequent improvement is connected with the development of new design solutions directed toward the increase in the efficiency of the process of discharge of the material from the installation by creating a complex trajectory of motion of the moving hearth, as well as toward the choice of the optimal number and shapes of the knives-scrapers and the use of substantiated power and force parameters of the drive of the unloading unit. In this case, it is necessary to perform the experimental investigations of design-basis and technological parameters of the improved system of unloading of the furnace with the use of the proper physical models and the original control and measuring methods. On the basis of experimental data, it is necessary to propose a method for the numerical analysis of the loads acting upon the drive of unloading unit of the shaft furnace depending on the actual productivity and develop possible methods of its adaptive adjustment.

The staff of the Chair of "Mechanical Equipment for the Plants of Ferrous Metallurgy" of Donetsk National Technical University and of the Chair of "Metallurgy and Materials Science" of the Ugarov Staryi Oskol Technological Institute, with regard for the advantages and disadvantages of the well-known systems of discharge of burnt lime, proposed a device for the unloading of burning shaft furnace equipped with a hearth capable of performing plane-parallel motions relative to its case [10]. The constructive scheme of the developed device is presented in Fig. 1a. It includes a round hearth 4 mounted with a gap relative to the lower part of shaft 16 of the furnace. In the lower supporting surface of the hearth, we made four cylindrical holes with pressed bearing bushings 2 with pins 3 placed inside them. Each of these pins is rigidly fixed on one of four gear wheels 7 horizontally mounted on the vertical axes 8. In this case, the pins are shifted in the same direction by the same distance from the vertical axes of the gear wheels 7. These wheels have identical sizes and are synchronized with each other by a driving gear 13 placed at the center and connected with a geared motor 5 by means of the bevel gear 11. The geared motor is mounted on the outer surface of a receiving hopper 14 neighboring from below with the furnace shaft and equipped with a sliding shutter 10. The gear wheels 7 rest on spherical rolling bodies 6 placed in annular races made in the supporting frame 12 concentrically with the pitch circles of the wheels. The supporting frame is rigidly fixed on bearing legs 9. A conic cap-splitter 1 rigidly connected with the furnace case is placed over the central part of the hearth in the gap between it and the lower end of shaft 16. Knives-scrapers 15 uniformly distributed along the perimeter over the upper surface of the hearth are attached to the cap-splitter from inside at the required angle of attack.

The device operates as follows: After the procedure of burning, pieces of lime are located on cap 1 and on the upper surface of hearth 4. They are distributed over its perimeter at the natural slope angle and completely fill the gap between the hearth and the lower part of shaft 16. As soon as shutter 10 is opened and the geared motor 5 is switched-on, the rotation of its output shaft is transferred to gear 13 through the bevel gear 11. Gear 13 guarantees the possibility of synchronous rotation of the gear wheels 7 on axes 8 in the bearing supports placed in the supporting frame 12. The vertical pins 3 placed in the cylindrical holes made in the lower supporting surface of hearth 4 rotate together with wheels 7 relative to axes 8. Since pins 3 are shifted by the same distance (eccentricity) in the same direction relative to the axes 8 of synchronously rotating gear wheels 7, hearth 4 performs plane-parallel motions on the rolling bodies 6 relative to the lower end face of shaft 16, receiving hopper 14, and knives-scrapers 15 (see Fig. 1b; dotted lines). Therefore, the lime layer whose thickness is equal to the gap between the lower part of shaft 16 and hearth 4 moves along a circle from the output annular hole of the shaft to the periphery of the hearth into the zones of location of knives-scrapers 15 realizing the discharge of material into the receiving hopper 14.

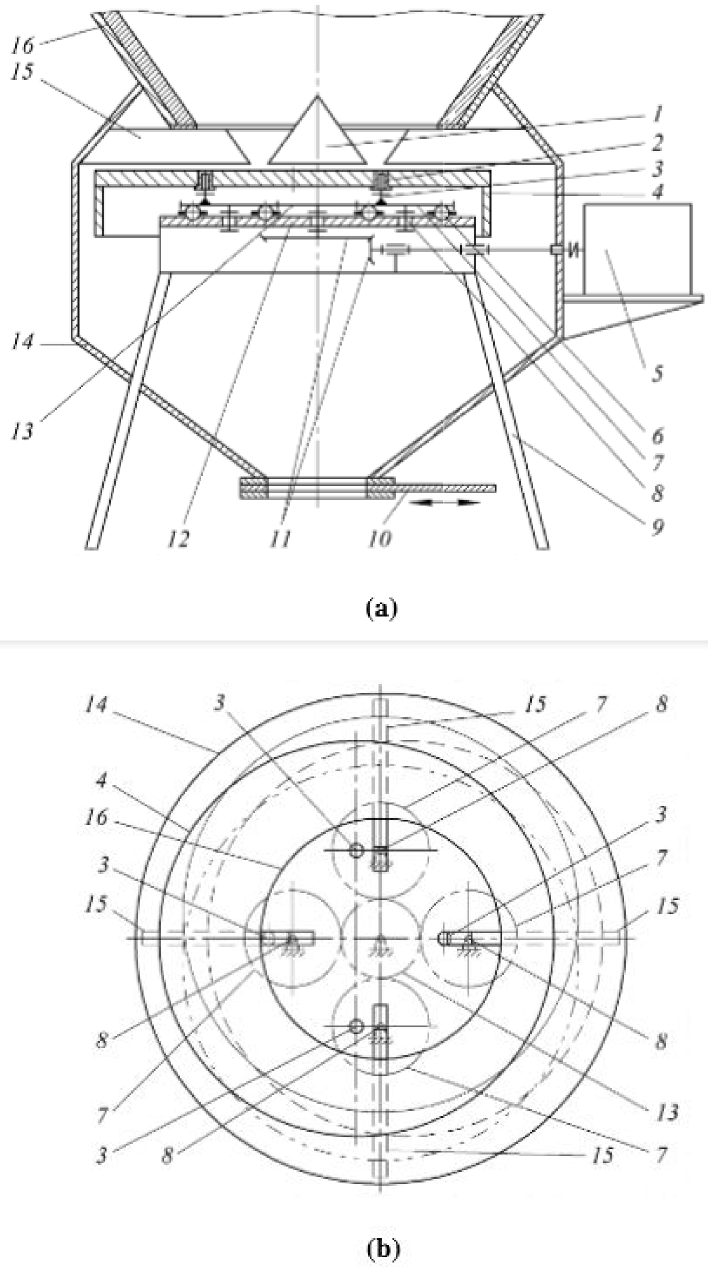

Fig. 1. Constructive scheme (a) and the location of moving hearth in the process of operation of the developed device for the unloading of a shaft lime-gas furnace (b).

According to the outlined principle of operation of the analyzed unloading unit, it is possible to assume that its productivity directly depends on the area of the so-called "sweeping zone" of knives-scrapers, their number, and the gap between the edge of the lower conic part of the shaft furnace and the hearth. According to the computational scheme presented in Fig. 2a, the formula for the evaluation of the ensured volumetric discharge takes the form

$$V = \frac{1}{3} S_{max} h Z f,$$

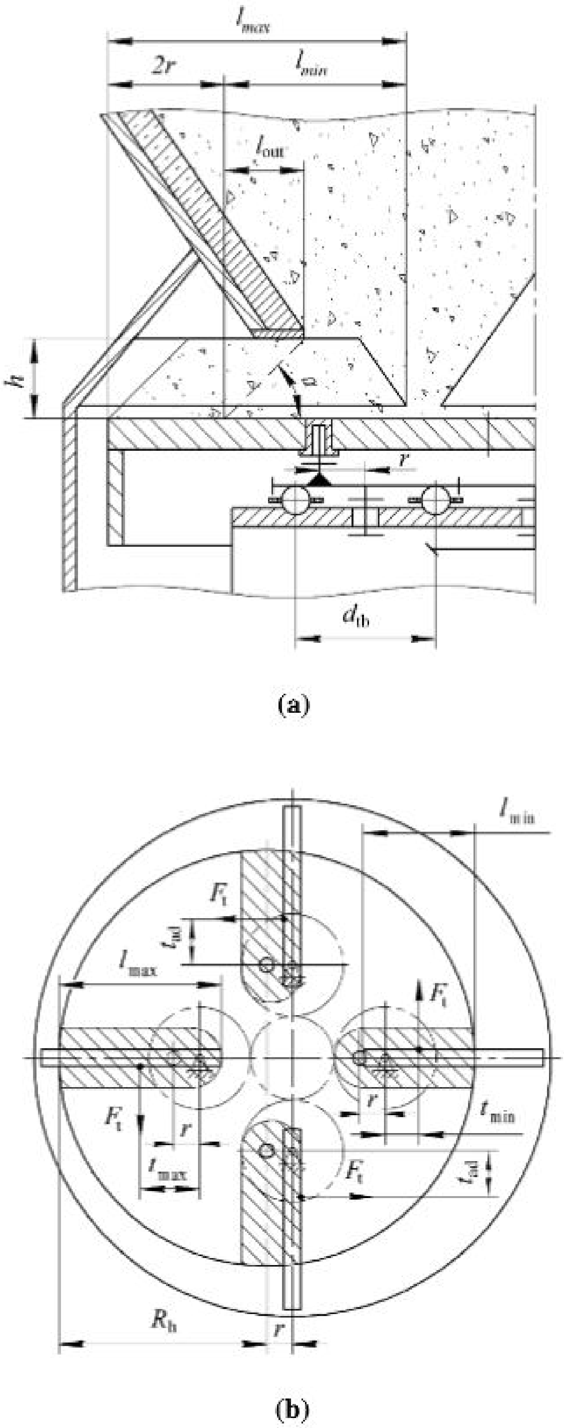

Fig. 2. Computational schemes for the evaluation of productivity of the system of unloading of lime (a) and the components of the total technological load acting upon the drive of moving hearth (b): the resistance moment of friction forces in the supports and the force of shear of the material layer.

where S_{max} is the maximum area of the "sweeping zone" of a knife-scraper, h is the gap between the surface of the moving hearth and the lower edge of the shaft furnace, Z is the number of knives-scrapers, and f is the working cyclic frequency of the moving hearth.

The area of the "sweeping zone" of a knife-scraper depends on the maximum length of the knife-overlapped part of the moving hearth (l_{max}) and on the eccentricity of the center of the hearth relative to the vertical axis of the supporting frame. The indicated eccentricity is equal to the displacement (r) of the pins supporting the hearth from the axes of the gear wheels on which they are mounted. In view of the shape of the "sweeping zone" of knives-scrapers (see Fig. 2b), we find

$$S_{max} = \frac{\pi r^2}{2} + 2rl_{max}.$$

Finally, we get

$$V = \frac{1}{3}\left(\frac{\pi r^2}{2} + 2rl_{max}\right) hZf.$$

We now analyze this formula. A part of the quantities appearing in this formula are independent. We specify their numerical values with regard for the design-basis features of the device. As these features, we can mention the crank radius r and the maximum length of a part of the knife-scraper l_{max} located over the hearth surface.

The values of the remaining three quantities cannot be set arbitrarily because they depend not only on the other geometric parameters of the unloading system but also on the physicomechanical properties of the unloaded material. Thus, the maximum admissible gap h for which the spontaneous discharge of the material from the furnace is impossible is connected with the minimum possible penetration of the edge of moving hearth beyond the limits of the throat edge of the shaft furnace by the formula

$$h = l_{out} \tan \alpha,$$

where α is the natural slope angle of the unloaded material.

The number of knives-scrapers also cannot be set arbitrarily because its choice specifies the efficiency of operation of the unloading unit if all other conditions are identical. The minimum productivity corresponds to the presence of a single knife-scraper. At the same time, the maximally admissible number of knives-scrapers is determined by the requirement that their "sweeping zones" do not overlap. This condition is fairly well illustrated by Fig. 3, where we present the characteristic patterns of the relative positions of the "sweeping zones" of knives-scrapers on the surface of the moving hearth for different numbers of the knives.

As follows from the presented information, the area occupied by the "sweeping zones" increases with the number of knives-scrapers due to the decrease in the total area of dead zones located outside the regions of action upon the layer of the material in the aperture between the surface of the moving hearth and the edge of the throat in the furnace case. However, if the "sweeping zones" of knives-scrapers start to overlap, then the subsequent increase in their number does not lead to the increase in the productivity of the unloading unit. In the analyzed versions of the design, the maximum number of knives-scrapers should not exceed seven. Since the problem of determination of the optimal number of knives-scrapers with the help of the plots requires significant amounts of time, it is reasonable to construct the dependence that would enable us to numerically determine the maximum value of this design-basis parameter for the unloading system of burning shaft furnace.

The condition of attainment of the optimal number of knives-scrapers has the form

$$2\pi(R_h - l_{max} + r) = 2rZ,$$

where R_h is the radius of moving hearth.

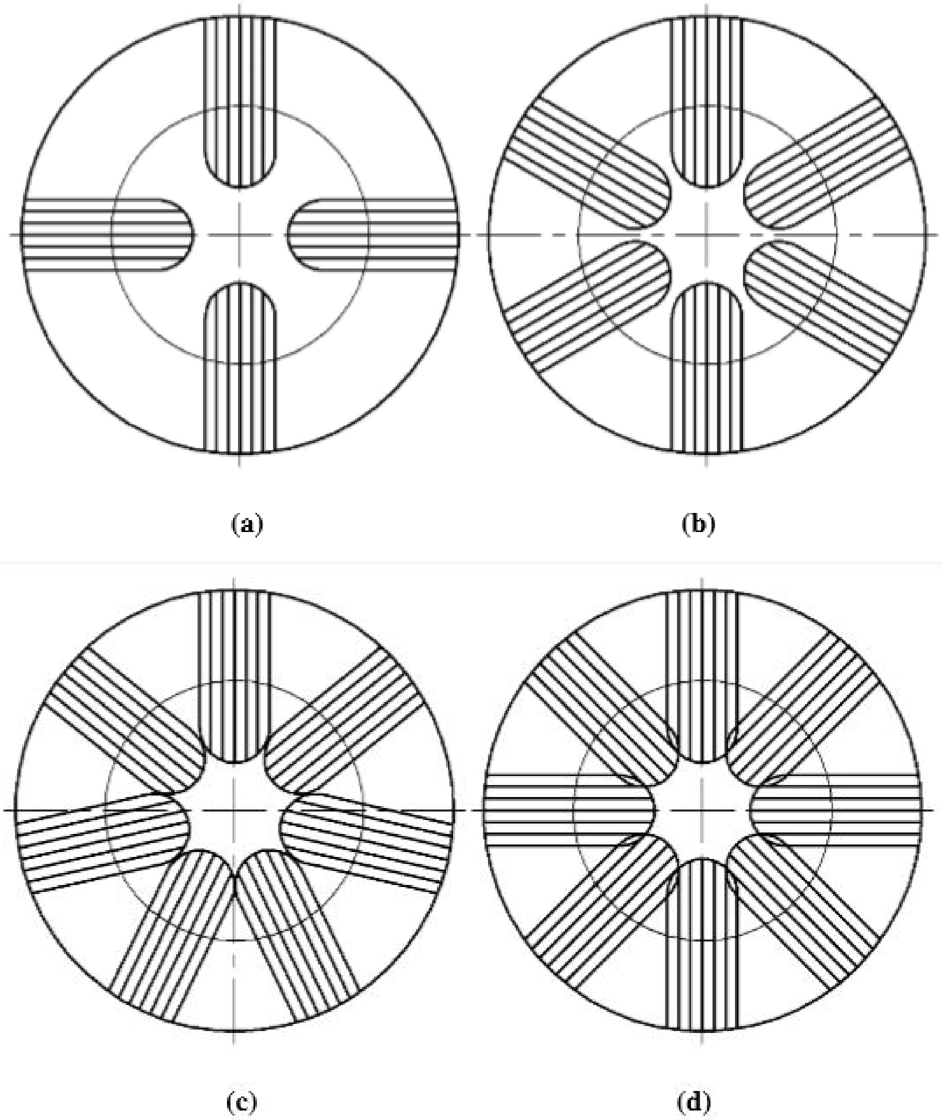

Fig. 3. Shape and arrangement of the "sweeping zones" for different numbers of the knives-scrapers: (a) $Z = 4$; (b) $Z = 6$; (c) $Z = 7$; (d) $Z = 8$.

This implies that the number of knives is given by the formula

$$Z = \pi(R_h - l_{max} + r)/2 .$$

The technological load acting upon the drive of the moving hearth has two principal components. *The first component is the total force needed to shift the layer of loose material by all knives-scrapers at a current time*

$$F_t = S_{sz}\tau_{ts} ,$$

where S_{sz} is the current value of the total area of the "sweeping zones" of all knives-scrapers and τ_{ts} are the tangential stresses in the shifted layer of the material.

According to the data presented in [11],

$$\tau_{ts} = \tau_0 + \sigma \tan \varphi,$$

where τ_0 is the initial shear resistance, σ are the normal stresses in the shifted layer of the material, and $\tan \varphi$ is the coefficient of internal friction of the material.

For the current value of the total area of "sweeping zones" of all knives-scrapers, we get

$$S_{sz} = ZS_{av},$$

where S_{av} is the mean value of the area of the "sweeping zone" of a knife-scraper.

In turn,

$$S_{av} = 0.5(S_{max} + S_{min}) = \frac{\pi r^2}{2} + 2rl_{av},$$

where l_{av} is the mean length of a part of the moving hearth swept by a knife. It is equal to $0.5(l_{max} + l_{min})$.

Thus, the total force opposing the displacement of the moving hearth in the process of relative shear of the material

$$F_t = Z\left(\frac{\pi r^2}{2} + 2rl_{av}\right)(\tau_0 + \sigma \tan \phi).$$

The resistance moment caused by F_t and simultaneously acting upon four gear wheels is given by the formula

$$M_1 = \frac{F_t t_{ad}}{r},$$

where t_{ad} is the mean value of the distance between the point of application of the concentrated force to a knife-scraper and the axis of rotation of the gear wheels used to fix the pins supporting the moving hearth.

The value of t_{ad} is determined as the arithmetic mean between the minimum and maximum values of this geometric parameter graphically determined with the help of a scaled chart of the analyzed unit of the computed mechanism.

The second component of the total force of technological resistance is caused by the friction in thrust roller bearings, which are supported by the gear wheels carrying the moving hearth. The resistance moment caused by the friction forces simultaneously acts upon four gear wheels and is given by the formula

$$M_1 = (G_h + G_{wl})k_{red}\frac{d_{tb}}{2},$$

where G_h is the weight of the moving hearth; G_{wl} is the weight of the lime column of height H located in the furnace shaft over the unloading hearth; k_{red} is the reduced friction coefficient of the bearing, and d_{tb} is the mean diameter of a thrust bearing.

Fig. 4. Physical model of the system of unloading of lime from the shaft burning furnace with strain-gauge transducer mounted in the kinematic chain of the drive for the monitoring of changes in the torque.

The power required to overcome the technological load is

$$N = \frac{(M_1 + M_2)\omega}{\eta},$$

where ω is the angular velocity of gear wheels used to fix the pins supporting the moving hearth and η is the total efficiency of the mechanism.

The angular velocity of the gear wheels transferring the motion to the hearth via pins with a cyclic frequency f is given by the formula

$$\Omega_{gw} = 2\pi f.$$

The required angular velocity of the shaft of a geared motor is

$$\Omega_{er} = \omega_{gw} i_{scg} i_{bg},$$

where i_{scg} and i_{bg} are the gear ratios of the straight cut and bevel gears, respectively.

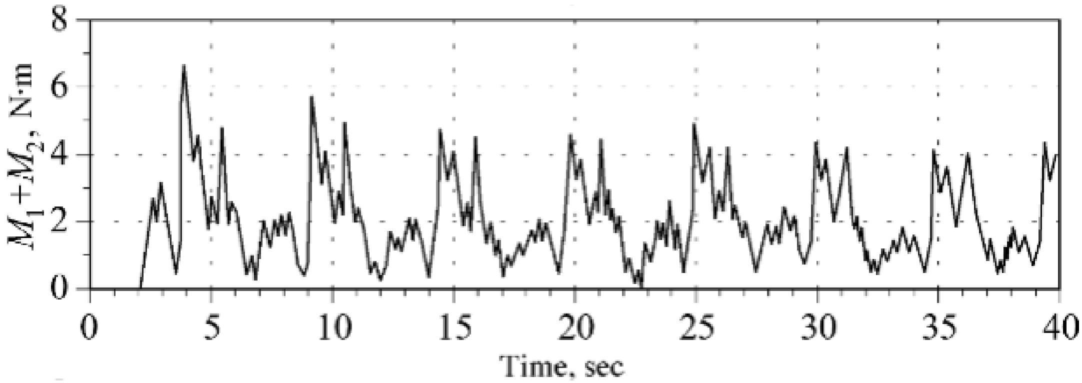

Fig. 5. Typical view of signals recorded in measuring the resistance moment to be overcome by the drive of the physical model of unloading system within a single operation cycle for the height of column of the loose material H = 60 mm.

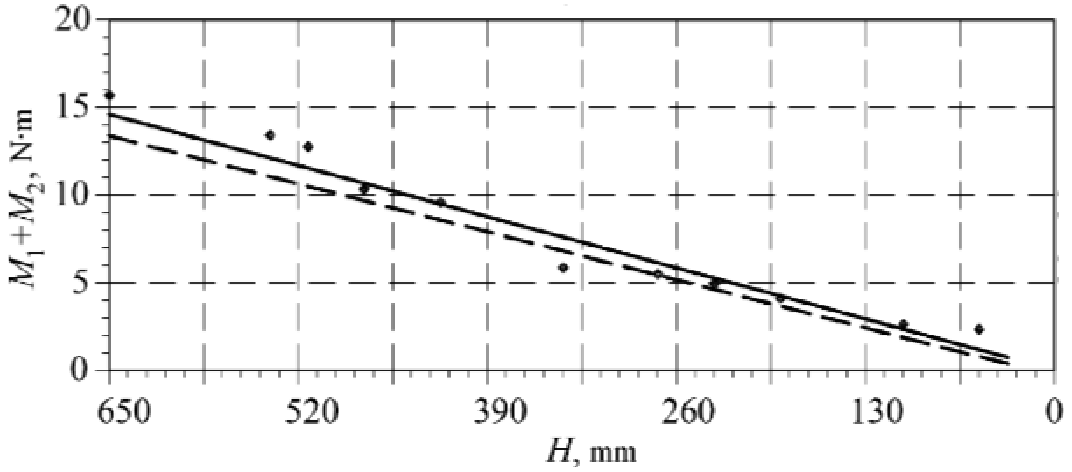

Fig. 6. Plot of the dependence of the averaged empirical (continuous line) and analytic (dashed curve) values of the total resistance moment to be overcome by the drive of the model of unloading system on the height of the material column placed in the shaft over the moving hearth.

The procedure of verification of the correctness of engineering solutions used in the design of a new system of unloading of loose materials from the burning shaft furnace, as well as of the correctness of obtained dependences for the evaluation of the design-basis and power-force parameters was carried out by using a physical model of the furnace with a productivity of 120 tons/day made on a 1:20 scale (Fig. 4) with preservation of the kinematic and dynamic similarity.

In the course of laboratory tests, we used a control-measuring complex for recording the resistance moment to be overcome by the drive of the model in the real-time mode. The complex included a specially made strain-gauge transducer, a UT4-1 four-channel ac amplifier, and an IBM-computer with an L-154 card of a 12-digit multichannel analog-to-digital transducer of the L-CARD Firm mounted on its bus. The strain-gauge transducer used to measure the torque overcome by the drive includes foil gauges with a resistance of 200 Ohm connected by the bridge scheme. The typical form signals recorded with its help are presented in Fig. 5.

The measured values of torques formed in the course of functioning of the model of system of unloading of lime from the burning furnace were compared with the analytic and computed values of the parameters of the model (Fig. 6). The difference between the computed and experimental data did not exceed 10%, which is acceptable for engineering calculations.

CONCLUSIONS

The introduction of the unloading mechanism with rational design-basis parameters in the production would make it possible to increase the uniformity of discharge of the material. This is guaranteed by the possibility of its realization in the continuous mode with simultaneous unloading of lime by all knives-scrapers along the perimeter of the moving hearth.

The developed procedure of evaluation of the design-basis and power-force parameters of the new system of unloading of lime from the burning shaft furnace can be used for the design of its pilot industrial prototype with regard for the mechanical characteristics of the discharged material.

REFERENCES

1. A. V. Monastyrev and A. V. Aleksandrov, *Furnaces for the Production of Lime. A Handbook* [in Russian], Metallurgiya, Moscow (1979).
2. N. P. Tabunshchikov, *Production of Lime* [in Russian], Khimiya, Moscow (1974).
3. A. V. Monastyrev, *Production of Lime* [in Russian], Vysshaya Shkola, Moscow (1978).
4. N. P. Tabunshchikov, È. T. Aksenov, R. Ya. Gurevich, and L. D. Shevtsov, *Production of Lime and Saturation Gases at the Sugar Plants* [in Russian], Legkaya Pishch. Promyshl., Moscow (1981).
5. A. S. Efremov, V. V. Lapshin, V. N. Lomagin, and M. A. Smirnov, "Automation of the technological process of unloading and transportation of burnt lime," *Vest. Kostrom. Gos. Tekhnol. Univ.*, No. 2 (35), 61–64 (2015).
6. V. P. Chmil' and Yu. V. Chmil,' "Concept of environmentally pure automated system for storage and feeding of chemically active loose materials," *Khim. Promyshl. Segod.*, No. 4, 29–34 (2014).
7. A. I. Pereskokov and D. A. Artov, "Combined installation aimed at burning limestone," *Èkol. Promyshl. Ross.*, No. 4, 14–16 (2005).
8. I. V. Pitak, P. V. Shaporev, A. V. Shestopalov, and V. P. Shaporev, "Improvement of the production of lime in shaft furnaces," *Technol. Audit Rezerv. Proizvod.*, No. 1, 59–63 (2014).
9. V. V. Madison, V. T. Ryazanov, A. A. Nabokikh, et al., "Experience of the technical reconstruction and mastering of the modes of operation of PFR furnaces aimed at burning limestone," *Stal'*, No. 3, 64–70 (2015).
10. E. N. Smirnov, S. P. Eron'ko, M. Yu. Tkachev, et al., *Device for the Unloading of Shaft Lime-Gas Furnaces* [in Russian], Patent 2623402RF, MPK F27B 1/20, Submitted 23.05.2016, Publ. on 27.06.2017, Byull. No. 18.
11. V. N. Dolgunin and V. Ya. Borshchev, *Fast Gravitational Flows of Granular Materials: Measuring Technique, Regularities, and Technological Applications* [in Russian], Mashinostroenie, Moscow (2005).