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IMPROVEMENT IN THE RELIABILITY OF MECHANICAL FLUX FEED SYSTEMS FOR CONTINUOUS SLAB-CASTING MACHINE MOLDS

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We discuss the operating principle and design features for an improved mechanical flux feed system to be used in continuous slab-casting machine molds; this system provides increased reliability and operational efficiency, and is easier to maintain. We describe experimental results for the operating parameters of a combined drive for use in such a mechanical flux feed system, as well as validation of the design, kinematic and power consumption parameters for such drives.

Keywords: Slab billet, mold, flux, mechanical feed, screw conveyor; drive; torque.

A primary factor with a substantial impact on the conditions governing the interaction between casting-machine mold walls and the slab-billet crust involves the uniformity of the flux distribution on the surface of the liquid metal after the flux is added during the continuous steel casting process [1]. Experience indicates that the layer of granulated or powdered flux on the free melt surface in the mold can only be maintained at a uniform thickness if the flux is mechanically fed on a continuous basis with a flow rate that is strictly commensurate with the billet drawing speed. Many foreign and select domestic metallurgical firms use a variety of continuous casting machines with pneumatic, pneumomechanical, or mechanical systems [2–4] to ensure the successful performance of this manufacturing process. Efforts to further improve these systems are currently designed to upgrade promising samples that make it possible to enhance the effectiveness of flux usage when casting large and extremely large billets [5]

It may be difficult to use such systems in continuous slab-casting machines with typical molds intended for casting continuous-cast billets with transverse cross sections between 150 × 1000 and 300 × 2400 mm (the production process may include the capability to cast billets of other standard sizes) because of the need to distribute the mixture over a large surface area of liquid steel and adjust the machinery to support this function. If the thickness and width of the billet being cast changes, both the speed of the feeder carriage that moves bidirectionally along guides parallel to the wide wall of the mold and the distance between these guides and the submerged nozzle must be adjusted. The submerged nozzle is reconfigured and moved with the tundish by an amount equal to half the planned increase (or decrease) in ingot thickness. In addition, a failed submerged nozzle must occasionally be replaced when casting a batch of steel, which requires free space around the submerged nozzle

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attached to the tundish. The fact that the flux-feed tip for the mold is located near the removable refractory materials makes it difficult for casting personnel to remove used refractory from the casting area.

These operating characteristics of mechanical flux feed systems for continuous casting of slab billets must be taken into account when developing this type of high-efficiency prototype equipment.

Under a cooperative agreement for research and development in the field of continuous steel casting, Donetsk National Technical University Ferrous Metallurgy Plant Mechanical Equipment Department and KORAD LLC (Moscow) have been collaborating since 2015 to design domestic equipment that will relieve casting personnel of the need to perform the monotonous and arduous task of manually dispersing powder or granulated compounds on the surface of the liquid metal in a continuous-casting-machine mold when casting very-large-cross-section slabs. In light of prior experience with the commercial use of such devices, we decided to develop a mechanical flux feed system that could easily be integrated into current continuous-casting equipment and that does not require installation of any additional equipment in the immediate vicinity of the submerged nozzle.

To this end, the engineering design solutions described in patents [6, 7] were used to propose a next-generation flux-feed system that make it possible to uniformly disperse flux over the surface of a liquid metal in a mold from a stationary hopper without using awkward horizontal screw conveyors mounted on self-propelled carriages. An additional advantage of this system is that a special mechanism can be used to automatically retract from the operating position to the parked position when the submerged nozzle discharge device is serviced. Figure 1 shows the design and operating principle of the proposed mechanical flux-feed system. The system consists of a service hopper 26 with the consumable mixture mounted on metal structure 24 and equipped with a lower chamber 8 connected to inclined feed nozzle 12 by flexible line 10. A vertical hollow drive shaft 6 containing screw conveyor 7 is installed on bearing supports 25 and 27 in hopper 26; the lower, cylindrical portion of this shaft is coaxial with, and mounted inside chamber 8, and the upper, conical portion of the shaft is located inside the hopper. An electric motor 3 is mounted to the top of this hopper and connected to the high-speed shaft of double-reduction right-angle reduction gear unit 1 via coupling 2. The low-speed shaft of the reduction gear unit is attached to vertical transmission shaft 6 via gear and pinion 28. A second shaft 5 is coaxially mounted inside a longitudinal cavity in this low-speed shaft; the top end of the second shaft is connected to the intermediate shaft of reduction gear 1 via coupling 4. The lower end of shaft 5 is attached to steel screw conveyor 9, which runs through the full length of flexible hose 10, and is capable of rotating relative to hose 10.

Inclined feed nozzle 12 is installed on carriage 16 with rollers 17 that move along C-shaped guides in a horizontal beam. The center portion of this beam is pivotly attached to the end of hollow rotating load-bearing beam 19 via bracket 11 and vertical shaft 18, which are rigidly attached to the beam; the other end of the beam is attached to metal structure 24 by vertical dogs 21 and 23. Bracket 11 includes lever 43, which is attached to structural metal component 44 via rod 33 and dogs 31 and 34. The dimensions of component 44, rod 33, lever 43, and hollow rotating load-supporting beam 19 are selected so that they form a parallelogram mechanism. This means that horizontal beam 39 is has plane-parallel freedom of motion in the horizontal plane relative to the wide wall of mold 15, which receives the liquid steel from flux feed 13 via submerged nozzle 14.

A second motor/reduction gear unit 20 mounted on the end of beam 19 furthest from mold 15 serves to move carriage 16 along horizontal beam 39, and is in turn attached (see Fig. 1, Section B–B) to the end of shaft 53, which is installed in bearing assemblies 51 and 52 located inside the cavity in the beam . The other end of this shaft is attached to beveled pinion 50, which meshes with beveled gear 49 that has freedom of rotation about vertical axle 18 that connects beam 39 and beam 19. Beveled gear 49 meshes with conical shaft/gear 48 which is installed in bearing assemblies 46 and 47 on beam 39 and has sprocket 45 attached to it; sprocket 45 (Fig. 1, Section C–C) meshes with plastic chain 39, whose ends are attached to opposite sides of carriage 16 via the two sprockets 37 and 41. Tension on sprocket 36 is maintained using two additional sprockets 35 and 42. Moving limit switches 38 and 40 are provided on each end of beam 39 to reverse motor/reduction gear unit 20.

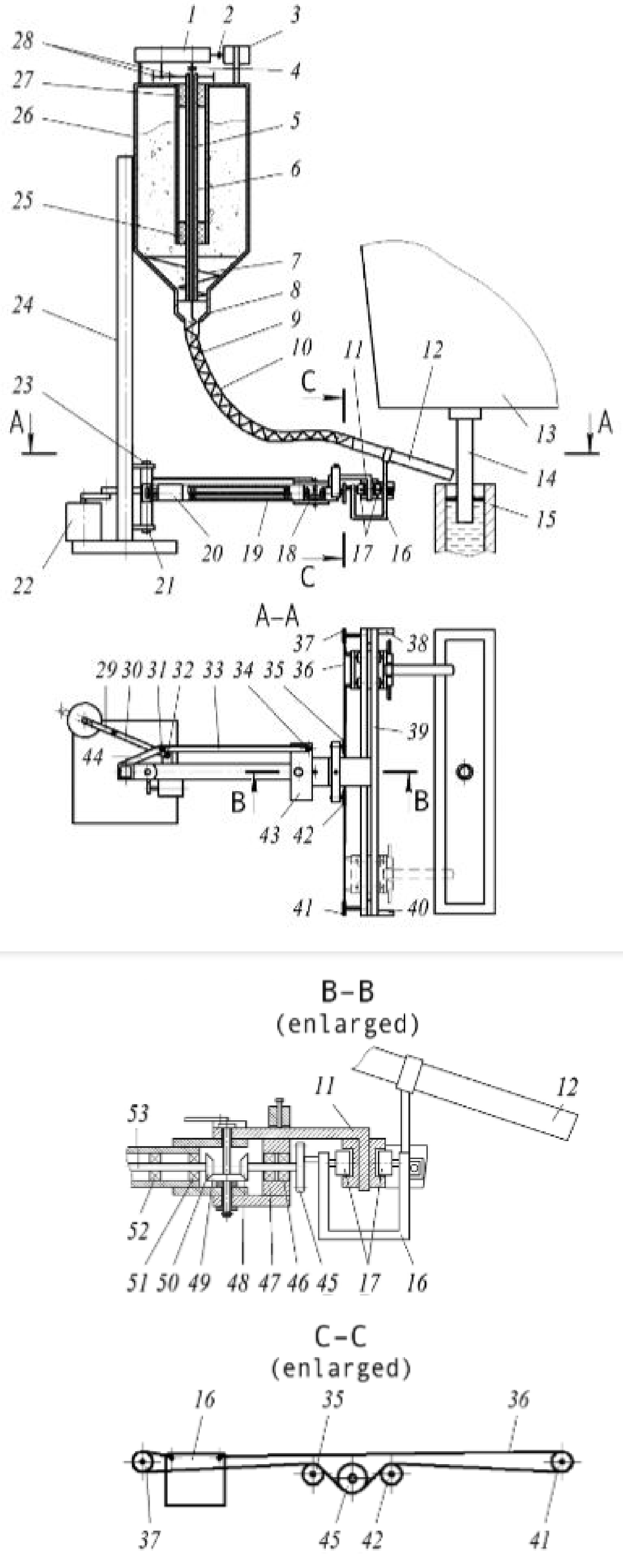

Fig. 1. Diagram showing design of improved flux feed system.

A third motor/reduction gear unit 22 is installed on metal structure 24; the output shaft of motor/reduction gear unit 22 is connected to beam 19 via crank 29, slider 30, and dog 32.

The design specifications for the structural components of the mechanical flux feed system lead to improved reliability , simplify the operations to be performed prior to continuous casting machine startup, and provide a more efficient flux feed system.

One of the most important operations to be performed when preparing a continuous casting machine for a heat is known to involve adjustment of the mechanical flux feed system relative to the mold. This operation requires that the position of the inclined feed tip relative to the nearest wide wall of the mold be adjusted so that it does not touch the submerged-nozzle discharge unit. This adjustment was simplified as much as possible by the aforementioned parallelogram mechanism, which forces the horizontal beam to move strictly parallel to the wide mold wall as the hollow load-bearing beam rotates, and also ensures that the required separation between the horizontal beam and the submerged nozzle contained in that mold wall is maintained; this separation depends on the thickness of the billet to be cast. In addition, the ability to use the electromechanical system to rapidly return the system to parked position improves personnel access to the submerged nozzle discharge device if it becomes necessary to replace a failed submerged nozzle during a heat.

The fact that the motor/gear reducer responsible for the reciprocating motion of the carriage is outside the most heat-affected zone improves the operational reliability of the motor/gear reducer and allows the power cable for the motor to remain stationary, thereby increasing the service life of the unit by eliminating deformation due to flexure.

The combined drive supports separate but synchronized operation of the rigid and spiral screws that support the feeding operation and translational motion of the hopper. This not only improves the uniformity of bulk-material feed from the hopper, supports smooth adjustment of the flow over a broad range, it also supports the stable movement of both granulated and powder fluxes via the flexible metal hose.

For preliminary verification that the engineering design solutions adopted were correct and in order to obtain initial information on the power and energy requirements for the drive on the controllable bulk-feed mechanism for movement of bulk material from the consumables hopper and subsequent transport of such material to the continuous-caster mold, a prototype for this mechanical flux feed system was constructed for continuous casting of slabs up to 1000 mm wide.

Preliminary testing of the resulting system was used to verify the functionality of the individual mechanisms involved, as well as the positional accuracy of the moving components relative to the mold when the moving components are in operating position (Fig. 2(a)) and after they are parked (Fig. 2(b)). In addition to overall visual verification that the auxiliary mechanisms were functioning properly, we also measured the operating loads to be overcome by the combined drive for separate rotation of the rigid and spiral screws, and electronic scales and a stopwatch were used to determine the overall production capacity Q.

The torque on the drive shaft was measured using a resistive strain gauge with an amplifier and an L-CARD 12-bit multichannel analog-to-digital converter (ADC) whose board was connected to the ISA bus in an IBM-compatible PC. The transducer (Fig. 3) which connects the motor shaft to the high-speed shaft of the reduction gear consists of a sleeve installed on friction bearings and placed in a metal housing with a transparent front wall. The resistive strain gauges were attached to the surface of the sleeve at an angle of 45° to the longitudinal axis of the sleeve, and the strain gauges were connected in a resistance-bridge configurations. Each foil strain gauge had a resistance of approximately 200 Ohm. The torque was determined by measuring the torsional deformations. The electrical signal was measured across the resistance-bridge diagonal being monitored, and power was applied to the resistance bridge, via copper rings which were installed on, and electrically insulated from, the sleeve; these rings were in contact with current buses on the outer surface, and the ends of these buses are wired to a connector mounted on the side of the housing.

The transducer calibration showed a maximum transducer measurement error of 5%.

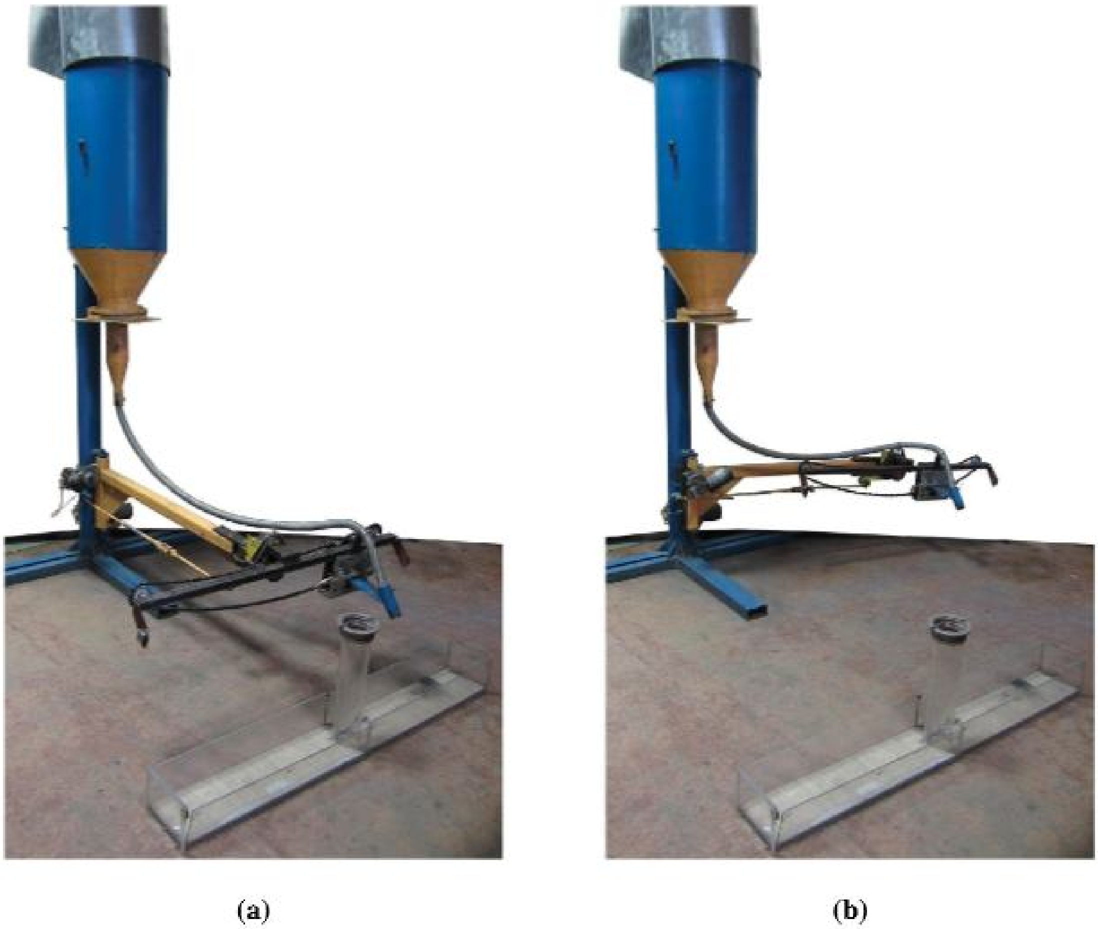

Fig. 2. Position of structural components in flux feed system in operating position (a) and parked position (b).

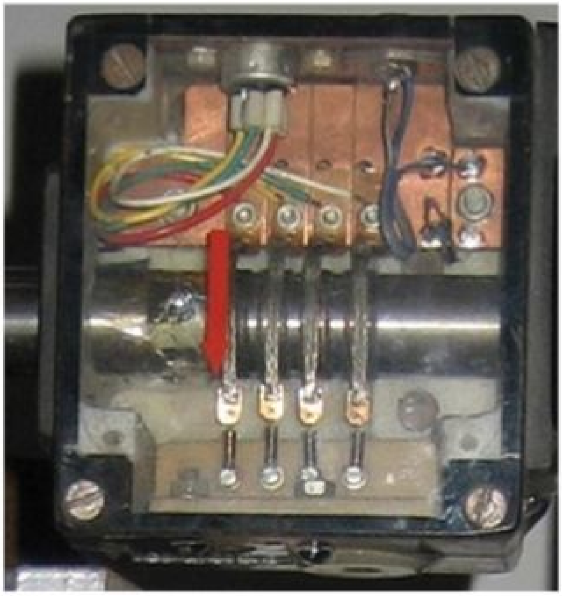

Fig. 3. Design of strain-gauge sensor for torque monitoring.

Table 1
Experimental Values for Functional Parameters of Combined Drive in Mechanized Flux Feed System

Dimensions and rotational speed							Flux-feed-system operating parameters						
Rigid screw				Spiral screw									
D_{out}, mm	d, mm	S_{vzh}, mm	n_{screw}, min^{-1}	D_r/d_{out}	S_{vs}/d_{vs}	n_0, min^{-1}	M_{ssh}, N·m	M_{rc}, N·m	M_{0_1}, N·m	n_{0_1}, min^{-1}	N_1, kW	Q, ton/h	N_1/Q (kW·h)/ton
30	20	15	120	15/11	0.43	300	0.39	0.60	1.0	900	0.132	0.021	6.3
			160			400	0.38	0.61	1.2	1200	0.148	0.027	5.5
			200			500	0.41	0.75	1.4	1500	0.155	0.029	5.3
			120		0.52	300	0.63	1.05	1.8	900	0.170	0.033	5.2
			160			400	0.60	0.80	1.9	1200	0.188	0.037	5.1
			200			500	0.70	1.15	2.0	1500	0.195	0.038	5.2
			120		0.64	300	0.70	1.25	2.1	900	0.220	0.035	6.3
			160			400	0.71	1.30	2.2	1200	0.240	0.036	6.3
			200			500	0.73	1.35	2.2	1500	0.251	0.038	6.6
30	20	15	120	20/16	0.43	300	0.87	1.30	2.4	500	0.226	0.037	6.1
			160			400	0.89	1.35	2.4	1200	0.301	0.055	5.4
			200			500	0.91	1.50	2.5	1500	0.392	0.072	5.4
			120		0.54	300	0.90	2.60	2.9	900	0.273	0.053	5.1
			160			400	0.90	1.75	2.9	1200	0.364	0.088	4.1
			200			500	0.95	1.95	3.0	1500	0.471	0.094	5.0
			120		0.76	300	0.90	2.05	3.0	900	0.282	0.055	5.1
			160			400	0.91	2.10	3.1	1200	0.389	0.073	5.3
			200			500	0.92	2.15	3.2	1500	0.502	0.093	5.4
30	20	15	120	25/18	0.45	300	1.30	2.00	3.3	900	0.310	0.068	4.5
			160			400	1.30	2.10	3.4	1200	0.427	0.094	4.5
			200			500	1.35	2.15	3.6	1500	0.565	0.128	4.4
			120		0.64	300	1.40	2.25	3.8	900	0.357	0.081	4.4
			160			400	1.50	2.45	4.2	1200	0.527	0.138	3.8
			200			500	1.60	2.50	4.5	1500	0.706	0.144	4.9
			120		0.85	300	1.50	2.65	4.3	900	0.405	0.076	5.3
			160			400	1.55	2.80	4.8	1200	0.602	0.109	5.5
			200			500	1.60	3.50	5.4	1500	0.847	0.136	6.7

The validation measurements were performed per a pre-drafted plan that required collection of both the combined-drive torque for the metered flux feed system and the fractions of the total moment associated with operation of the rigid vertical screw conveyor and operation of the flexible screw conveyor, respectively. The two conveyors were operated separately by breaking the kinematic train for the combined drive in the appropriate location. The experiments were performed for three fixed values of the electric drive motor where

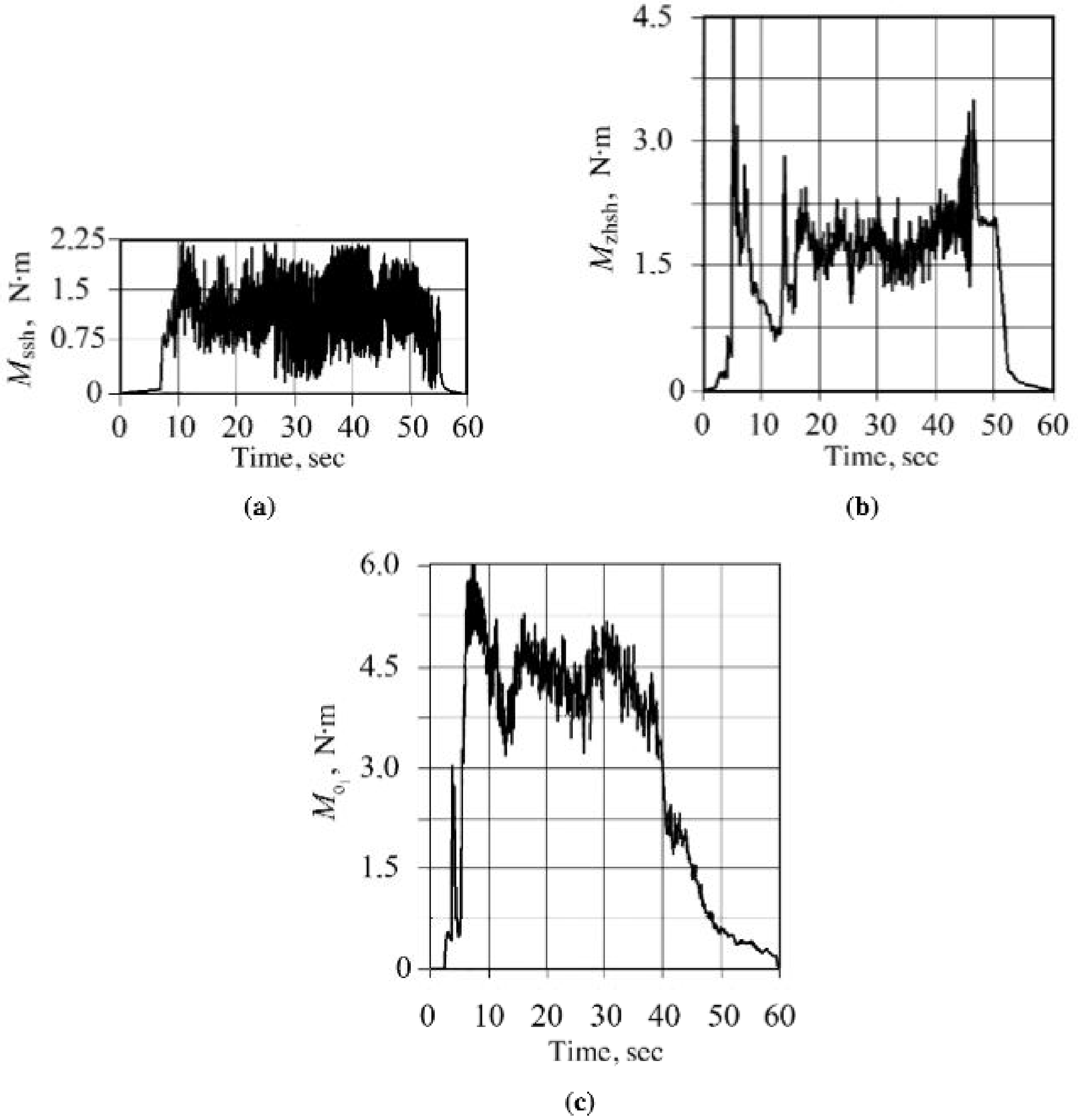

Fig. 4. The flux feed system drag torques for the movement of bulk material in the hose (a), controllable movement driven by the rigid screw (b), and for the regular operation mode (c).

both screws could operate in a stable manner. The operating speed for the rigid screw ($n_{\rm screw}$) was varied from 100–200 $\min^{-1}$, while the operating speed for the spiral screw (n_0) was varied over the range 300–600 $\min^{-1}$.

In addition to this effort, successive combinations of a single vertical screw were implemented with shaft diameter $d = 20$ mm, outside diameter $D_{\rm v} = 30$ mm and pitch $S_{\rm vzh} = 15$ mm for the cylindrical section, with flexible screw diameter ratios $D_{\rm r}/d_{\rm v}$, diameter $d_{\rm vs}$ and pitch $S_{\rm vs}$, $D_{\rm p}/d_{\rm v}$ = (25/18; 20/16; 15/11) and $S_{\rm vs}/d_{\rm vs}$ = (0.5; 0.7; 1). A diagram showing the appearance of the recorded signals is provided in Fig. 4.

Analysis of the power, energy, and flow rate results for the upgraded flux feed system enabled us to determine the optimum design parameters for the flexible conveyor that would support the desired flow rate at the lowest possible energy consumption (see Table 1).

The drag torques acting on the flexible ($M_{\rm ssh}$) and rigid ($M_{\rm zhsh}$) conveyors were, respectively, 30–35% and 60–65% of the total torque overcome by the motor (see Fig. 4).

The power consumption N_1 calculated for the combined drive based on the measured drag torque M_{0_1} at the specified rotation speed n_{0_1} and the overall mechanical efficiency enabled us to estimate the operational energy efficiency. This was achieved using the ratio of the power N_1 developed by the drive at a specified rotation speed n_{0_1} to the corresponding flux flow rates Q. This ratio can be used to determine the geometric parameters and rotation speed of the flexible and rigid conveyors that will minimize power consumption [8].

CONCLUSIONS

The upgraded flux feed system for a continuous slab casting machine mold and the corresponding design, energy, and power consumption recommendations served to enhance the structural functionality, operability, and operational efficiency of continuous-casting machines.

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