ISSN 0967-0912, Steel in Translation, 2022, Vol. 52, No. 11, pp. 1051–1055. © Allerton Press, Inc., 2022.
Russian Text © The Author(s), 2022, published in Izvestiya Vysshikh Uchebnykh Zavedenii, Chernaya Metallurgiya, 2022, No. 11, pp. 824–830.

Upgrading Hopper Cars for Transportation of Sinter and Other Materials

**A. F. Nefedov[a], *, T. G. Shkurko[a], **,
N. A. Chichenev[b], *** (ORCID: 0000-0002-9019-4675), and N. V. Kholodova[c], ******

[a] *Novotroitsk Branch, National University of Science and Technology MISIS, Novotroitsk, 426359 Russia*
[b] *National University of Science and Technology MISIS, Moscow, 119049 Russia*
[c] *Vyksa Branch, National University of Science and Technology MISIS, Shimorskoe, Vyksa District, 607036 Russia*
**e-mail: cosnovotr@rambler.ru*
***e-mail: nfmisis@yandex.ru*
****e-mail: chich38@mail.ru*
*****e-mail: nv.kholodova@misis.ru*

Received October 17, 2022; revised October 20, 2022; accepted October 22, 2022

Abstract—The paper considers the results of the operability analysis of transporting equipment used at sintering shops of metallurgical enterprises located in the Urals. It is established that the long-term operation of hopper cars for transporting hot sinter is attended by the sedimentation of dust on the car walls, formation of packed dust bumps as well as by arching. The compaction and thickening of the dust layer reduces the useful volume of the hopper car; in its respect, this raises the need for performing dangerous works to eliminate the dust directly inside the hopper car. The internal hopper car surface is cleaned by manual labor. High dust content and risks of injury make these works very hazardous to human health. To cope with the arching issue and eliminate dust accumulated on the car walls, it is proposed to install two false wall vibration devices together with a vibrating batter board (vibrating beam). The vibrating element of the device is a plate mounted on flexible suspensions on the inner wall (round-link chain). The plate and the hopper wall are separated with the help of a rubber-fabric conveyor belt used as rubber shock absorbers. A vibrator is mounted to the plate through the support rack, and vibrations are transmitted to the sinter using a vibrating batter board welded to the plate (false wall). The designed device reduces unscheduled downtime of a set of hopper cars and allows giving up on the hopper cleaning works hazardous to human health. The economic calculation confirms the feasibility of the steps made for re-engineering hopper cars at sinter production shops of metallurgical enterprises.

Keywords: sinter production, hopper car, sinter arching, platform vibrator, false wall
DOI: 10.3103/S0967091222110109

INTRODUCTION

The reliability of engineering systems has recently acquired an ever growing importance and is becoming one of the main research and technological tasks for metallurgical machines and equipment [1–5]. Insufficiently reliable technological machines and their constituent parts and devices require high expenditures on their maintenance and result in a significant decline in metallurgical production capacities [6–9]. The severization of quality requirements on technological machines and equipment for cutting material, labor and financial costs of their maintenance and repairs raises the need for equipment upgrades and revamping [10–13]. That said, a lot of attention is paid to re-engineering ore mining and smelting production equipment [14–17]. This work considers the issues of upgrading hopper cars for transporting hot sinter of metallurgical enterprises situated in the Urals.

FORMULATION OF THE PROBLEM

The sinter carrier (hopper car) is designed to transport ready-made sinter from the sinter shop to the blast-furnace department. Hopper cars for transporting hot sinter allow transporting about 60% of the whole output of sinter to the blast-furnace shop. The remaining 40% are transported on conveyor belts.

A hopper car is the self-unloadable railroad car used for transporting bulk materials (sinter, coal, iron ore). The car body is a metallic bunker-like container with discharging doors in the lower part. In case of the need for discharging, they are opened to allow the bulk material to leave the car section by gravity.

The sinter carriers used in metallurgical production are open hopper cars top-loaded with ready-made sinter. The hopper body lining is made so that, unlike other types of hoppers, it has no rigid connection with the weight-bearing frame of the walls. This minimizes

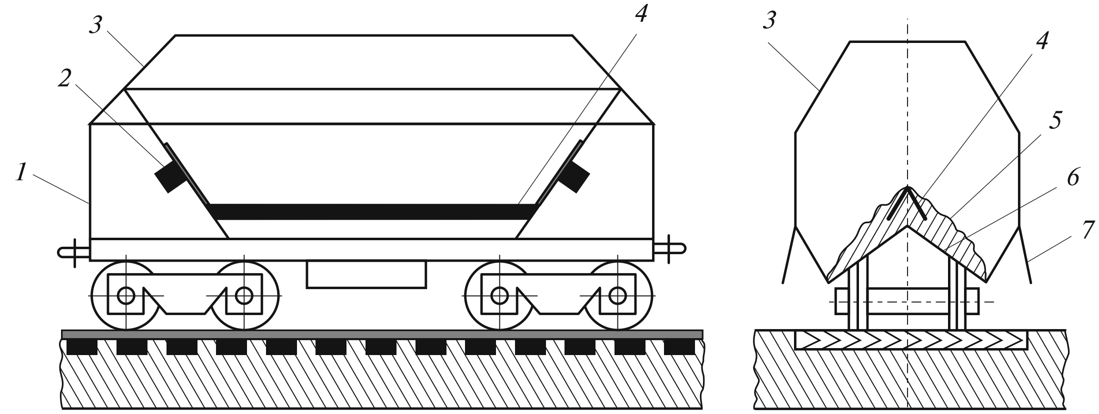

Fig. 1. Layout of an upgraded hopper car: (*1*) the body; (*2*) the vibrator; (*3*) the bunker; (*4*) the vibrating beam (vibrating batter board); (*5*) sinter arching; (*6*) the ridge beam; (*7*) the unloading hatch.

body buckling due to high temperatures and facilitates easy repairs of damaged parts.

Hopper cars are not self-mobile railroad vehicles and set in motion by a locomotive. Sinter carriers are used solely at industrial sites and do not leave their territories. Hopper cars for hot sinter are driven to the blast-furnace shop with the help of at least seven-car trains.

The raw materials are unloaded on both sides of the railroad tracks. The discharging process is fully mechanized without any manual cleaning of the hopper from the cargo residues. In terms of pouring the hopper cars used at sintering shops are side-discharged cars, with internal funnels spaced to the opposite sides and the wall tilt varying from 41° to 60°. This design ensures discharging by gravity. The hopper car is discharged on both sides of railroad tracks. The most popular hopper cars so far are cars 20-9749 for transporting hot sinter and pellets. These cars allow carrying up to about 31 cubic meters of sinter with a total weight of up to 62 tons.[1, 2]

The walls of hopper cars used for transporting hot sinter for many years are covered with dust that forms dust growths, and the arching effect is produced (Fig. 1). As a result of multiple shippings, the dust layer on the slantwise end walls turns thicker and denser. An especially intensive thickening and compaction process is observed in winter due to precipitation.

The compaction and thickening of the dust layer reduces the efficient space in the hopper car; in its respect, this raises the need for hazardous works to eliminate the dust from the internal part of the car. High dust content and risks of injury make these works very hazardous to human health.

The transporting of sinter in the cold period is attended by a heavy sticking of wet pieces onto the car wall and the ridge beam. As a result, they are stuck inside the hopper car, which can completely stop the egress of the material.

The hopper car for transporting hot sinter is cleaned manually. This kind of works is hazardous to human health because the car does not have any spaces inside that would allow conducting safe discharging procedures. Every time it is necessary to discharge the hopper car loaded with sinter, it is necessary to beat off frozen and packed materials with the help of a sledge hammer. This work is done by one or two persons and takes five to twenty minutes. In addition, the production of sinter is attended by the generation of dust containing bonded and free silicon dioxide, iron oxide, lime, and coke. 80–85% of the dust particles are smaller than 2 μm in size. Production dust is one of the unfavorable factors influencing human health. Sinter dust can cause problems with lungs and lung diseases (anthracosis, lithicosis, silicosis, asthma, lung cancer).

To eliminate the dust arching and sticking on the car walls, various methods of solving these problems were analyzed; as a result, it was proposed to expose sinter to vibration. The method has proven to be efficient in various production processes [18–22]. In this case, it has been decided to install the flat-plate vibrator onto the hopper car wall.

STUDY METHOD

The flat-plate vibrator can be fixed directly on the hopper car wall by welding. This kind of installation prevents hopper hangups; however, due to the heavy weight of the bunker, the wall vibration amplitude will not be enough for the efficient performance of the device. However, using more powerful vibrators will

[1] Reference album "Freight cars for 1520 mm gage railroads" URL: https://myrailway.ru/wagon/ (Accessed November 11, 2022.

[2] Hopper 20-9749 for hot pellets and agglomerate. URL: https://vagon.by/model/20-9749/ (Accessed November 1, 2022).

make the design far more expensive and the upgrade method will be inexpedient.

The installation of two false wall vibration devices together with a vibrating beam (see Fig. 1) is suggested for collapsing the dust that collects in hopper cars. The vibrating member of the false wall device is plate *2* (Fig. 2) mounted on the inner wall on flexible hangers *4* (round-link chain).

The plate and the hopper wall are separated with the help of a rubber-fabric conveyor belt used as rubber shock absorbers. The minimal conveyor belt thickness is 20 mm. The plate has a canopy above that does not allow the material to fall under the vibration plate. Vibrator *7* is mounted to the plate through support rack *6*. Batter board 1 welded to plate (false wall) *2* transfers the vibrations to the sinter.

The strength of this variant is that the vibrations are transmitted directly to the material, not to the car walls (when the vibrator is fixed on the wall). As a result, a high efficiency of eliminating compacted dust is ensured at a relative low power of the vibrator.

Connected to the mains, vibrators set false sheets in motion and the compacted dust on the end walls is eliminated. Together with this, the vibration batter board transmitting the vibration to the sinter near the ridge beam, which encourages a more intensive egress of the material from the bunker. Using this system allows giving up on works hazardous to human health as well as using the entire effective space of the car.

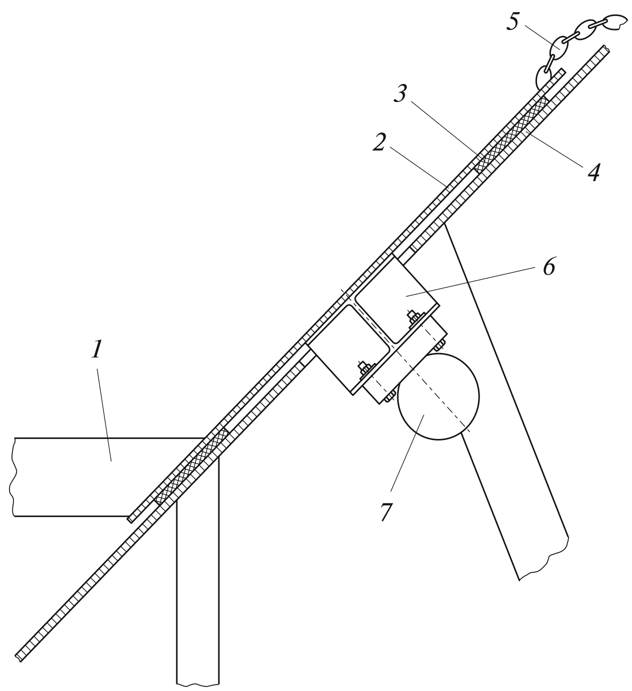

Fig. 2. False wall vibrating device: (*1*) the vibrating beam (vibrating batter board); (*2*) the plate (false wall); (*3*) the shock absorber (conveyor belt); (*4*) the bunker wall; (*5*) the chain; (*6*) the vibrator support; (*7*) the vibrator.

RESULTS AND DISCUSSION

The vibrator is a debalance centrifugal device with a coercitive force that is generated by the rotation of an inertia member. The vibrator is an electric motor with balance weights on the rotor shaft extensions. In rotary mode, these weights generate a centrifugal (coercitive) force. The vibrator's coercitive force is adjusted by changing the reciprocal position of the weights on both shaft extensions. The circular oscillations of the vibrator are transmitted to the structure, where the vibrator is installed.

A suitable vibrator is chosen by a required coercitive force value. It is recommended to discharge bunkers using vibrators with a frequency of 3000 min^{-1} (IV-01-50, IV-05-50, IV-11-50, IV-20-50, IV-40-50, IV-60-50; IV-98B 42 V). That said, coercitive force F_{cf} must be equal to about 1/5 of the weight of the material in the bunker cross section.[3,4] If two vibration devices are used, that is, on both sides of the bunker (see Fig. 1), the coercitive force for a vibrator is

$$F_{cf} = \frac{m_{aggl}}{5 \times 2} = \frac{62}{5 \times 2} = 6.2 \text{ kH},$$

where $m_{aggl} = 62$ t is the maximal weight of the sinter in the hopper car.

According to design coercitive force $F_{cf} = 6.2$ kN, the device chosen from the catalog is high-performance general-purpose flat-plate vibrator IV-98B-442 with techspecs that are shown below.[5,6]

The synchronous vibration frequency is 3000 min^{-1}; the maximal coercitive force at synchronous vibration frequency is 11.3 kN; the highest rated consumed capacity is 0.9 kW; the nominal voltage is 380 V; the current frequency is 50 Hz; the vibrator weight is 20 kg; the minimal MTTF is 700 h.

The vibrator uses a debalance adjustable vibration device and an induction three-phase electric motor with a short-circuited rotor.

At a synchronous rotation frequency of 11.3 kN, the coercitive force corresponds to GOST R 52776–2007 operating mode S3 40%, that is, repeated short-

[3] How to Select Vibrator That Generates Sufficient Vibration Depending on Its Application. Bunker Discharging. URL: https://www.antikorpokraska.com.ua/articles/26 (Accessed November 1, 2022).

[4] Application of Vibrators. URL: https://promvibrator.ru/ploshadochny_vibrator.html (Accessed November 01, 2022).

[5] Vibrator IV-98B 42 V. URL: https://yarvibro.ru/catalog/item/iv-98b-1185/ (Accessed November 1, 2022).

[6] Vibrator IV-98B 42 V. URL: https://rusvibro.ru/vibratory/ poverkhnostnye/obshchego-naznacheniya/iv-98b/ (Accessed November 01, 2022).

time operation with a startup period of four minutes and an idle period of six minutes. In some cases, however, the vibrator can run in extended operating mode S1 that corresponds to a coercitive force of 7.6 kN.

The advantage of the false wall consists in the direct transfer of vibrations and oscillations of precipitating dust on the hopper car walls, which reduces the necessary coercitive capacity of the vibrator. The false wall allows saving on the consumption of electricity and monetary expenditures on buying the vibrator. The false wall of 1000 × 2000 mm in size and minimal thickness of 10 mm is made from hot-rolled St3ps steel sheet [23].

To fix the vibrator to the false wall, a support member is needed, for example, a welded structure from rolled metal parts or a solid-cast support. Since welded seams are prone to failure and cracking at dynamic loads, which is typical at vibration loads, we choose the solid-cast support of grade 20H13L steel recommended for industrial applications, in particular, for manufacturing parts exposed to impact loads [24, 25].

The false wall is hung with the help of welded chains fixed on the car wall from the inside. A 13 × 36 round link chain widely used as a traction part or hangers is used [26].

The vibrating batter board is a metal section placed parallel to the ridge beam contour. The vibration of this member will contribute to a more intensive egress of sinter from the hopper car. Moreover, the vibrating batter board prevents the dust arching above the ridge beam. This board is made from 200 × 200 × 12 mm hot-rolled equilateral rolled angle [27]. Because of the lack of contact with the ridge beam, the damping of the angle is not required. The batter board will execute vibrating motion due to a rigid connection with false sheets that is ensured by electric-arc welding.

The additional capital expenditures needed for re-engineering the hopper car include the purchasing of vibrators and the fabrication and mounting of false walls, solid-cast supports. The total capital expenditures on logistics, buying the equipment and spare parts, and mounting of the new equipment for eight hopper cars do not exceed 350000 rubles.

CONCLUSIONS

The possibility of re-engineering hopper cars for transporting sinter and other bulk materials is considered, which includes the design of a vibrating device for removing sticky materials from the end walls and ridge beam of these cars. Engineering solutions for the designing of vibrating devices and their application in sinter production have been determined; respective units and components have been chosen and designed. The proposed investment project has been assessed for economic efficiency and payback. The adoption of the designed device reduces unscheduled downtime of hopper cars and allows giving up on bunker cleaning works hazardous to human health. The economic calculation confirms the expediency of the steps made for re-engineering hopper cars at modern metallurgical production enterprises.

REFERENCES

1. Efremov, D.B., Stepanov, V.M., and Chicheneva, O.N., Modernization of rapid pressing of DUO rolling stand rolls in mill 2800 of JSC Ural Steel, *Stal'*, 2020, no. 8, pp. 44–47.
2. Nefedov, A.V., Svichkar', V.V., and Chicheneva, O.N., Reengineering of skip lift for loading the furnace in foundry shop of JSC RIFAR, *Stal'*, 2020, no. 7, pp. 50–53.
3. Nefedov, A.V., Kitanov, A.A., and Chichenev, N.A., Reengineering of the roller hardening machine of the sheet-rolling shop of JSC Ural Steel, *Chernye Met.*, 2022, no. 3, pp. 22–26. https://doi.org/10.17580/chm.2022.05.04
4. Nefedov, A.V., Tanchuk, A.V., and Chichenev, N.A., Modification of car tippler drive at Donskoy Ore Mining and Processing Plant, *Gorn. Zh.*, 2022, no. 8, pp. 52–56. https://doi.org/10.17580/gzh.2022.08.07
5. Chichenev, N.A., Chicheneva, O.N., Karfidov, A.O., and Pashkov, A.N., Selection of laser processing parameters for hot stamping tools based on mathematical planning of the experiment, *CIS Iron Steel Rev.*, 2021, vol. 22, pp. 37–40. https://doi.org/10.17580/cisisr.2021.02.07
6. Mairkhofer, A., Fartl' F., Rorkhofer A., Shtol' K. Condition monitoring of equipment in steel production, *Chernye Met.*, 2018, no. 9, pp. 28–33.
7. Bardovskiy, A.D., Gorbatyuk, S.M., Keropyan, A.M., and Bibikov, P.Ya., Assessing parameters of the accelerator disk of a centrifugal mill taking into account features of particle motion on the disk surface, *J. Frict. Wear*, 2018, vol. 39, no. 4, pp. 326–329. https://doi.org/10.3103/S1068366618040037
8. Nefedov, A.V., Svichkar, V.V., and Chicheneva, O.N., Re-engineering of equipment to feed the melting furnace with aluminum charge, *Proc. 6th Int. Conf. on Industrial Engineering (ICIE 2020)*, Lecture Notes in Mechanical Engineering, Cham: Springer, 2021, pp. 1198–1204. https://doi.org/10.1007/978-3-030-54817-9_139
9. Chichenev, N.A., Reengineering of the slab-centering unit of a roughing mill stand, *Metallurgist*, 2018, vol. 62, nos. 7–8, pp. 701–706. https://doi.org/10.1007/s11015-018-0711-1
10. Gorbatyuk, S.M., Zarapin, A.Yu., and Chichenev, N.A., Modernization of vibration rumble of Katoka Mining Society (Angola), *Gornyi Inf.-Anal. Byull.*, 2018, no. 1, pp. 143–149.
11. Gorbatyuk, S.M., Morozova, I.G., and Naumova, M.G., Reindustrialization principles in the heat treatment of die steels, *Steel Transl.*, 2017, vol. 47, no. 5, pp. 308–312. https://doi.org/10.3103/S0967091217050047
12. Samusev, S.V., Fadeev, V.A., and Sidorova, T.Yu., Development of effective roll-pass designs for production

of longitudinally welded pipes of small and medium diameters, *Metallurgist*, 2020, vol. 64, nos. 7–8, pp. 658–664.
https://doi.org/10.1007/s11015-020-01042-4

13. Sekretov, M.V. and Gubanov, S.G., Experimental research of vertical feed drive loads in saw frame of strip sawing machine, *Gornyi Inf.-Anal. Byull.*, 2019, vol. 2019, no. 1, pp. 154–161.
14. Eron'ko, S.P., Gorbatyuk, S.M., Oshovskaya, E.V., and Starodubtsev, B.I., Development of automatic system of gas-dynamic cut-off of slag for converter with rotating vessel shell, *Izv. Vyssh. Uchebn. Zaved., Chern. Metall.*, 2017, vol. 60, no. 11, pp. 863–869. https://doi.org/10.17073/0368-0797-2017-11-863-869
15. Gorbatyuk, S.M., Pashkov, A.N., Morozova, I.G., and Chicheneva, O.N., Technologies for applying NiAu coatings to heat sinks of SiC–Al metal matrix composite material, *Mater. Today: Proc.*, 2021, vol. 38, part 4, pp. 1889–1893. https://doi.org/10.1016/j.matpr.2020.08.581
16. Busygin, A.M. and Stelmakhov, A.A., Mathematical model for determining kinematic parameters of a bulldozer ripper mechanism, *Proc. 8th Int. Conf. on Industrial Engineering. ICIE 2022*, Radionov, A.A. and Gasiyarov, V.R., Eds., Lecture Notes in Mechanical Engineering, Cham: Springer, 2022, pp. 131–141. https://doi.org/10.1007/978-3-031-14125-6_14
17. Rumyantsev, M.I., Some approaches to improve the resource efficiency of production of flat rolled steel, *CIS Iron Steel Rev.*, 2016, no. 2, pp. 32–36. https://doi.org/10.17580/cisisr.2016.02.07
18. Bridgwater, J., Mixing of powders and granular materials by mechanical means—A perspective, *Particuology*, 2012, vol. 10, no. 4, pp. 397–427. https://doi.org/10.1016/j.partic.2012.06.002
19. Weinekotter, R. and Gericke, H., *Mixing of Solids*, Kluwer Academic Publishers, 2000.
20. Dubey, A., *Powder flow and blending, Predictive Modeling of Pharmaceutical Unit Operations*, Pandey, P. and Bharadwaj, R., Eds., Woodhead, 2017, pp. 39–69. https://doi.org/10.1016/B978-0-08-100154-7.00003-X
21. Rogers, A. and Lerapetritou, M.G., Discrete element reduced-order modeling of dynamic particulate systems, *Am. Inst. Chem. Eng. J.*, 2014, vol. 60, no. 9, pp. 3184–3194. https://doi.org/10.1002/aic.14505
22. Bradley, R.K., Education in plastics manufacturing: Aluminum mold making and injection molding, *Int. J. Mech. Eng. Educ.*, 2022, vol. 50, no. 3, pp. 726–738. https://doi.org/10.1177/03064190211051105
23. *GOST* (State Standard) *19903–74: Hot-rolled flat products. Assortment*, 2005.
24. *GOST* (State Standard) *977–88: Steel castings. General specifications*, 2004.
25. *GOST* (State Standard) *5632–2014: Alloy stainless deformable steels and alloys—Corrosion-resistant, heat-resistant and heat-resistant. Grades*, 2005.
26. *GOST* (State Standard) *2319–81: Round link and traction chains of normal strength. General specifications*, 2004.
27. *GOST* (State Standard) *8509–93: Steel hot-rolled equilateral corners. Assortment*, 2005.

Translated by S. Kuznetsov