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A CLEANING OF INTERNAL SURFACES OF BUNKERS WITHOUT THE PRESENCE OF OPERATING PERSONNEL INSIDE THE BUNKER

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Abstract: *Bunkers are an integral part of the infrastructure of enterprises in various industries processing bulk materials. Corrosion processes and the formation of dust deposits on the internal surfaces of bunkers are irreversible and often lead to disruptions in the technological process and equipment performance parameters, and in some cases, to accidents. The stability and continuity of technological processes for processing bulk materials largely depend on the cleanliness of the internal surfaces of bunkers. Even the best technical characteristics of technological equipment only indicate the technical capabili-ties of the operation of technological lines. Their reliable and effective operation can be ensured by proper maintenance of the condition of internal surfaces and cleaning from corrosion and deposits. Increased dustiness, poor visibility, and confined spaces significantly complicate the conditions for performing work by service personnel inside bunkers. The enclosed space inside bunkers is a very dangerous place not intended for the work of service personnel. In order to avoid endangering ser-vice personnel and prevent people from entering the bunker, methods are proposed to easily, quickly, and, most importantly, safely clean the surfaces inside the bunkers.*
Keywords: *bunker, internal surface, deposits, corrosion, cleaning.*

1. The Problem and Its Connection to Scientific and Practical Tasks

A characteristic feature of technological processes in modern industrial productions that handle bulk materials is the presence of a significant number of containers, bunkers, and other equipment, the efficiency of which is determined by the condition of their internal surfaces. During the operation of bunkers, inevitable contamination of their internal surfaces with dust deposits occurs.

Most industrial equipment and bunkers are made of metal. The main cause of damage to internal surfaces, in most cases, is the deposition of dust and corrosion, the resistance to which determines the lifespan of the equipment.

Damages resulting from the deterioration of internal surfaces are not only associated with technological losses but also with the failure of bunkers and equipment, as it compromises their strength and tightness, leading to accidents.

Corrosion and dust deposits on the internal surfaces of bunkers compromise the cleanliness and smoothness of the walls, alter operational parameters, unloading efficiency, material flow, etc. In some cases, deposits and contamination on bunker walls disrupt the technological process, reduce process productivity, and can even lead to a complete production stop. For hazardous industrial facilities where bunkers operate in aggressive environments, the safety of technological processes and personnel may depend on the technical condition of bunkers rendered unsuitable due to dust deposits and damage to internal surfaces caused by corrosion.

Bunker walls are damaged by corrosion and erosion, and over time, they become less receptive to material impact than when new. This issue is particularly acute when working with abrasive materials. Abrasive wear of the surface layer must be removed to prevent it from spreading deeper into the bunker wall and weakening its structure [1, 2, 3].

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The solution to this problem is relevant for industries such as oil refining, chemical, construction, as well as for enterprises in the food industry, etc [4, 5]. The problem is especially relevant for mining and beneficiation plants and metallurgical enterprises with developed bunker facilities [6, 7]. Many bunkers can be found in grain processing plants, elevators, woodworking plants, and other large industrial facilities. Almost all bunkers with an operational lifespan of more than 5-10 years have deposits on their internal surfaces.

Removing dust from crushing plants, ore handling nodes, mine working supports, etc., is done through aspiration systems, which include bunkers, the internal surface of which rusts and is covered with dust deposits. During prolonged operation, the thickness of the adherent dust layer can reach tens of millimeters, changing the load parameters on the walls, causing deformation, and even damage. Eventually, this can lead to a bunker accident.

According to some researchers [1, 2], one of the main causes of bunker accidents is improper maintenance. The lack of regular technical inspections during operation and, as a result, the formation of dust deposits on the internal surfaces of bunkers can lead to negative consequences, as such structures have increased wear and tear of elements.

Practice shows that the wear of the lining immediately leads to the wear of bunker walls, a decrease in their thickness, and, accordingly, load-bearing capacity. On the other hand, the cause of bunker accidents can be the corrosion of its steel structures. Often bunkers operate in aggressive environments, such as bunkers for coke, agglomerate, salts, etc. The corrosion rate of unprotected areas in this case can reach up to 0.5 mm per year [2]. In some cases, it is impossible or very difficult to qualitatively apply anti-corrosion coating to surfaces in hard-to-reach areas inside the bunker [2].

In case of insufficient attention to the cleanliness of the internal surfaces of bunkers, corrosion of its structures can reach 60-80%, inevitably causing accidents. During bunker maintenance, it is necessary to clean its internal surfaces from corrosion and deposits. If this is not done, deposits transform into dense sediments, increasing the roughness of bunker walls, improving the adhesion of bulk materials, etc. The enterprise is forced to remove the bunker from the production process for the period of cleaning works. To save costs and reduce downtime, bunker cleaning is carried out by the enterprise's own efforts – with the help of production personnel. In this case, this type of work is labor-intensive, dangerous, and involves harmful working conditions [8].

Since corrosion processes and the formation of deposits on the internal surfaces of bunkers are irreversible and often lead to disruptions in the technological process and equipment performance parameters, cleaning deposits on the internal surfaces of bunkers without the presence of operating personnel inside the bunker is one of the important problems of modern industrial production.

2. Analysis of recent research and publications

A known method of cleaning deposits on the internal surfaces of bunkers without the presence of personnel inside the bunkers is proposed by the company Cardox International. This method involves the operation of three systems: Cardox, Mole and SiloWhip (Fig.1) [9].

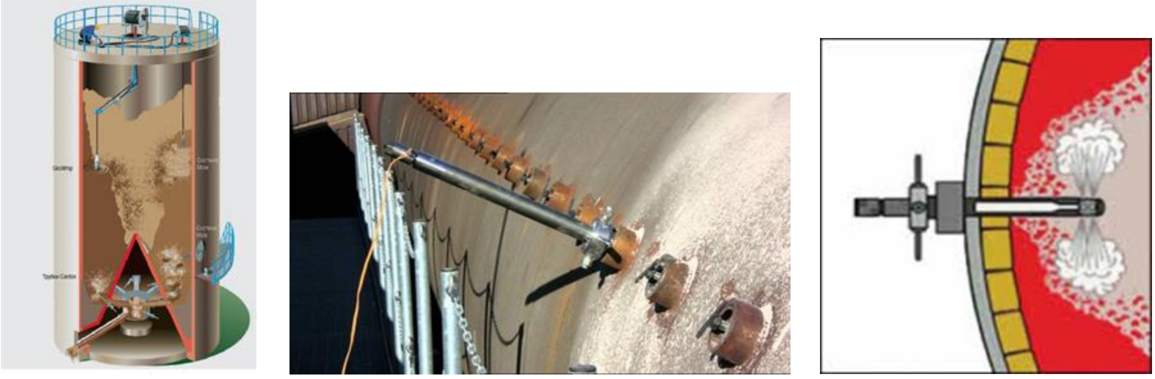

Fig.1. Cardox Systems in a Silo-Type Bunker

The Cardox system is utilized in numerous plants for removing solid deposits on bunker walls and around the discharge opening of various types of bunkers. The principle of the Cardox system involves the instantaneous transformation of liquid carbon dioxide into gas.

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Liquid carbon dioxide is contained in steel multiple-use tubes (similar to fire extinguishers), which are installed through the external wall into the material deposited on the bunker walls. The tubes are securely fixed in socket devices attached to the external surface of the bunker. With a small electric charge, the chemical heater instantly converts the liquefied carbon dioxide gas into a gaseous state. This phase transition leads to an increase in the volume of carbon dioxide gas and an elevation of pressure inside the tube, causing the rupture disc at the end of the tube to break. This results in the release of carbon dioxide gas in a quantity 660 times greater than the volume of carbon dioxide gas in its liquid state. The released carbon dioxide gas exits through a special head under pressures up to 3000 bar and moves in various directions. Due to the powerful action of the gas from the Cardox tubes, the deposited material is crushed and separated from the wall. This entire process takes only a few milliseconds.

Carbon dioxide gas is inert, making it safe for use without the risk of secondary reactions with gases in vessels or bunkers. Additionally, the rapid release causes cooling of the gas discharge, reducing its temperature to levels low enough to prevent ignition of any air-gas mixture in a confined space.

The Mole system is a device equipped with a specially adapted Cardox tube that directs this tube directly into the deposits. The tube is then activated to remove the material, after which the device is pulled outward. This device can be introduced through hatches located on the walls or in the upper part of the bunker, or through the bunker's discharge opening.

The SiloWhip system operates on a hydraulic principle, making it much more powerful than pneumatic devices. Bunker cleaning is done using a suspended (up to 50 m) hydraulic cutter that rotates 360 degrees clockwise and counterclockwise. The rotation speed is adjustable. This system is safely operated from the top and external sides of the bunker, thus eliminating the need for workers inside the bunkers. The system effectively breaks down accumulations of all types of materials (cement, clinker, agricultural products, lime, etc.).

There is also a known method of cleaning deposits on walls without the presence of workers inside the bunkers, proposed by Standard Industrie International. For cleaning bunkers and other containers, the company has developed a unique innovative Gironet system, ensuring complete human safety (Fig.2) [10].

Fig.2. Gironet System for Bunker Cleaning

The control unit of the Gironet system (Fig.2) consists of three main components: the base block, the drum for winding the hose, and the pneumatic installation. Attached to them are the control block, the elbow, and the motor with rotating chains. The hinged lever elbow rotates 360°, ensuring effective cleaning of all types of bunkers with different diameters up to a depth of 45 meters.

Depending on the hardness of the material, Gironet systems are used in pneumatic or hydraulic versions. The cleaning motor operates at a pressure of 6-7 bar, and the working flow is 360 m^3/h. The Gironet system comes with various attachments (steel and brass chains, plastic brushes for thin layers, polyamide belts) for cleaning concrete, metal, and even lined containers. Attachments are attached to the motor and rotate at speeds of 2500 and 3000 rpm (for pneumatic and hydraulic versions, respectively), breaking up the material on the bunker walls.

The mechanism, consisting of a hinged lever and a cleaning motor, is located inside the silo (bunker). The operator controls the Gironet system devices from the top of the bunker using a remote control setup.

The Gironet system is fully mechanized and remotely controlled, ensuring safety during these operations, as the operator does not need to be inside the container.

The Gironet system is entirely made of aluminum, and the chains are made of brass to prevent the risk of sparks when working in explosive zones. A similar method of cleaning deposits on the internal surfaces of bunkers without the presence of workers inside the bunkers is proposed by Martin Engineering (Fig.3) [11].

Fig.3. Martin Engineering Bunker Cleaning System

The cleaning device is hydraulically driven and is installed on the bunker's roof. Monitoring the cleaning process through a regular inspection opening, a technical worker remotely controls the cleaner's motor, located inside the bunker. Steel or brass chains or plastic whips, depending on the material properties, are used as impact tools attached to the motor.

Despite the advantages, these devices have some drawbacks. Hydraulic cleaning systems involve significant water and energy consumption. The separated material mixed with water forms sludge, leading to the need for a water supply recycling system (settling tanks, transfer pumps, etc.), thus increasing the cost of cleaning. Moreover, the use of water for metal bunker cleaning increases the corrosive wear of metal structures, especially in the presence of aggressive gases. Additionally, hydraulic cleaning systems are limited in their use during winter and transitional seasons when the air temperature is below 0°C.

Pneumatic cleaning systems, based on their principle of operation, are less powerful than hydraulic systems and are effective in cleaning surfaces with a thick layer of material. However, such systems cannot provide cleaning of metal surfaces from corrosion.

An established method for cleaning internal bunker surfaces involves the controlled use of explosive substances such as dynamite, explosive mixtures, and detonating cords, which are strategically placed in areas requiring cleaning. Cleaning is achieved through the combined impact of shock waves, acoustic vibrations, and surface vibration.

A drawback of this method is the generation of powerful explosive energy during detonation, which can damage bunker structures. Precision is crucial in determining the charges, and the application of explosive substances is challenging when dealing with active equipment.

Another known method for cleaning technological surfaces (electrostatic precipitators, scrubbers, bunkers, silos) utilizes shockwave-generating explosive mixtures formed by the explosion of a gas-air mixture consisting of a combustible gas (e.g., propane, methane, hydrogen) and an oxidizer, such as air or oxygen [12].

The disadvantage of this method is that the explosive gas-air mixture is injected into a plastic bag, which must be placed inside the bunker without damaging its integrity, posing certain difficulties. Additionally, the integrity of the pipes used to inject the gas-air mixture into the bag must be maintained to prevent the formation of an explosive mixture outside the bunker.

3. Problem Statement

Bulk material processing technologies involve the use of various machines, mechanisms, devices, and structures. In this context, one indispensable technological operation is material storage. Bunkers are an integral part of the infrastructure of enterprises processing bulk materials. The stability and continuity of bulk material processing operations depend significantly on the cleanliness of the internal surfaces of bunkers. Even the best technical characteristics of technological equipment only indicate the technical capabilities of processing lines. Their reliable and efficient operation can be ensured by proper care for the condition of internal surfaces and cleaning from corrosion and dust deposits.

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However, elevated dust levels, poor visibility, and enclosed spaces significantly complicate the working conditions for service personnel inside bunkers (Fig.4).

Fig.4. Working conditions during bunker maintenance

The enclosed space inside bunkers is a highly dangerous area not intended for servicing personnel. Bunkers often have a reduced opening (hatch) and are characterized by limited air exchange with the external environment, which can be either very low or completely absent. The lack of air exchange makes the enclosed space suitable for storing bulk materials but hazardous for servicing personnel. Unfortunately, this characteristic also affects the dispersion of dangerous gases in the space.

To avoid endangering servicing personnel and prevent their entry into the bunker, it is necessary to search for justified methods of cleaning the internal surfaces of bunkers.

Therefore, cleaning deposits on the internal walls of bunkers without the presence of servicing personnel inside the bunker is one of the important issues in modern industrial production.

4. Presentation of the material and results

Deposition of dust on the internal surfaces of bunker results from the adhesion and autoagglomeration of dust particles [13]. Adhesion of particles occurs at the initial stage when particles adhere to the clean internal surfaces of the bunker, forming a monolayer of dust. The interaction of particles with surfaces is mainly governed by molecular and electrical forces, and in the presence of moisture (air or dust), capillary forces also come into play.

Adhesion forces depend significantly on the nature of the dust, the size and shape of its particles, the humidity of the air and dust, as well as the nature of the material and roughness of the bunker walls' surfaces, and their temperature [14, 15]. For example, particles adhere better to cold internal surfaces than to hot ones. The enrichment of the monolayer of dust with fine particles, which strongly adhere to the surface, enhances adhesion [16]. Enrichment of the monolayer of dust occurs because larger particles are more easily dislodged from the surface by the airflow, and their place is taken by fine particles. As a result, a monolayer of dust consisting of fine particles forms on the walls of the bunker, which is challenging to remove without mechanical intervention. The smaller the particle size, the larger the contact surface, and hence dust particles deposit better on surfaces.

The thickness of the monolayer of dust on the internal surfaces of the bunker corresponds to the size of fine particles. In this case, the dust layer on the internal walls of the bunker promotes autoagglomeration of dust, leading to the adhesion of dust and an increase in the size of deposits. The adhesion of dust to the bunker walls depends on the properties of the material, the particle size, the dust humidity, temperature, and other factors [13].

Autoagglomeration of dust (particle agglomeration) is determined by molecular, cohesive, mechanical, and electrical interactions. The presence of moisture contributes to the emergence of capillary forces.

Molecular interaction forces are characterized by Van der Waals forces, which manifest between molecules at a distance ranging from one to several hundred times their diameters. These forces depend on the nature of the dust, the shape and size of particles, and the distance between the particle and the surface [13].

Cohesive interaction forces manifest when particles come into contact with each other, but their presence is conditioned by external forces capable of disrupting adsorption and oxide films that impede cohesion. Cohesion is the connection between molecules (atoms, ions), leading to the formation of an aggregate (a single body). Cohesive forces also act in the formation of "bridges" between particles, for example, during sintering, crystallization, and other physicochemical transformations in the contact zone.

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Electrical interaction forces consist of Coulombic and electric forces. Coulombic forces manifest in the presence of excess charges on dust particles. Electric forces arise from the potential difference between individual charged particles that come into contact. Most dust particles have electric charges formed due to friction of particles against the surface or the medium they move in, or due to friction with other dust particles, or when particles enter an electric field or adsorb ions from the air.

When particles collide with a surface, electric charges on the particle surface attract charges of opposite sign and varying magnitudes on the surface. Mechanical interaction forces are characteristic of a large number of irregularly shaped particles constituting a dust layer. Mechanical coupling occurs when the particle shape deviates from a sphere. The emergence of mechanical coupling forces is due to the mechanical interaction between neighboring particles, forming a supportive force. The more complex the particle shape, the higher the likelihood of mechanical coupling and, consequently, agglomeration. Plate-shaped dust particles exhibit an increased tendency to agglomerate due to the significant contact area between two particle surfaces.

Capillary forces manifest when the humidity of the dust increases. Research data indicate that capillary forces appear at relative air humidity above 65% [15]. If the dust is not sufficiently saturated with moisture, the liquid in the pores attempts to bind particles together through capillary pressure forces. In the case of complete saturation of the dust with moisture, droplets with solid particles inside form, maintaining their shape due to surface tension forces. Therefore, moistening the dust enhances particle agglomeration, regardless of their dispersity, shape, and other properties.

Molecular and electrical interaction forces occur independently and are characteristic of both individual particles and a large number of particles (dust layer). Cohesion and capillary interaction forces are also characteristic of both individual particles and a large number of particles, but their appearance requires specific conditions: external forces pressing particles together or the presence of moisture. Mechanical coupling forces and capillary pressure forces (in the case of filling the pores of bulk material with liquid) are characteristic of autogenous agglomeration only in a large number of particles.

Thus, dust autogenous agglomeration can be influenced by the simultaneous interaction of all forces that ensure the strength of individual contacts between particles. However, simultaneous interaction of capillary and electrical forces is impossible, as an increase in humidity increases the number of neutrally charged particles.

Therefore, cleaning the internal surfaces of bunkers from adhered dust is associated with overcoming adhesion and autogenous agglomeration forces, which depend on both the properties of the contacting bodies and the properties of the surrounding environment.

To avoid exposing personnel to danger and prevent access to the bunker during cleaning, methods are proposed for easy, quick, and, most importantly, safe cleaning of internal surfaces within bunkers.

For cleaning the internal surfaces of bunkers with bulk materials, a method involving the use of abrasive kinetic elements is proposed. The proposed method is implemented as follows. After emptying the bunker of bulk material, kinetic elements, such as irregularly shaped gravel, are loaded into the bunker in an amount equal to the bunker's volume. In this case, the fraction size of the gravel should exceed the thickness of the dust layer deposits on the bunker walls.

If the fraction size of the kinetic elements is smaller than the thickness of the dust layer deposits, their kinetic energy will be insufficient to overcome adhesion forces, and the kinetic elements' particles will be retained on the surface of the dust layer by mechanical coupling forces. In other words, the achieved level of cleaning the bunker from dust deposits will remain unknown.

During unloading of gravel from the bunker, its fractions start moving downward under their own weight, and with the abrasive surface, they scrape off the dust layer deposits from the bunker walls, overcoming the adhesion forces of dust particles to the bunker's surface.

Unloaded gravel, after washing with water, can be reused as kinetic elements for bunker cleaning or for other purposes.

Practical implementation of the proposed method allows for effective cleaning of the internal surface of bunkers from dust deposits and reduces costs for cleaning work. The method of cleaning the internal surfaces of bunkers can be used in all containers where bulk materials are unloaded.

Additionally, a method for cleaning deposits on the internal surfaces of bunkers using shock airwaves generated by a high-voltage source is proposed. The proposed method is implemented as follows. Electrodes are placed inside the bunker, and a high voltage is applied to them. The electric discharge generates a shock airwave that facilitates the breakdown and cleaning of deposits. The high-voltage supply is applied sequentially, starting from the electrodes installed in the upper part of the bunker (Fig.5).

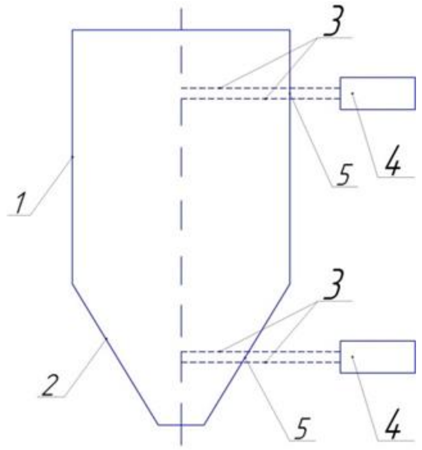

Fig.5. Diagram of cleaning deposits inside the bunker
1) bunker; 2) funnel; 3) electrodes; 4) high-voltage power source; 5) opening

The installation consists of a bunker 1, a funnel 2, electrodes 3 placed inside the bunker 1 through openings 5, and a high-voltage power source 4 to which electrodes 3 are connected. The high-voltage power source 4 is sequentially connected to electrodes 3, applying high voltage to them. An electric discharge occurs between electrodes 3, generating a shock airwave that propagates in the bunker cavity in all directions.

Acting on the deposit layer, the shock airwave induces a wave of pressure and a reflected wave within it, breaking the strong bonds between particles, pulverizing them, and detaching them from the walls of bunker 1. Subsequently, electrodes 3 are moved to other openings located at lower marks in the funnel 2, and the cycle repeats.

The distance between electrodes depends on the intensity of the shock airwave, the physico-mechanical properties of deposits (dust, rust), the size of the bunker, etc., and can be experimentally determined after the first discharge and inspection of the internal surfaces.

5. Conclusions

It has been demonstrated that corrosion and the formation of deposits of dust on the internal surfaces of bunkers are irreversible processes that often lead to disruptions in technological processes and equipment performance, and in some cases, to accidents. The stability and continuity of bulk material processing technological processes largely depend on the cleanliness of the internal surfaces of bunkers. It has been proven that cleaning the internal surfaces of bunkers from adhered dust involves overcoming adhesion and autogenous agglomeration forces, which depend on both the properties of contacting bodies and the properties of the surrounding environment. Methods have been proposed that allow for easy, quick, and, most importantly, safe cleaning of surfaces inside bunkers without the presence of personnel inside the bunker.

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