ATLANTIS PRESS
Advances in Economics, Business and Management Research, volume 129
III International Scientific Congress Society of Ambient Intelligence 2020 (ISC-SAI 2020)

Ways to Activate Sludge Thickening for the Purpose of Implementing 4.0 Technologies in Industrial Enterprises

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ABSTRACT
Based on the analysis of the circumstances of formation, collection and transportation of significant sludge volumes to the place of their storage, the possibility of a significant reduction in the tailings areas as well as infiltration of sludge deep into the soils and their pollution with inorganic substances is considered. The methodology is based on the analysis of the physics of the process of stable sludge separation into a solid and liquid component as well as the activation of the sedimentation process of particles contained in the slurry suspension both in its static state (when stored in sludge storages) and during the movement of sludge from the place of formation to the storage place. The regularities for calculating solid phase sedimentation rate both in statics and motion on the basis of influence of initial solids concentration and dynamic water viscosity on sedimentation have been obtained and proved. The scientific novelty of the work lies in the fact that a formula for determining the dependence of the deposition rate on the hydrodynamic conjugation of particle motion in the direction transverse to the fluid flow depending on the type of flow determined by the Reynolds number has been found. The practical value consists in defining the sludge solid phase deposition rate in statics and dynamics as a result of influence of solids concentration and dynamic water viscosity.
Keywords: *slurry suspension, viscosity of the medium, deposition rate, activation of the process, dynamic viscosity*

1. INTRODUCTION

About 2-2.5 billion tons of mineral resources are exploited annually in Ukraine of which approximately 90% are converted into wastes. The total amount of wastes accumulated in the country exceeds 30 billion tons. They are located in dumps, tailings ponds, sludge pits, landfills with the total area of more than 180 thousand hectares, and this area is increased by 3-6 thousand hectares each year. The main sources of industrial wastes in Ukraine are the enterprises of mining, metallurgical, energy, and chemical industries. The accumulated mass of wastes degrades natural resources quality and eliminates them numerically, primarily arable land, surface water and groundwater.

Dust and sludge form about 20% of the total amount of wastes. Over 70 million tons of sludge has been accumulated at Ukrainian steelmaking enterprises, of which 21 million tons are recyclable. [5]

The chemical composition of metallurgical sludge is shown in table 1. The dispersion of all chemical basic values is sufficiently large but does not exceed $\sigma c < 0.4$.

Sintering sludge can be characterized as having the highest iron content (up to 60% of the mass), and the lowest one is in blast furnace sludge (up to 30%). Metallurgical sludge is used partially as a component of the charge in the agglomerate production, but most of it remains in the sludge storage. According to the State Science Technical Center "Energostal", 30 million tons of metallurgical sludge has been accumulated in the sludge storage facilities of Ukrainian metallurgical plants. It contains about 15 million tons of iron.

The problem of wastes can only be solved on the basis of the complexity of primary and secondary use of raw materials, as a result of the low-waste technologies introduction, increasing the level of inter-sectoral cooperation, coordination of scientific work in the field of industrial waste utilization and environmental protection.

Huge volume of water circulation and excess masses of contaminated mine and industrial water occur in the Kryvyi Rih basin. Industrial water is improved by diluting with high-quality drinking water, which is quite limited. From our point of view, drinking water is the basic resource of civilization, and we must make every effort to limit its improper using. We think it can be done exclusively by reducing the mineralization of the liquid part of the sludge.

Wastes can be classified by phase composition, that is into solid ones (dust, sludge, slag), liquid solutions (solutions, emulsions, suspensions), gaseous wastes (oxides of nitrogen, carbon, sulfur compounds, etc.), as well as according to production cycles: enrichment wastes (tails, sludge, overflowers), the ones produced in pyrometallurgy (slags, sludge, dust, gases), and in hydrometallurgy (solutions, precipitation, gases). [5]

A waste containing a large amount of water is formed in the process of iron ore enrichment and is a by-product that includes part of the crude ore volume that is processed.

Enrichment waste is divided into waste from current production that has not yet been discharged into the sump after ore dressing, and waste from tailings, the grain size of which is different and depends on the place of their selection. The waste of current production in grain composition is a fine-grained material containing 70-75% of grains with the size of 0,085-0, 16 mm and 7,7-17,3% of grains with that of 0,16-3,0 mm. In grain composition they are approximately the same for all mining and processing plants. This is due to the same technological process and production equipment of the enrichment factories. Waste from tailings is more coarse-grained in the coastal part of the repositories and are not the same at different plants. These products are quartz-ferrous raw materials with a bulk density of 1060-1700 kg/m^3, depending on the content of iron ore minerals.

Table 1 Chemical composition of metallurgical sludge according to the main components

Sludge	Mass fraction of components %					
	Fe tot.	**CaO**	**Si0$_2$**	**M$_g$0**	**C tot**	**Zn**
of sintering factories	55,5-60	4,9-5,5	6,5-9,6	0,75-1,2	1,7-3,5	0,02-0,1
of gas purification domain furnaces	30-50	5,0-8,5	6,0-12	1,5-2,0	2,5-30,0	0,05-5,3
of Bunker premises domain furnaces	33-35	8-28	7-11	1-3	15,0	0-0,02
of open-hearth furnaces	58-60	3,0-5,5	3,1-5,0	0,87-2,65	1,8-4,65	1,9
of gas purification converters	43,0-45,0	15,0-16,0	3,0-4,0	6,0-6,5	3,2-4,0	0,74
of stockpiled metallurgical sludge	39,0-52,8	7,8-9,6	4,2-10,4	2,77-4,14	2,41-14,66	1,9-3,7

Full-cycle metallurgical waste (cast-steel-rolled metal) can be of two types: dust and slag; wet gas cleaning is often used, then dust is represented by sludge.

Sludge of metallurgical production can be divided into: sludge of metallurgical plants, and, separately, gas purification of blast furnaces, bunkers of blast furnaces; gas purification of open-hearth furnaces; gas cleaning of converters; electric furnaces.

According to iron content they are divided into: iron rich (55-67%) - gas purification sludge of open hearth furnaces and converters; relatively rich one (40-55%) - sludge of blast furnace production; poor one (30-40%) - gas purification sludge of electric smelting production.

The main characteristics of sludge are chemical and particle size distribution; however, when preparing sludge for disposal, it is necessary to know their parameters such as the apparent density of the solid component, humidity, specific yield, etc.

Sludge from dust-collecting devices of blast furnaces is generated when cleaning gases, usually in scrubbers or Venturi pipes. Radial or tangential dry dust collectors are installed before them, which capture the largest blast furnace dust that is returned to sinter production as a component of the charge.

The chemical composition of the solid part of such sludge by major components, is the following (%): $Fe_{tot.}$ 30-50;

CaO 5,0-8,5; SiO_2 6,0-12; $A1_2O_3$ 1,2-3,0; M_gO 1,5-2,0; P 0,015-0,05; $S_{tot.}$ 0,2-0,9; $C_{tot.}$ 2,5-30,0; Zn 0,05-5,3.
The relative density of the solid part of the sludge fluctuates within (2.7.....3,8)x10^3 kg/m^3. The utilization rate of this sludge varies (for different companies) quite significantly - from 0.1 to 0.8. They are used as an additive to the sintering charge. The comparatively low level of their use is explained by the relatively low proportion of iron in them (Fe <50%), as well as the increased zinc content (> 1%), which requires preliminarily dezincification of sludge.
Ore and foundry yards are also the source of blast furnace dust. In the ore yard, dust is emitted when unloading wagons, reloading ore, feeding ore to the bunker trestle, etc. Specific dust emission in the ore yard is approximately 50 kg per 1 ton of pig iron, and on the bunker overpass it is 20 kg per 1 ton of pig iron. The concentration of dust in the ore yard and bunker trestle ranges from 20 to 1000 mg/m^3. After cleaning, an average of about 90 g of dust per 1 ton of pig iron is emitted into the atmosphere.
The sludge of the sub-bunker rooms of blast furnaces is formed during the hydraulic cleaning of spills from the floors. Dust from the suction units of these rooms is also an integral part of this sludge. In its chemical composition this sludge is similar to the sludge of sinter factories as it has all the components of sinter. The sludge of the bunker rooms (solid part) in terms of particle size distribution is medium size materials (particles with a size of 0.063-0.1 mm consist 20-40%). The relative density of the solid part of the bunker rooms sludge varies within (3,5-4,5)x10^3 kg/m^3. This sludge is commonly used as an admixture to the sintering charge. [3-6]
In fact, the use of sludge in conjunction with activated peat in sinter production has become the most significant technical solution in the field of metallurgical charge production in the last 25 years. [6]
The priority tasks of Ukraine in the field of waste management are:
- inventory, complete assessment of the volume and cost of accumulated industrial wastes, creation of their problem-oriented classifiers;
- development of industrial waste management strategy, stimulating the enterprise to create low-waste schemes for their processing and sale of processing products in the cross-sectoral market;
- determination of ecological and economic damage to the environment, which is applied and prevented before and after the introduction (use) of the developed technologies.

The research problem consists in intensification of the deposition rate with a simultaneous decrease in the sludge store areas and an increase in the sludge initial height in the store; specification of the circumstances for the complete retention of the sludge solid part as well as the exception of sludge storages using.
Currently applied mineral processing technologies use magnetic separation at the final stage and involve high consumption of process water, reaching up to 4.5 ... 5.5 m^3 per ton of enriched ore (concentrate), which forms some slurry in a mixture with solid magnetic separation waste.
The formation of such volumes of sludge involves significant costs for their movement to the place of their storage called tailings.
At large metallurgical enterprises of a full cycle (for example, PJSC ArcelorMittal Kryvyi Rih), the functions of tailings are combined with the corresponding functions of slurry pits, in which the product formed during the cleaning of premises and equipment of technological shops and the waste part of the enrichment process are stored and prepared for subsequent disposal. [1-4]
The distinctive feature of mechanical mixtures of tailings and sludge (pulps) is the low concentration of the solid component in them. When such a mixture interacts with the bottom of an artificial or natural container into which it merges, it infiltrates, penetrates deeper into the soil through natural pores, and contaminates it with inorganic substances. After some 2 or 3 years of soil interaction with a suspension artificially introduced into it, its physical and biological properties degrade and its full-scale recultivation becomes impossible (under recultivation, we mean the possibility of using land in agriculture upon completion of their use for pulp storing).
The limitation of the areas allocated to technological reservoirs (sedimentation tanks) is possible due to the acceleration of the mixtures sedimentation processes, and, as a result, the area of land occupied by the reservoirs can be decreased significantly. The deposition rate, in this case, should be increased in proportion to the decrease in the area used.
Our experimental studies have shown that a significant reduction in the areas allocated to sedimentation tanks can be achieved by generating a vibration field in the column of the medium (sludge, slurry) on the surface of the slurry pit from a vibrating surface moving along the body of the pit-store.

2. BACKGROUND

The main type of force action on solid particles during the deposition process is the action of gravity, as well as a cyclone process, that is sedimentation and deposition under the influence of centrifugal forces. [5-6]
Settling is applied in industry for suspension thickening or classifying them by fractions of solid particles, as well as for emulsions separating. Due to the low driving force (gravity) in the process of settling, only large chats can be separated with sufficient efficiency. It is this method of clarification of mine and process water that is used in mining and mineral raw materials processing enterprises of Kryvyi Rih. The advantage of settling is the minimum unit energy consumption for the process.[7-8].
Any decrease in the area allotted for technological reservoirs (sedimentation tanks) is possible only with an increase in the process of suspensions sedimentation. The most effective way to control the energy of the deposition process is to create a field of centrifugal forces within the suspension. Thus, the activation of the process of suspension particles deposition during its continuous movement, is possible only while maintaining the

rotational movement of its flow with given geometric and speed characteristics.

A centrifugal effect can be created either by forcing a fluid flow to run along a twisted channel of a certain curvature and roughness (cyclone process), or by passing a fluid flow through a rotating container (centrifugation process).

The physics of the process of stable separation in the field of centrifugal forces by rotation at an angular velocity ω, is determined by the equality of the hydrodynamic resistance forces of the deposited particle and the centrifugal force. [10]

We assume that gravity does not act in the separation plane (the flow rotates around its central vertical axis). In this case the inertia force acting on the flow mentioned, taking into account the influence of the Archimedean force, refers to the forces of volumetric action. Then the following normal separating force N acts on the particle:

$$N = \frac{\pi d^3}{6} \cdot \omega^2 r(\rho_h - \rho_v) \quad (1)$$

where d is the particle size; r is the radius of rotation of the particle in the fluid stream; ρh is the particle body density; ρv is the fluid density; ω is the angular velocity of rotation of the fluid containing the particle.

The resistance force to the steady deposition of a particle in the radial direction depends on the midship area of the particle and will be:

$$R = c_x \frac{\pi d^2}{4} \cdot \frac{\rho_v \cdot v^2}{2} \quad (2)$$

c_x is the empirical coefficient of resistance to particle motion; v is the rate of steady-state deposition of a particle in a liquid.

The steady-state deposition process in the field of centrifugal forces is determined by the balance of the separating force and the resistance force:

$$N - R = 0$$

After the corresponding formulation, we obtain the equation:

$$\frac{\pi d^3}{6} \cdot \omega^2 r(\rho_h - \rho_v) = c_x \frac{\pi d^2}{4} \cdot \frac{\rho_v \cdot v^2}{2} \quad (3)$$

From equation (3), the deposition rate is determined under the action of centrifugal force taking into account the Archimedes force:

$$v = \omega \sqrt{\frac{4}{3} \cdot \frac{d}{c_x} \cdot r \cdot \left(\frac{\rho_h}{\rho_v} - 1 \right)} \quad (4)$$

The main difficulty in calculating the deposition rate according to formula (4) is that it includes the coefficient of hydrodynamic resistance to particle movement in the direction transverse to the fluid flow (deposition occurs across the flow). This coefficient is empirical in nature and depends on the type of flow flowing around the moving particle. With laminar flow, this coefficient is less than with turbulent flow, and is determined by the criterion of the movement mode (Reynolds number):

$$\mathrm{Re} = \frac{v \cdot d \cdot \rho_v}{\mu_v} \quad (5)$$

where μv is the coefficient of dynamic viscosity of water.

The dynamic viscosity coefficient depends on the water temperature (t^0C) and the concentration of solid particles in the pulp.

Experimental data show the dependence correlation of the resistance coefficient on the solid particles concentration in the pulp:

- at Reynolds number Re ≤ 1.85; $c_x = \frac{24}{\mathrm{Re}}$; (6-a)
- at Reynolds number of 1.85 <Re <500 $c_x = \frac{18.5}{\mathrm{Re}^{0.6}}$; (6-b)
- at Reynolds number Re ≥ 500 $c_x = 0.44$. (6-c)

It is obvious that for small particles with a size of several microns (Re ≈ $5 \cdot 10^{-5}$), which are required to clarify industrial water, the (6-a) expression is applicable. In this case, expression (4) is converted to the form:

$$v = \frac{d^2}{18\mu_v} \cdot \omega^2 \cdot r \cdot (\rho_h - \rho_v). \quad (7)$$

Thus, within the process of clarifying process water by means of a centrifugal force field, the deposition rate depends on the particle diameter, the angular velocity of the rotational motion of the flow carrying the particle, and on the radius of the particle rotation.

Analysis (7) shows that for the deposition of mineral particles, the use of the cyclone method is sensible only for particle sizes d> 350 ... 500 microns.

The dependence of the particles deposition rate of 1, 5, 10, 100 microns size on the working body frequency of rotation with a radius of 1 m is shown in **Figure 1**.

Figure 2 shows the dependence of the time of particles deposition with a size of 50 microns (with a radius of a rotating tank with slurry of 1 meter) on the rotation frequency of the working body.

Figure 3 shows the dependence of the working body length of a centrifugal precipitation apparatus at an axial velocity of the flowing sludge stream of 1 m per second and various flow thicknesses (0.1, 0.2, ..., 0.5 m) for particles with a size of 50 microns on the speed of the working body rotation.

With a water layer thickness of 0.5 m and its axial velocity of 1 m/s, the productivity of the device is about 3 $м^3$/s.

The separation of solid particles in the thickness of the stream during the movement of the mixture along the bend of the pipeline is shown in **Figure**. **4**.

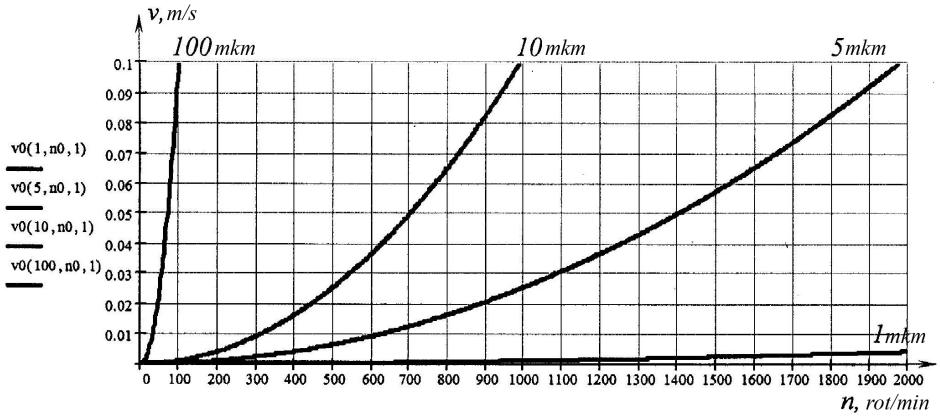

Figure 1 The dependence of the particle deposition rate on the working body with a radius of 1 m on the speed of the centrifuge, and the particle size

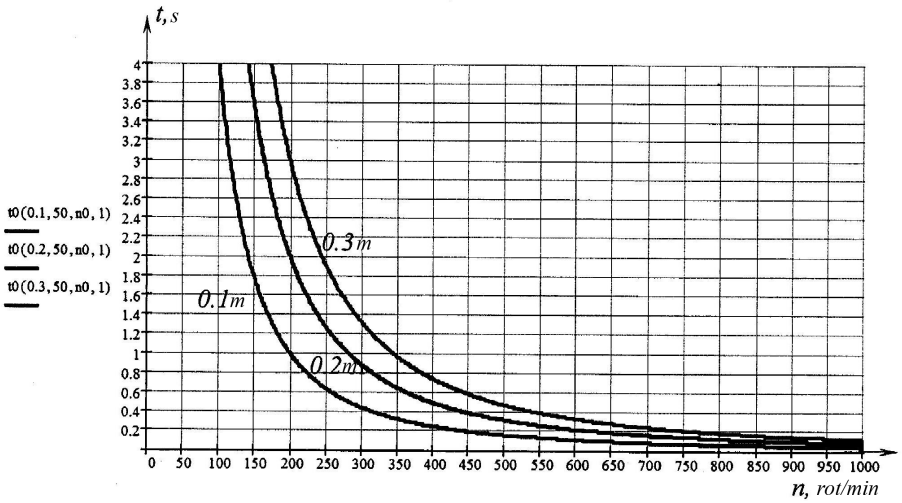

Figure 2 The dependence of the time of particles deposition on the working body with a radius of 1 m on the centrifuge speed at different thicknesses of the water layer in it.

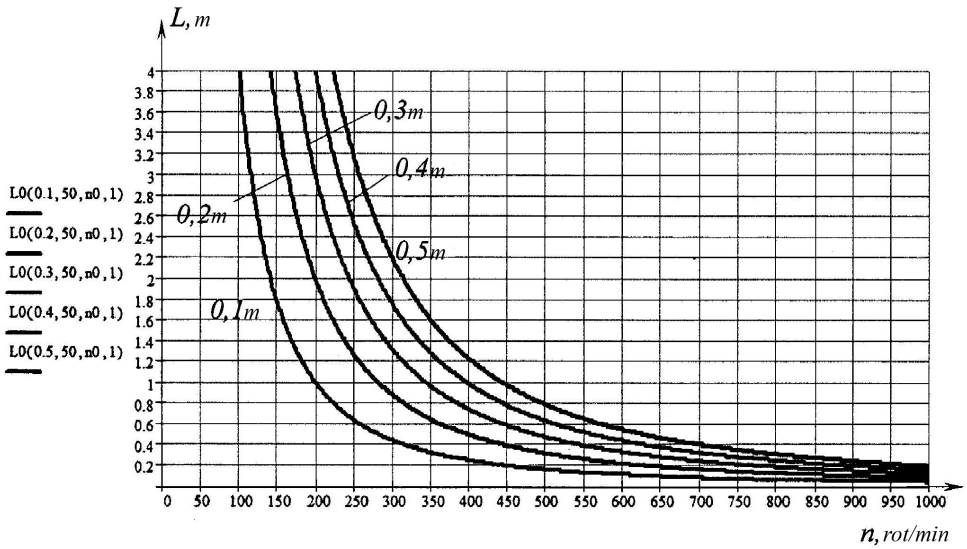

Figure 3 The dependence of the working body length with a radius of 1 m on the centrifuge rotational speed at different thicknesses of the water layer in it.

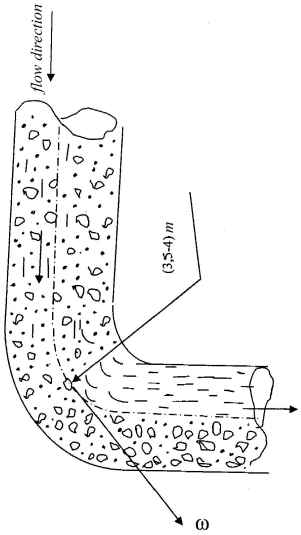

Figure 4 Segregation of solid particles within the flow

3. CONCLUSION

It was established that the rate of particles deposition in their mixture with water depends on their size and the concentration of the mixture: the higher the particle size, the higher the rate of deposition; the higher the particles concentration in a non-Newtonian fluid, the lower the deposition rate.

It is shown that the established dependences are nonlinear, i.e. any mechanical mixture of water with small particles forming slurry can be represented as a non-Newtonian fluid.

A system has been created for intensive deposition of the solid part of sludge on the shop floor with a closed cycle for returning the solid part of the sludge to the sinter charge, and the water to the in-plant water circulation.

The economic costs of the society for the production waste processing are increasing every year and require their optimization in terms of the balance of operating costs and liquidity of the product resulting from the waste processing. To solve this problem, it is necessary to introduce information technology in production management and planning, which is impossible without developing mathematical models of field processes for their subsequent transfer to digital environment of 4.0 technologies.

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