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Measuring and regulating parameters for the concentrate production process in the conditions of gravity concentration

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ABSTRACT

Mineral gravity concentration processes use combined effects of: grain mass, volume, density, size and shape so as to obtain different trajectories in a dynamic classification environment. Together with selecting minerals by hand, gravity concentration is one of the oldest methods for mineral concentration and most frequently conducted on cyclone separators which operate on the basis of differences between the masses and densities of "heavy", useful and "light", useless classes (intermediate products) in a centrifugal field within an optimal density suspension, most frequently a mixture of water and a suspensoid. Upon measuring and analysing the processed samples, disturbances that directly reflect the quality of manganese grain output fractions with disturbances in the suspension density stability and the operation of a heavy liquid cyclone with reflections upon the total condition of this part in the process were registered. This paper provides a systematic assessment of the incurred disturbances in manganese mineral gravity concentration within a heavy environment along with the selection of main process parameters that impact the quality of process operations and products, with special attention being paid to the managing measuring and regulation equipment.

Keywords: Heavy environment, disturbances, measuring and regulation.

The role of enriching mineral raw materials

Enriching or preparing mineral raw materials is recognised as the methods of selecting minerals by type, classifying them according to their size, fracturing, pulverisation, micronisation, separation of the useful from abortive materials, and for complex mineral configurations, separation of certain components with the goal of concentrating useful minerals, by using the selected methods, where their chemical composition remains unchanged. The systems of refining mineral raw materials are implemented by physical, physical and chemical or chemical methods so as to separate useful from the useless minerals and vice versa, with the goal of obtaining products that the market finds interesting. Likewise, refining mineral raw materials is recognised as all the thermal and chemical methods implemented in order to improve the characteristics and value or mineral raw materials where their chemical composition is not significantly changed.

The significance of mineral concentration

During the preparation of mineral raw materials, a significant role is attributed to technological operations: pulverisation, classification, floatation, gravity and electromagnetic concentration. The procedures of concentrating useful minerals by applying artificial conditions of enriching in a gravitational field aims at the efficient separation of useful metal from the useless and harmful impurities out of the ore serving as the raw material. The concentrate is mostly composed of a useful mineral component, and apart from it, on a smaller scale, it also contains the useless ones, while the tailing, apart from the useless, contains some of the useful mineral component. The cause of this is the fact that mineral raw materials are, in view of their mechanical properties, chemical and granulometric composition, as well as mineral and petrographic structure, highly heterogeneous and complex due to which complete separation of mineral (useful or useless) components cannot be achieved.

Chemical properties of manganese ore minerals

According to the location where it is found in nature, manganese falls within lithophilic and hydrophilic elements. In the lithosphere, it is quite extensive in the composition of different minerals (0.1%mas.). Manganese oxide minerals are widespread in the world, namely the mineral pyrolusite MnO_2, followed by the minerals kurnakite/bixbyite $Mn_2 O_3$ and manganite Mn_2O_3-H_2O. Manganese is also present in the composition of: silicate mineral braunite Mn_2O_3, $MnSiO_3$, carbonate mineral rhodochrosite MnCO and other minerals. Minerals of pyrolusite (MnO_2) and minerals of manganite [(MnO(OH)], are the most present in the minerals that create the ore reserve of Bužim mine, Table 1.

Table 1: Manganese mineral properties

Mineral	formula	density ρ [gr/cm³]	hardness [⁰] Mohs	structure
pyrolusite	MnO_2	5.06	2 to 6	tetragonal
manganite	MnO(OH)	4.33	4	monoclinic

The present mineral tailings: illite, tuff, serpentinite, quartz, limestone, opal and pyroxene are separated from the mineral intended to be concentrated by washing, sifting and classifying within the limits that are enabled by the technological solutions of the section "L".

Classification methods of enrichment

Classification is a procedure of separating ores and other mealy materials into products of different sizes. Depending on the requirements and conditions of conducting a process, sieves, sifters, nets or bars are used for this purpose. The goal of enriching manganese minerals is achieving the necessary granulometric property, enhancing the Mn proportion in relation to the ore entering the process in order to achieve market competitiveness and decrease the proportion of undesirable (harmful) components that affect the product quality, for example, the presence of oxide Fe, Ti, Al and Cr. On the current level of development pertaining to the mineral enrichment technology, the access to classification methods in liquid or gaseous environments and the associated procedures are applicable and, as such, they can be called hydraulic (when the operating environment is water) or pneumatic (when the operating environment is air), while the devices are generally called classifiers. The function of classifiers is based upon different drop speeds of large and small particles pertaining to materials suspended in an immobile or mobile environment.

Gravity concentration methods application scope

Gravity concentration is a set of procedures for separating mineral grains on the basis of their density differences, i.e. it is based on the differences between the specific mineral mass and the density of the operating environment. It is usually conducted in water and water suspensions as the operating medium, but the operating environment can also be air. The procedure is performed on devices (classifiers) in which separation occurs due to the effects of the gravitational force accompanied by hydrodynamic and centrifugal forces, as well as the friction force. The upper limit of granulating grains that can be successfully separated is usually determined by the characteristics of the device, while the lower limit is approximately 0.02 mm. If the separation process is not conducted in air or in water, but in a suspension, we can talk about FS (float-sink) concentration (separation in a heavy medium, separation in a heavy environment), and the devices used for this purpose are different FS classifiers. Hydrocyclone devices use gravitational separation in the field of centrifugal forces and do not have any mobile parts. The rotation trajectory of the fluid (a mixture of particles and water) is created due to the fluid flow through the device. Just as the fluid follows a rotational trajectory through the cyclone, particles of greater density than water move, under the influence of the centrifugal force, towards the outer cyclone walls in a spiral trajectory towards the exit (apex). Water and lighter particles are, in the eddy current, ejected into the spillway (vortex).

Manganese mineral gravity concentration

Gravity concentration and manganese ore mineral separation are most frequently conducted on the density differences between "heavy", useful and "light", useless classes (intermediate products) in orchestrated suspension conditions of water and ferrosilicon mixture. The density of Mn ore depends upon the structure and chemical composition of the present minerals and represents a diagnostic property in the function of locating the manganese ore deposits and emanations. It is conducted on heavy liquid separators, jig concentrators, tumbling mills, sluices and hydrocyclones (image 1).

Separation usage degree (R) grows alongside the increase of suspension dilution at the heavy liquid cyclone inlet, and also with a smaller proportion of solid particles in a suspension.

Image 1: Heavy liquid separator appearance pos. SF-2 type DSM

By conducting laboratory and semi-industrial examinations published in the Mining Institute Zemun (RS Serbia), a "Report on concentration examination" in d.d. Manganese mine Bužim was submitted with an emphasis on:

- the fact that the division of manganese mineral, silicon and other elements was balanced in all size classes, except a somewhat lower concentration of Mn in smaller classes,
- by conducting an "F-S" analysis (float-sink) an optimal suspension density, Δ=2.20 [gr/cm³], suitable for the concentration of all size classes from the "L" section plant was chosen,
- the product "heavy phase", as a useful component contains $_{max}$35 [%] Mn, Mn uptake of 36 [%] with a division of mass amounting to 18.87 [%]. The Mn concentration in the "light phase" amounts to 30.28 [%] Mn, which refers to the need of conducting additional operations.
- with an increase of suspension density over 2.20 [gr/cm3] there is an increase in Mn concentration in the heavy phase and a proportional decrease of mass uptake, which is not acceptable from an economic point of view.

A description of the enrichment plant

The industrial plant of the manganese ore enrichment process has the following technological sections:

- "L" - wetting, crushing, sifting, washing, wet classification and desludging,
- "SF" - the washed and classified product concentration in a heavy environment,
- "CH" - supplying water, purifying liquid waste, densification and
- "J" - draining and disposing of hard sludge to the landfill

Section "L"

Washed and classified ore in the amount of Q_{OR}=39.20 [t/h], kr=-15+0.5 [mm] density, Mn grain density and impurities indissoluble in water ρ=4.9 [gr/cm³] and wetness w=20 [%], is, from the input bunker L-20, over the vibrating feeder and a system of belt conveyors, transported to the SF-1 tub and mixed with ferrosilicon and water suspension.

There is a built-in automatic scale L-23 on the belt conveyor L-22 for measuring the mass flow rate of the washed ore that is not connected to the system of monitoring suspension density regulation in section "SF".

Section "SF"

The mixed and washed ore and suspension in the amount of $Q_{OR\Delta}$=110 [m³/h] are, by way of gravitation, inserted into the heavy liquid cyclone SF-2, type DSM, upon the concentration in the field of gravitational and centrifugal forces. Suspension preparation and regeneration are conducted in the SF-19 container. It serves as a process reservoir. It is composed out of

two parts:
- the first part for suspensoid regeneration, SF-19/1 and
- the second part for preparation and suspension reserve, SF-19/2.

The concentrated part of the separated heavy liquid from the concentration process (SF-3) gravitationally falls into SF-19/1 containers in the amount of $Q_{k\Delta}$=96 [m³/h]. A diluted suspension from the SF-19/1 container is, through a centrifugal pump SF-20, type SCC 3x3'', with the power of P=18.50 [kW], transported to the hydrocyclone (HC densifier) SF-21 in which the heavy mixture of water and FeSi (and impurities) in the amount of $Q_{k\Delta}$=11.60 [m³/h] is inserted into the other part of the container SF-19/2. SF-19/2 container part is at the bottom linked with the centrifugal pump type ISC 8x6'' with an electromotor power of P=40 [kW], which hydraulically transports the suspension in the amount of Q_{Δ}=102 [m³/h] to the tub SF-1 (H=26 m).

The pressurised pipeline for transporting the suspension to the height of 18 [m] in relation to the SF-19 container, has a built-in radioisotope gauge for suspension density type Cs 137 (Absc HIRM material Pb), produced by Hartman Brun, Germany. Ferrosilicon is, where necessary, manually inserted into the SF-19/2 container. The SF-19/2 container part is inserted with:

- a magnetic fraction from the magnetic separator SF-14 (separated ferrosilicon) in the amount of $Q_{k\Delta}$=11.40 [m³/h],
- a heavier fraction from the hydrocyclone SF-21 in the amount of $Q_{t\Delta}$=11.40 [m³/h],
- spillway water from SF-19/1 in the amount of Q_{pv}=71.00 [m³/h],
- additional water for stabilising density in the amount of Q_{tv}=15.87 [m³/h] and
- fresh FeSi in the amount of $Q_{\Delta s}$= 2.13[m³/h] or $Q_{m\Delta s}$=13 [t/h].

"Heavy environment"

In the suspension, as a crude dispersion system (S:L), solid particles of ferrosilicon are dispersed in water as a suspensoid in the size greater than 1 µm (10–6 m). Determining suspension parameters in industrial process conditions is based upon the obligatory determination of impurities and admixtures proportion by type and proportion, as well as the procedure of suspensoid regeneration with demagnetisation upon magnetic separation.

The suspension is usually dark brown. Upon completing the procedure of separating heavy from light manganese grains in DSM cyclone, the suspension is, together with the heavy fraction, elutriated on sieves, and then separated on magnetic separators and prepared for reuse. If the suspension contains greater particles (for example, clay particles from water or ore), after a long period of immobility, the used suspension can be separated into suspensoids and impurities by way of sedimentation, and the water can be clarified (technical water). "Knapsack" FeSi suspension and water, as a solid-liquid system (S:L) belongs to the group of homogeneous weakly structured suspensions. Pure technical water from the SF-24 reservoir is used as a dispersive environment.

A schematic arrangement of positions in the section of suspension preparation with measurement and regulation parameters is shown in Image 2.

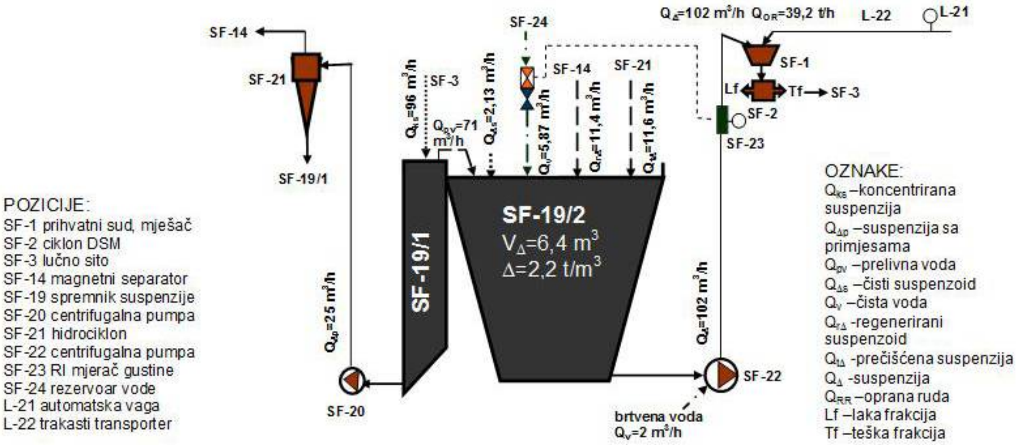


Image 2: A schematic overview of the suspension preparation process with measurement and regulation parameters

Technical indicators of the concentration process

1. Input technical values:

- =102.00 [m3/h], volumetric flow rate of the suspension
- Δ_r=2.20 [t/m3], referent heavy liquid suspension density dependent upon the implemented suspensoid density and its proportion in the suspension,
- suspensoid: atomised ferrosilicon (FeSi-15) in the density of Δ_s=6.10 [gr/cm³], the size of 95 [%] -55 [µm], concentration of Si in the amount of 15 % , with spherical particles, produced by Knapzack, Germany,
- ferrosilicon consumption: 13 [kg/h] or 200 [gr/t] of input ore. It belongs to the group of ferromagnetic suspensoids (Si concentration in the amount of 15%).

2. Suspension flow equations

- volumetric flow rate: $q_z = v_\Delta \cdot A$ [m³/s],
- mass flow rate: $q_m = \Delta \cdot q_z = \Delta \cdot v_\Delta \cdot A$ [kg/s], for Δ=2.20 [t/m³], amounts to q_m =224.40 [t/h]
- The mean velocity of suspension flow in the pressurised pipeline, for the pressurised pipeline diameter D_n=152 [mm], full profile amounts to:

$$v_\Delta = \frac{q_z}{A} = \frac{102.0}{0.01814}$$ =5622.93 [m/h] =1.562[m/s]

3. Active SF-19 container volume:

total volume: V=8.80 [m³], out of which:
-$V_{r\Delta}$=2.20 [m³], suspension regeneration part, SF-19/1
-$V_{a\Delta}$=6.60 [m³], active SF-19/2 volume
-$V_{r\Delta}$=6.40 [m³], operating SF-19/2 volume
-M_Δ=14.08 [t], operating suspension mass in SF-19/2

4. Material mass balance

- For Δ=2.20 [t/m³] and Δ_s=6.10 [t/m³] from the suspension parameters diagram (1) the following values are obtained:

- suspensoid mass concentration: $w_{\Delta s}$=1.44 [t/m³]
- suspensoid mass ratio: $x_{\Delta s}$=66 [mass %]
- suspensoid volume ratio: $\varphi_{\Delta s}$ =24 [%] or in relation to 1: $\varphi_{\Delta s}$=0.24
- water mass concentration: w_v=0.76 [t/m³]
- water mass ratio: x_v=34 [mass %]

- Balance of suspension masses in the SF-19 container in relation to $V_{r\Delta}$:

- Initial preparation with fresh FeSi and technical water:

$$M_\Delta = M_{\Delta s} + M_v$$

$$M_\Delta = V_{\Delta s} \cdot \Delta_s + V_v \cdot \rho_v$$

$$M_\Delta = 1{,}52 \cdot 6{,}10 + 4{,}85 \cdot 1{,}0$$ =14.12 [t]

- suspension volume verification:

$$V_\Delta = \frac{M_\Delta}{\Delta} = \frac{14.12}{2.20}$$ =6.42 [m³]

- during the process:

$$M_\Delta = V_{\Delta s} \cdot \Delta_s + V_{\Delta s(r)} \cdot \Delta_{s(r)} + V_v \cdot \rho_v + V_p \cdot \rho_p$$

additional measurements are required.

5. Suspension density:

$$\Delta = \frac{\Delta_s}{x_s + \Delta_s(1 - x_s)} = \frac{6.10}{0.67 + 6.10(1 - 0.67)}$$ 2.27[t/m³],

6. Suspension parameters:

- suspensoid mass: $M_{\Delta s}$=9.23 [t]
- dispersive environment (water) mass: Mv=4.85 [t]
- suspension volume: V_Δ=6.40 [m3]
- suspensoid volume: $V_{\Delta s}$=1.52 [m3]
- water volume: V_v=4.85 [m3]

where:

$V_{\Delta s}$, $V_{\Delta s(r)}$, V_v, V_p –suspensoid, regenerated suspensoid, technical water and water with impurities volume [m³]

Δ_s, ρ_v, ρ_p – suspensoid, water and water impurities density [t/m³]

Δ_s $\Delta_{s(r)}$ –fresh and regenerated suspensoid density [t/m³]

7. Verification of the obtained results:

- suspensoid mass ratio in the suspension:

$$x_{\Delta s} = \frac{M_{\Delta s}}{M_\Delta} = \frac{9.27}{14.12}$$ =0.66

- water mass ratio in the suspension:

$$x_v = \frac{M_v}{M_\Delta} = \frac{4.85}{14.12}$$ =0.34

- suspensoid volume ratio in the suspension:

$$\varphi_{\Delta s} = \frac{V_{\Delta sv}}{V_\Delta} = \frac{1.52}{6.40}$$ =0.24

- water volume ratio in the suspension:

$$\varphi_v = \frac{V_v}{V_\Delta} = \frac{4.85}{6.40}$$ =0.76

- suspensoid mass in the suspension volume unit:

$$w_{\Delta s} = \frac{\Delta_s \cdot (\Delta - 1)}{\Delta_s - 1} = \frac{6.10 \cdot (2.20 - 1)}{6.10 - 1}$$ =1.44 [t/m3]

- suspensoid mass and volume in relation to $V_{r\Delta}$:

$$M_{\Delta s} = \frac{V_{r\Delta} \cdot \Delta_s \cdot (\Delta - \rho_v)}{\Delta_s - \rho_v} = \frac{6.40 \cdot 6.10 \cdot (2.20 - 1.0)}{6.10 - 1.0}$$ =9.20[t]

$$V_{\Delta s} = \frac{M_{\Delta s}}{\Delta_s} = \frac{9.20}{6.10} = 1.51 \text{ [m}^3\text{]}$$

8. Density regulation parameters, liquid/solid component

- Suspension density: Δ_r=2.20 [t/m³]

$$M_v = \frac{V_{r\Delta} \cdot (\Delta_s - \Delta)}{\Delta_s - \rho_v} = \frac{6.40 \cdot (6.10 - 2.20)}{6.10 - 1.0} = 4.89 \text{ [t]}$$

- Suspensoid mass (M_s) in the volume unit necessary for an increase of suspension density from Δ^d to the referent density Δ:

a) through density:

$$M_s = \frac{\Delta_s(\Delta - \Delta^d)}{\Delta_s - \Delta} \text{ [t/m}^3\text{]}$$

b) through volume and density:

$$M_{\Delta x} = \Delta^d \cdot V_\Delta \text{ ; } M_\Delta = \Delta \cdot V_\Delta \rightarrow M_s = M_\Delta - M_{\Delta x} \text{ [t]}$$

- Disturbances and value deviations *Δ* (±Δ or $\Delta^g\Delta_d$):
Water mass (M_{dv}) necessary for diluting the suspension in the density of Δ^g to the referent density Δ:

- mass of the suspension in the density of Δ^g: $M_{\Delta^g} = \Delta^g \cdot V_{\Delta^g}$
- mass of the suspension in the density of *Δ*: $M_\Delta = \Delta \cdot V_\Delta$

By comparing: $M_{\Delta^g} = M_\Delta$ a relation is obtained:

$V_{\Delta^g} = \dfrac{\Delta \cdot V_\Delta}{\Delta^g}$ so the necessary amount of water is:

$V_{vd} = V_\Delta - V_{\Delta^g}$ [m³], [x10³ litres]

Technical indicators of the concentration process

According to the data from the main technological project of enriching manganese ore, the quality of Mn concentrate from the plant amounts to $K=_{max}$35% Mn. The minimal manganese concentration in the input ore reserve is 18%.

After the period of technological tests ended, the output quality of Mn concentrate from the plant amounted from 26 to 29%, with the Mn size +5 to 15 mm which significantly decreased the economic production effects with the problem of placing the concentrate on the global market. The recorded defects of the concentration process operations and product quality were:

1. The appearance of variable hydraulic impacts upon the mixture of ore and suspension at the inlet to the heavy liquid cyclone,
2. Based upon practical data, the degree of separation (R) upon the heavy liquid cyclone is approximately 60%, i.e. it shows how many particles with the size under 5 mm there are in the heavy fraction, which increases the concentrate mass balance in the heavy fraction, but it significantly decreases the concentration of Mn element.
3. Controlling or adjusting the pressure drop in the 12 [m] high vertical pipe with a reflection upon an increase in the degree of separation and a more balanced formation of heavy and light masses inside the cyclone.
4. The process or regenerating the used suspension does not include suspensoid demagnetisation flow on the demagnetiser
5. Measuring residual magnetism on the devices - magnetometers is not conducted after magnetic separation is performed on the separator SF-14,
6. The frequency of using the regenerated suspensoid is unfamiliar, i.e. how many times one and the same particles can be used in the recirculation system considering the appearance of friction, pulverisation, fracturing, appearance of corrosion on the deformational surfaces of FeSi particles and the like,
7. Locations and amounts of suspensoid loss: with concentrate, with tailings, with water, and due to the loss of suspensoid like abilities. Practical data shows that the loss goes up to 0.50 [kg/t] of product. In the TT concentration plant, the planned losses amount to 1.22 [kg/t] of product.

Identifying process disturbances

Upon measuring and analysing the processed samples, disturbances that negatively reflect the total condition of this part in the process are evident. The size of washed ore at the inlet is -15+0.5 [mm], while the mass ratio of washed ore and suspension amounts to m_{or}:m_s=1:5.72 (normal limits 1:3 to 1:5). During the process of manganese ore refinement, the radioisotope gauge for suspension density did not fully function due to technical reasons, which is why the suspension density could not be solely stabilised by adding water (the instance of increased density +Δ) because with -*Δ* it is necessary to regulatively add fresh FeSi.

Technical and technological qualifications of the TT cyclone concentrator, type DSM, position SF-2 in real conditions are expressed through operation parameters:

- input pressure p and pressure drop Δp,
- mass ratio of washed ore and suspension (m_{or}:m_s),
- centrifugal acceleration variations at the cyclone inlet,
- obstructed movement of grains in different density and size within the centrifugal field,
- the effectiveness of separation with a mass ratio of subclasses and superclasses in the heavy and light fraction,
- suspension stability is not the same in all parts of the container SF-19/2, which negatively reflects the concentration of Mn minerals, the operation and SF-22 hydraulic pump transport during the operation process,
- suspension homogeneity and maintaining the density on a referent value for multi-shift operation is not sustainable due to the loss of suspensoid alongside unstandardised values and the presence of mineral impurities from the washed ore that disturb the rheological suspension properties and the viscosity of the dispersive environment,
- introducing heavy fraction as a TT cyclone product +5–15mm in size on the II degree of classification due to the presence of -5mm class in this product
- effective duration of the procedure and the like.

The condition and importance of measuring physical values:

- a flow scale L-5 at the inlet to the plant for measuring the inflow of ore into the process “L”,
- a flow scale on the washed and classified ore belt conveyor L-22 (towards the concentration),
- a radioisotope gauge for suspension density type Cs 137,
- a flow scale on the belt conveyor SF 11 for the final Mn concentrate.
- measuring and regulating suspension density is conducted in the measuring and control system: container SF-19 → density gauge SF-23 → technical water regulation valve in case of an increase in the density value +Δ. A regulating circuit for dosing fresh FeSi in case of a decrease in the density value -Δ has been left out,
- washed ore mass flow L-23 is not connected to the system of mixing washed ore and suspension, ratio: Q_{OR}:Q_{Δ}, as an important technical value,
- the final concentrate mass flow SF-11 is not related to the washed ore mass flow and balancing concentration masses in the SF-2,
- losses, demagnetisation and magnetised suspensoid regeneration are not on the suitable technical and technological level with consequences for the suspension homogeneity and economic losses,
- the water balance has not taken into account the water flow for sealing the SF-22 pump (connection to the EM) in the amount of 2 [m³/h].

The pressurised pipeline for transporting the suspension to the height of 18 [m] in relation to the SF-19 container, has a built-in radioisotope gauge for suspension density type Cs 137 (Absc HIRM material Pb), produced by “Hartman Brun”, Germany. It is encased and placed inside a stainless steel capsule (case) and it is resistant to chemical and mechanical influences, so contamination is disabled. The minimal protection of these sources is defined by ISO 2919 standard. Practically, the material (a mixture of water and suspensoid) is exposed to radioactive emissions coming from the source, and then the radiation is weakened and as such comes to the detection device. This measurement signal is transformed into an output signal directly related to the “heavy suspension” density. It is related to the technical water flow regulation into the SF-19/2 container for the purpose of adjusting and stabilising density on the referent value. The Cs 137 half-life duration is around 30 years.

Impact factors for the suspension quality

a) suspension density ($\Delta = m_{\Delta}/V$, kg/m³)
Suspension density is the fundamental suspension characteristics that determines the conditions and ability of separating Mn mineral grains of different densities to: The heavy fraction (HF), Mn concentrate (ρ_T) and light fraction (LF), intermediate product (IP) + tailings (T) (ρ_L). In order for the washed Mn ore to be concentrated, the following condition has to be met:

$$\rho_L < \Delta < \rho_T.$$

By performing a float - sink (“F-S”) analysis on the basis of the washed ore properties, the optimal density of the suspension, Δ=2,20 [gr/cm³], suitable for concentrating all the washed ore size classes from the “L” section, has been selected.

In relation to the implemented suspensoid properties and dispersive environment, the main impact factors for the physical suspension properties are: density, viscosity, presence of impurities- tailing admixtures, stability, homogeneity and entirety. The functional dependence of density can be provided through numerous values: suspensoid, water and impurities volume ratio, suspensoid particles diameter and shape, suspensoid and dispersive environment density, suspension viscosity, i.e.:

$$\Delta=f(\varphi_{\Delta s}, \varphi_v, \Delta_s, \Psi, \eta_\Delta, v_{kr}, d_s, \rho_v, \varphi_p)$$

Suspension density depends upon the implemented suspensoid density, its contribution in the suspension and the presence of impurities in the regeneration cycle. The suspension system is defined by the amount of components or phases present tin the observed system, and it is expressed by the mass and volume component ratios. Therefore, suspensions with a volume suspensoid ratio $\varphi_{\Delta s}$ greater than 10% show non-Newtonian properties, most frequently highly plastic or pseudo plastic ones. Practice shows that small classes of ore minerals can be concentrated in a centrifugal field with the existence of stationary conditions alongside the size limitations of -5 do +0.5 mm.

b) viscosity factor
Suspension viscosity is defined as the resistance of a dispersive environment to the motion of suspensoid particles and it is proportionally increased with an increase of suspension density. It remains almost unchanged with pressure variations, but with an increase in suspension temperature, it proportionally decreases. Suspension viscosity is smaller if the particles ds are in a wide range of sizes due to better packing of particles in different sizes. Taking into account that atomised FeSi in the size of 95 % -55 [μm] is used as a suspensoid, the existence of an increased viscosity can be assumed.

By increasing the concentration of solid particles, there is a viscosity increase, which is characteristic for the notion of the so called interrupted sedimentation, because the speed of suspended particle sedimentation grows in proportion to the viscosity decrease. The viscosity of heavily dispersive systems is most frequently expressed by dynamic viscosity η[Pa·s]. It is familiar that high viscosity negatively impacts the process of separating heavy from light fractions because there is an increased resistance to the motion and separation of Mn mineral grains.

According to the researched diagram of suspension viscosity dependence on suspension density, the preparatory suspension viscosity is $\eta=8\times10^{-3}$ [Pa·s]. The present impurities also have an impact on suspension viscosity: sludge (colloids), mineral dust particles. In normal conditions, the viscosity value for water is:
$\eta_v \approx 1\cdot10^{-3}$[Pa·s]

c) solid particles concentration factor
Suspensions with a suspensoid volume ratio greater than 10% show non-Newtonian properties, most frequently highly plastic or pseudo plastic ones. Effective viscosity is used as a value for controlling the state of suspension within the process:

$$\eta_{\Delta e} = \eta_o(1+2{,}5\varphi_{\Delta s}+7{,}349\varphi_{\Delta s}^2+16{,}2\varphi_{\Delta s}^3)$$

The impact of solid particles concentration on the rheological behaviour of a suspension and its viscosity can be expressed through Einstein's equation that takes into account the impact of particle size, as well as the existence of other particles (impurities) having an impact on the suspension viscosity. This is valid for suspensions with $\varphi_{\Delta s}$<0.44 and η_Δ to 0.03 [Pa·s]:

$$\eta_\Delta = \eta_o(1+2{,}5+6{,}2\varphi_p^2)$$

where:
η_0 - dispersive environment (water) viscosity
$\varphi_{\Delta s}$ - suspensoid volume ratio
φ_p - the volume ratio of impurities in the suspension

The value of relative viscosity given through the relation of suspension viscosity η_Δ and dispersive environment (technical water) viscosity η_{ds} can refer to possible changes in the suspension condition, which is given through the formula:

$$\eta_r = \frac{\eta_\Delta}{\eta_{ds}}$$

d) suspension stability factor (homogeneity and entirety)
Represents its ability to retain the same density in all the container levels or in all the transport devices in static and dynamic conditions of the suspension state (immobility and mobility).

- Static stability functions as the suspensoid sedimentation characteristics, suspension viscosity $\varphi_{\Delta s}$ and the sedimentation speed. With static stability, the speed of suspensoid particle sedimentation for Δ=2.20 [t/m³] amounts to: v_t=7.25 [cm/min].
- Dynamic stability can be achieved through a forced suspension whirl in the SDF-19/2 container (mechanical stirrer, air currents of compressed air or water currents), especially when SF-19/2 is filled with fresh FeSi.

Dynamic stability of a suspension has a greater impact than the static one due to the need for maintaining suspension homogeneity in the SF-19/2 container, the continual encumbrance of the SF-22 centrifugal pump and measuring the suspension density in a part of the pressurised pipeline. When needed, ferrosilicon suspension can be stabilised by adding bentonite in the amount of 0.6 to 1% of the suspensoid weight.

e) impurity impact factor on the suspension density and viscosity
When the suspensoid grain moves in a dispersive environment enriched by deformed suspensoid particle mineral impurities and scum, there is a collision with the present impurity particles and an increase of suspension viscosity. The results of this condition directly reflect the quality of the separation process in the TT cyclone concentrator.

f) operational temperature change factor
The highest intensity of the TT separation plant operation comes during summer where, due to high operational temperatures, FeSi particles can become oxidised and the suspension density disrupted. A similar phenomenon is related to the so called acidic environments.

g) regenerated suspensoid demagnetisation factor
FeSi is a magnetic suspensoid, and as such has to undergo a demagnetisation procedure, which is not the case in the Bužim mine TT separation plant. The result is that a suspensoid without any traces of residual magnetism should be introduced in the concentration process. Otherwise, magnetised FeSi floccules with "trapped" impurity particles are formed and they are quickly (disruptively) sedimented in the SF-19/2 container.

h) the process equipment functionality factor
From the TT cyclone concentrator, the heavy phase falls upon the arc sieve with a 0.5 mm opening for the drainage and ferrosilicon separation procedures. Data gained through practice recommend the sieve openings to be 0.15 mm.

i) heavy liquid cyclone operation hydraulic factors

- *appearance of cavitation in the vertical pipeline leading to the TT cyclone* - Cavitation can decrease the TT cyclone operation efficiency degree due to vibrations. Namely, cavitation erosion of the hydraulic components with an appearance of air pockets due to uneven mixing of the washed ore and T-T suspension causing internal impacts on the technical line: stirrer - vertical pipe - DSM cyclone with reflections upon the irregular TT cyclone operation, and the concentration quality.
- *pressure drop or the height of the hydraulic drop upon the TT cyclone* - A hydraulic impact represents a sudden and large pressure increase due to the increased variation of washed ore and suspension flow speed in a vertical pipeline. The pressure increase depends on the initial mixture speed (velocity v_m and density ρ_m). There are several options to avoid or mitigate the hydraulic impact: by decreasing the initial fluid flow speed (for example using a wider pipe), decreasing impedance at the end of the pipe (installing valves for restricting pressure and flow), or a slow closure of the valve, as well as elongating or shortening the height of the pipeline and with it the possibility of regulating the pressure drop values at the TT cyclone inlet.

Managing and regulating the process, a new approach

The methodological foundation of building a new regulation and management system encompasses engineering the integral technological process of manganese ore processing with the already established control centre within the plant (command panel). The intensity of the Mn washed ore concentration process adapts, over time, to variable demands for movement and the quality of materials, as well as information.

The source of the most favourable technological solution for the suspension preparation system and material masses depends upon meeting the set demands and criteria.

Demands:

- enhance the existing qualitative technological schematics of the process in accordance with the set measurement and control parameters, while determining the mutual dependence and interactive effects on the management system,
- place an additional container with a stirrer for the purpose of homogenising the washed ore and suspension mixture (SF-1),
- examine the constructive and technical functionality of the existing measurement and process equipment,
- determine the optimal number of the measured

values and the measurement methods that will fully describe the complete concentration process, as well as the possibilities of obtaining derived values from several directly measured values (the automatization management system).

- due to the insufficient classification of light and heavy fractions and the presence of +0.5-5 mm class in the heavy fraction (degree of separation R) from the TT cyclone, it is necessary to classify and sort the resulting products on the sieves according to the size +0.5-5 mm and +5-15 mm (separating ferrosilicon by elutriation at the same time),
- the new laboratory tests have to research the possibility of a two-stage classification in the TT cyclones or sedimentation machines in the heavy environment,
- select the measuring equipment with the task of constantly measuring and regulating the main suspension parameters (the subsystem of regulating suspension and concentration), as the basic measurement values: suspension density Δ, the flow of the washed ore and suspension mixture Qm and the pressure drop Δp upon entering the TT cyclone, with adjusting the changes in the mixture flow and the height of the mixture's hydraulic drop, as synthesised indicators.

Criteria:

- accuracy of the primary and derived values, using both the direct and mathematical processing, as well as their operating applicability (interventions),
- the speed of processing input values, signal transmission, reaction and the time necessary for exchanging information within the suspension preparation subsystem and the total Mn ore processing system, a closed management system,
- the quality of technical equipment, current and perspective (measurement, and regulation devices, computer equipment and communication infrastructure), as well as the programme basis for supporting the activities related to gathering, processing and using information.
- a regulated concentration process, together with transforming information that affect it in the regulation function make a connected dynamic system of overall control and managing the concentration process (Image 3.)

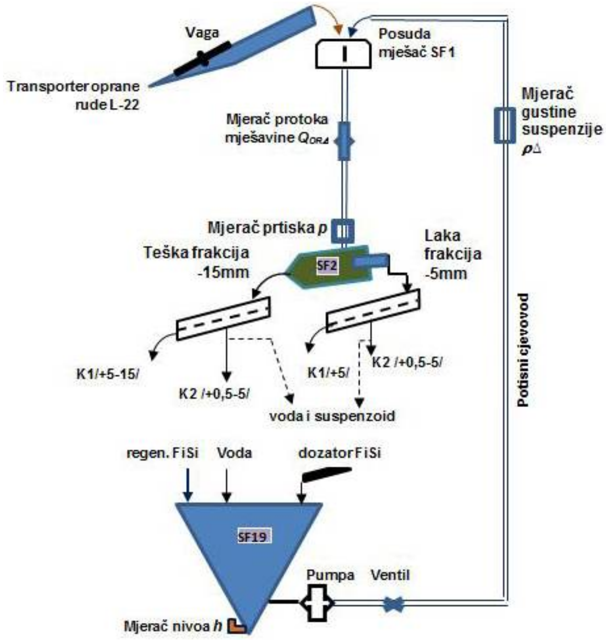


Image 3: A schematic overview of the suspension preparation process with measurement and regulation parameters, a new approach

Solutions for regulating the suspension preparation process are based upon selecting technical values that have to be measured and regulated:

- suspension density in the function of monitoring the maintenance of the set value. In case of deviations from the referent suspension density value, it is necessary to affect the ferrosilicon dispenser and water flow, as well as monitor the suspension level in the SF-19/2 (h) container in a closed management system, and thereby indirectly measure the suspension volume in the container.
- washed ore and suspension mixture flow in the 12m vertical pipeline by monitoring the mixture mass and pressure at the TT cyclone inlet. This value represents a sum of the washed ore mass flow QR and suspension flow Q_Δ , and it reflects the actual flow through the SF 2 TT cyclone accompanied by the operating pressure values.

The grounds for the selection:

- Measuring suspension density Δ in the SF-19/2 container is directly connected to the washed ore concentration process in heavy suspension, in the centrifugal field of separation on the Hp (heavy phase) and Lp (light phase). It can be changed in accordance with the variations in the quality of the washed ore,
- suspension mass flow Q_Δ, is a process value in the function of maintaining the appropriate ratio

of suspension and washed ore mixture (TΔ:$\check{C}_{OR}$), and
- suspension height (h) reflects the suspension volume size in the SF-19/2 container related to the density changes and protecting the SF-22 pump operation under load.

Automatic regulation and SCADA systems
Automatic regulation is based upon the operation of the measurement converter with executive elements, that is previously adjusted based upon the management algorithm by comparing the formation of the projected output value at the end of the process with the appropriate activity at the beginning of the process using measurements. This regulation process automatically institutes and maintains the condition necessary for achieving the desired process condition.
Systems based upon SCADA systems (Eng. Supervisory Control and Data Acquisition System). They are used to automatically collect relevant data related to the function of the manganese ore technological process of enrichment into concentrated products, collected data analysis and, based upon them, management process . A system automated in such a way is frequently called an acquisition system that only possesses the ability of automatic gathering, in other words, gathering and analysing data.
Supervisory Control And Data Acquisition (supervision, monitoring, managing and collecting data) implies a wide spectrum of equipment, systems and solutions that enable gathering data on the enrichment process, their analysis, supervision and, in certain cases, reacting in an appropriate way.
A closed loop system, i.e. a system of automatic management with a negative feedback is shown in image 4. and defined as follows: A closed loop system uses the output signal measurements and comparisons with its desired value with the goal of generating the error signal that is then transmitted to the regulator (actuator).

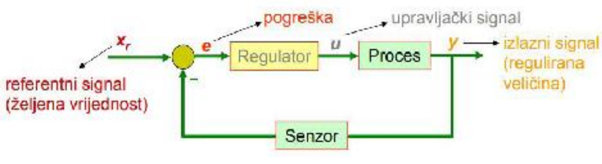


Image 4: A general schematics of the closed management system with a regulatory loop

Designing such a system of management begins with conducting a feasibility study. It is followed by the main project design that deals with electronics (SCADA process instrumentation and computer equipment) and information technology (SCADA application - programme support) by using a computer for the supported process management system - discrete linear management system. The principle block diagram of the process management system with feedback.

The central management unit (the existing command panel), as a higher level of management, principally visualises the process that is being managed and the necessary communication with the operators (initiating and stopping operations, changes in the operation regime, adjusting various parameters and the like).

The washed manganese ore concentration process management subsystem is created by managing process units consisting of PLC (Eng. Programmable Logic Controller-PLC) devices and a distant control centre in which most of the applicative management support is conducted.

Each process unit is in charge of data acquisition from multiple sensors and managing from several management loops where the connection with the instrumentation (transmitters, positioners,...) is frequently established by using wires, analogue current signal.

Measurements in open and closed loops
Directly measured and regulated values measured by an operator, as well as the measured values in an open loop such as: the level of washed ore in the L-20 bunker, washed ore mass flow (L-21) and the final product mass flow (SF-12), with the new measurement locations, with and without feedback: a) the residual remnant magnetism in the regenerated suspensoid, b) suspension viscosity and c) pressure drop in the pressurised pipeline with directly measured values and their resulting calculated derived values, d) the densified sludge density and others, can be connected using programmes and information technology into a unique management system.

Normally, the management system represents a complex structure that includes management levels, processing computer devices, regulators and information technology infrastructure. For example: automatic control over the washed ore concentration process depending on the mass flow and suspension density can be ensured by using a local PLC device, which is connected to the PC with a LAN and modem, as well as the SCADA management system.

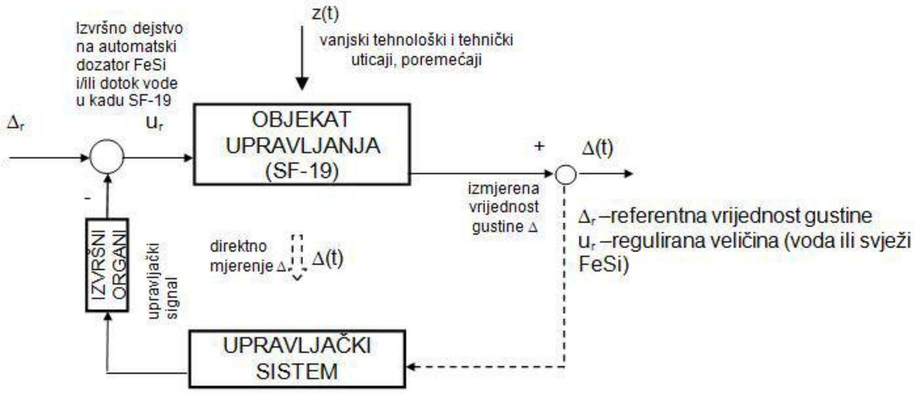


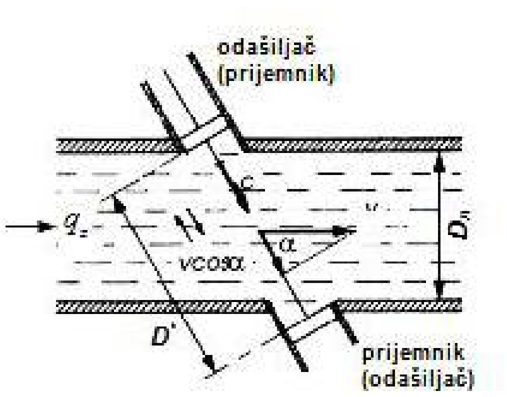
Image 5: A schematic overview of the suspension management and control in the SF-19 container

Selecting flow measurement devices

a) ultrasound flow measurement technique

It is selected on the basis of understanding that the sensors are not directly connected with the suspension due to the FeSi characteristics, given that otherwise the measurement device operating elements can become worn-out, and resistance to movement can occur. Devices that implement the principles of this techniques operate on the basis of various ultrasonic wave rates of propagation down and up the suspension stream in the pipeline.

Ultrasonic wave rate of propagation is much greater than the suspension stream velocity (Image 6.).



Volumetric flow rate (m^3/s):

$$q_z = v_\Delta \cdot A$$

$$q_z = \frac{D^2 \cdot \pi \cdot c^2}{8 \cdot D \cdot \cos\alpha}\Delta t = K \cdot \Delta t$$

where:

D - the normal space between the measured locations

c - ultrasonic wave rate of propagation

Δt –the difference between periods of ultrasonic flow down and up the suspension stream

α -the angle formed by the suspension speed vectors ($v\Delta$) and

Image 6: Suspension flow measurement schematics

B) electromagnetic flow measurement devices

Besides the previously stated flow measurement technique, electromagnetic devices useful for measuring the movement of conductive suspension are also used. When the fluid velocity is not equal in average, but if it is symmetric in relation to the medial axis, the generated electromotive force can be calculated by solving Maxwell's flow equations and using the mean suspension movement speed.

Conclusion

Gravity concentration in a heavy environment demands an active maintenance of suspension density at a referent level, the support from the managing and regulation technique, device functionality, control over the size and the washed ore "degree of purity", technical functionality of the ancillary equipment, organising measurements of the primary values (mass flow rate, density, viscosity) and monitoring the process efficiency of classification when using the degree of separation and the quality of creating the "heavy" and "light" fractions in the DSM cyclone.

Suspension density, as the primary manganese washed ore concentration parameter, is functionally dependent upon the process values: suspensoid, water and impurities volume ratio, suspensoid particles diameter and shape, suspensoid and dispersive environment density, suspension viscosity, the applied suspensoid, its contribution in the suspension and the presence of impurities in the regeneration cycle, etc.:

$$\Delta = f(\varphi_{\Delta s}, \varphi_{v}, \Delta s, \Psi, \eta_{\Delta}, v_{kr}, d_{s}, \rho v, \varphi_{p})$$

Based upon the registered process disturbances, the observed defects in the technological preparation process and manganese mineral concentration, as well as defects (and existing measurement equipment dysfunction) in the key process values measurement devices, this paper provides a systematic approach to improving the process with special attention being paid to the part related to measuring and control. The regulated concentration process, together with transforming information that affect it in the regulation function make a connected dynamic system of overall control and managing the concentration process.

By implementing (designing and executing operations) the solutions given within the plant modernisation project, we can expect a better control over the concentration process, an increase in the mass of the useful Mn concentrate and stability in the course of process operations.

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Mjerenje i regulacija parametara u procesu proizvodnje koncentrata u uslovima gravitacijske koncentracije

SAŽETAK
Gravitacijski procesi koncentracije minerala koriste kombinovane efekte: mase, zapremine, gustine, krupnoće i oblika zrna bi se dobile različite putanje u dinamičkoj sredini klasifikacije. Gravitacijska koncentracija, zajedno sa ručnim odabiranjem minerala, spada u najstarije metode za koncentraciju minerala i najčešće se izvodi na ciklon-separatorima koji rade na bazi razlika masa i gustina „teških“ korisnih klasa i „lakih“ nekorisnih klasa (međuproizvoda) u centrifugalnom polju, u suspenziji optimalne gustine, najčešće mješavine vode i suspenzoida. Nakon mjerenja i analize obrađenih uzoraka evidentirani su poremećaji koji se direktno odražavaju na kvalitet izlaznih frakcija zrna mangana sa poremećajima sabilnosti gustine suspenzije i radu teško-tekućinskog ciklona sa refleksijama na ukupno stanje ovog dijela procesa. U radu je data sistemska ocjena nastalih poremećaja gravitacijske koncentracije minerala mangana u teškoj sredini sa izborom glavnih procesnih parametara koji utiču na kvalitet procesnih operacija i proizvoda, sa posebnim akcentom na upravljačku mjerno-regulacionu opremu.

Ključne riječi: Teška sredina, poremećaji, mjerenje i regulacija.

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