IDENTIFICATION OF FACTORS TO REDUCE THE ENERGY COSTS OF DISPERSING IN JETS

This paper reports the operational indicators for industrial-sized jet grinding plants (JGP). The dependences of specific energy consumption on productivity have been generalized. The technological patterns in the working process were considered in terms of reducing energy costs using the operation of gas-jet and steam-jet mills at the Vilnohirsk Mining and Metallurgical Plant (VMMP) involved in crushing zircon to 60 μm as an example. The acoustic activity in the grinding area has been studied relative to the concentration of μ and in combination with the technological assessment of the mill's performance. A broadband piezo sensor was used in the assessment of acoustic emission (AE). It is shown that the acoustic activity of the grinding zone contains information about the effects of dispersion and energy costs for grinding, which makes it possible to estimate and minimize the specific energy costs. It has been established that the principal factors of JGP energy intensity are the initial temperature of the energy carrier, which sets the speed of the jet, and the concentration of solid phase in the jet, which changes the effects of dispersing. A technique has been proposed for the current assessment of energy costs in the working process of dispersion based on the experimental acoustic data and a pattern of the acoustic dimensional effect. The estimated acoustic indicators of the energy cost of a jet mill for the conditions of VMMP were derived. To reduce the energy cost of dispersion ($\gamma_s \cong 0.42\,J/cm^2$), the effect of adjusting the loading of jets to $\gamma_N \cong 1.8\,J/pulse$ is employed. Thus, this study has investigated the dispersal of solid loose material in jets with the involvement of acoustic information about the operation of jet mills, which makes it possible to comprehensively assess and minimize (optimize) the specific energy costs of grinding

Keywords: jet mill, dispersion, dispersing, energy carrier temperature, solid-phase concentration, acoustic activity

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1. Introduction

The jet mill refers to the gas-dynamic type of grinding equipment, which enables dispersing by colliding the particles at their relative speed of about double the speed of sound in the air. Grinding utilizes the energy of working gas (natural gas combustion products, overheated steam, compressed air – cold or heated) at a pressure in the range of 0.2...2.0 MPa. Variating the energy and counter two-phase flow parameters (speed, temperature, the concentration of solid phase) makes it possible to change the frequency of loading pulses, kinetic energy, and the speed of dynamic deformation of particles at impacts. The mill's performance G is correlated with the speed W and the energy-carrier temperature T according to the following ratios:

$$W = \varphi\sqrt{2\frac{k}{k-1}RT_k\left[1-\left(\frac{P_a}{P_k}\right)^{\frac{k-1}{k}}\right]}; \quad \frac{W}{W_o} \cong \sqrt{\frac{T}{T_o}} \cong \sqrt{\frac{G}{G_o}}, \quad (1)$$

where W_o, T_o, W, T are the parameters, respectively, for a cold and heated energy carrier; P_k, P_a is the pressure before the outflow and in the grinding zone; k is the adiabatic exponent; φ is the speed loss ratio ($\varphi=0.8$–0.9).

There is a known experience of using gas-jet grinding to refine the micro powders of solid loose materials: synthetic diamonds, zircon and ilmenite concentrates, zirconium dioxide, silicon and boron carbides, slag, plaster, cement clinker, quartz sand, talcum powder [1–3]. Processing the material in the jet grinding plants (JGP) is combined with the separation for largeness, the deposition of the product, the purification of spent energy-carrier from dust. The jet grinding technology is assessed by performance of G and product quality based on the size S_{sp} of the specific surface and the amount of residue R on the sieve whose hole size is about a dozen μm. Industrial JGPs operate in a closed cycle with a classification apparatus, so that the conditions for the delivery of a starting material to the mill are determined by the operational mode of the classifier. The dispersal is governed by the rotor rotation frequency n (min^{-1}) of a reflecting-vortex classifier.

To estimate the specific energy-carrier consumption, we use the statistical treatment of data on the grinding of a series of materials (slag, sand, clinker, zircon, etc.).

Fig. 1 shows the generalized dependences of the specific consumption q (m^3/kg) of an energy carrier (cold or heated air, overheated steam) on the performance of jet units for a series of dimensions: $G=2$; 200; 2,000 kg/h; $q=10^{1.7}/\sqrt{G}$ ($r=0.97$). The maximum size of the cyclone's product particles is 40...60 μm, the average is 10...20 μm, the specific surface $S_{sp}=0.4...0.6$ m^2/g. One can see that with an increase in the JGP dimensions the energy intensity of the grinding decreases.

The process of dispersing by jets is accompanied by significant energy consumption, especially when using cold compressed air. The experience of operating gas-jet mills at the Vilnohirsk Mining and Metallurgical Plant (VMMP) (Ukraine) and Volgograd Ceramic Plant (VCP) (Russia) has shown that *the leading factor* in the cost-effectiveness of this process is *the temperature of an energy carrier*.

Fig. 2 shows a photograph of an industrial gas jet unit, which includes a set of assemblies and nodes. The set is designed to convert supplied energy into the work of grinding, transporting, and classifying the particles, separating the solid and gas phases, purifying the spent energy carrier. Fig. 3 shows the scheme of an industrial gas-jet mill with a capacity of up to 2.5 t/h equipped with combustion chambers of the VK-1 turbojet engine.

Table 1 gives the JGP indicators (when using a cold or heated energy carrier) whose performance $G=1.2$–4 t/h when crushing talcum-magnesites, zircon, slag, sand to produce glass or ceramics. The experimental data have shown that when using heated jets under the mode of $T_0=500...650$ °C, $P_0=0.24...0.38$ MPa there is a decrease in energy costs. When crushing zircon, slag, sand, talcum to the dispersity of an order of $S_{sp}=22...1.15$ m^2/g, this decrease is from 275 to 75...34 kWh/t.
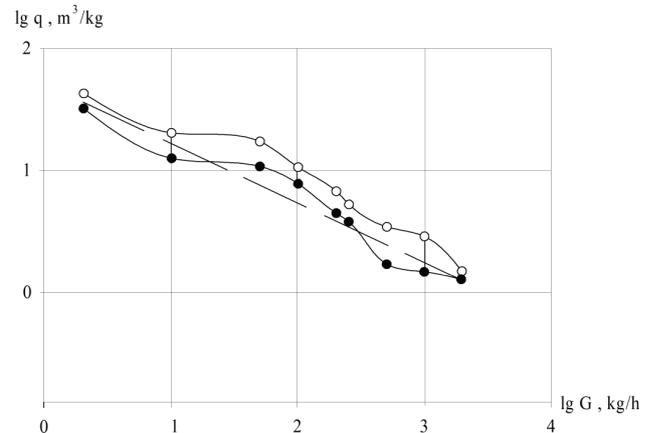
Fig. 1. Dependence of the specific energy carrier consumption on the performance of a jet unit: o — maximal; • — minimal; — — — the estimation value
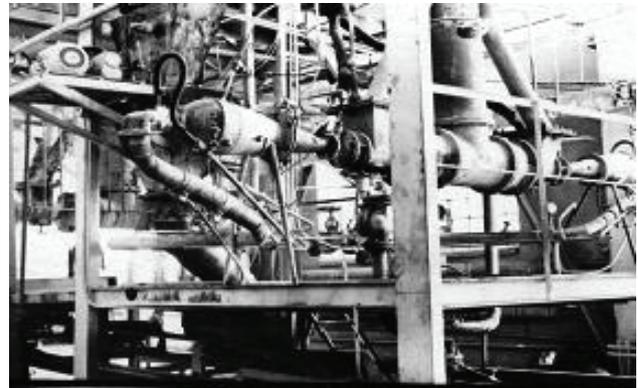
Fig. 2. General view of an industrial gas-jet plant (VMMP) [4]
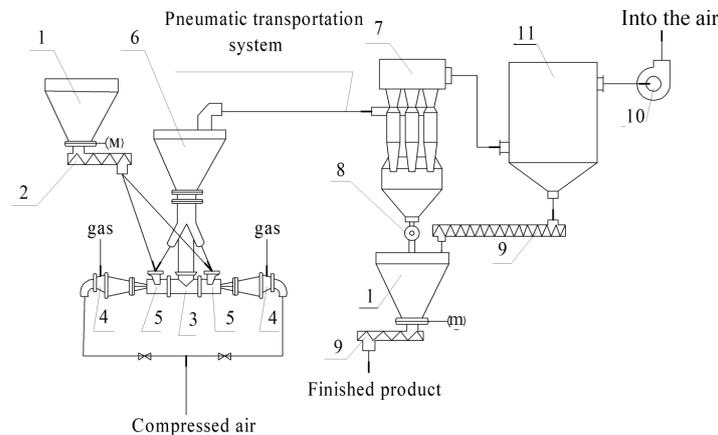
Fig. 3. An industrial gas-jet plant scheme (VMMP):
1 — bunker; 2 — feeder-dispenser; 3 — grinding chamber; 4 — combustion chambers; 5 — injectors; 6 — classifier; 7 — cyclone unit; 8 — vacuum-dispenser; 9 — product dispenser; 10 — fan; 11 — a unit of filters-dusters

Table 1

Performance indicators of jet plants of industrial dimensions

Indicator	Dimen-sionality	Talcum-magnesite, CP	Zircon[***], CP	Zircon[***], CA	Slag[*], CP	Sand[*], CP	Sand[**], CP	Sand[**], CA
G	t/h	4.0	2.2	1.2	1.8	2.5	2.2	1.8
P_0	MPa	0.24	0.38	0.5	0.34	0.34	0.38	0.39
T_0	°C	500–600	650	35	600	600	600	35
Specific consumption: – air; – natural gas; – electricity	nm^3/t nm^3/t kW·h/t	2,000 30–50 34	1,250 22 75	– – 275	1,280 29 75	920 20.9 54	1,140 19 61	1,480 – 136
d	mm	25–0	0.2	0.2	5–0	0.5–0	to 1	to 1
R	%	$R_{40}=5.2$	$R_{60}=0.5$	$R_{60}=0.5$	$R_{60}=1$	$R_{60}=2$	$R_{100}=4$	$R_{100}=1.5$
S_{sp}	m^2/g	1.15	0.23	0.24	0.26	0.22	0.24	0.25

Notes: CP – natural gas combustion products; CA – cold compressed air; * –Volgograd Ceramics Plant; ** – Ufa Textile Fiberglass Factory; *** – Vilnohirsk Mining and Metallurgical Plant

It is worth noting the expansion of the application scope of dispersing in jets, in particular, to make solid polysulfone nanocomposites [5], to produce gray cast iron powder, to prepare powders in the pharmaceutical industry [7]. Thus, dispersing in jets is currently used in a series of industries for the fine grinding of mineral products and other loose materials; it is a relevant task to identify factors that could bring down energy costs in this process.

2. Literature review and problem statement

Studies [2, 3] show that mill performance is a function of the jet's energy and the amount of material added. The issue related to reducing energy costs in jet processing includes the condition of finding and maintaining the maximal performance mode for a conditioned product with a minimum value S_{sp} of the dispersion index. In this regard, it is important to understand the role of the principal technological factors and to monitor them during the mill's workflow.

Ukraine has considerable experience in studying the basic parameters of jet mills of different dimensions [3, 8]. The characteristics of the jets (consumption, pressure, the energy carrier temperature, the amount of solid phase downloaded), static pressure (rarefaction) along the installation tract, the mode of operation of the classifier were investigated. The classifier's rotor rotation frequency determines the circulation multiplicity and the largeness of the particles of the circulating load and the finished product.

Papers [8, 9] addressed some technological patterns in terms of reducing energy costs using the examples of operation of the gas-jet and steam-jet mills at VMMP when crushing zircon to 60 μm. Fig. 4–6 [3, 20] show the effect exerted on the performance G (t/h) and specific consumption q (nm^3/t) of an energy carrier by its temperature T, initial pressure P, and consumption G_a.

The diagrams in Fig. 5, 6 demonstrate that the equivalent performance ($G=2$ t/h) is achieved at a lower initial pressure ($P=0.27$ MPs) of the energy carrier, heated to 600 °C, compared to the operation involving overheated steam ($P=1.1$ MPa).

The practical application of JGP revealed the consumption of the overheated steam energy of $q=1.33$ Gcal/t at $G=4.82$ t/h; for combustion products – the consumption of natural gas $q=22.4$ nm^3/t, $Q_{ng}=56$ m^3/h, air consumption $Q_a=2,600$ m^3/h, $q=1,085$ nm^3/t. Actually, replacing steam

with a gas energy carrier made it possible to reduce energy costs by 1.6 times with a simultaneous increase in the output of the finished product by 2–3 %.
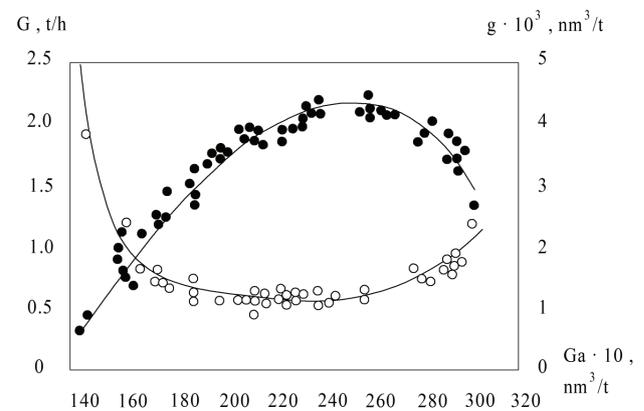
Fig. 4. Dependences of the performance G (t/h) (1) of a gas-jet plant and specific consumption q (nm^3/t) (2) on the total amount G_a (nm^3/h) of an energy carrier ($T=600-640$ °C; $P=0.1-0.18$ MPa)
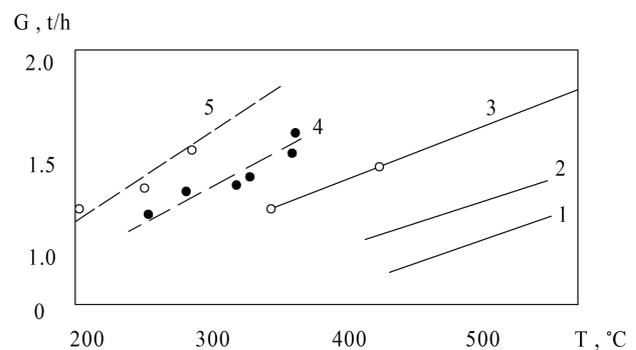
Fig. 5. Effect of the energy carrier temperature on the performance of a gas-jet (1, 2, 3) and steam-jet (4, 5) mills: pressure P (MPa): 1 − 0.15; 2 − 0.18; 3 − 0.27; 4 − 0.9; 5 − 1.1

A large volume of experimentally-acquired data related to reducing the energy cost of grinding in jets is given in works [2, 8, 9]. The optimal JGP workflow control strategy is to achieve maximal productivity in the region of stable regimes. It was established that in order to maintain the

maximal performance G (t/h) and minimum energy costs, the concentration factor $\mu = f(Q_a)$ of the solid phase in the energy carrier flow is a critical parameter. The change in μ level can be traced by an indirect indicator ΔH of the specific pressure drop (per 1 m of pipeline length: ΔH (kPa/m)$=f(\mu)$). When μ is above the optimal level, the rate of oncoming particle collisions decreases, which is accompanied by a decrease in performance G. Fig. 7 shows a change in the G of a gas-jet mill depending on ΔH.

Paper [8] proposed a gas-jet mill control algorithm based on the criteria for optimizing the dispersing process: $dG/d\mu = 0$ at $d\mu/dQ_a < 0$. Studies have confirmed that under the condition $d\mu/dQ_a < 0$ the stable operation is maintained (without blockage by the material); at $d\mu/dQ_a \geq 0$ – unstable [2].
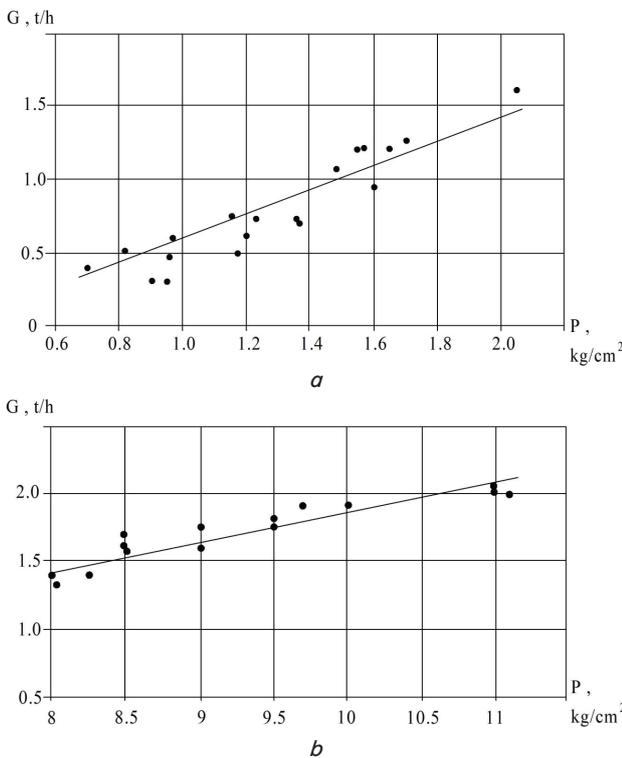
Fig. 6. The impact of the energy carrier pressure on performance G: a — natural gas combustion products; $T = 400...600$ °C; b — overheated steam; $T = 200...230$ °C
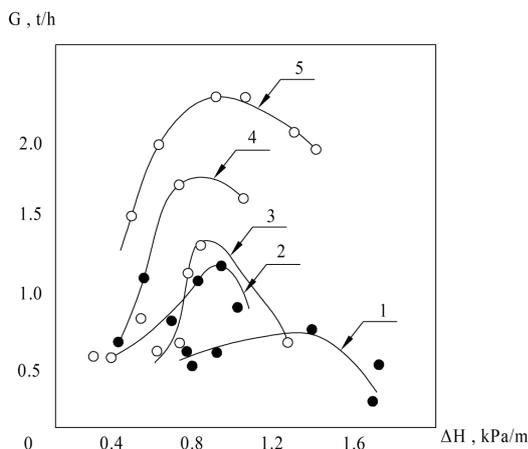
Fig. 7. Dependences of G (t/h) on the drop ΔH (kP/m) at R (MPa) [3]: 1 — 0.08; 2 — 0.14; 3 — 0.16; 4 — 0.2; 5 — 0.27

A test of the algorithm of extreme control over a mill's working process at VMMP showed an increase (up to 20 %) in the maximal performance. Special systems to enable/disable a mill, to control and manage the process are used to maintain the optimal level of the principal parameters. It should be noted that the data were subsequently used in work [10] to design control over the loading of the jet mill.

Several studies addressed the development and investigation of individual structures, varieties of jet shredders – with a reflecting plate [11, 12], with different geometry of the grinding chamber [12, 13], and other structural features. Those results, as well as the data reported in papers [1–3, 8–10], are mainly the accumulation of the material acquired experimentally. Scientific research is often of an exploratory, applied, or generalizing nature [15–17].

Our analysis of the scientific literature reveals that the above studies tackled the effect exerted on the process of jet grinding by individual regime parameters – the consumption, pressure, and temperature of an energy carrier, the amount of the loaded solid phase, the operational mode of the classifier. The issue of systemic research into the general patterns related to factors of reducing energy costs during dispersion in jets remains unresolved. Particularly important is the task to identify key factors in reducing energy costs when dispersing in jets. One way to address this issue is to find a universal assessment of energy consumption at dispersing. The selection of such a universal parameter and defining a method for measuring (calculating) it would make it possible to use it as an output parameter for the optimal systems of automated control over a jet mill by deviation.

3. The aim and objectives of the study

The aim of this study is to find and analyze those factors that determine the reduction in energy costs when dispersing material in jets. This would make it possible to define the most rational channel for the automated control over a gas-jet mill.

To accomplish the aim, the following tasks have been set:
– to analyze principal factors of energy reduction when dispersing in jets by employing acoustic information about the operation of jet mills;
– to explore the role of transforming energy consumption into acoustic radiation under an optimal jet mill operational mode – a mill operation mode at minimal energy costs.

4. Analysis of the factors that determine energy costs when dispersing in jets

The jet mill refers to a type of quasi-fragile destruction machines, in which the energy of accelerated particles is transformed into the energy of acoustic radiation, the kinetic and surface energy of flying fragments. The dispersing efficiency factor η_d of such a machine corresponds to the physical essence of the quantum efficiency η_q of the acoustic emission.

Dispersing in jets was studied using the acoustic monitoring of a grinding area in JGP of industrial and laboratory dimensions [18–20]. The working process in the oncoming jets is organized at a frequency of loading pulses $\dot{N} = 1/\tilde{T} \cong 10^6$ s^{-1} and a rate of deformation of $\dot{\varepsilon} = v/d > 10^5$ s^{-1}, $v \cong 10^2$ m/s (v is the speed of an impact, is the period of destruction, d is the diameter of particles). The period of particle collisions (the pumping energy time) is commensurate to the time of destruc-

tion, which accelerates the state of auto-resonance with maximal transformation into acoustic energy of the energy acquired by the substance [21]. Hence, it follows that the acoustic activity of the grinding zone reveals information about the effects of dispersion and energy costs in the grinding technology.

The theoretical possibilities of using the acoustic emission (AE) method to assess the effectiveness of gas-jet grinding were tested at the Volgograd Ceramic Plant [22]. Table 1 gives the conditions and performance indicators of mill operation when grinding slag from phosphorus production (less than 5 mm) as a main component of the raw materials for manufacturing cladding tiles.

Here are the methodology and the research results generalized for the set purpose. A brass waveguide (diameter, 22 mm; length, 500 mm) was used to measure the internal acoustic emission. One end was inserted into the grinding chamber, the other was connected to a signal sensor [13]. The external acoustic activity (at a distance of 0.25–0.5 m from the body of the grinding chamber) was registered using the microphone and amplifiers «Brüel & Kjær» (Denmark), «Robotron» (Germany). A relative change in the external AE (5–7 dB in a frequency band of 2–16 kHz) and the internal AE (20–25 dB in a frequency band of 125 kHz) was established. The growth of jet loading (up to the state of the blockage) is accompanied by a decrease in the frequency of acoustic signals from 10 to 2 kHz. The N signal count is inversely proportionally dependent on the static pressure H at the outlet from the grinding zone. Fig. 8 compares the kinetics of the number N for acoustic events (a) and the magnitude of H (b): $H = -40...+60$ mmH$_2$O.
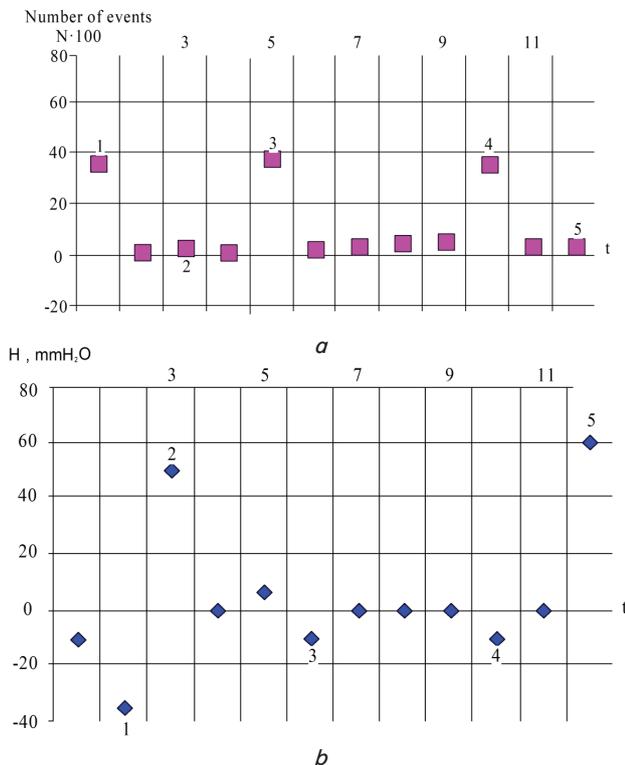
Fig. 8. Time-dependent change in acoustic radiation N and static pressure H: a — a change in the acoustic radiation $N(t)$; b — a change in the static pressure $H(t)$

The comparison of changes in acoustic radiation $N(t)$ and static pressure $H(t)$ confirms the correspondence of the *maximal* number N of acoustic events (AcE) (points 1, 3, 5)

to the *minimum* pressure H values with a certain time lag (up to 1 min). The observed effect implies that the increase in AE activity characterizes the increase in productivity and in the amount of the finished product feed to the cyclone, which is accompanied by a decrease in pressure H.

Conversely, the decrease in the number N (that is, a decrease in the growth of AE activity) is accompanied by an increase in pressure (points 2, 5) due to the reduction of the grinding fraction and the accumulation of the circulating product in the JGP system. Fig. 9 shows the grinding acoustograms for different jet states.
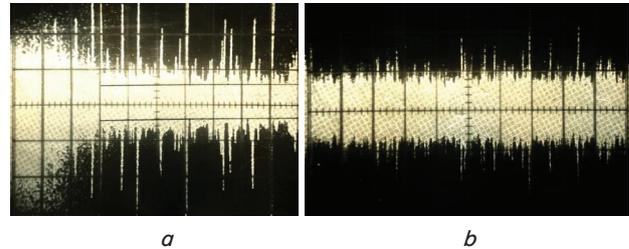
Fig. 9. Change in the spectra of the AcE amplitudes under different jet states: a — unloading; $G = 1.5...1.7$ t/h; $H = 0...-5$ mm H$_2$O; b — overload (blockage); $G = 0.9...1$ t/h; $H = +20$ mm H$_2$O

Our study has shown useful informativeness of the acoustic observation, which confirmed the natural relationship between the acoustic activity $\dot{N}$ in the grinding zone with the concentration of material in the jet, combined with the technological assessment of the indicators (G, H) of the mill's operation. However, given the long time spent on establishing the $G = f(H)$ dependence, there is a delay in the process entering the optimal state of the jet loads; as a result, the mill's maximal performance is not achieved in a timely manner while energy costs exceed minimum possible ones.

A new approach to using acoustic data is needed to evaluate and maintain minimum energy costs for dispersing. Paper [23] outlines the theoretical aspects of the single mechanism and common patterns in the destruction of loaded bodies with the effects of acoustic emission and dispersing, including the acoustic dimensional effect – the dependence of the density of acoustic energy during destruction on the size of the body being destroyed. Note that the acoustic estimate of the magnitude γ_s of effective surface energy under an optimal grinding mode is determined from the following expressions:

$$W_V d \cong \text{const}; \ W_V d \cong \gamma_s \cong 0.3 \text{ J/cm}^2,$$

where W_V is the critical energy density, J/cm^3; d is the predominant amount of destruction, cm.

In this regard, we introduce the indicator N_S (pulse/cm^2) for the acoustic energy intensity in the formation of a new surface, which is taken as a constant similar to the dynamic dimensional effect (DDE).

$$N_V \text{ (pulse/cm}^3) \cdot d \text{ (cm)} \cong \text{const} \cong N_S \text{ (pulse/cm}^2). \quad (2)$$

The essence of the new proposed method for assessing and maintaining the minimum energy cost of jet mill operation implies the following:

– the initial data included the grinding modes and indicators at the optimal and suboptimal jet loading, all other things being equal;

– the leading role was given to the γ_N (J/pulse) factor of transforming energy consumption into acoustic radiation under an optimal mill mode operation (at a maximal performance);

– the γ_N indicator was calculated as the ratio of supplied work (energy) to the count of acoustic signals in the grinding zone under an optimal mode;

– the current energy costs $E_{\Delta\tau}$ (J) over the period $\Delta\tau$ (a) during operation were estimated considering γ_N (J/pulse) and the averaged (over the interval $\Delta\tau$) acoustic activity $\dot{N}$ (pulse/s);

– the condition of compliance with the minimum acoustic energy cost of operation was the rapid adjustment of jet loading, which ensures a «conditionally constant» value of the γ_N coefficient (J/pulse), that is the value of the γ_N coefficient for a particular material and a specific jet-mill grinding technique.

Several technological and acoustic indicators were used in the calculation:

– performance G (g/s, t/h), the product dispersity S_{sp} (cm^2/g), the power N of the drive of the mill's energy system compressor;

– AE activity $\dot{N}$, pulse/s;

– specific acoustic energy intensity $N_G(\text{pulse/g}) = \dot{N}/G$;

– $N_S(\text{pulse/cm}^2) = \dot{N}/G \cdot S_{sp}$.

The provisions and formulae for calculating energy costs are as follows:

1. The calculation of the acoustic dispersion indicator N_S (pulse/cm^2) was performed considering the values of acoustic activity $\dot{N}$ (pulse/s) and technology indicators (G, N, S_{sp}) in each experiment from the following formula:

$$N_S(\text{pulse/cm}^2) = \dot{N}/G \cdot S_{sp}. \qquad (3)$$

2. The calculation $\gamma_N(\text{J/pulse}) = N/\dot{N}$ employed information on the acoustic activity $\dot{N}$ (pulse/s) of the grinding zone and the power N f the energy system ($N = 285$ kW).

3. The value of γ_s (J/cm^2) of the effective surface energy for a minimum energy intensity regime was calculated from the following formula:

$$N_S(\text{pulse/cm}^2) \cdot \gamma_N(\text{J/pulse}) \cong \gamma_s(\text{J/cm}^2) \cong \text{const}. \qquad (4)$$

4. The calculation of the current energy costs $E_{\Delta\tau}$ over the period $\Delta\tau$ of the mill's operation was performed from the following formula:

$$E_\Delta(\text{J}) \cong \gamma_N(\text{J/pulse}) \cdot \dot{N}(\text{pulse/s}) \cdot \Delta\tau(\text{s}). \qquad (5)$$

Equations (3) to (5) have made it possible to calculate energy costs for dispersing in jets based on acoustic information.

5. Results of studying the energy intensity of dispersing in jets

Thus, the new approach to using acoustic data for the current assessment of the energy intensity of dispersing is

based on the acoustic dimension effect [23]. In this regard, the N_S (pulse/cm^2) indicator of the acoustic energy intensity of the formation of a new surface is taken as a constant.

The research methodology is based on acquiring the initial experimental data and the estimated acoustic indicators of the energy intensity of grinding in jets. The recorded experimental data such as the performance G of a jet mill (g/s, t/h), the dispersion S_{sp} (cm^2/g) of the resulting product, the acoustic activity $\dot{N}$ (pulse/s) are given in columns 1–3 in Table 2. The dispersity S_{sp} was determined by the Tovarov method; the acoustic activity $\dot{N}$ – by the acoustograms of grinding; the examples are shown in Fig. 9. Formulae (3) to (5) were used to derive the estimated indicators (columns 4–7, Table 2) such as the specific acoustic energy intensity N_G (pulse/g), the acoustic indicator of dispersing N_S (pulse/cm^2), the indicators γ_s (J/cm^2) and γ_N (J/pulse).

Table 2

Experimental data and estimated acoustic energy cost indicators of the industrial jet mill

G, g/s	S_{sp}, cm^2/g	$\dot{N} \cdot 10^{-5}$, pulse/s	N_G, pulse/g	N_S, pulse/cm^2	γ_N, J/pulse	γ_s, J/cm^2
Performance G = 1,416–1,020 kg/h						
393.3	1,753	1.5	381	0.217	1.9	0.41
390.6	1,809	1.6	410	0.226	1.78	0.4
316.1	1,861	1.76	557	0.3	1.62	0.54
304	2,513	1.37	451	0.18	2.08	0.37
284	2,342	1.9	669	0.29	1.5	0.43
283.3	1,515	0.91	321.2	0.21	3.13	0.38
Performance G = 902–354 kg/h						
250.7	1,911	1.7	678.2	0.35	1.68	0.63
237.2	1,536	2.0	843	0.549	1.43	0.98
204	1,547	1.8	882	0.57	1.58	1.03
173.3	2,605	1.8	1038	0.4	1.58	0.72
142.2	1,542	1.8	1,265.6	0.82	1.58	1.48
120	2,209	1.7	1,417	0.64	1.676	1.15
98.3	2,451	1.8	1,830	0.75	1.58	1.34

Our experiments were carried out at the Vilnohirsk Mining and Metallurgical Plant. The shredded material is ilmenite-rutile-zircon sands from the Maleshev loose deposit. The grinding was performed in an industrial gas-jet plant (Fig. 2, 3). In the assessment of acoustic emission, a broadband piezo sensor was used [24]. The sensor was connected to a brass waveguide installed in the study area. The signal from the sensor was sent to an analog-digital converter. The duration of recording acoustic information for computer processing and pulse recognition is sufficient in the 0.1–1 s range.

Our analysis of the comprehensive acoustic and technological information on mill operation shows that for the crushed sand the γ_N indicator (J/pulse), which characterizes the actual transformation of the energy consumed into acoustic radiation under an optimal mode of mill operation at the maximal performance G = 390.6–393.3 g/s, equals $\gamma_N \cong 1.8$–2.0 J/pulse (first two lines in Table 2). At the same time, there is a difference of up to 2.5 times in the values of the

γ_s indicator, which characterizes effective surface energy under a mode of minimum energy intensity of dispersing: under an optimal mode ($\gamma_s = 0.40-0.42$ J/cm^2; $G \geq 1,000$ kg/h), from γ_s for sub-optimal operation ($G < 1,000$ kg/h, $\gamma_s = 1.05$ J/cm^2).

6. Discussion of results of studying the energy intensity of dispersing in jets

All regime parameters of jet grinding such as consumption, pressure, the temperature of an energy carrier, the amount of solid phase loaded, the classifier mode of operation predetermine the occurrence in the shredded material of dislocations, micro, meso, and macro fractures, and, as a result, the destruction of particles of the starting material. Each elementary act of destruction (from the occurrence of dislocation to the propagation and opening of a crack) corresponds to the pulse of acoustic emission [25]. The sum of these pulses is a recorded acoustic signal – acoustic activity $\dot{N}$ (pulse/s), which essentially shows the number of acts of destruction of the material. This is well illustrated by Fig. 8, 9, which show the relation of acoustic activity to the modes of jet mill operation – under a normal mode with active destruction and under the «blockage» when there is a sharp decrease in grinding fraction. Therefore, the acoustic activity $\dot{N}$ (pulse/s) is a generalized, integrated, and universally informative parameter to assess the activity of the process of destruction of the starting material in the mill's working chamber.

We propose assessing the conversion of energy consumption into acoustic radiation by the ratio of power N of the energy system to the acoustic activity $\dot{N}$ (pulse/s) of the grinding zone – the factor γ_N (J/pulse) $= N / \dot{N}$. This coefficient, as well as the energy cost γ_s (J/cm^2) of dispersing zircon, at the maximal performance and minimum energy costs, were determined by calculation based on empirical information (Table 2), formulae (2) to (4).

The theoretical warranty of keeping, during the working process, a minimum energy cost (the order of $\gamma_s^{\min} = 0.40 - 0.42$ J/cm^2, Table 2) is based on the current acoustic assessment $\dot{N}$ of the grinding zone and the calculation (5) of the optimal energy cost value E_Δ^{opt} (for the «conditionally constant» value $\gamma_N = 1.8-2.0$ J/pulse, Table 2). For example, at the acoustic activity in the grinding zone of the order of $\dot{N} = 1.5 \cdot 10^5$ pulse/s in the interval $\Delta\tau = 3,600$ s, the value E_Δ^{opt}, calculated from formula (5), is:

$$E_\Delta^{opt} = 1.8 \cdot 1.5 \cdot 10^5 \cdot 3,600 = 9,720 \cdot 10^5 \; J = 972 \; MJ.$$

Calculating the current energy cost indicator E_Δ and checking it for compliance with the set E_Δ^{opt} could become a practical base for the automated control over JGP workflow. Note that existing methods do not use acoustic information to assess the energy intensity of dispersing in jets and to automatically control this process.

Therefore, in order to maintain the minimum energy cost of jet mill operation, it is advisable to determine the γ_N (J/pulse) parameter of the transformation of the energy consumed into acoustic radiation under an optimal mill operation mode (maximal performance) and maintain it at this level (for each material, different, for the examined zircon sand $\gamma_N = 1.8-2.0$ J/pulse) by adjusting the loading of jets with the shredded material.

Our proposed application of γ_s and γ_N parameters as output ones for the jet mill's management system for deviation

agrees with the data reported in [3, 21, 23]. In this case, the input parameters are the characteristics of the shredded material and the degree of loading the jets with them.

The limitations of a given method are related to the hardware support to the automated systems that control acoustic information, its conversion, and use to automatically adjust the process. High-precision acoustic signaling sensors and specialized computer signal processing software are needed.

One of the proposed areas to advance this study is the decomposition of the acoustic signal into harmonics (a Fourier series). As well as determining the connection between the amplitudes and frequencies of these harmonics and the assessment of the energy intensity of dispersing in jets.

7. Conclusions

1. The main factors in the energy intensity of JGP workflow:

1) the initial temperature of an energy carrier, which sets the speed of the jet;

2) the concentration of solid phase in a jet that changes the speed of oncoming particle impacts;

3) the acoustic activity in the grinding area, the speed of dynamic deformation during destruction, and the effects of dispersing. At the same time, the concentration μ of the material in the energy carrier stream determines the indicator of the acoustic activity $\dot{N}$ of the grinding zone. The product of the N_V value (pulse/cm^3) of the specific AE by the predominant size d (cm) of the dispersed fractions characterizes the N_S (pulse/cm^2) indicator of the acoustic energy intensity of the formation of a new surface, which is taken as a constant. We have confirmed the usefulness of the integrated acoustic-technological evaluation of JGP operation (the AE activity $\dot{N}$ of the grinding zone, performance G, static pressure H, ΔH).

2. In the proposed method of assessing and maintaining the minimum energy cost of jet mill operation, the leading role was given to the γ_N (J/pulse) coefficient of the transformation of energy consumed into acoustic radiation under an optimal mode of mill operation. A series of experiments of gas-jet zircon grinding at VMMP has established a «conditionally constant» γ_N value at the level $\gamma_N = 1.8-2.0$ J/pulse. Achieving a minimum energy cost ($\gamma_s = 0.40-0.42$ J/cm^2) for dispersing zircon, which predetermines the maximal performance, is based on the effect of rapid jet loading adjustment to a «conditionally constant» level of γ_N ($\gamma_N \cong 1.8-2.0$ J/pulse). The energy cost $E_{\Delta\tau}$ over the period $\Delta\tau$ (s) of mill operation is estimated considering the γ_N (J/pulse) coefficient and the averaged (over the interval $\Delta\tau$) estimate $\dot{N}$ (pulse/s) of acoustic activity.

The specific % increase in the performance of a jet mill when applying the proposed method depends on the input and disturbing effects on the process.

Note that acoustic information could be used to optimize other types of mills [26–28].

Acknowledgments

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