Experimental Studies of the Process of Crushing Coal Charge on Hammer Mill with the View of Introducing Technologies and Products 4.0 at the Industrial Enterprises

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ABSTRACT
In conditions of fierce competition in the market of mining and metallurgical products the need to reduce its cost, which is achievable through optimization power consumption. One way to solve this problem, in conditions transformation of industrial clusters and technology development 4.0, is energy optimization through the development of digital production models processes based on functional dependencies of power consumption on design, kinematic and dynamic parameters of equipment, as well as characteristics of processed raw materials. To solve this problem on the developed physical model of hammer crusher studies have been conducted to determine the power spent on crushing the coal charge and overcoming the resistance rotation of its rotor from a dusty coal atmosphere, and a check was also performed the adequacy of existing analytical dependencies to calculate appropriate energy costs. As a result of studies, it was found that the discrepancy between calculated and experimental values does not exceed 6 ... 11%, also a correction factor is determined that takes into account the influence of the grate on calculated power.
Keywords: *coal charge, hammer mill, granulometric composition, energy costs*

1. INTRODUCTION

In the current market conditions, when the demand for metallurgical products remain constant or decline; development of the metallurgical industry possibly due to the introduction of new technologies to optimize operating costs. [1] German specialists formulated the basic principles for building the Industry 4.0, following which companies can implement the fourth industrial scenario revolution in their enterprises. One of the proposed principles is «Transparency» that appears as a result of the interaction of machines, devices, sensors and people by creating in the virtual world digital copies of real objects, systems of functions that accurately repeat everything that happens to her physical clone, this requires the ability to collect all this data from the sensors based on the context in which they are generated. [2-3]. Resulting the operation is the creation on the basis of the obtained data of mathematical models, describing the process, the adequacy of which can be confirmed on the basis of verification of the results by modeling the process on a full-scale model in laboratory conditions with the subsequent determination of the necessary correction coefficients.

At the Ukrainian coke-chemical enterprises, for the coal charge preparation to coke, the technological schemes of CGC (components group crushing) and CC (charge crushing) are used [4-5]. Where hammer mills are installed in the apparatus chain, the electric motor power is 60...70 % of the installed capacity coal preparation process shop, and the specific energy consumption for crushing coal charge in a hammer mill in the range of 1 to 3.5 kW·h/ton [6]. Therefore, the work aimed at studying the granulometric composition effect of the coal charge, its physical and mechanical properties on the energy-strength parameters of hammer mills, contributing to the reduction of energy consumption, is an urgent task.

In [7-10], theoretical dependences were obtained of the power expended determination on crushing the coal charge and on overcoming the resistance to rotation of the hammer mill's rotor from a dusty coal medium, however, experimental studies confirming the adequacy of the results obtained were not carried out.

So, the purpose of this work was to carry out experimental studies that would allow us to verify the adequacy of the dependences obtained.

2. BACKGROUND

2.1. The Laboratory Model Design

To carry out the research, a laboratory model of the apparatus for crushing the coal charge is on in figure 1.

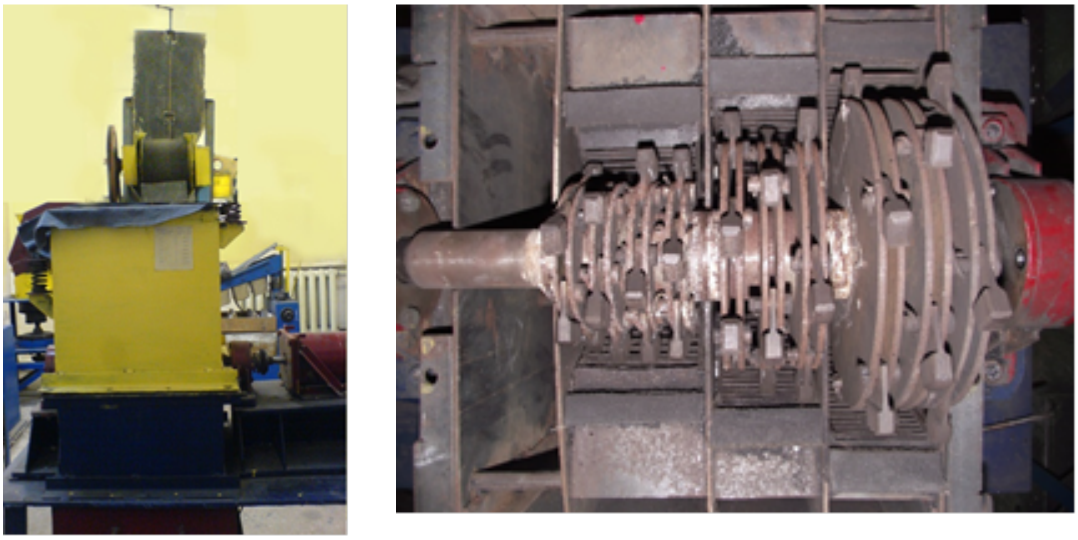
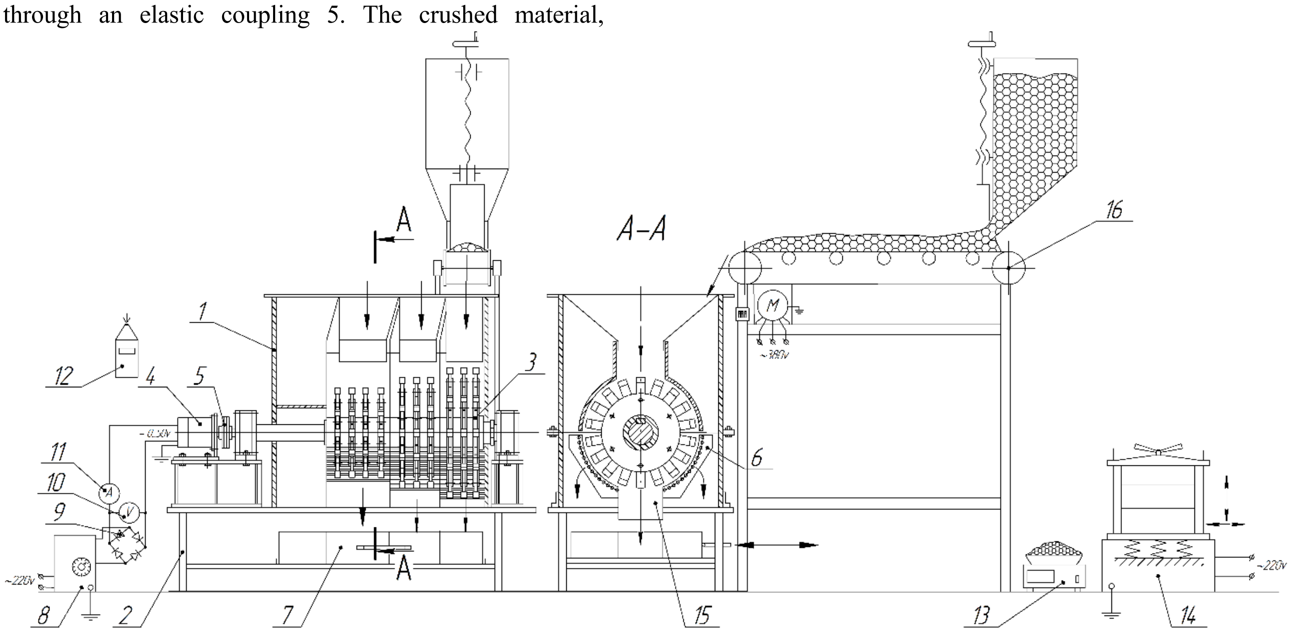


Figure 1 Laboratory model of the unit for coal charge crushing

Figure 2 is a schematic diagram of an installation with measuring equipment for carrying out experimental studies, which consist on welded body 1 located on frame 2, a 3-stage rotor 3 with diameters of 150, 200 and 250 mm, respectively. The rotor is driven by a DC motor 4 through an elastic coupling 5. The crushed material, spattering through the grate 6 and the unloading window 15, enters the receiving box 7, which is divided into sections corresponding to the installed rotors' diameters. The conveyor 16 carried out the material feed in the crusher section.



1. Body; 2. Frame; 3. Rotor; 4. Engine; 5. Coupling; 6. Grate; 7. Receiving box; 8. Autotransformer; 9. Diode bridge; 10. Voltmeter; 11. Ammeter; 12 Photo tachometer; 13. Scales;14. Analyzer; 15. Unloading window; 16. Belt conveyor

Figure 2 Scheme of installation to crush the coal charge with measuring equipment

The frequency of the motor shaft rotation was varied by adjusting the voltage from 0 to 50 V using a voltage regulator RNO-250-5 (pos. 8) and a diode bridge 9 included in the circuit. To measure the voltage and the amperage in the engine, a voltmeter M381 75V (pos. 10) and an ammeter M381 30A (pos. 11). The weighing of coal charge before and after crushing was carried out on lab electronic scales called "CERTUS BALANS" (pos. 13).

2.2. The Laboratory Procedure

To carry out the researches, a charge was used consisting of a coals mixture of 0-20 mm size, humidity 3 %, the granulometric composition and content of which are given on the table 1.

Table 1 Granulometric composition of the charge

Class, mm	0-0.5	0.5-3	3-10	10-20
Content , %	25	25	25	25

To ensure the specified kinematic and power parameters of the hammer mill laboratory model, which are necessary to carry out basic research, a few of preliminary experiments were carried out.
In the first one, the dependence of the rotor shaft rotational speed on the voltage was determined using the ATT 6000 photo taximeter (figure 2, pos. 12) and voltmeter pos. 10 (it is linear for linear motors).
In the second one, the minimum work required to hit the hammer mill on a piece of the most durable coal (20 mm max) with a minimum diameter of 150 mm was determined.
Equating the work done for the impact and the work required to crush a piece of a given volume, with the known design parameters of the hammer mill and the physical and mechanical properties of the coal, the rotor speed required for the experiments, which was 3000 rpm, was determined by calculation. In this case, for the rotors used in the experiments, diameters of 150, 200, 250 mm with a hammer mass equal to 0.04 kg, the force action was 296, 395, 494 N, respectively.
To test the chosen parameters, the experiment was conducted in which a sample of coal of 20 mm class of 1 kg was crushed in the first stage of hammer mill with a minimum rotor diameter of 150 mm. The experiment confirmed the selected parameters, since the entire class of 20 mm was crushed.
During the experiments, the power consumption was determined when the hammer mill was operating at idle and under load, with or without a grate.
The power expended to crush was determined as the difference between the power consumption of the engine (N_{en}) and the idling power ($N_{id.p}$) by the formula of

$$N_{cr} = N_{en} - N_{id.p} \quad (1)$$

The experiments were carried out in the three stages. At the first stage of the charge consisted of 4 classes in accordance with the table 1, conven-tionally assuming that the charge passed the preliminary screening with the screening efficiency E_s = 50 %.
A series of experiments was carried out with both a grate (slot size 3 mm) and without it. The prepared samples each 1 kg total were filled in a section (step) with the smallest hammer mill rotor diameter of 150 mm. During the coal charge crushing, with the help of an ammeter and a voltmeter included in the circuit, the current and voltage were recorded, that is allowed to determine the power consumption of crushing. Then, the experiments were repeated for a rotor diameter of 200 and 250 mm.
At the second stage, the studies were carried out for a coal charge consisting of two classes of 3-10 mm and 10-20 mm, the finished class 0-3 mm was removed (conditionally considering the screening efficiency E_s = 100 %). The experiments were similar to the first ones.
At the third stage, studies were carried out for a coal charge of 0-2 mm, which has represented its pulverized-coal part. The prepared samples each weighing 2 kg was loaded into the crushing chamber of a hammer mill with a rotor diameter of 250 mm. A series of experiments was conducted without a grate to eliminate losses on abrasion of the coal charge on it. During the experiments, energy costs were determined for overcoming the resistance of the rotor of a crusher of dust-air coal meal.
In laboratory studies, mathematical methods were used processing the rest of the experiment. The amount of K_{exp} dosage experiments required obtaining reliable results was determined in accordance with the requirements of the theory mathematical statistics [11] by staging a series of previous experiment sat constant parameters

$$K_{\exp} = \frac{t^2 \cdot \sigma_m^2}{\Delta j^2}, \quad (2)$$

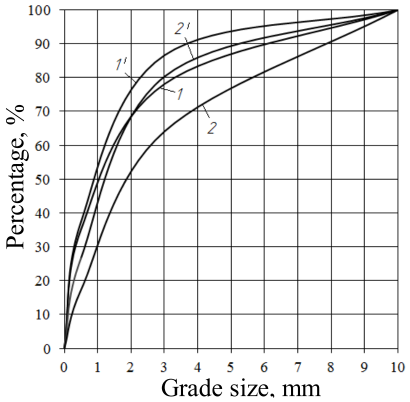
where t is the normative factor, with the reliability of the experiment 0.95 $t = 2$; σ_m – standard error of measurements

$$\sigma_m = \sqrt{\frac{\sum_{i=1}^{z_{\exp}} (j_i - \bar{j}_m)^2}{z_{\exp} - 1}}, \quad (3)$$

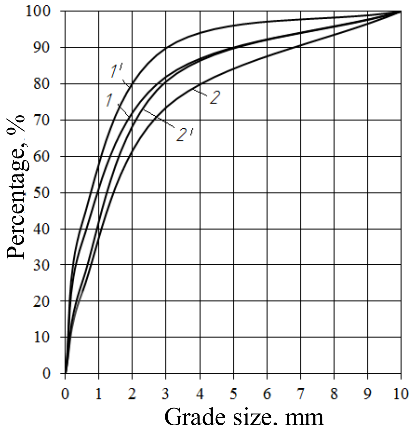
where $z_{\exp}$ – number of repetitions of experiments; j_i – measured value; $\bar{j}_m$ – average the value of the measured value

$$\bar{j}_m = \frac{\sum_{i=1}^{z_{\exp}} j_i}{z_{\exp}}, \quad (4)$$

Δj – a valid error of the arithmetic mean of the subject parameter



a)



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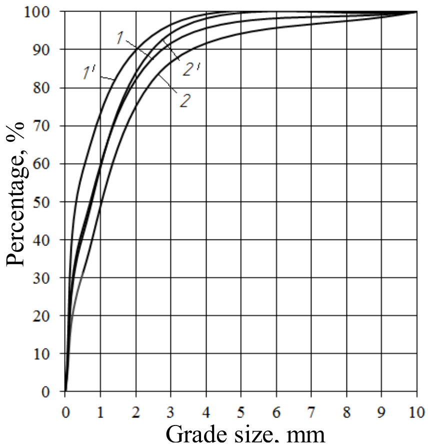


c)

Figure 3 Integral characteristic particle size distribution of coal charge after crushing at different the effectiveness of the snapping finished grade 0-3 mm: a – for the diameter of the rotor 150 mm; b – for rotor diameter 200 mm; c – for a rotor diameter of 250 mm; 1 - screening efficiency of 50 % without lattice; 1' – the effectiveness of screening 50 % with lattice;
2 – efficiency screening 100 % without lattice;
2' – screening efficiency 100% with lattice

$$\Delta j = \frac{t \cdot \sigma_m}{\sqrt{z_{\exp}}}, \quad (5)$$

According to [9], the results of experiments were excluded as uncharacteristic if the measured value j_i was such that

$$\bar{j}_m - j_i > 3\sigma_m . \quad (6)$$

The magnitude of the error, calculated in the described way, was considered negligible small, if it did not exceed 4… 5% of the average value of $\bar{j}_m$ that was measured j_i.

The parameters of the empirical formulas were selected according to standard ones techniques using the least squares method.

2.3. Results and Discussion

Determination of the effect of elimination of finished grade 0-3 mm from the input coal charge for energy consumption of the crushing process, mode and design parameters of a hammer crusher

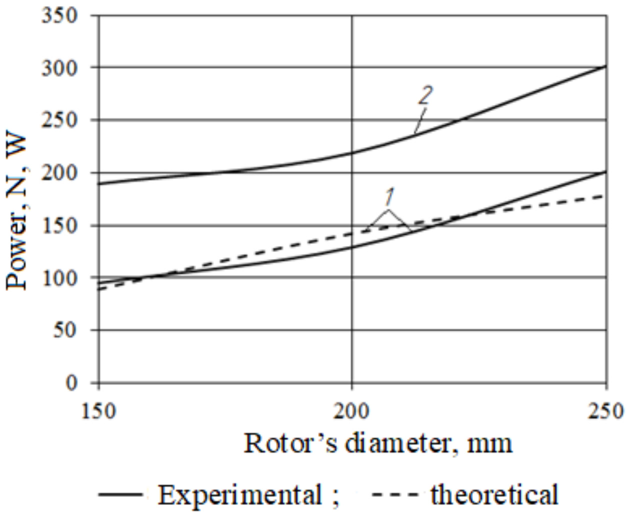
In figure 3 shows the integral characteristics of the particle size distribution the composition of the coal charge after crushing for the rotor diameter of 150, 200 and 250 mm accordingly, with different screening efficiency of the finished class 0-3 mm.

According to requirements that are in qualities crushing, with the given dependences it is visible that the best indicators were received at crushing of coal furnace charge with efficiency of a screening of a ready class of 0-3 mm before crushing of 100 % without grid-iron lattice for diameter of a rotor of 250 mm (figure 3, in curve 2). Contents of a ready class of 0-3 mm made 86 %, and dust-like class of 0-0.5 mm in it did not exceed 32 %, the large class of 6 mm made no more 5%. The worst figures it is received when crushing coal furnace charge with efficiency screening of a ready class of 0-3 mm before crushing of 50 % from grid-iron lattice for diameter of a rotor of 250 mm (figure 3, in, a curve 1′). Contents of ready class of 0-3 mm in furnace charge made 96 %, a dust-like class of 0-0.5 mm in it 58%, class of 6 mm no more than 1 %.

Also, a series of experiences with the coal furnace charge raised was carried out humidity of W = 13 % for diameter of a rotor of 250 mm. Experiences showed that humidity significantly affects quality of crushing. So, when crushing from grid-iron lattice practically all dust-like class that is in coal furnace charge to crushing, and formed crushing in process, hammered cracks grid-iron lattices also stuck on walls of the case of laboratory model to "gold" also part of big classes (only 37 % of lump tests).

When crushing without grate with pre-screening finished class 0-3 mm (screening efficiency equal to E_s = 50 %) the situation is somewhat has improved, but it's still practically the whole small class, which binds partially more (only 33 % of the total sample weight), stuck to the walls of the camera it is not possible to determine the quality of the crushing.

Thus, it is obvious that the crushing of the charge with high humidity the use of the grate is inappropriate.
As a result of the researches, the dependence of the coal charge crushing power on the diameter of the hammer mill's rotor was obtained with the conventional screening efficiency of the finished class 0-3 mm before the crushing E_s = 50 %, both from the grate and without it, shown on figure 4.



1 – Without grate; 2 – With grate

Figure 4 The dependence of coal crushing power on diameter of the rotor hammer mill at efficiency screening of finished class 0-3 mm *Es* = 50 %

We can see from the dependences obtained that when the rotor diameter is increased, the crushing power increases (curves 1 and 2). On figure 3 the dashed line shows the calculated crushing power of the coal charge at the same design parameters of the hammer mill, size and physical and mechanical properties of the crushed material, but without taking into account the interaction of the material with the grate. Comparing the theoretical and experimental information (curves 1 and 2), it is evident that the error in the results without the grate does not exceed ±11 %, and with the grate, the energy consumption to crush the coal charge increases by 1.5...2 times. Therefore, in the theoretical calculation of the power required to crush the material with the installed grate, it is necessary to introduce a correction factor — k_c, then the formula to determine the power in accordance with [8] is:

$$N_{o\upsilon} = 4.2 \cdot 10^{-6} \cdot k_c \cdot Q \cdot \frac{\sigma^2}{E \cdot \rho} \cdot \sum_{i=1}^{n} \gamma_i \cdot \left(\frac{d_{mi}}{d'_{mi}} - 1 \right), (7)$$

where $4.2 \cdot 10^{-6}$ is the tons conversion coefficient in kilograms, hours per second, percentages in fractions of a unit, wool per kilowatt; k_c is the correction factor (k_c = 1 without a grate, k_c = 1,5 ... 2 with a grate); Q is the hammer mill productivity, t/h; σ is the ultimate strength of coal, Pa; E is the modulus of the coal elasticity, Pa; ρ is the coal apparent density, kg/m^3; γ_i is the content of the given class in the charge, %; d_{mi} is the average size of a piece of the i-th fraction to be crushed, m; d'_{mi} is the average size of a piece of i-th fraction after being crushed, m.
It should be noted that the obtained dependence is valid when we calculate the power to crush the dry (moisture content W = 3 %) coal charge. When the charge is crushed with a moisture content of W = 13 % with a screening efficiency of the finished class of 0-3 mm and E_s = 50 % with a rotor diameter of 250 mm without a grate, the power spent to crush is 2.3 times higher than the power expended to crush the charge with a moisture content W = 3 % under the same conditions of crushing.
As it was established in [12], the coal charge fed to crush into the hammer mill contains a large amount of the 0-3 mm class, which does not participate in crushing and forms a dusty coal medium.
Figure 5 shows the dependence of the power spent on overcoming the resistance of the dusty coal medium to the rotation of the hammer mill rotor from its productivity, obtained experimentally and by calculation using the formula

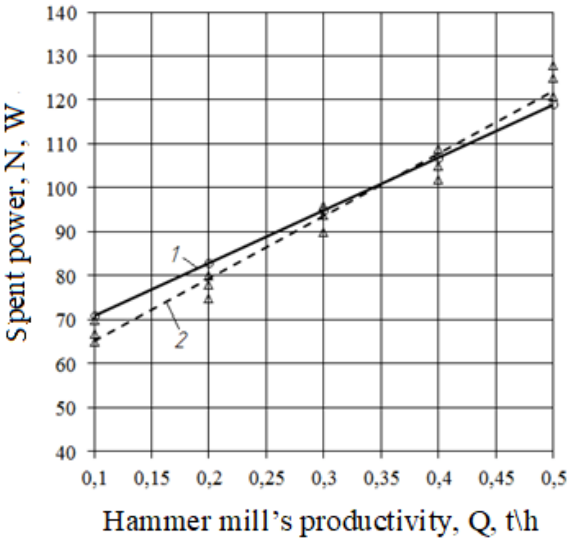
$$N_{oa} = 12.5 \cdot 10^{-5} F \cdot \omega_r^3 \cdot D_m^3 \cdot \left(\frac{1.74 \cdot Q \cdot \gamma_{pc}}{\omega_r \cdot k_r \cdot V} + \rho_{air} \right), (8)$$

where $12.5 \cdot 10^{-5}$ and 1.74 is the conversion factor; F is the cross-sectional area of the active part of the rotor (the area of one row of hammer mills and the open part of the suspension axis of the hammer mills along the length of the rotor), m^2; ω_r is the angular velocity of the rotor, s^{-1} ; D_m is the average diameter of the path of the dust-air medium in the hammer mill, m, which is determined in accordance with [13]; γ_{pc} is the share of the pulverized coal part in the charge; k_r is the number of hammer mills' rows in the hammer mill; V is the "clean" volume of the sector (replacement volume in the space of the hammer mill, without the volumes of the elements of the rotor and the material), m^3; ρ_{air} is the air density, kg/m^3 (ρ_{air} = 1.225 kg/m^3 – under atmospheric conditions standard).
From the obtained graph it can be seen that the spent power to overcome the resistance of a dusty coal medium grows in proportion to the productivity of a hammer mill, and the difference between calculated and experimentally obtained values does not exceed ±6 %.

3. CONCLUSION

As a result of the pilot studies, the following results were obtained:

− the laboratory model of the hammer mill has been developed, as well as the research methodology;
− the adequacy of the analytical dependence connecting the power necessary to crush the coal charge with specified technological, physical and mechanical properties, on the size and content of the corresponding classes in the initial coal charge, is checked. It was found that the discrepancy between the calculated and experimental values of the power spent to crush does not exceed ±11 %, as well as a correction factor that takes into account the influence of the grate on the calculated power – k_c, which is in the range 1,5...2;
− the adequacy of the obtained analytical dependence that allows one to determine and estimate the level of influence of a dusty coal environment on energy consumption in a hammer mill during the coal charge crushing is carried out. It was found that with increasing pulverized coal content in the crushing chamber, the consumption of power consumption of the hammer crusher proportionally increases; the discrepancy between the calculated and experimental values of the received power does not exceed ± 6 %.



1 – Calculated data; 2 – Experimental data

Figure 5 The dependence of the power spent on overcoming the resistance of the dusty coal environment to the rotation of the hammer mill rotor rotation on its productivity

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