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THE INFLUENCE OF ELECTRIC MOTOR POWER ON THE PARAMETERS OF THE MOON REGOLITH EXTRACTION SITE

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Abstract. The purpose of the article is to establish the dependence of the area of regolith extraction using a screw conveyor and the possible extraction volumes on the parameters of the electric motor used, taking into account the parameters of the screw conveyor, the characteristics of the deposit, and the properties of the regolith. To achieve this goal, we used already known dependencies for calculating the parameters of the screw conveyor and the fundamental laws of loose media mechanics, the basic equations of electrodynamics of asynchronous motors, as well as the peculiarities of the behavior of loose media when moved by a screw, which were experimentally studied by domestic authors. It was possible to investigate the influence of such parameters of an asynchronous squirrel-cage motor as critical slip, maximum possible torque, and permissible value of electric motor power on the permissible limits of screw length change, extraction area, and regolith extraction volume. The permissible values of the transport distance from the diameter of the screw conveyor and its other geometric parameters, as well as the degree of screw filling, which are possible with the selected electric motor parameters, were determined. It has been established that the area of the regolith extraction site and the volume of its extraction, within the range of variation of the main parameters studied, depend almost linearly on the relative permissible power of the electric motor, and the coefficients of this dependence are determined by the critical slip value. At the same time, for all values of critical slip, the graphs of functions corresponding to larger values of this parameter are located above the graphs corresponding to smaller values. The dependencies proposed for calculating the area of the regolith extraction site and the probable volume of its extraction when using a screw conveyor driven by an asynchronous squirrel-cage motor, from the parameters of the electric motor, the geometric dimensions of the screw, the characteristics of the deposit, and the properties of the regolith, allow the design of technological schemes for the extraction of minerals on the planets of the Solar system and the determination of their permissible and optimal parameters.

Keywords: Moon, regolith, screw, electric motor, extraction area, extraction volume.

1. Introduction

Technologies for extracting minerals on the Moon, combined with technologies for processing them in extraterrestrial conditions or transporting them to Earth, as well as delivering equipment and personnel to the Moon, open up the prospect of accessing new types of minerals that are not found on Earth, as well as the possibility of obtaining minerals whose reserves on Earth have already been exhausted [1–3]. In addition, the desire to extract minerals outside Earth contributes to scientific and technological progress, as it requires the creation of fundamentally new technologies and technical solutions designed for use in other conditions. Since the beginning of the 21st century, this topic has been fully included in the technological achievements of the near future [4–9]. A number of domestic and foreign companies, such as NASA, Komatsu, Design Bureau Pivdenne, and others, are developing and testing the latest robotic models [4–12], while construction equipment manufacturers are adapting their best designs to lunar conditions and the possibility of autonomous operation [13, 14].

There have been well-known attempts to geologically substantiate possible types of minerals, as well as to assess the power of their deposits and the geographical features of the location of deposits on the surface of our planet's only natural satellite [7, 8], as well as in the Solar system [15–17]. Some design developments for Moon settlements, both automated and adapted for long-term human habitation, are in the

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final stages of readiness [9, 16]. One of the leading problems is the transportation of extracted minerals on the Moon from the place of extraction to the place of processing or shipment to Earth [10–14, 18].

Most experts working on solving the problems of Moon exploration are inclined towards autonomous technologies for the extraction and transportation of minerals, which can function without direct human intervention or be controlled remotely, and do not require the repair and restoration of individual technical components. Such technologies must also meet requirements for protection from Solar wind and electromagnetic fields, and the fact that the only source of energy that does not need to be delivered from Earth is Solar energy [10–14, 18].

All this makes screw conveyor transport the most promising for use in Moon conditions for transporting Moon regolith deposits. This type of transport can use electric motors of various power ratings, powered by Solar panels and equipped with appropriate energy storage devices. The body of the screw conveyor has small geometric dimensions in cross-section, which allows it to be placed in a pipeline. The design of such a device allows the screw to be assembled from sections of standard length using hinged or gimbal joints, which facilitates delivery and installation, repair of the conveyor, and also ensures its flexibility. The parameters of the screw in terrestrial conditions are determined by the need to overcome the friction of the material, which is due to the force of its weight and the weight of the screw itself [19], which are significantly lower in Moon conditions [10–14, 18].

A well-known study of the potential of a screw, as an Archimedes screw turbine, depending on its length, outer and inner diameters, pitch, and number of blades, the results of which indicate that the output power and overall efficiency of the device are affected by the speed of material movement and the angle of its rotation [20–24]. However, methods for calculating the parameters and operating modes of screw conveyors in terrestrial conditions do not usually consider the power limitations of the electric motor used [25–28]. Meanwhile, in lunar conditions, this limitation is one of the most important, since all equipment must be transported from Earth, overcoming the force of Earth's gravity. And since the screw conveyor is proposed to be used both for extraction and transportation of regolith, the geometric dimensions of the deposit area that can be developed by such a device will primarily depend on the power of the electric motor.

2. Methods

Thus, studying the effect of electric motor power on the parameters of the Moon regolith extraction site is an adaptation of the methods for calculating such technologies to lunar conditions and creates opportunities for determining the optimal parameters of technical means and technologies for extracting minerals on the planets of the Solar system.

Thus, the purpose of the publication is to establish the dependence of the area of regolith extraction using an screw with the determination of possible extraction volumes on the parameters of the electric motor used, taking into account the parameters of the screw, the characteristics of the deposit, and the properties of the regolith.

2. Theoretical part

Known methods for calculating the parameters and operating modes of screw conveyors adapted to Moon conditions, where, unlike Earth conditions, friction forces will be significantly lower [1, 2, 10 – 14, 18, 29]:

$$Q = \frac{R^2 e \omega_0 c}{15.268} G \eta^{1.44}; \quad P = \omega_0 M_m (1 + c) \Gamma; \tag{1}$$

$$G = \frac{2 + c}{c} - x - \sqrt{x^2 - 2x - 3}; \quad \Gamma = \frac{2 + c}{cx} - 1 - \sqrt{1 - \frac{2}{x} - \frac{3}{x^2}}; \quad \eta = \frac{h_0}{R};$$

$$x = \frac{2.081 M_m (1 + c)}{\eta^{1.5} k_g g (1 - m) \rho_s L R^3 f \cos\psi}, \tag{2}$$

where Q – volume flow rate of the transported material, m^3/s; P – power consumed by the electric motor, W; G – relative volumetric flow rate of the transported material; Γ – relative power of the electric motor; R – screw blade radius, m; e – screw pitch, m; ω_0 – electromagnetic field rotation frequency, s^{-1}; c – critical slip of the electric motor [2]; x – electromechanical parameter; η – degree of filling of the screw conveyor; M_m – maximum possible torque of the electric motor, N·m [2]; k_g – coefficient of change in free fall acceleration under lunar conditions compared to Earth conditions, 0.1655 [2]; g – free fall acceleration under Earth conditions, m/s^2; m – porosity of the transported material layer varies from 0.42 to 0.54, dimensionless units [2]; ρ_s – density of the transported material varies from 1300 to 2000 kg/m^3 [2]; L – length of the screw conveyor, m; f – generalized coefficient of friction of the transported material against the inner surface of the pipe; ψ – angle between the screw blade and its axis of rotation, rad; h_0 – maximum thickness of the transported material layer, m.

Formulas (1) allow us to estimate the parameters of the Moon regolith extraction site if the parameters of the electric motor to be used are known. Taking into account the recommendations of experts on the prospects of using small-sized electric asynchronous squirrel-cage motors on the Moon, it is necessary to consider limiting the electric motor power to its nominal value [18]:

$$P \le [P],$$

where $[P]$ – permissible electric motor power, W.

Considering the inequality and the second equation from (1) together, after the appropriate transformations, we obtain a quadratic equation with respect to the length of the screw, the solution of which allows us to write the following restrictions characterizing the permissible transportation distance

$$\Lambda A \le L \le \Lambda B; \tag{3}$$

$$A = \frac{0.5p}{1+c}\left(1 - \sqrt{1 - \frac{q}{p^2}}\right); \qquad B = \frac{0.5p}{1+c}\left(1 + \sqrt{1 - \frac{q}{p^2}}\right); \ \Lambda = \frac{1.04M_m}{g'\rho R^3\eta^{1.5} f\cos\psi};$$

$$p = \frac{1+ab\nu}{1+a}; \ q = \frac{1+a\nu}{1+a}\nu; \ \nu = \frac{[P]}{\omega_0 M_m}; \ a = \frac{1}{(1+c)c}; \ b = 1+0.5c,$$

where Λ – screw length scale; A – minimum permissible relative screw length; B – maximum permissible relative screw length; a – reverse critical slip of the electric motor; b – effective critical slip of the electric motor; p – screw length limit coefficient; q – screw length limit variation parameter; ν – relative permissible power of the electric motor.

Inequality (3) determines the possible parameters for safe use of the screw conveyor when transporting regolith under lunar conditions and defines the permissible values of the transport distance for known values of the screw conveyor diameter and its degree of filling, which are possible with the selected electric motor parameters.

Assuming that the end of the screw conveyor, which ensures the extraction of regolith, describes a circle or part of a circle, in the center of which there is a power supply station and a receiving hopper, then using (3) the area of possible regolith extraction is calculated as follows

$$S = \frac{\varphi}{4}\Lambda^2\Omega; \tag{4}$$

$$\Omega = \left[\sqrt{p^2 - q} + 2p\right]\frac{\sqrt{p^2 - q}}{(1+c)^2},$$

where S – area of the regolith extraction site, m^2; φ – central angle of the extraction site, at 6.28 this is a circle, rad; Ω – electrical-mechanical coefficient.

Knowing the area of the regolith extraction site, formula (4), we calculate the corresponding volume of its extraction

$$W = (1-m)\eta RS, \tag{5}$$

where W – volume of regolith extraction from the area, m^3.

Considering formulas (2)–(5) together, we obtain a dependence in which each of the factors is taken into account as a separate multiplier:

$$W = \frac{w_M w_E}{w_S}; \tag{6}$$

$$w_S = \eta^2\cos^2\psi R^5; \qquad w_M = \frac{0.27(1-m)\varphi}{(g'\rho f)^2}; \ w_E = M_m^2\Omega,$$

where w_S – a coefficient that takes into account the parameters of the screw conveyor; w_M – a coefficient that takes into account the parameters of the deposit and the properties of the regolith; w_E – a coefficient that takes into account the parameters of the electric motor.

3.Results and discussion

Using formulas (1)–(6), calculations were made of the main parameters and values, namely: formula (1) allows us to investigate the dependence of the relative volumetric flow rate of the transported material and the relative power of the electric motor on the electromechanical parameter at different values of the critical slip of the electric motor (Figures 1 and 2). Figures 1 and 2 show that the value of the electromechanical parameter at which these values are positive is limited by the actual critical slip.

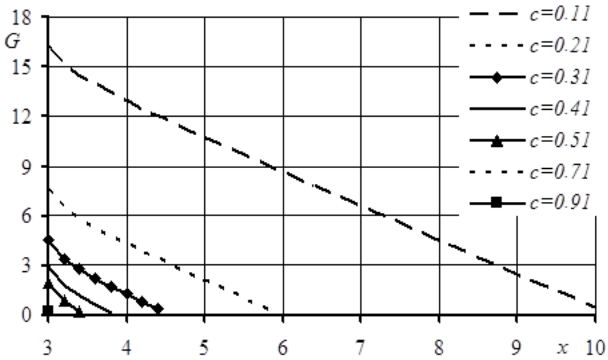


Figure 1 – Dependence of the relative volumetric flow rate of the transported material on the electromechanical parameter at different values of the critical slip of the electric motor

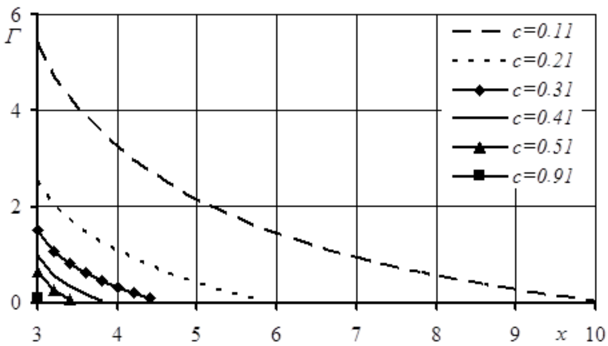


Figure 2 – Dependence of the relative power of the electric motor on the electromechanical parameter at different values of the critical slip of the electric motor

Thus, the requirement that the motor power and the volumetric flow rate of the transported material must be positive and not imaginary leads to the following limitation of the electrical-mechanical parameter

$$3 < x < X; \qquad X = \frac{c^2 + c + 1}{c}, \qquad (7)$$

where X – the maximum possible value of the electrical-mechanical parameter (Figure 3).

As can be seen from Figures 1 and 2, the maximum values of the volumetric flow rate of the transported material and the power consumed by the electric motor are achieved at the minimum value of the electrical-mechanical parameter and are determined by the critical slip of the electric motor (Figures 4 and 5):

$$G^* = 2\frac{1-c}{c}; \quad \Gamma^* = \frac{2}{3}\frac{1-c}{c},$$

where G^* – maximum relative volumetric flow rate of the transported material; Γ^* – maximum relative power of the electric motor.

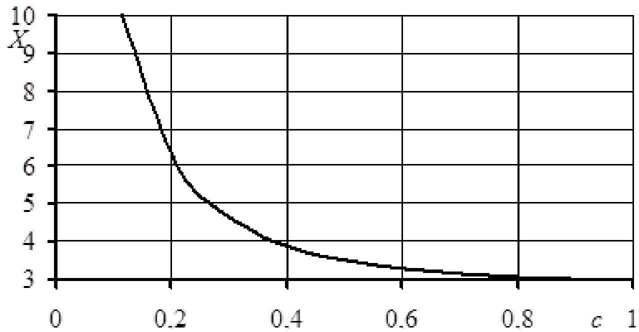


Figure 3 – Dependence of the maximum possible value of the electromechanical parameter on the actual critical slip of the electric motor

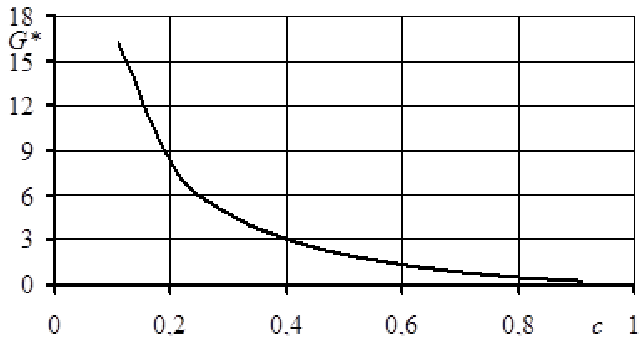


Figure 4 – Dependence of the maximum value of the relative volumetric flow rate of the transported material on the actual critical slip of the electric motor

As can be seen from formula (3), the interval of change in the length of the screw is influenced by such characteristics of the electric motor as critical slip, maximum possible torque, and permissible value of the electric motor power. The maximum possible torque of the electric motor is taken into account when calculating the scale of the screw length. Based on the critical slip value, the inverse critical slip of the electric motor and the effective critical slip of the electric motor are calculated (Figures 6 and 7), which are used as parameters when taking into account the influence of the permissible value of the electric motor power in terms of the screw length ratio coefficient and the screw length variation parameter (Figures 8 and 9).

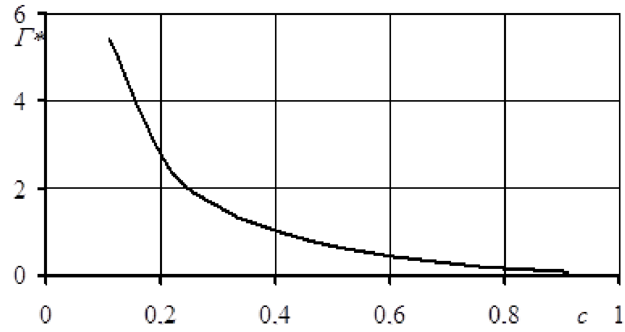


Figure 5 – Dependence of the maximum value of the relative power of the electric motor on the actual critical slip of the electric motor

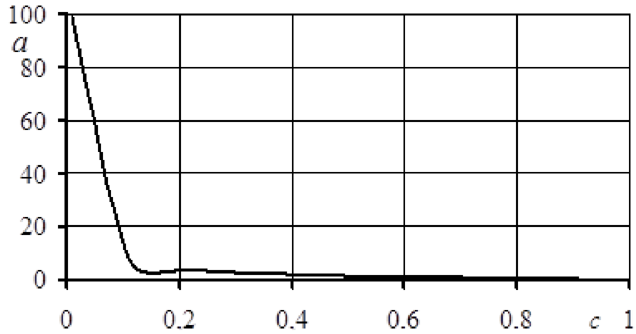


Figure 6 – Dependence of the inverse critical slip of an electric motor on the actual critical slip of an electric motor

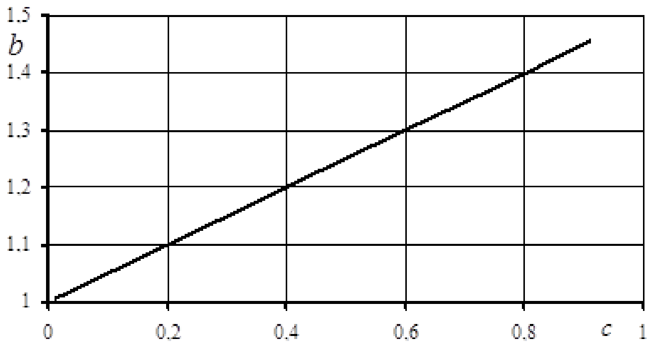


Figure 7 – Dependence of the effective critical slip of an electric motor on the actual critical slip of an electric motor

All these parameters allow calculating the minimum and maximum permissible relative lengths of the screw (Figures 10 and 11), which depend exclusively on the parameters of the electric motor, since all other factors, such as the parameters of the screw, the characteristics of the deposit, and the properties of the regolith, are taken into account by the scale of the screw length. The values of the screw length limit coefficient and the screw length limit variation parameter (Figures 8 and 9) also allow us to calculate the value of the electromechanical coefficient, which is actually the relative area of the regolith extraction site (Figure 12).

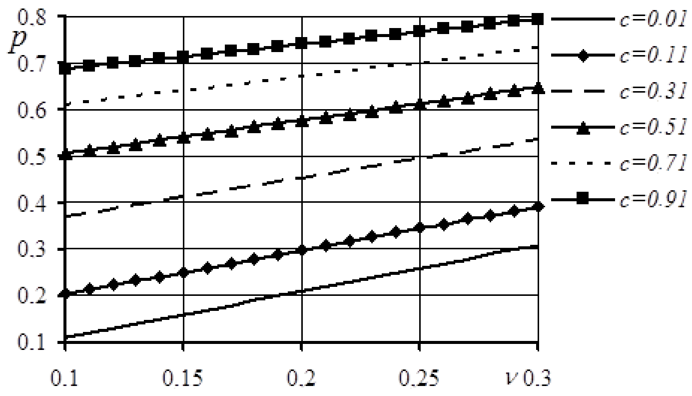


Figure 8 – Dependence of the screw length limit coefficient on the relative permissible power of the electric motor at different values of the critical slip of the electric motor

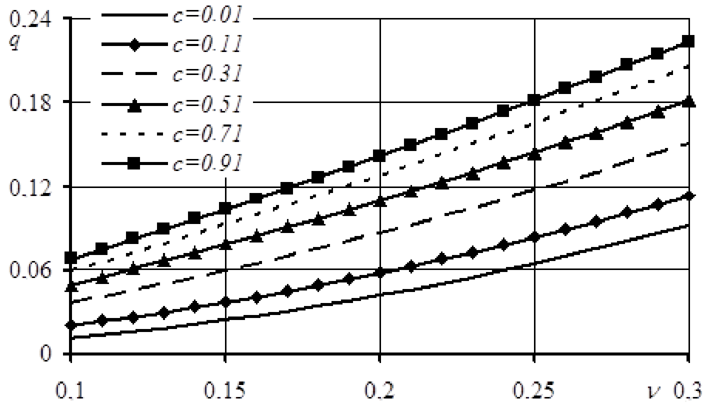


Figure 9 – Dependence of the parameter of variation of the screw length limit on the relative permissible power of the electric motor at different values of the critical slip of the electric motor

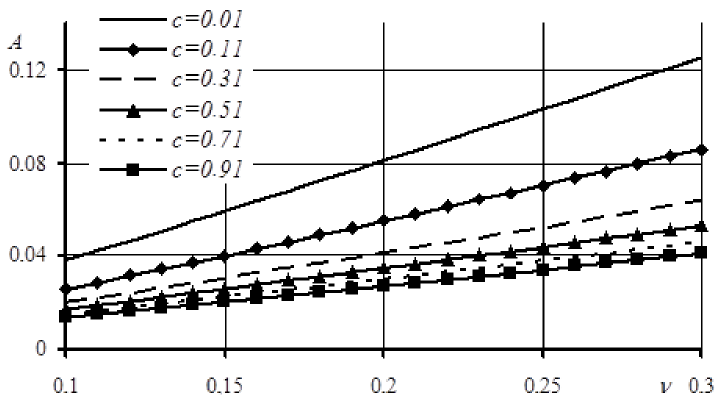


Figure 10 – Dependence of the minimum permissible relative length of the screw on the relative permissible power of the electric motor at different values of the critical slip of the electric motor

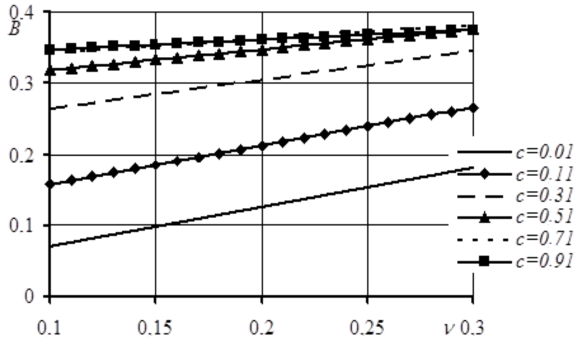
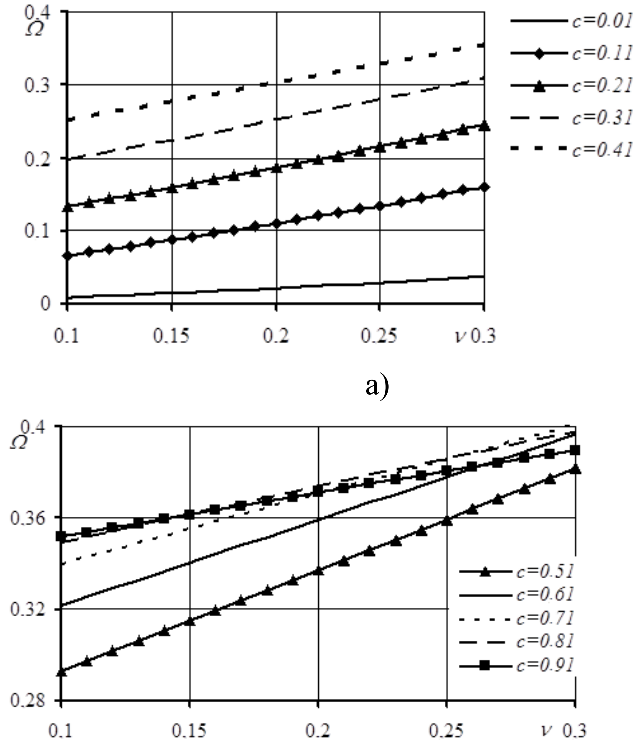


Figure 11 – Dependence of the maximum permissible relative length of the screw on the relative permissible power of the electric motor at different values of the critical slip of the electric motor



a)

b)

Figure 12 – Dependence of the value of the electromechanical coefficient on the relative permissible power of the electric motor at different values of the critical slip of the electric motor

Based on the physical meaning of the electromechanical coefficient, there is a requirement that it be positive and not imaginary, which is the case when the following restriction on the relative permissible power of the electric motor is applied

$$\nu < t; \qquad t = \frac{1+c}{1{,}5}\left[\frac{1-c^2}{c} + \sqrt{3+\left(\frac{1-c^2}{c}\right)^2}\right], \tag{8}$$

where t – is the maximum possible value of the relative permissible power of the electric motor (Figure 13).

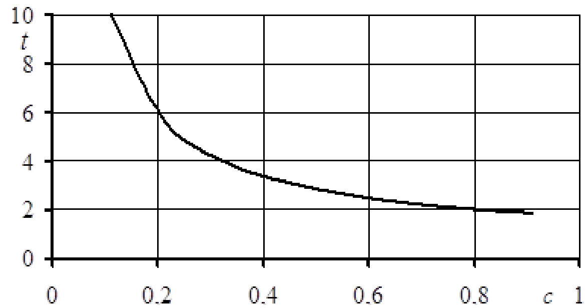


Figure 13 – Dependence of the maximum possible value of the relative permissible power of an electric motor on the actual critical slip of the electric motor

4. Conclusions

Thus, using formulas (1)–(8), it is possible to determine the area of regolith extraction using a screw conveyor and the possible volume of its extraction depending on the parameters of the electric motor used, taking into account the parameters of the screw conveyor, the characteristics of the deposit, and the properties of the regolith.

It has been established that the value of the electromechanical parameter, which determines the volumetric flow rate of the transported material and the power consumed by the electric motor, varies from $c = 3$ to the upper limit, which is unambiguously determined by the critical slip of the electric motor. The maximum values of the volumetric flow rate of the transported material and the power consumed by the electric motor are achieved at the minimum value of the electrical-mechanical parameter and are also unambiguously determined by the critical slip of the electric motor. Note that the maximum value of the relative power consumed by the electric motor is three times less than the maximum value of the relative volumetric flow rate of the transported material.

The length of the screw with which it is possible to extract regolith with an electric motor of this type is limited at the top and bottom by the product of the screw length scale and dimensionless coefficients determined by the parameters of the electric motor, i.e., the relative permissible power of the electric motor and its critical slip. The scale of the screw length is a dimensional parameter determined by the ratio of the maximum possible torque of the electric motor to the torque on the screw conveyor shaft, which is spent on overcoming the friction force of the transported material against the inner surface of the pipe in nominal mode.

The dependence of the electrical-mechanical coefficient, which takes into account the influence of the electric motor parameters, considering the area of the regolith extraction site on the volume of its extraction, within the range of variation of the main values studied, depends almost linearly on the relative permissible power of the electric motor, and the coefficients of this function are determined by the value of the critical slip. At the same time, for all values of critical slip, the graphs of functions corresponding to larger values of this parameter are located above the graphs corresponding to smaller values.

The proposed dependencies for calculating the area of the regolith extraction site and the probable volume of its extraction when using a screw conveyor driven by an asynchronous squirrel-cage motor, from the parameters of the electric motor, the geometric dimensions of the screw, the characteristics of the deposit, and the properties of the regolith, allow the design of technological schemes for the extraction of minerals on the planets of the Solar system and the establishment of their permissible and optimal parameters.

Conflict of interest

Authors state no conflict of interest.

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ВПЛИВ ПОТУЖНОСТІ ЕЛЕКТРОДВИГУНА НА ПАРАМЕТРИ ДІЛЯНКИ ВИДОБУТКУ МІСЯЧНОГО РЕГОЛІТУ

Семененко П., Позднишев М., Заверуха В., Татарко Л.

Анотація. Мета статті полягає в встановленні залежності площі ділянки видобутку реголіту за допомогою шнеку та можливих обсягів видобутку від параметрів електричного двигуна, що використовується, з врахуванням параметрів шнеку, характеристик родовища та властивостей реголіту. Для досягнення мети були використанні вже відомі залежності для розрахунку параметрів шнеку-транспортеру та фундаментальні закономірності механіки сипкого середовища, основні рівняння електродинаміки асинхронних двигунів, а також особливості поведінки сипких середовищ при переміщенні шнеком, що були експериментально досліджені вітчизняними авторами. Вдалося дослідити вплив таких параметрів асинхронного короткозамкнутого двигуна як критичне ковзання, максимально можливий момент та припустиме значення потужності електродвигуна, на припустимі межи змінення довжини шнеку, площу ділянки видобутку та на обсяг видобутку реголіту. Визначено припустимі значення відстані транспортування від діаметру шнеку-транспортеру та інших його геометричних параметрів а також ступеню наповненості шнеку, які можливі при параметрах електродвигуна, що обрано. Встановлено, що площа ділянки видобутку реголіту та обсяг його видобування в межах інтервалу змінення основних величин, які досліджено, майже лінійно залежать від відносної припустимої потужності електричного двигуна, а коефіцієнти цієї залежності визначаються величиною критичного ковзання. При цьому для всіх значень критичного ковзання графікі функцій, що відповідають більшим значенням цього параметру, розташовані вище за графіки, які відповідають меншим значенням. Залежності, що запропоновані для розрахунку площі ділянки видобутку реголіту та ймовірного обсягу його видобутку при використанні шнеку, що рухається за допомогою асинхронного короткозамкнутого двигуна, від параметрів електричного двигуна, геометричних розмірів шнеку, характеристик родовища та властивостей реголіту, дозволяють проектування технологічних схем видобутку корисних копалин на планетах сонячної системи та визначати їх припустимі й оптимальні параметри.

Ключові слова: Місяць, реголіт, шнек, електродвигун, площа ділянки видобутку, обсяг видобутку.