THEORETICAL SUBSTANTIATION OF THE SCRAPER INSTALLATION PARAMETERS FOR REMOVING MANURE
/
ТЕОРЕТИЧНЕ ОБҐРУНТУВАННЯ ПАРАМЕТРІВ СКРЕПЕРНОЇ УСТАНОВКИ ДЛЯ ПРИБИРАННЯ ГНОЮ

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ABSTRACT

The mathematical model of the interaction of the working surface of the scraper plant scrubber with manure, which determines the trajectory of manure movement on a cylindrical surface with variable radius of curvature under the action of the support forces, is given, and it allows determining the shape of the scrubber surface. The influence of the scrubbers' inclination angle and the scraper movement speed on the power consumption, productivity, specific energy consumption of the advanced scraper plant is investigated. The theoretical calculations of productivity, traction resistance and the choice of electric power of a scraper plant for cleaning manure have been carried out.

РЕЗЮМЕ

Приведено математичну модель взаємодії робочої поверхні скребка скреперної установки з гноєм, яка визначає траєкторію руху гною по циліндричній поверхні зі змінним радіусом кривизни під дією сил підпору і дозволяє визначити форму поверхні скребка. Досліджено вплив кута нахилу скребків та швидкості руху скрепера на споживану потужність, продуктивність, питому енергоємність удосконаленої скреперної установки. Проведено теоретичні розрахунки продуктивності, тягового опору та вибору потужності електродвигуна скреперної установки для прибирання гною.

INTRODUCTION

In the work of scraper plants, there is an inadequate quality of manure removal, which leads to the development of new structures of delta scrapers *(Revenko et al., 2009; Boltianskaia, 2012; Marcussen and Krog Laursen, 2008)*, therefore, the study of the principles of interaction between the scraper plant working bodies and manure, as well as justification of the scraper plant rational parameters are relevant.

Measurements of activity of cows' cardiac function during manure removing with scraper showed that milk cows are experiencing minor stress during manure removal. Cows sometimes perceived negatively manure removal with scrapers during feeding, but they showed an immediate reaction and avoided collisions with scrubbers *(Buck et al., 2013)*. This suggests that manure removal with scrapers, especially considering their simplicity and reliability, is today one of the most effective means of removing manure from livestock houses.

Comparison of manure removal with scraper and manually showed that emissions of ammonia NH_3, methane CH_4 and carbon dioxide CO_2 were significantly lower while removing manure with scraper. This suggests that such systems are more environmentally friendly *(Cai et al., 2015)*.

Modeling of scraper and screw transport systems for manure removal showed that the screw system has no advantages in terms of the rate of manure unloading from the houses *(Landry et al., 2006)*.

Measurement of harmful gas emissions in naturally ventilated rooms for keeping milk cows with different types of floors and manure removing systems showed that scrubbers increase ammonia emissions during manure removal *(Baldini et al., 2016)*.

A model has also been developed to demonstrate that manure acidification is the most effective method for reducing NH_3 emissions, especially when manure removal is combined with its acidification (NH_3 emission reduction efficiency is 44-49%) *(Mendes et al., 2017)*.

There have been also carried out studies showing that manure removed from the houses with scrubber conveyors to the barn storage has higher NH_3 emissions than the manure removed with the help of washing *(Venkata et al., 2011)*. This fact must be taken into account when calculating the standards of the bedding material, as well as its influence on the change of physical and mechanical properties of manure, which is removed from the houses.

It was also established that loss of nitrogen during manure removal was less than half of the losses during the summer *and the frequency of manure removal had little or no effect on nitrogen loss* (Moreira and Satter, 2006).

The efficiency of using the corrugated floor in the manure removal with scrubbers was also proved, which in turn leads to reduction in ammonia emissions *(Dennis et al., 2017)*. This suggests that there is a significant potential for improving the efficiency of manure removal with scrubbers.

It was also established that mechanical scrapers greatly improve the hygiene of keeping cows (evaluated for the cleanliness of the stalls, udder and dugs of cows), especially on the rubberized lattice floor *(Magnusson et al., 2008).*

It is also established that, regardless of the type and purpose, transporting working bodies should be designed in the form of linear surfaces specified by the curvilinear guide *(Tyshchenko, 2010; Tyshchenko, 2012)*. In this case, the law of motion of surface generator is substantiated taking into account the requirements for transportation.

The given data indicate that the substantiation of the parameters of the scraper plant for manure removal from the manure channels of cow barns requires further studying.

MATERIALS AND METHODS

The theoretical trajectory of a particle motion on a sloping plane was studied using the technique of the accompanying Frenet trihedral. The solution of the obtained differential equations is carried out with the help of symbolic mathematics of the software envelope "Mathematica".

Experimental studies were carried out using a scraper plant (fig. 1) and a frequency converter FR-D700, which changed the speed of the scraper in the range from 0.04 to 0.18 m/sec, kilowatt meter "Lovato elektrik DMK 40" and personal computer HP Pavilion dv6000 with software DMK Remote Control, which fixed the power to move the scraper. The angle of inclination of the scraper scrubbers to the surface of the manure channel was varied from 30 to 90 degrees. The time of each passage of the scraper was fixed by a stopwatch. The quality of manure removal was determined by additional cleaning of the manure channel surface manually and weighing the manure mass on the scales.

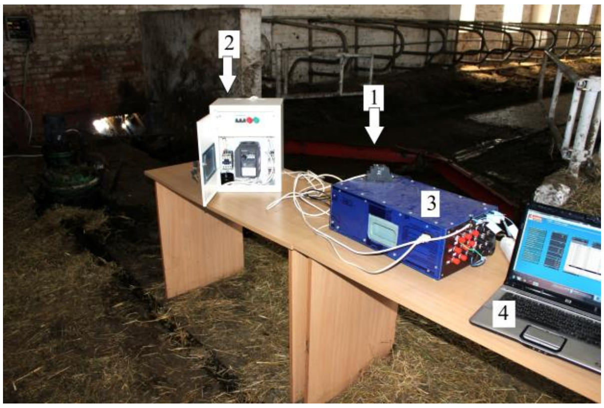

Fig. 1 - Instruments and equipment for scraper plant experimental studying
1 – scraper; 2 – frequency converter FR-D700; 3 – kilowatt meter "Lovato elektrik DMK 40"; 4 – personal computer HP Pavilion dv6000 with a software DMK Remote Control

RESULTS

For efficient operation of scraper plant it is necessary to provide constant pressure of manure, which moves on the working surface of the scraper. To achieve this, the scraper dump should have variable radius of curvilinear (fig. 2). The working surface of scraper scrubbers in the form of a dump allows the layer of manure to partially accumulate on the surface of the scrubbers and create additional pressure on the scrubber, pushing it to the bottom of the manure channel. Such a design of scraper scrubbers improves the quality of manure removal, and as a result reduces the number of working passages of the scraper.

Manure particles move along the scrubber surface under the action of the support forces with constant speed, so it is necessary to find such a trajectory of the curve as when moving on it, at constant speed, the particles make a constant pressure on the scrubbers working surface.

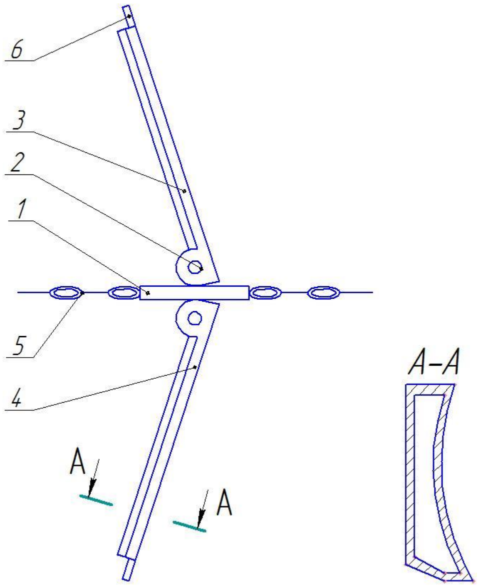

Fig. 2 - Modernized scraper plant for manure removal
1 – ram; 2 – rotary device; 3 – right scrubber; 4 – left scrubber; 5 – chain; 6 – rubber cleanser

Assume that under the action of the support force the manure particle moves upward along the cross-sectional curve of the surface with constant velocity, and also that the velocity of the particle motion along the scrubber is equal to the velocity of the scrubber itself on the manure channel. On the basis of this, a curve (Fig. 3) is constructed, which, at a given speed, will provide a steady surface reaction, and therefore a constant pressure on the entire surface of the scrubber. Such a surface will be less prone to sticking manure and will evenly wear out.

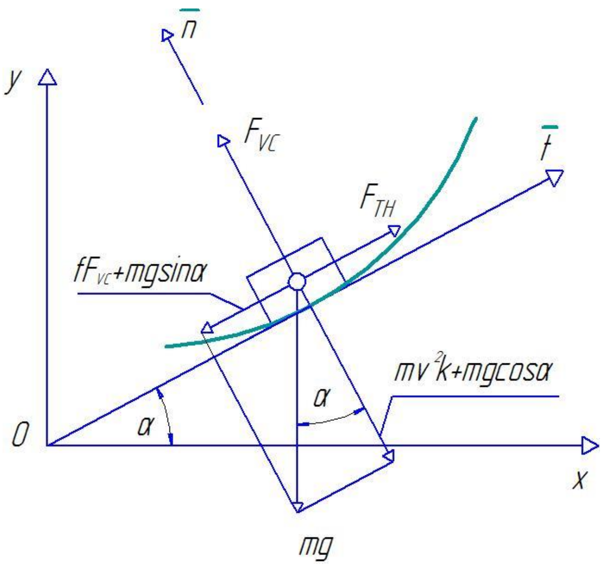

Fig. 3 - Scheme of forces effect on the scrubber

Having designed all the forces acting on the main normal of this curve, we obtain the equation:

$$mg\cos\alpha + mv^2k = F_{VC}, \tag{1}$$

where m – particle mass, [kg];

g – gravitational acceleration $g = 9.81$ [m/sec^2];

α – the angle formed by the unit vector $\bar{t}$ (tangential to the trajectory) with the axis Ox, [grad].

v – speed, [m/sec];

$k = \frac{1}{r}$ – curvature of curve at this point, [m];

r – the radius of curvature, [m];

F_{VC} – stable reaction of the surface, [H].

Divide the left and right sides of the equation (1) by particle weight mg and write the curvature k by the ratio $k = \frac{d\alpha}{ds} = 1 : \frac{ds}{d\alpha} = \frac{1}{s'}$, where s, s' – the length of the arc of the curve and its derivative, we obtain the equation:

$$\cos\alpha + \frac{v^2}{s'g} = \frac{F_{VC}}{mg} \quad (2)$$

Ratio $\frac{F_{VC}}{mg} = a_{VC}$ is a magnitude that shows the fraction of the particle weight in the total force of pressure, when the particles move along the concave side of the surface a_{VC} >*1.* On the basis of the interconnections of the curve differential characteristics, the transition from equation (2) to parametric equations is carried out:

$$x = \frac{2a_{VC}v^2}{g\sqrt{a_{VC}^2 - 1}} \operatorname{arctg}\sqrt{\frac{\sqrt{a_{VC}^2+1}}{\sqrt{a_{VC}^2-1}}} \operatorname{tg}\frac{\alpha}{2} - \frac{v^2}{g}\alpha, \qquad y = \frac{v^2}{g}\ln(a_{VC} - \cos\alpha) \quad (3)$$

The cross-sectional curve of the surface, the pressure at which it is larger than particle weight by 1.2 times (a_{VC} *=1.2*), at a given speed $v = 0.18$ m/sec is shown in Fig. 4. The fragment of the curve AB is taken as a scraper scrubber profile model.

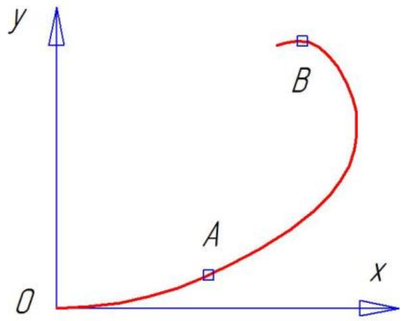

Fig. 4 - The curve providing constant pressure at constant particle velocity

Let's suppose that the lower edge of the scraper is located at a certain angle γ, but not perpendicular to the direction of its displacement. Proceeding from this, when the particle is pushed onto the scrubber (Fig. 5), the direction of its velocity will make an angle γ with the lower surface generator (the straight edge of the scrubber). As the curve of the scrubber cross section we accept a parabola. In projections on a plane xOz, it is written by the equation $z = ax^2$ (a – constant).

At the current point A, the tangent to the parabola with the axis Ox forms an angle ε (Fig. 6). Having switched to a new variable – angle ε, we obtained the parametric equations of the cylindrical surface:

$$X = -\frac{\operatorname{tg}\varepsilon}{2a}; \quad Y = -u; \quad Z = \frac{\operatorname{tg}^2\varepsilon}{4a}. \quad (4)$$

In equations (4), the symbol "u" is the length of a straight-line surface generator, the second independent variable. The minus signs provide the required compartment of the surface according to its location on the system $Oxyz$. If two independent variables of the surface ε and u (4) interconnect with each other by certain dependence, then the corresponding line will appear on the surface. We consider it a trajectory of the particle equation that must be found. Between the variables ε and u establish dependence through the third variable – time t, i.e. $\varepsilon=\varepsilon(t)$ and $u=u(t)$. Replacing uppercase letters in the equations (4) by lower-case ones, we obtain the equation of the trajectory - the line on the surface with unknown dependencies $\varepsilon=\varepsilon(t)$ and $u=u(t)$, that we need to find.

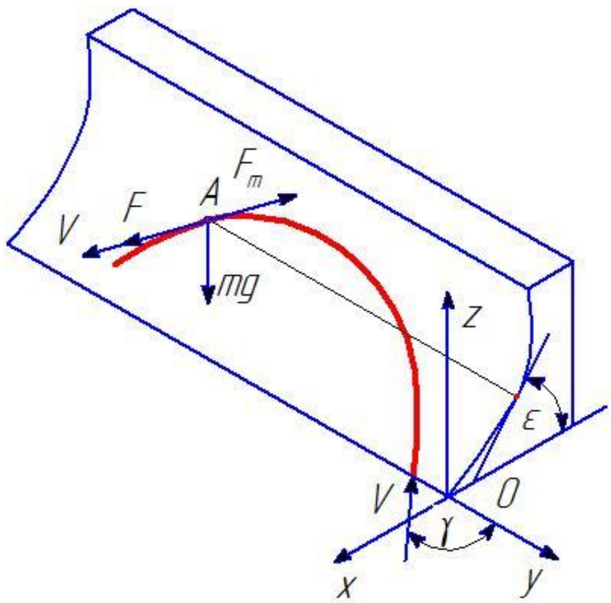

Fig. 5 - The scheme of the effect of forces on a particle at the point and trajectory of its motion on a cylindrical surface

Thanks to the time-differentiation t of the trajectory (4), equations were obtained for determining the acceleration of the particle:

$$x''=-\frac{\varepsilon''+2\varepsilon'^2\mathrm{tg}\varepsilon}{2a\cos^2\varepsilon},\qquad y''=-u'',\qquad z''=\frac{\varepsilon''\mathrm{tg}\varepsilon+\varepsilon'^2\left(3\sec^2\varepsilon-2\right)}{2a\cos^2\varepsilon}. \qquad (5)$$

where $x'', y'', z''-$ projections of particle acceleration.

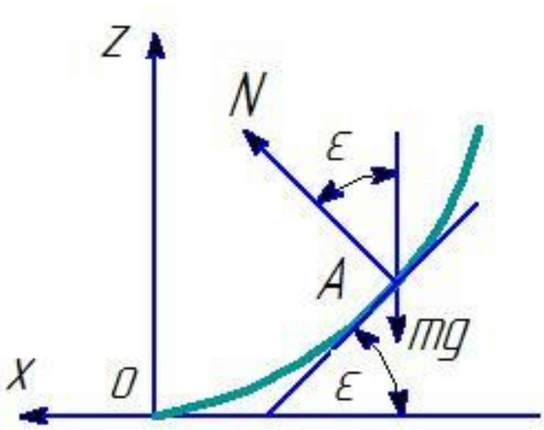

Fig. 6 - The scheme of determining the direction of the normal to the surface at the current point (the axis is projected to the point)

The particle is forced to move along the surface of the scrubber, under the action of the force of the support, F, at a speed v that we will accept equal to the speed of the scrubber movement. The particle is also influenced by other forces, beside force F directed in the direction of speed v; the friction force F_{FR} directed to the opposite side of the particle velocity v; the force of the surface reaction N, which coincides with the direction of the normal to it, and the weight mg directed vertically downwards.

On the basis of Newton's second law, the differential equations of a particle motion on the scrubber surface were composed and expressions of forces applied to the particle were obtained, i.e., their direction and magnitude, which depend on the point on the trajectory, being functions of the curvilinear coordinates ε and u. In turn, ε and u are connected with each other by the constancy of the particle velocity v. After transforming the system of differential equations, we obtain the following expressions:

$$\varepsilon'' = \frac{\varepsilon'^2 \sin\varepsilon}{2av^2\cos^3\varepsilon}\left(g - 6av^2\cos^2\varepsilon\right) - ag\sin 2\varepsilon\cos^2\varepsilon \tag{6}$$

$$F = m\frac{4g\varepsilon'\sin\varepsilon + Vf\left(4\varepsilon'^2 + 4ag\cos 2\varepsilon + ag\cos 4\varepsilon + 3ag\right)}{8av\cos^3\varepsilon} \tag{7}$$

$$N = m\left(g\cos\varepsilon + \frac{\varepsilon'^2}{2a\cos^3\varepsilon}\right) \tag{8}$$

The differential equation (6) is independent, namely, it can be solved concerning the function $\varepsilon = \varepsilon(t)$. However, it is not possible to do this in an analytical form, therefore, numerous methods have been applied. To construct the trajectory of a manure particle on a scrubber cylindrical surface, it suffices to add the dependence $\varepsilon = \varepsilon(t)$ in equation (4). To the initial conditions of integration refers the angle γ, which is determined by the differential characteristics of the trajectory (Fig. 7).

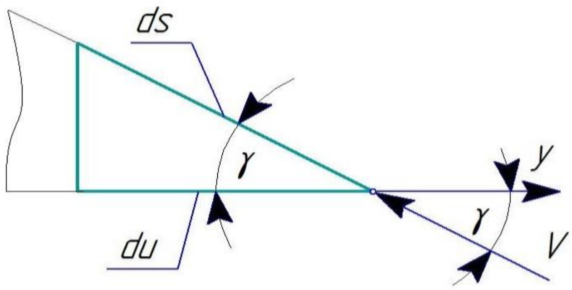

Fig. 7 - To determine the angle γ of particle entering on the surface

Thus, the obtained mathematical model allows us to calculate the optimum working surface of the scraper plant scrubber, in which a layer of manure will press on the scrubber and press it to the bottom of the manure channel, which will improve the quality of manure removal.

The calculation of the scraper plant (fig. 8) is reduced to the definition of the performance, traction resistance and the choice of the electric motor power. Assume that the scrubber is immersed in the manure with maximum effort $(k_{1MAX} = 1)$ at the optimal angle of inclination of the scrubber, and the minimum value (take $k_{1MIN} = 0.75$) at the least effective angle of inclination of scrubbers, namely $90°$ for scraper plant USH-3.

The efficiency of the scraper plant is determined by the formula:

$$Q_{SM} = h_{AV} b \rho v_{SC} k_1 \frac{C_2 + K_{OV} - K_R}{C_2 + K_{OV} + C_{1IV}}, \tag{9}$$

where Q_{SM} – performance of scraper plant, [kg/sec];

h_{AV} – average thickness of manure layer in the manure channel, [m];

b – width of the manure channel, [m]; $b = 3.3$ m;

ρ – manure density, [kg/m³]; for the floor manure we accept $\rho = 750$ kg/m³;

v_{SC} – average speed of the scraper movement in one cycle, [m/sec];

k_1 – delivery rate that takes into account the angle of inclination of the scrubber; $k_1 = 0.3...1$ *(Boiko, 2006)*;

C_2 – step between scrapers, [m];

K_{OV} – the distance of the scraper overlaps so that the manure from scraper № 2 (fig. 8) was passed to the scraper № 1, [m]; K_{OV} = 4 m;

K_R – the path needed to open the scrubbers, [m]; K_R = 2 m;

C_{1IV} – total length of motion of the first scraper in reverse, [m].

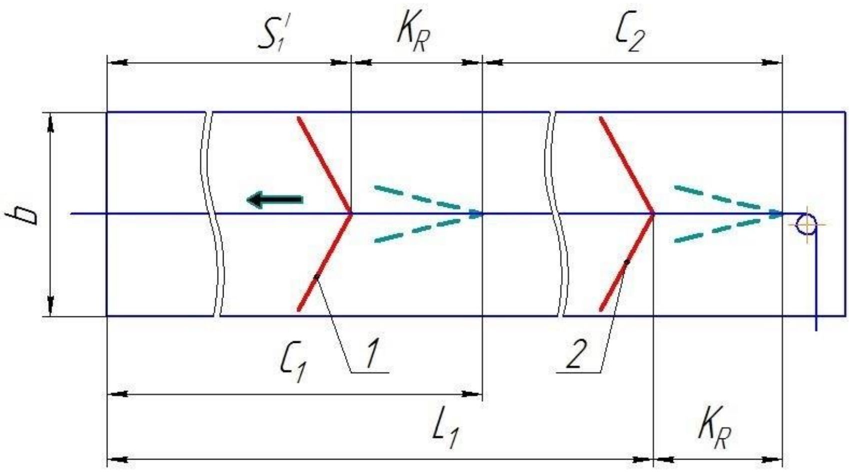

Fig. 8 - Schematic diagram of scraper plant

1 – scraper № 1; 2 – scraper № 2; S_1' – working length of the motion of the first scraper, m; C_1 – total length of movement of the first scraper, L_1 – working length of the manure channel, m

Fig. 9 shows graph for changing productivity according to equations 9.

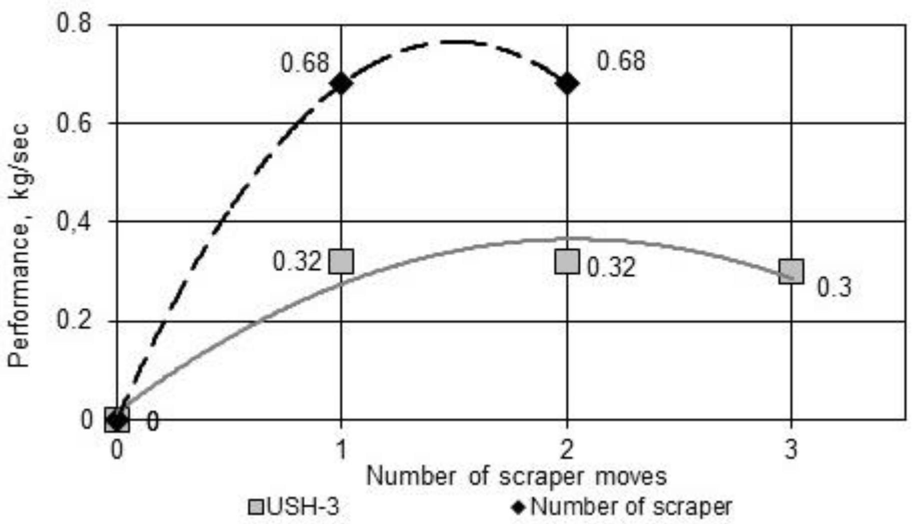

Fig. 9 - Schedule for changing the performance of the scraper plant according to the results of theoretical calculations

The comparison results of the calculated and experimental values of the scraper plant performance showed that the average deviation between them did not exceed 4.4% (Fig. 10).

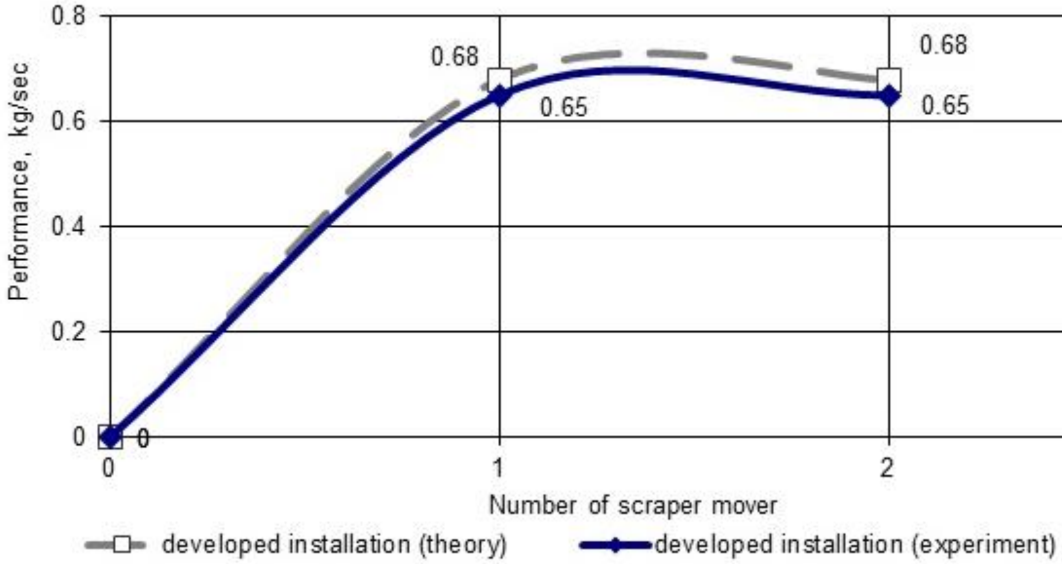

Fig. 10 - Schedule of changes in the productivity of the developed scraper plant according to the comparison of computational and experimental studies

The engine power is determined by the expression:

$$N_{ENG} = kv \frac{(m_1 + m_2) f_{MN} g + \frac{h^2}{2} m_{SCR} l_{AVE} \rho g \xi f_{MN} + Mgf_{ST} + m_{SCR} \rho_{WD}}{1000 \eta_{DRI}} \tag{10}$$

where N_{ENG} – engine power, [kW];

k – coefficient taking into account the resistance of the tension on the drive sprocket; $k = 1.1$;

v – speed of scraper movement, [m/sec];

m_1 – mass of the manure transported by the first scraper, [kg];

m_2 – mass of the manure transported by the second scraper, [kg];

f_{MN} – coefficient of manure friction along the bottom of the manure channel. For manure friction on concrete at speed 0.085 m/sec, $f_{MN1} = 1.1$, and at speed 0.15 m/sec, $f_{MN2} = 0.9$ *(Tsarenko, 2003);*

h – scraper scrubber height, [m];

m_{SCR} – number of scrubbers, [un.];

l_{AVE} – mean value of the length of traction prism, [m];

ξ – side-thrust coefficient; $\xi = 1.2 \ldots 1.4$ *(Boiko, 2006)*;

M – mass of moving part of scraper plant (chain, scrapers), [kg];

f_{ST} – coefficient of friction of steel on concrete. At speed 0.085 m/sec $f_{ST1} = 0.8$, and at speed 0.15 m/sec $f_{ST1} = 0.5$ *(Tsarenko, 2003)*;

ρ_{WD} – the effort necessary to overcome the jamming in one scraper, [H]; $\rho_{WD} = 15 \ldots 30$ H *(Boiko, 2006)*;

η_{DRI} – efficiency factor of transmission and drive $\eta_{DRI} = 0.75 \ldots 0.85$, for our gearbox $\eta_{DRI} = 0.82$ *(Boiko, 2006)*.

Energy intensity of the full speed of the scraper is:

$$N_{SCR} = \frac{L_{PC}}{v m_{MN}} \left(N_{END.WF} + N_{END.IW} \right) \tag{11}$$

where N_{SCR} – energy intensity of the full speed of the scraper, [kW h./t];

L_{PC} – the length of the manure channel, [m];

v – speed of scraper movement, [m/h];

m_{MN} – mass of the manure removed from the manure channel, [t];

$N_{END.WF}$ – engine power during operating stroke, [kW];

$N_{END.IW}$ – engine power during idle stroke, [kW].

Fig. 11 shows graphs for changing specific energy consumption according to equation 11.

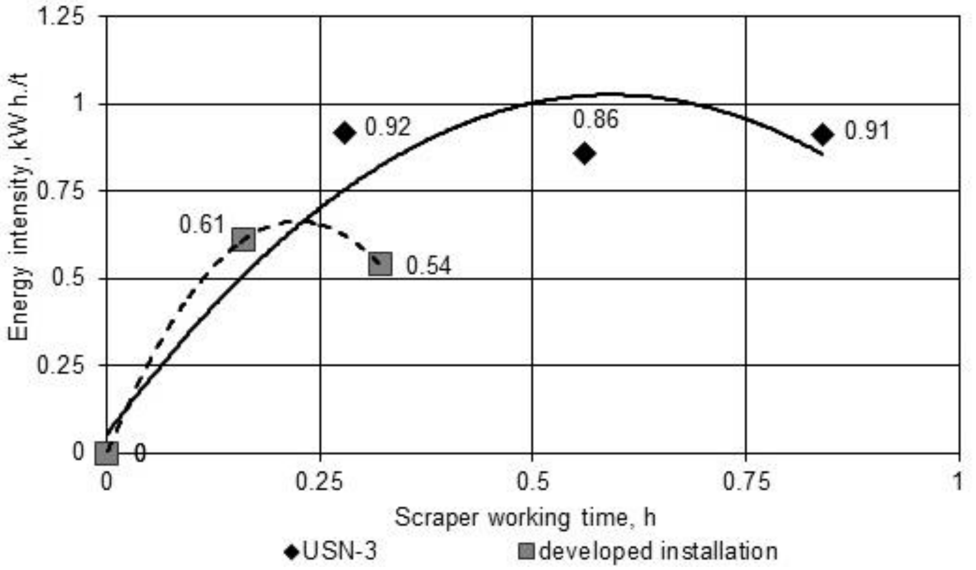

Fig. 11 - Graph of changes in specific energy consumption of a scraper plant based on theoretical calculations (mean values)

Comparison of calculated and experimental values of specific energy consumption showed that the mean value of deviations was 7.4% (Fig. 12).

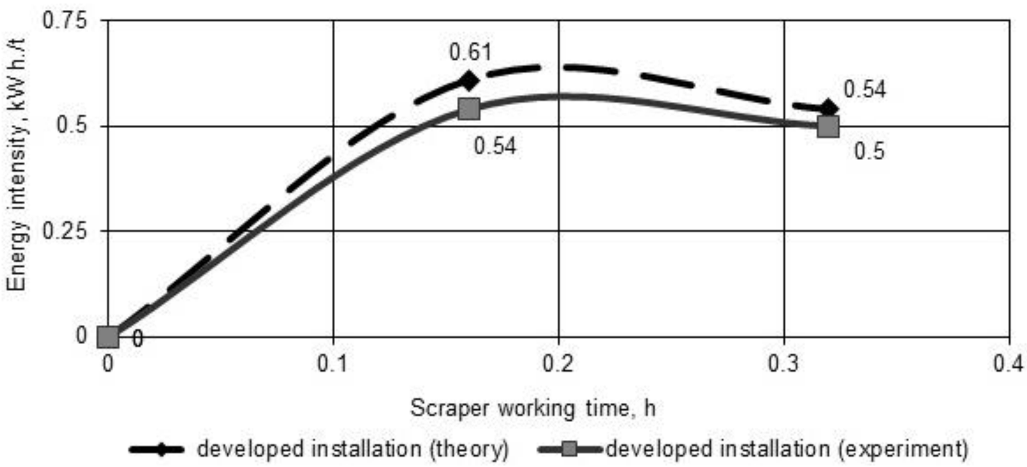

Fig. 12 - Comparison of calculated and experimental values of specific energy consumption for the developed scraper plant

Thus, theoretical and experimental results comparison of the research on productivity and specific energy intensity of the scraper plant indicates the legitimacy of using the obtained analytical expressions in the calculations for scraper plants.

CONCLUSIONS

The conducted researches revealed the possibility of directed adjusting of the energy intensity of the manure removal process by changing the parameters of the scraper plant.

The researches have determined that the performance of the advanced scraper plant when compared to the scraper plant USN-3 increased from 0.3 to 0.68 kg/sec and the specific energy consumption decreased from 0.91 to 0.54 kW h/t.

The results of the calculated and experimental values comparison of the scraper plant performance showed that the average deviation between them did not exceed 4.4%, and the average value of deviations of the calculated and experimental values of specific energy consumption was 7.4%.

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