Експериментально досліджено закономірності впливу кута розкриття скрепера, кута нахилу скребків і швидкості руху скрепера на питому енергоємність удосконаленої скреперної установки.

Експериментально обґрунтований графік погодинного накопичення гною, і графік включень скреперної установки, запропоновано 5-ти разове прибирання гною на добу, в 7, 9, 14, 18, 22 години, що призведе до значного зменшення енергетичних витрат ресурсів і спрацьовування конвеєра.

Експериментальними дослідженнями визначено конструкційні (кут розкриття скрепера і кут нахилу робочої поверхні скребків) та технологічні (швидкість руху скрепера) параметри, за яких удосконалена скреперна установка буде мати мінімальні питомі витрати енергії.

Встановлено, що оптимальними параметрами скреперної установки, за яких удосконалена скреперна установка буде мати мінімальні питомі витрати енергії, є: кут розкриття скрепера в межах від 105 до 115°; кут нахилу робочої поверхні скребків – 60°; швидкість руху скрепера – 0,13 м/с. За цими показниками був розроблений та виготовлений скрепер для прибирання гною.

Проведено порівняльні експериментальні дослідження роботи розробленої скреперної установки для прибирання гною і прототипу, скреперної установки заводського виготовлення УСГ-3. Ці дослідження показали перевагу розробленої скреперної установки в порівнянні з УСГ-3, питомі витрати енергії зменшуються на величину від 44 до 48 % до значення 0,34–0,36 кВт год./т.

Встановлені раціональні параметри і режими роботи скреперної установки знижують енерговитрати на видалення гною із тваринницьких приміщень при необхідній якості очищення гнойового каналу, що підтверджує доцільність впровадження її у виробництво.

Результати приведених досліджень також можна застосувати при проектуванні бульдозерів та іншої меліораційної техніки

Ключові слова: прибирання гною, графік включень, кут розкриття скрепера, кут нахилу скребків, швидкість скрепера, енергоємність

UDC 631.333.092
DOI: 10.15587/1729-4061.2018.139490

EXPERIMENTAL STUDY INTO ENERGY CONSUMPTION OF THE MANURE REMOVAL PROCESSES USING SCRAPER UNITS

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1. Introduction

To ensure the required sanitary conditions and microclimate at livestock facilities, it is necessary to create effective and safe systems of technical means. This applies to the systems for cleaning stalls and machines from manure, transporting manure to storage sites, avoiding the dilution of manure with water [1]. The loose box technique for keeping bovine animals, at which manure is removed from premises using stationary scraper units [2], has been popular in the world, including Ukraine.

During operation of scraper units, there is an insufficient quality in cleaning the manure channels, which requires developing the new designs of working elements of scrapers [3]. Therefore, it is a relevant task to undertake the research aimed at identifying and elucidating the principles of interaction between working elements of the scraper unit and manure, as well as to substantiate the rational structural and technological parameters of the scraper unit.

2. Literature review and problem statement

The cost of energy to perform manual operations to clean up the stalls from manure, as well as manure channels, when the cows are tethered, reaches 54.28 kJ per head. The redesign of cowsheds to keep the animals loose in boxes could reduce energy consumption by 50 %. The work that relates to the disposal of manure takes the second place in the structure of costs for animal husbandry, which is why manure- removal equipment needs improvement [4].

Scraper units have longer operation time and lower productivity compared with frontal mini loaders; they, however, have smaller energy consumption indicators when converted per animal [5]. Given this, there is a need to increase the motion speed of scraper to ensure greater performance.

It was also found that ammonia emissions at livestock farms are mostly related to the efficiency of the system for manure removal. Thus, the farm that was cleaned from manure by scraper on a daily basis had 1.9 g of NH_3 emissions from 1 square meter per day versus 13.3 g at a fortnightly manual removal of manure from solid floors [6]. Therefore, there is a need to remove manure more often; however, in order to reduce energy costs and to operate a conveyor, it is required to make up a schedule for turning the scraper unit on.

The main factors that affect the NH_3 emissions are the type of floor, the manure removal system, climatic conditions inside a facility, diet, and feed efficiency of animals [7]. Using a partially latticed floor helps reduce the emissions of NH_3. The emissions are lower if concrete slabs are replaced with smooth materials, such as metallic or plastic lattices. Frequent removal of manure, washing and separation of urine from faeces using a *V*-shaped scraper or belt conveyors reduces the NH_3 emissions at livestock premises by about 50 %. That also demonstrates the importance of agreeing on the terms of the accumulation and removal of manure by scraper units.

Paper [8] demonstrated that the drainage capacity of hard floors is insufficiently effective, which is why there is considerable potential to improve the drainage of urinary puddles. It was also established that there is the potential to enhance the effectiveness of cleaning from manure using scrapers by improving their design parameters.

A research was also conducted that suggests that the manure removed from premises by scraper transporters to a manure storage facility produces larger emissions of NH_3 than the manure removed by washing [9]. This points to the necessity to improve the design of scraper unit's scrapers so that they cut a layer of manure rather than tear it from the surface of a manure channel, which would lead to a decrease in the emissions of NH_3. These facts need to be considered when calculating norms for a substrate material, as well as its influence on a change in the physical and mechanical properties of manure that is removed from premises.

Measurements of the cardiac activity of cows when cleaning from manure using a scraper showed [10] that lactating cows experience stress during manure removal. Cows negatively perceived the event of manure removal using a scraper during feeding; they showed immediate reaction and avoided contact with the scrapers. This points to the necessity to develop a schedule for turning a scraper unit on so that the feeding and manure removal by a scraper do not coincide in time.

Increasing the frequency of manure removal using scrapers in cowsheds to two times a day showed a reduction of pathogens that cause mastitis. Coliograms decreased from 2.11 to 1.56 ± 0.14 log10 CFU/g ($P=0.01$). The number of e. coli decreased from 1.86 to 1.30 ± 0.14 log10 CFU/g ($P=0.01$). Streptococci decreased from 5.06 to 4.10 ± 0.19 log10 CFU/g ($P=0.01$) [11]. However, an increase in the frequency of removal leads to a rise in energy consumption, therefore there is a need to improve the structural and technological parameters of scraper units in order to enhance their energy efficiency.

When exploring the life-cycle assessment (LCA) of cattle manure as an object with different directions for further disposal, the authors of [12] note the benefits of scrapers to remove manure by reducing the consumption of water. In addition, the authors stress the need to calculate the cost of electric energy for manure removal and propose a procedure for calculating the indicators of energy efficiency. One of the priorities in the implementation of further research, in view of the authors, is the estimation of performance of various scraper tools for the removal and relocation of manure.

Paper [13] devised a procedure and a demonstration mechanistic model of production processes at a dairy farm, which makes it possible to assess the impact of technical or managerial decisions on electricity consumption. Despite the cost of electricity in a range from 6.4 to 7.8 % of the total costs, the authors note the complexity of forecasting the indicators for a decrease in energy expenditures for manure removal. However, the authors' proposed solutions to increase energy efficiency make it possible to reduce the cost of electricity by 7.5 to 25 %.

Papers [14, 15] studied the life cycles of products received from cattle farms, performed one of the calculations for LCA, defined energy efficiency as the ratio of the amount of energy per product unit to the total quantity of the consumed energy. Reducing a general energy cost on manure removal could improve effective performance indicators of processing products, such as composts and biogas.

The cited studies allow us to conclude that prolonging the time between manure removal using scrapers increases the supply of ammonia to livestock facilities. In order to reduce the emissions of ammonia at livestock premises, to reduce the number of pathogens that cause mastitis, there is the necessity to increase the frequency of manure removal; it, however, leads to an increase in energy consumption. Therefore, there is a task on the minimization of energy consumption by improving the scraper units, including the selection of structural and technological parameters of scraper units. The lack of alignment between a schedule for turning a scraper unit on and the time of operation of the scraper unit could lead to that the processes of feeding and manure removal coincide in time, which might be negatively perceived by cattle. Because the manure that is removed from premises by scraper transporters produces larger emissions of NH_3 than the manure removed by washing, it is necessary to improve the quality of performance of scraper units. Given this, the improvement of design of scraper unit's scrapers aimed at cutting a layer of manure at the surface of a manure channel should provide a reduction in the emissions of ammonia.

Ensuring a decrease in the energy intensity of the process of manure removal based on the substantiation of parameters for a scraper unit requires further research.

3. The aim and objectives of the study

The aim of our study was to define the rational parameters and operation modes for a scraper unit for manure removal based on establishing the regularities of influence of structural and technological parameters on specific energy intensity of the process. That would reduce the energy intensity of manure removal.

To accomplish the aim, the following tasks have been set:

– to determine the effect of parameters of the scraper unit on energy intensity of the process of manure removal;

– to conduct comparative experimental studies into operation of the designed scraper unit for manure removal and of the prototype, commercially available scraper unit USG-3;

– to define parameters for the scraper unit, at which energy consumption would be minimal;

– to develop, in order to minimize energy costs, an hourly schedule for manure removal.

4. Materials and methods to study energy consumption of the scraper unit

Experimental studies were conducted under industrial conditions using the scraper unit of brand USG-3. We also used scrapers with working surfaces in the form of a blade (Fig. 1). The study was carried out maintaining stable statistically averaged physical-mechanical properties of a manure mass that is characterized by a fractional composition, moisture content, density, stickiness, coefficient of friction, hygroscopicity of particles, and other properties.

Fig. 1. Scraper unit with scrapers in the form of a blade

Experimental studies were conducted in line with the generally accepted procedures that implied the statistical processing of data and planning a multifactorial experiment [16].

Results of experimental studies were processed based on the application of provisions from the probability theory and mathematical statistics; the tabular processor Microsoft Excel was used.

Experimental study implied determining the influence of the opening angle of the scraper, the scraper unit's scrapers inclination angle, and motion speed of the scraper, on specific energy consumption of manure removal. We also conducted a comparative test of the commercially available scraper unit USG-3 and the designed scraper unit. The structure of the working body for manure removal at the scraper unit USG-3 has a similar design to the hydraulic scraper unit DML and the delta-scraper DW made by De Laval (Sweden), a combi scraper unit made by company JOZ (Holland), a delta-scraper made by company «AgroComplex» (Poland).

To determine the influence of factors on specific energy consumption of manure removal, we conducted an experiment based on the matrix with three levels in line with the *D*-optimal Box-Behnken design for the three examined factors [17]. Intervals of values and variation levels of the examined factors are given in Table 1.

Table 1

Intervals of values and variation levels of the examined factors

Factor and its designation	Levels of factors			Variation intervals
	–1	0	+1	
Scraper opening angle, γ, degrees	70	120	170	50
Scraper unit's scrapers inclination angle, ε, degrees	30	60	90	30
Scraper unit motion speed, υ_{SCR}, m/s	0.04	0.11	0.18	0.07

The study was repeated 3 times in the following order:

– we determined the hourly accumulation of manure throughout the day;

– we developed the schedule of turning the unit on, splitting it into intervals, roughly equal in the volume of manure;

– the surface of the manure channel was completely cleaned from manure;

– we evenly placed manure at the surface of the manure channel, in the amount of 1,736 kg (weighted in advance), which corresponds to the maximum accumulation of manure per a single cleaning;

– the opening angle of the scraper unit's scrapers was changed using two brackets with holes to provide a change in it in the range from 70 to 170 degrees;

– we changed the inclination angle of the scraper unit's scrapers to the surface of the manure channel in the range from 30 to 90 degrees;

– the scraper unit motion speed was changed using the frequency converter FR-D700 (Mitsubishi Electric) in the range from 0.04 to 0.18 m/s (Fig. 2);

– the time of each run of the scraper unit was registered with a stopwatch;

– the consumption of power for the resistance to the scraper unit displacement was registered using the kilowatt meter «Lovato elektrik DMK 40» and the PC HP Pavilion dv6000 with the software package DMK Remote Control (Fig. 2);

– we additionally cleaned the surface of the manure channel manually and weighted the manure mass at a scale.

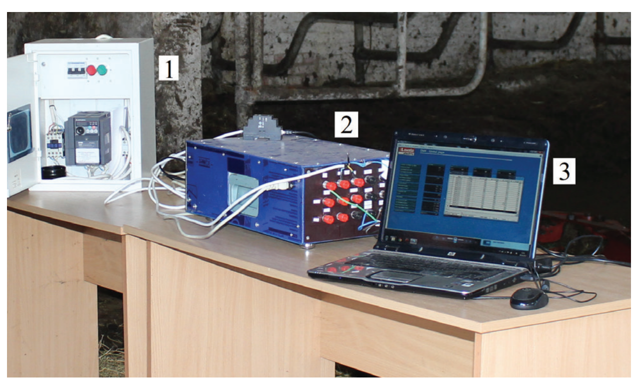

Fig. 2. Instruments and equipment to conduct experimental study into a scraper unit: 1 — frequency converter FR-D700; 2 — kilowatt meter «Lovato elektrik DMK 40»; 3 — personal computer HP Pavilion dv6000 with the software package DMK Remote Control

The study was carried out at a farm where 130 milking cows are kept by a loose box technique. To remove manure from the cow barn, we used: a scraper unit, transverse and inclined conveyors (Fig. 3).

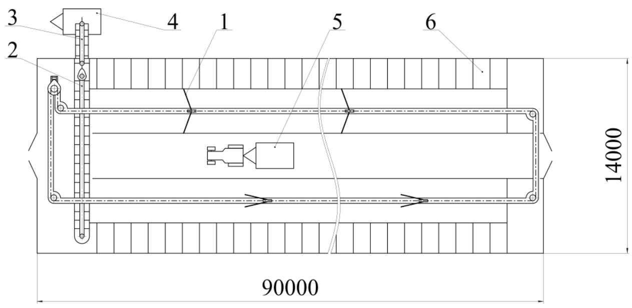

Fig. 3. Schematic of a technological line for manure removal when cattle are kept loose in two rows: 1 — scraper unit; 2 — transverse conveyor; 3 — inclined conveyor; 4 — trailer; 5 — feeder; 6 — stall

We carried out a practical experiment at the test farm to determine the hourly accumulation of manure throughout the day.

5. Results of experimental study aimed at substantiating the parameters of a scraper unit for manure removal

Based on the results obtained, we built a chart of the hourly accumulation of manure (Fig. 4).

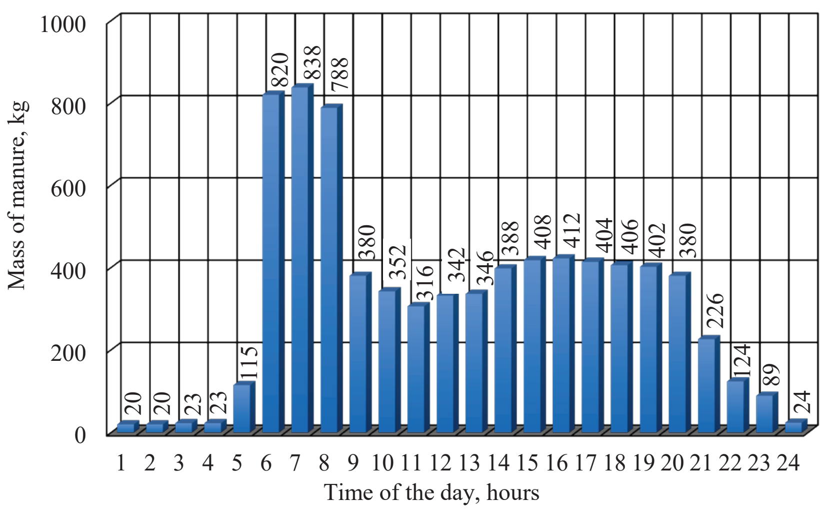

Fig. 4. The hourly accumulation of manure from a group of 130 cows

The volumes of manure accumulation based on time intervals are given in Table 2.

An analysis of the chart reveals that manure must be removed 5 times per 24 hours. Specifically, at 7, 9, 14, 18, and 22 o'clock.

An uniform load on the scraper unit makes it possible to select an electric motor to drive it at minimum capacity, which in turn leads to a decrease in energy costs.

The regression equation for the dependence of specific energy consumption on opening angle of the scraper unit, inclination angle of the scrapers, and motion speed of the scraper unit, based on results of the conducted full factorial experiment, in decoded form takes the following form:

$$E_{CUR} = 0,8866 - 0,001\gamma - 0,0084\varepsilon - 3,427\nu_{SCR} + \\ + 0,0001\varepsilon^2 + 14,1065\nu_{SCR}^2 - 0,0052\gamma\nu_{SCR} - 0,0028\varepsilon\nu_{SCR}, \quad (1)$$

where E_{CUR} is the specific energy consumption, kW h/t; γ is the scraper unit opening angle, deg.; ε is the inclination angle of scrapers, deg.; υ_{SCR} is the motion speed of the scraper unit, m/s.

Table 2

Volumes of manure accumulation based on time intervals

Manure accumulation interval	Volume of manure accumulation, kg	Manure removal time
from 22:00 to 7:00	1,259	7:00
from 7:00 to 9:00	1,626	9:00
from 9:00 to 14:00	1,736	14:00
from 14:00 to 18:00	1,622	18:00
from 18:00 to 22:00	1,414	22:00

Statistical evaluation of the results obtained was tested for the homogeneity of variances by the Cochran criterion. The adequacy of the constructed mathematical model and its applicability for the description of the examined process were checked by the Fisher criterion [18]. Determining the significance of regression coefficients was conducted by the Student criterion [19]. A hypothesis about the adequacy of the equation is confirmed and it could be used to describe the process.

An analysis of the mutual influence of the opening angle and the inclination angle of the scraper unit's scrapers (Fig. 5) has revealed that an increase in the inclination angle of the scraper unit's scrapers γ from 30° to 90° leads to a change in specific energy consumption E_{CUR} in line with the parabolic function, which has an optimum – the minimum value of specific energy consumption is in the range of the inclination angle of the scraper unit's scrapers from 55° to 65° and varies from 0.33 to 0.35 kW h/t.

This is explained by the fact that the inclination angle of scrapers at 30° will lead to the accumulation of a large amount of manure at the surface of the front walls of scrapers, which would press the scrapers to the bottom of the manure channel with excessive effort.

At the inclination angle of scrapers from 55° to 65°, a layer of manure would be cut by the wedge-shaped scrapers and the surface of scrapers would accumulate such an amount of manure, which should provide for the optimal pressing of scrapers to the bottom of the manure channel.

At the inclination angle of scrapers at 90°, manure would not climb the scrapers, and the lack of a wedge at the front wall of a scraper would lead to that the manure is not cut, but torn from the bottom of the manure channel, and that would require more power to move the scraper.

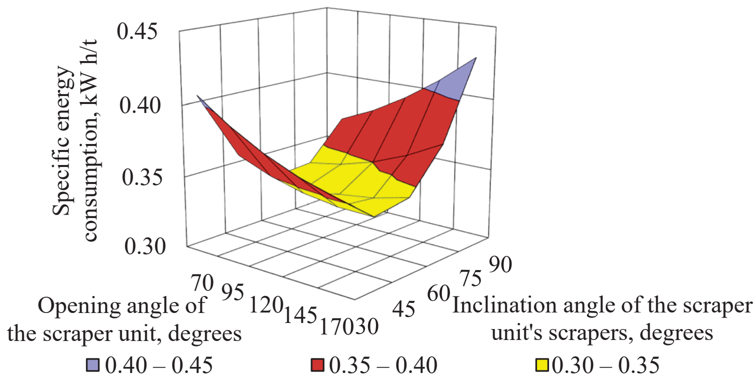

Fig. 5. Dependence of specific energy consumption of the improved scraper unit on opening angle of the scraper unit per and inclination angle of the scraper unit's scrapers

An analysis of the mutual influence of motion speed and opening angle of the scraper (Fig. 6) has revealed that an increase in the motion speed of the scraper v_{SCR} from 0.04 m/s to 0.18 m/s leads to a change in specific energy consumption E_{CUR} in line with the parabolic function. This function has an optimum – the minimum value of specific energy consumption in the range of speed of 0.13...0.15 m/s and varies from 0.32 to 0.34 kW h/t.

This is explained by that an increase in speed leads to an increase in productivity, and hence specific energy consumption decreases. When reaching the speed of 0.15 m/s, specific energy consumption starts to grow due to the fact that an increase in speed leads to that the intensity of growth in the power consumed outperforms the intensity of the speed growth.

Based on an analysis of influence of the scraper unit's opening angle on the specific energy consumption of manure removal (Fig. 5, 6), minimum energy consumption is 0.32 kW h/t; it could be reached at the scraper unit's opening angle from 105 to 115°.

An analysis of the mutual influence of inclination angle of scrapers and motion speed of the scraper unit (Fig. 7) has demonstrated that an increase in the scraper unit's scrapers inclination angle γ would lead to a change in specific energy consumption E_{CUR} in line with the parabolic function. The minimum indicators of specific energy consumption ranging from 0.32 to 0.34 kW h/t will be attained at the scraper unit's scrapers inclination angles in the range of 50–70°.

At the scraper unit's scrapers inclination angle in the range of 30–50°, the front walls of the scraper will accumulate manure, which, as already noted above, would press it to the bottom of the manure channel with excessive effort. At the scrapers inclination angle from 50° to 70°, a layer of manure would be cut by the wedge-shaped scraper, which would lead to a decrease in energy consumption. At the scrapers inclination angle in the range of 70–90°, as already noted above, manure will not be cut, but rather torn, from the bottom of the manure channel, which would lead to an increase in energy consumption.

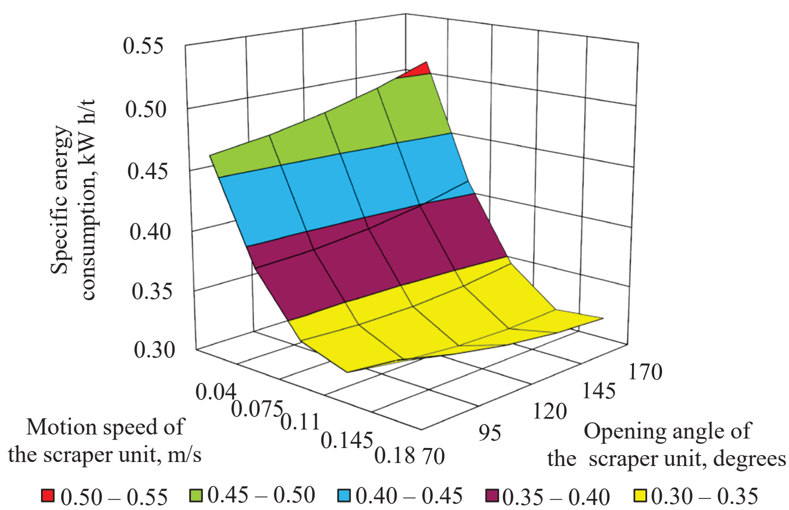

Fig. 6. Dependence of specific energy consumption of the improved scraper unit on motion speed of the scraper unit and opening angle of the scraper unit

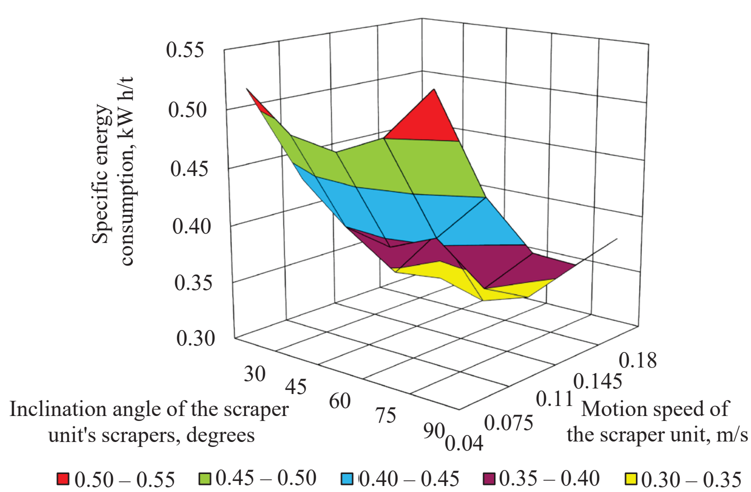

Fig. 7. Dependence of specific energy consumption of the improved scraper unit on the scraper unit's scrapers inclination angle and motion speed of the scraper unit

It was determined that an increase in motion speed of the scraper unit v_{SCR} will lead to a change in specific energy consumption E_{CUR} in line with the parabolic function, which has an optimum – the minimum value for specific energy consumption at a value for motion speed of the scraper unit in the range from 0.13 m/s to 0.15 m/s and varies from 0.32 to 0.34 kW h/t. This is explained by that an increase in speed leads to an increase in productivity, and hence specific energy consumption decreases, respectively.

6. Discussion of results of studying the energy consumption of scraper unit

Based on the experimental study, we established rational parameters for the developed scraper unit, at which energy consumption would be minimal. It follows from an analysis of the influence of opening angle of the scraper unit on specific energy consumption of manure removal (Fig. 5, 6), the minimum energy consumption can be achieved at the scraper unit opening angle γ from 105 to 115°. A decrease in the scraper unit opening angle from 105 to 70° will result in an increase in the length of scrapers, and therefore their weight, which as a consequence would increase energy consumption. An increase in the scraper unit opening angle from 115 to 170° will lead to a decrease in the length of scrapers; however, an increase in the angle between the motion direction of the scraper unit and the plane of the frontal wall of the scraper, and the absence of sliding cut of manure, plunges the scraper into manure with a greater effort, which as a consequence would increase energy consumption.

At the scrapers inclination angle from 50° to 70°, a layer of manure will be cut by the wedge-shaped scraper, which would lead to a decrease in energy consumption. To manufacture a scraper unit, it is rational that scrapers should have inclination angle ε=60°. Based on Fig. 6, 7, one can conclude that an increase in speed increases the productivity, and hence specific energy consumption decreases. When reaching the speed of 0.15 m/s, specific energy consumption starts to grow due to the fact that at an in increase in speed the intensity of growth in the power consumed outperforms the intensity of the growth in speed. In order to avoid any harm to animals, it is advisable to choose motion speed of the scraper unit at the level v_{SCR}=0.13 m/s.

Based on these indicators, we assembled a scraper for manure removal, and conducted comparative experimental study.

According to the design of experimental study, we measured specific energy consumption by USG-3 and the developed scraper unit (Fig. 8). The developed unit has lower indicators of specific energy consumption, by 44 to 48 %.

Reduction of the indicators of specific energy consumption is achieved due to that USG-3 must make 3 working runs of the scraper unit in order to achieve the required quality of cleaning the manure channel.

The developed scraper unit could make only 2 working runs to achieve the required quality of cleaning the manure channel.

Owing to the peculiarities of scrapers made with a front working surface in the form of a blade, manure will not be torn from the surface of the manure channel, but cut instead, which would the reduce resistance, and therefore power consumption. In addition, manure will climb the surface of scrapers thereby pressing them against the surface of the channel that leads to the improvement in the quality of manure removal, and hence reduces the number of runs required by the scraper unit to achieve the required quality.

The established rational parameters and operation modes of the scraper unit reduce energy consumption of the scraper unit while maintaining the quality of cleaning a manure channel.

Further improvement of the manure removal efficiency using a scraper unit is limited by the fact that there are animals in the area of scraper operation. In order to prevent cattle injuries, a further increase in the motion speed of the scraper unit is inacceptable.

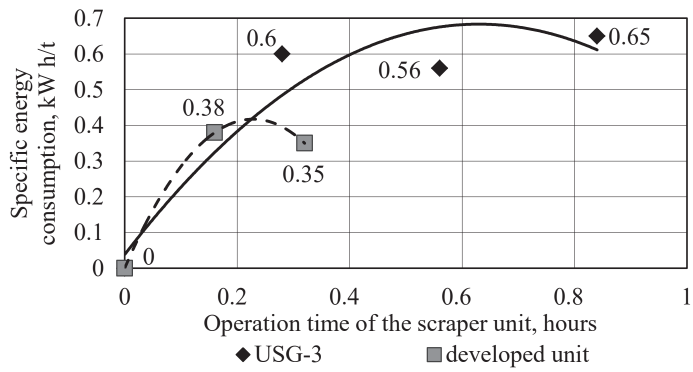

Fig. 8. Chart of change in specific energy consumption based on the results of experimental study (mean values)

The development of a given study could be a substantiation of the operation process of the scraper whose working front surface holds the fixed specialized devices in the form of triangular prisms to ensure removal of compacted manure. No animal was hurt in the course of our studies reported in this paper.

However, it is advisable to set the upper threshold for the height of the scraper unit's scrapers to prevent animal injury.

This study could be applied in the design of bulldozers and other melioration equipment. Research results might be also used for improving the design of foreign scraper units whose working bodies are similar to USG-3.

7. Conclusions

1. We have established a possibility to reduce energy consumption in the process of manure removal using scraper units; the application of working bodies with optimal parameters makes it possible to decrease by a third the number of working runs of the scraper unit while maintaining the quality indicators of manure removal.

2. Based on the research conducted we substantiated optimal parameters for a scraper unit for manure removal, at which energy consumption would be minimal, specifically, the scraper unit opening angle ranged from 105 to 115°, inclination angle of the working surface of scrapers is 60°, motion speed of the scraper unit is 0.13 m/s.

3. We have conducted experimental study into operation of the developed scraper unit for manure removal and the

commercially available unit USG-3, which demonstrated a decrease in specific energy consumption by 44 to 48 % to 0.34–0.36 kW h/t for manure removal when applying the improved working body with optimal design parameters.

4. Based on the performed analysis of the hourly accumulation of manure at a livestock farm, we developed a schedule for manure removal using the scraper unit, which implies the removal of manure five times over 24 hours.

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