Vibratory thickening of grass mass

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Abstract. Flat surface inertia type vibrators in which the excitation force for thickening grass mass is received by turning the unbalanced mass were analyzed and evaluated. Directed and undirected action vibrators were manufactured and tested. The amplitude frequency characteristics of pressed grass mass were evaluated using a directed action grass mass pressing vibrator. It was concluded that resonant frequency depends essentially only on mass toughness qualities, and changes from 7.0 Hz when there is fodder goat's rue (*Galega orientalis* Lam) mass of greater toughness, up to 15 Hz when thickening chopped maize mass of lesser toughness. The amplitude of grass mass pressure during resonance depends only on the mechanical resistance of the pressed mass. The amplitude of excitation power of goat's rue and its mixes during resonance increased from 2.5 to 3 times but efficiency of mass pressure reduced. The calculated coefficients of pressure enhancement were equal to 5.5-5.8 when vibratory thickeners were used for pressing grass mass. The established repression of pressure on plant mass layer, while pressing mass on the surface and from the bottom of container, was 3.0-7.5 when using the directed action vibrator, and 4.8 when using the undirected action version. After evaluating the application of various tractors and vibratory grass mass thickeners for grass mass pressing it was found that in both cases the received efficiency rates of grass mass layer were similar. However, while using vibratory grass mass thickeners, these rates were even higher than using a wheeled tractor T-25A. The efficiency of mass thickening by centrifugal-directed action vibrator was evaluated by using an experimental trial. The results indicated that during vibratory thickening the grass layer was thickened intensely for 5-10 min. Therefore, it is advisable to use vibrators of this type for thickening grass layers of 0.4-0.6 m thickness. This vibrator resulted in good density of chopped maize – after 20 min of thickening (2×200 kg) the density of 510 kg/m^3 was achieved and while thickening the first mix of 200 kg layer after 10 min 571 kg m^{-3} density was achieved. The densities of dry matter were 143 kg m^{-3} and 161 kg m^{-3} respectively. The investigation of the forage quality showed that it met the requirements of the highest-class silage.

Key words: grass mass, container, vibratory thickeners, pressure, density

INTRODUCTION

Silage is the predominant cattle fodder throughout the world. More and more swards are allocated to silage in Western Europe states, as evidenced by the data on the percentage of harvested swards used for silage production: in Holland it is 99%, in Denmark – 93%, in Northern Ireland – 90% and in Norway – 75%, etc. (Sirvydis, 2001). To reduce energy deficit, ensiling of grass forages has been and will continue to be the main way of their preservation. It is predicted that the production of chopped grass silage in trenches, heaps, containers and bales will remain in the immediate future. Silage quality depends on the time spent filling trenches, containers used, and mass pressing. In Lithuania, until 1990, silage was pressed only by caterpillar tractors. Later heavy wheeled tractors K-701, T-150K, average draught class MTZ and other tractors began to be used for this purpose. In 2001 research on using low capacity tractors (T-25A, etc.) in pressing chopped grass was carried out (Spirgys, 2001).

In Lithuanian climatic conditions the production of hay should be decreased and the production of silage should be increased (Sirvydis, 2001). Adequate pressing of plant mass is necessary to produce good quality silage. Since grass mass surface is unstable, a tractor driver can be injured or killed if a tractor turns over while pressing the mass. Recently the Institute of Agricultural Engineering of Lithuanian University of Agriculture (IAE LUA) has been carrying out investigations related to applying the vibratory grass mass pressing method as an alternative to mass pressing by tractors. At present, Lithuanian farmers are not used to this vibratory grass mass pressing method in practice, but in accordance with the research results, recommendations for usage of these vibrators for silage pressing in the farms will be prepared. In order to evaluate such methods a comprehensive analysis of physical characteristics of the pressed mass has to be performed as the types of vibrators used and their operational parameters depend on them.

The research goal is silage production technology which presses grass mass by vibration. *The research objective* is evaluation of a silage thickening technology using a directed action vibrator and the establishment of amplitude frequency characteristics of such a vibrator's operation with plants having different physical characteristics. Comparison of the efficiency of ensiled grass pressing with the use of directed and undirected action vibrators and wheeled tractors has been made.

REVIEW OF LITERATURE

In Lithuania silage is prepared in trenches and stacks. Recently production of non-chopped grass silage in bales has become more popular (Williams, 1992; Antonov, 1995; Sirvydis, 2001). In small-scale farms it is advisable to produce chopped silage in section- type trenches and in container storages. Container manufacturing does not require huge capital investments. The vibratory method could be used for mass thickening in containers (Sirvydis, 2001).

The analysis of literature sources (Sirvydis, 2001; Ferevičius & Jasinskas, 2005) proved that a vibratory method of grass mass thickening had not been analysed properly. In using vibratory thickeners it is important to establish the frequency at which grass mass is most efficiently pressed, the mass of the equipment and the area that it can press. Pressing of grass mass with the help of different wheeled tractors in the first stage of pressing resulted in mass deformation of 275 mm (Spirgys, 2001). It was also established that, when thickening by tractors, the vertical pressure force increased at the particular frequency of the tractor engine revolutions. At 20–26 Hz frequency the measured vibration speed when pressing grass with Caterpillar tractors increased by 5 dB and it increased up to 13 dB when using tractors T-150K compared with static gravity of these tractors. The research results presented in one literature source (Spirgys, 2001) proved that in later stages of grass thickening, deformation decreased and resonance-specific frequency of pressed grass mass increased.

The research (Ferevičius & Jasinskas, 2005) showed that experimental vibrators with direct current engine and undirected action vibrators with alternative current engine did not meet all requirements. Only coarse-stemmed well-chopped grass plants and their mixes were thickened efficiently to some extent. The vibrator operation was not stable; it is beside the purpose to use them for thickening red clover and Caucasian goat's rue. It is provided for analysing the most important parameters of a directed action vibrator, to establish the optimum modes of its operation and to compare this technology with a traditional ensiling technology, using pressing by tractors (Jasinskas & Ferevičius, 2004).

One of the indicators characterizing the pressing of fibre-plant mass is its density. In analysing the process of fibre-plant mass thickening the majority of authors adhere to the following assumptions:

1) the amount of static load force does not depend on grass deformation speed;
2) pressure fluxion by mass density is a function of added pressure (Darby & Jofriet, 1993; Langlen, 2000).

These assumptions are used in describing simplified models of grass mass pressing (Sirvydis, 2001). Individual grass features are described mathematically by applying idealized strain components of real materials and their different combinations. Deformation and relaxation of elements forming a model are described by differential equations (Spirgys, 2001). Most often the equations are complicated as the elements of pressed mass form systems having numerous degrees of freedom and resonance frequencies. This task is not so complicated when a model can be analysed as a vibratory system having one degree of freedom.

According to the classical theory of mechanical oscillations in analysing equations of forced vibration such a system can be analysed as concentrated mass on a spring with its end tightly fixed. In addition internal friction is present in this system. The elements of mass resilience mechanical resistance corresponding to its internal friction are separated from each other in this system (Augustaitis, 2000; Cizmadia & Hegedur, 2002; Hegedur & Cizmadia, 2002). We choose to influence the system by excitation force changing by sinusoid. In this case the vibratory equation is as follows (Augustaitis, 2000):

$$m\ddot{x} + \mu\dot{x} + qx = F_m \sin \omega t, \quad (1)$$

where: m – system mass, kg;

q – spring resilience equal to the force required to affect the spring in order to cause its deformation, N m^{-1};

x – momentary extent of vibration change of the spring, m;

$\dot{x}$ = dx/dt – momentary velocity of vibration, m s^{-1};

$\ddot{x}$ = dv/dt – momentary acceleration of mass vibration, m s^{-2};

μ – constant of mechanical resistance (internal friction), Ns m^{-1};

F_m – amplitude of excitation force, N;

ω – frequency of excitation force, s^{-1}.

A common solution of this equation has two components: the first component corresponds to free vibrations of the system which in this case are fading due to the internal friction of the system, and the second component corresponds to forced vibrations which in our case are very important. Having expressed a vibration shift in a complex form: $X = A_m e^{i\omega t}$ (here A_m – shift amplitude m) and having written this value (1) into the formula we find the equation of the proportion of vibration velocity and excitation force amplitudes:

$$v_m = \frac{F_m}{\sqrt{\mu^2 + (m\omega - q/\omega)^2}} . \qquad (2)$$

This equation establishes dependence between vibration velocity and the excitation force amplitude. Knowing mechanical resistance of grass mass and having measured vibration velocity (2) by the equation it is possible to establish the values of excitation force F_m and to compare these values with the calculated ones.

MATERIALS AND METHODS

The research object is chopped maize (experiment variant I), a mixture of maize and goat's rue (experiment variant II) and goat's rue (experiment variant III) thickened by a directed action vibrator, a mixture of red clover and maize (trial variant IV) thickened by an undirected action vibrator. Chopped plants of 67-72% moisture (chop length 15-20 mm) were used for the trials. The research was carried out in 2004-2005 in laboratory trial facilities of IAE LUA.

The trial was carried out in a laboratory stand the scheme of which is shown in Fig. 1. The grass mass was thickened in a container storage at the bottom of which an opening had been made and a sensitive pressure plate of 0.25×0.25 m size had been fitted. A centrifugal undirected action vibrator of the total mass of 115 kg and a centrifugal directed action vibrator with two masses rotating in counter-clockwise directions were used for grass thickening. The centrifugal directed action vibrator was rotated by an asynchronous engine of 1.1 kW, 1500 min^{-1}. Weights of 7.0 kg mass were fitted to rollers in the vibrator; their mass centres were 40 mm away from the axis. The total mass of this vibrator was 125 kg.

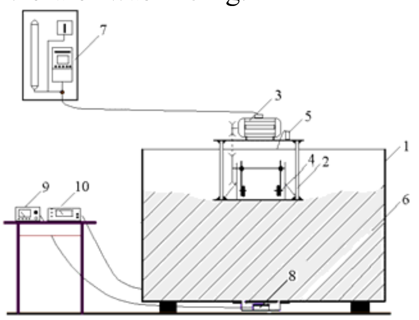

Fig. 1. Scheme of grass thickening in container storage using vibratory device: 1 – container storage; 2 – centrifugal-undirected action vibrator; 3 – electrical engine; 4 – changeable weights; 5 – vibration sensor; 6 – mass of thickened grass; 7 – electric current frequency converter; 8 – tensometer sensor; 9 – pressure measurement device; 10 – vibration measurement device.

In order to achieve more accurate evaluation of the influence of the vibrator's excitation force on the pressure of thickened grass and to avoid the influence of grass and the vibrator's mass and other factors on the pressure data obtained, pressure was recalculated into relative pressure p_s (Jasinskas & Ferevičius, 2004). This pressure shows percentage increase of pressure in a grass layer during vibration compared with the pressure when only the vibrator gravity force is applied:

$$p_s = [(p_2 - p_1)/p_1] \times 100 \; ; \tag{3}$$

where: p_s – relative pressure, %;
p_1 – pressure in grass layer applying only vibrator's gravity force, kPa;
p_2 – pressure in grass layer during vibrator operation, kPa.

The efficiency of vibratory thickening in trials was assessed according to variation of density ρ. The amount of dry matter (DM) in thickened grass was established and the density for dry matter was calculated. The volume of grass mass was calculated using a ruler (accuracy ±0,001 m) for measuring filling of the container at 4 points. The grass mass in the container was weighed by the scales with a weighing range of 20-500 kg and accuracy of ±0.5 kg. After putting two silage layers of 200 kg each into the container and pressing both layers the silage was sealed by polyethylene film and pressed by using the gravity force of the centrifugal-directed action vibrator. Two months later, after storage in the similar ambient weather conditions, silage samples were taken and the quality of feed was evaluated by using standard methods (Sirvydis, 2001).

Each experiment had three replications and the trial data was processed using mathematical-statistical methods by calculating arithmetic mean, average square deviation and selecting Student's coefficient – errors at 0.95 reliability. All calculated meanings of research results in the tables are average meanings, without deviations.

The velocity and acceleration of a flat vibrator vibrations were measured by a vibrometer 2511 with a band adjustable filter 1621 manufactured by a Danish company "*Brull & Kjaer*" according to the established methods (Ferevičius & Jasinskas, 2005).

To measure pressure force on grass mass at the bottom of the container a tensometer sensor was used (Fig. 2). The pressure on the surface of grass mass and at the bottom of the container is made by the vibrator's static and dynamic forces (gravity and excitation, respectively). The vibrators' operation parameters, variation of grass mass density and other parameters were recorded using the above described methods. The pressure on the tensometer sensor 5 was measured by a pressure measuring device 1526 manufactured by the Danish company "*Brull & Kjaer*". .

The commutation scheme of pressure (tension) measuring and the mechanical and electrical schemes of tensometer sensor DST 0.8-0.6-2 No 5199 had been redesigned in order to increase measuring sensitivity and to adjust it to "*Brull & Kjaer*" pressure measuring equipment. The sensitive element of the tensometer sensor was membrane 4 of dimensional design. Tenso-converters 5 were stuck on its wings on both sides and they transformed the pressure transmitted from the sensitive plate into an electrical signal. During the vibrator's operation grass mass pressure was transmitted to the tensometer fitted at the bottom of the container.

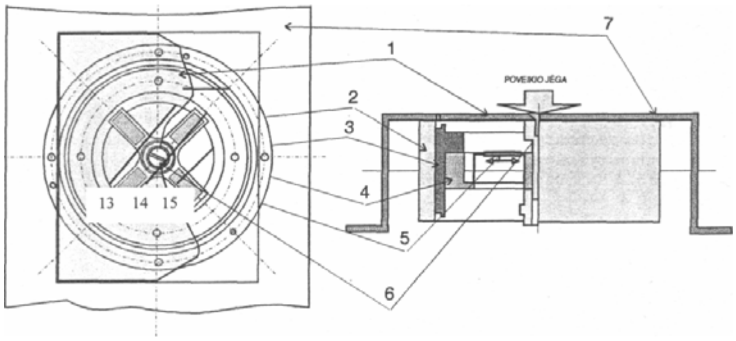

Fig. 2. Scheme of tensometer sensor: l – sensitive plate; 2 – tensometer body; 3 – tensometer liner; 4 –tensometer membrane; 5 – tenso-converter; 6 – fastening screw of sensitive plate; 7 –tenso-block body.

Its electrical signals were registered by tenso-indicator 1526. The complete system of measuring equipment consisted of three main blocks: tenso-indicator 1526, channel switching and commutation block 1544, and control and digital information block 1545.

All pressure measuring equipment was calibrated; schedules of meter calibration had been made. The tensometer was calibrated after taking it out of the tenso-block body and fitting it on a specially manufactured calibration stand.

RESEARCH RESULTS

While analysing a homogeneous free vibrations differential equation of general expression of linear one freedom degree stationary system (1) it is established that resonance characteristics of the system depended on spring resilience and amplitude characteristics depended on the value of mechanical resistance (internal friction of grass mass) coefficient μ. To prove these assumptions vibration accelerations and velocities on the vibration plane of the directed action vibrator for grass mass pressing were measured. The results of vibration acceleration measurements within 1-27 Hz range (three experiment variants carried out) are presented in Fig. 3.

Specific resonance frequency of the measured system varies depending on grass mass composition and structure. The mass of different plant origin is characterized by different resilience. When thickening the mass of goat's rue and its mixtures of higher resilience, vibration amplitude increases reasonably, nevertheless, it does not mean that the grass mass is pressed more effectively. In this case it is obvious that the reactive part of the grass mass resistance increases and when suppression decreases, the system operates inefficiently. That was proved by characteristics of grass mass pressure amplitude and the final results of mass pressure.

In summarizing the results it can be stated, that the denominator in equation (2) $\sqrt{\mu^2 + (m\omega - q/\omega)^2} = z_m$ describes resistance of the system to excitation force. Value μ shows the active part of mechanical resistance and value $(m\omega - q/\omega)$ – a reactive part of this resistance. The reactive part is made of two resistances: elastic q/ω and inert ones $m\omega$. Reactive resistance is equal or close to zero at resonance.

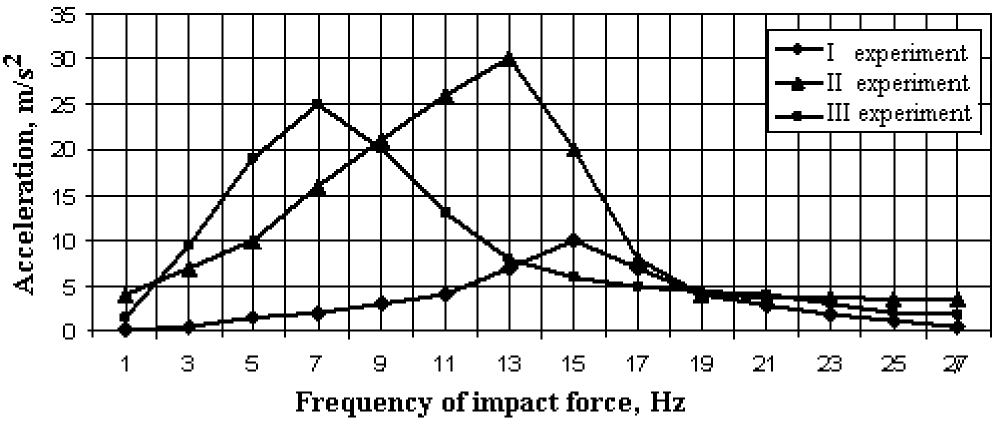

Fig. 3. Characteristics of amplitude frequency, while pressing chopped grass forage by directed action vibrator: experiment I – mass of chopped maize; experiment II – mix of maize–goat's rue; experiment III – chopped goat's rue.

In this case the system resists excitation force only due to the system's active losses. In such a mode the vibration amplitude increases dramatically and active losses are maximal due to mass mechanical resistance which corresponds to our ultimate goal. In order to establish mechanical resistance coefficient μ of the pressed grass mass, we measure the average mass pressure in the container Δx by using the vibrator and setting adequate momentary pressure time Δt. The results of measurements and calculations are given in Table 1.

Table 1. Measurement of mechanical resistance coefficient μ of grass mass in a container.

Vibrator (experiment variant)	Vibrator gravity G, N	Mass pressure in container Δx, m	Momentary time Δ t, s adequate to mass pressure Δx	Mechanical resistance coefficient μ, Ns/m
1. Directed action (exp. var. I)	1226±4	0.47±0.04	4	$1.07 \cdot 10^4$
2. Directed action (exp. var. II)	1226±4	0.57±0.05	6	$1.32 \cdot 10^4$
3. Directed action (exp. var. III)	1226±4	0.55±0.05	7	$1.59 \cdot 10^4$
4. Undirected action (exp. var. IV)	1128±2	0.45±0.04	8	$1.86 \cdot 10^4$

In order to assess and compare the efficiency of operation of manufactured vibrators we have to calculate contact pressure created under the flat surface:

$$\sigma_0 = k_p \frac{P+G}{S}, \qquad (4)$$

where: σ_0 – pressure caused by vibrator, kPa;

P – vibrator's excitation force, N;

G – vibrator's gravity, N;

S – pressed surface area, m^2;

k_p – coefficient of pressure increase.

As we can see from equation (4), created pressure σ_0 depends on the total effect of vibrator's excitation and gravity forces and pressure increase coefficient k_p. The latter value is mainly dependent only on the ratio of excitation and gravity forces and in the specific case it can be established experimentally. The calculations of undirected action vibrator's excitation forces are presented in the following source: (Ferevičius & Jasinskas, 2005).

At undirected action vibrator's excitation force P = 0.89 kN pressure increase coefficient $k_{p\,1}$=5.8 was calculated. Referring to the calculation results we can state that with an increase of effect force frequency its amplitude increases significantly as well (up to 5.6 kN). However, it does not mean that the increase in pressure coefficient will cause higher pressure efficiency.

In assessing the use of directed action vibrator for grass mass pressing the excitation force was calculated by the formula:

$$P = \frac{G\pi^2 \cdot n^2 \cdot r}{900g}, \qquad (5)$$

where: G_b – disbalance gravity, N;

r – rotation radius of disbalance centre of gravity, m;

n – disbalance rotation frequency, min^{-1};

g – free fall acceleration, m s^{-2}.

For calculated directed action vibrator's force P=1.08 kN a pressure increase coefficient $k_{p\,1}$= 5.5 was calculated. The calculated and experimentally established indicators of grass mass effect are given in Table 2.

Table 2. Evaluation of vibrator pressure and effect forces.

Vibrator (experiment variant)	Calculated vibration pressure σ_0, kPa	Measured amplitude of excitation force F_m, kN	Measured pressure force to meter plane F_0, N	Measured pressure force amplitude to meter plane F_m, kN	Experimentally established pressure increase coefficient k_{p2}
1. Directed action (experiment variant I)	26.7	1.61±0.06	0.40±0.02	0.53±0.04	1.49±0.06
2. Directed action (experiment variant II)	26.7	7.37±0.25	0.65±0.04	0.88±0.05	6.82±0.18
3. Directed action (experiment variant III)	26.7	5.89±0.15	0.62±0.03	0.78±0.05	5.45±0.16
4. Undirected action	37.3	2.98±0.08	0.25±0.02	0.62±0.03	3.35±0.12

In evaluating the results in Table 2 it can be stated that using the directed action vibrator, efficient mass pressing does not depend on the pressure increase coefficient but rather on a chosen vibratory effect force frequency and mass mechanical resistance. In this case the assumption (Jasinskas & Ferevičius, 2004) was proved that when using the vibrator at all times a horizontal and vertical excitation force components appear and as the vibrator frequency and effect force amplitude increase, the vibrator's operation is unstable, an undesirable 'swimming' effect appears and the pressing efficiency decreases.

In order to compare the analysed vibratory grass mass thickening method with mass pressing by tractor's gravity one has to assess the circumstances in which the tractor conveys the load to the thickened mass over an area of limited size composed of contact surfaces of four wheels. In our case, when assessing grass mass loads and pressure indicators they were calculated individually for front and rear tractor wheels. When the load is distributed evenly over the whole area, it can be seen that all base points are sunken as well. However, complex calculations result in the contact tension diagram bearing a typical saddle-backed shape (Spirgys, 2001). The highest tensions can be found under the basing surface edges and the least tensions – at the middle.

With a view to facilitating and simplifying the calculations, it was assumed that contact tension diagrams under the tractor's wheels were linearly dependent on gravity and they could be described analogically to an evenly loaded vibrator's basing surface. To calculate pressure in a certain depth of grass mass, it was far more convenient to use curve graphs of even tensions (Spirgys, 2001). In our calculation vertical normal tensions were evaluated in the depth of 0.56 m under tractor wheels or were measured in an analogous mass depth (at the container bottom), when the vibratory method was applied for grass mass pressing. The results of calculations and measurements are given in Table 3.

Table 3. Comparison of different methods for grass mass thickening.

Mass thickening tools (method)	Static grass mass load, kN	Static pressure on grass mass, kPa	Static pressure in 0.56 m depth of grass mass (or container bottom), kPa	Measured pressure increase due to vibratory effect, kPa	Pressure efficiency indicator (Pressure force suppression repeatability)
Tractor T-25A (front/ rear wheels)	4.2/6.45	144/55	26/2.75	no data	5.56/20.00
Tractor MTZ-80 (front/ rear wheels)	9.9/94	215/82	114/16.3	no data	1.89/5.00
Tractor T-150K (front/ rear wheels)	27.6/18	192/96	121/57.7	151/88	1.59/1.66
Tractor K-701 (front/ rear wheels)	39.4/26.4	124/110	no data	no data	no data
Directed action vibrator (Experiment I)	1.25±0.04	27.3±0.7	6.28±0.16	8.34±0.26	3.05
Directed action vibrator (Experiment I)	1.25±0.04	27.3±0.7	10.22±0.30	13.83±0.43	5.07
Directed action vibrator (Experiment III)	1.25±0.04	27.3±0.7	9.81±0.24	12.26±0.38	4.50
Undirected action vibrator	1.15±0.03	29.4±0.9	3.92±0.14	9.81±0.19	3.33

Having compared the tools of grass mass pressing indicated in Table 3, it can be stated that better pressing is achieved when the pressing efficiency indicator is lower. This provision stands also for tractors which can produce rather great pressure but have low gravity. Comparing specific results of directed and undirected action vibrator experiments resulted in a conclusion that in individual cases an undirected action vibrator pressed grass mass more effectively than a directed action one. Having appreciated that, we can state that a higher pressure force suppression determines better pressing of a grass mass layer (the value of pressure force suppression repeatability is inversely proportional to pressing efficiency). It is also obviously related to the fact that when other conditions are similar, better pressed mass is characterized by higher mechanical resistance to excitation force.

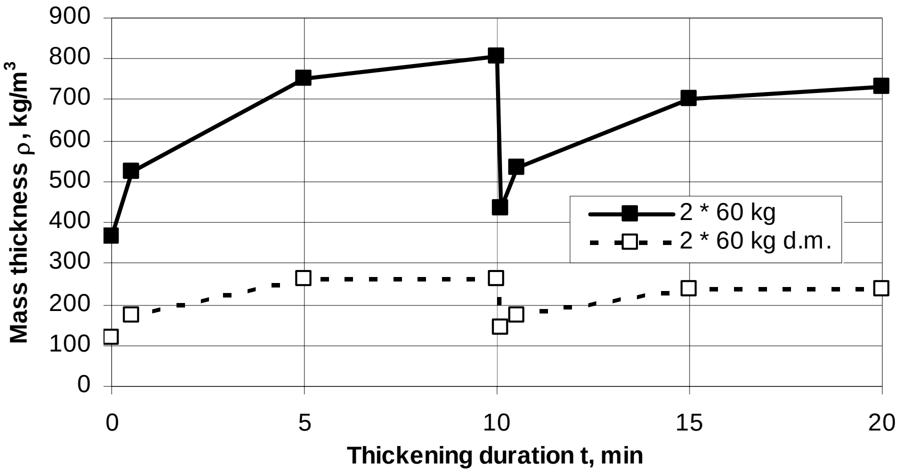

Fig. 4. Dependences of maize mass density ρ variation on thickening duration t while thickening mass by undirected action vibrator.

The influence of thickening duration on variation of maize mass density when the feed is thickened by a centrifugal-undirected action vibrator is presented in Fig. 4. Moisture content of maize mass was 67.3±0.4%. The first 60 kg load corresponds to 10 min duration thickening and the second additional 60 kg load corresponds to additional 10 min duration thickening.

It was established that the analysed vibrator achieved rather high density of maize mass: after 20 min of thickening 120 kg maize mass the achieved density was 730 kg m^{-3} and 239 kg m^{-3} of dry matter respectively. While thickening the first maize mass layer of 60 kg, after 10 min even 808 kg m^{-3} (264 kg m^{-3} of dry matter) density was achieved. It is sufficient to achieve 600 kg m^{-3} density (Sirvydis, 2001) to produce high quality silage.

Lower density of maize mass is achieved when a centrifugal-directed action vibrator is used for thickening chopped maize (Fig. 5). Moisture content of maize mass was 71.9 ±0.6%. The first 200 kg load corresponds to 10 min duration thickening and the second additional 200 kg load corresponds to additional 10 min duration thickening. After 20 min of thickening both silage layers of 510 kg m^{-3} density was achieved and when thickening the first mixture layer of 200 kg mass after 10 min 571 kg m^{-3} density was achieved. Dry matter densities were 143 and 160 kg m^{-3} respectively. An assumption can be made that the thicker layer of thickened mass had some influence on that.

On the ground of the results of these experiments we can state that the vibrator of the analysed design would be expedient to use for thickening maize and partly for thickening maize-Caucasian goat's rue mixtures.

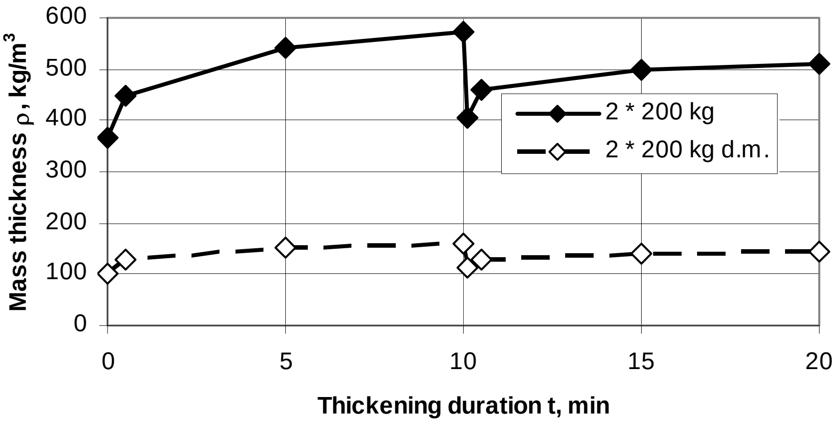

Fig. 5. Dependences of maize mass density ρ variation on thickening duration t while thickening mass by directed action vibrator.

While assessing the experimental technology of grass ensiling in a container storage using vibratory thickening, the attention was focussed on grass mass chopping, loading into the container and thickening with the vibratory mechanism (harvesting and transporting operations were not analysed). This technology was assessed by three parameters: time required to perform each operation and the complete production cycle, production efficiency, and the feed quality.

Time t_g required for a production cycle starting with grass chopping is equal to:

$$t_g = t_{sm} + t_p + t_u + t_t + t_s, \quad (6)$$

where: t_{sm} – duration of grass chopping, min;
t_p – duration of grass loading into container, min;
t_u – duration of lifting up of vibrator, min;
t_t – duration of grass thickening, min;
t_s – duration of sealing and pressing grass in a container, min.

Technological indicators of grass thickening are given in Table 4. Depending on consistency and parallelism of technological operations 17–41 min are needed to perform a production cycle with a full container (150 kg of grass). At adequate planning and distribution of operations a silage production cycle (without grass harvesting and transporting operations) can be shortened to 9-26 min, i.e., down to the total time of carrying out the vibrator, its lifting and lowering, and grass thickening operations.

The efficiency of a production cycle was limited by a technological operation of the lowest efficiency. In this case it was grass thickening – 0.4-0.9 t h^{-1} (Table 4).

Table 4. Technological indicators of vibratory grass thickening.

Technological indicators	Technological operations					
	Grass chopping	Grass loading into container	Vibrator lifting up and down	Grass thickening	Grass sealing and pressing	Complete production cycle
Duration of technological operation t_i, min	7.5-10	3-5	4-6	5-20	5-10	17-41
Efficiency of technological operation N_i, t h^{-1}	1-1.5	2-3	0.4-0.9		-	-

Note: in the column of *Duration of technological operation* (line two) the time was registered when the operation was carried out with 150 kg of grass.

After feed quality analysis (DM amount, pH, amount of acids, and digestibility of organic matter) it was established that it met the requirements for the highest quality silage. Although silage density in the container was not sufficient (510 kg m^{-3} density achieved), but taking into account that maize was chopped very well (because it is a coarse-stemmed plant) and it is considered to be a plant variety good for ensiling, a very good quality feed was produced.

CONCLUSIONS

1. After the assessment of the measured characteristics of amplitude frequency of pressed grass mass it was established that resonance frequency depended only on mass resilience and changed from 7.0 Hz at greater resilience of goat's rue mass (experiment III) to 15 Hz while thickening chopped maize mass of lower resilience (experiment I).
2. The pressure force amplitude of grass mass during resonance depends only on mechanical resistance of the pressed mass. During resonance the excitation force amplitude of goat's rue and its mixture mass characterized by lower suppression features increases from 2.5 to 3 times, however, mass pressing efficiency decreases.
3. When vibratory grass mass thickeners were used to press grass mass 5.5-5.8 pressure increase coefficients were found. Measured suppression of a mass layer (decrease of pressure force in times over the total height of all pressed mass) in terms of created pressure on the mass surface and at the container bottom changed from 3.0 to 7.5 using a directed action vibrator and was equal to 4.8 using an undirected action vibrator.
4. After the comparison of possibilities of different tractors and vibratory grass mass thickeners to press grass mass it can be stated that, when static pressure of a vibratory thickener is much lower due to pressure increase and a vibratory effect the efficiency indicators of pressing a grass mass layer are similar to those when using heavy-weight and average draught-type tractors. However, the efficiency indicators of pressing with vibrators are higher than those when using a tractor T-25A.
5. The experimental research results showed that centrifugal vibrators were expedient to use for thickening maize and partly maize–goat's rue mixtures.

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