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Energetic loading of forage harvester working units depending on cutting length of the plant material

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Abstract: *Energetic loading of forage harvester working units depending on cutting length of the plant material.* Basing on the developed mathematical models and carried out calculations on the forage harvester energetic loading there are presented changes in the effective power and specific energy related to a dry matter mass, needed to drive the withdrawing-compacting rolls and the chopping unit depending on cutting length of the plant material. Simulation investigations were carried out for the flow intensity of moist plants in the range of 1.5–5.3 $kg \cdot s^{-1}$, knife disk rotational speed 1000 rpm and theoretical cutting lengths 5 and 10 mm. It is evident from energetic loadings of the withdrawing-compacting rolls set and the chopping unit, that at certain disk rotational speed a decrease in the number of cutting knives at constant flow of the chopped plants and the same theoretical cutting length causes a decrease in effective power requirement of forage harvester, in spite of the increased loading of withdrawing--compacting rolls set. More distinct differences in energetic indices at the small theoretical plant cutting lengths at the reduced number of knives result from the lower speed of withdrawing-compacting rolls; it causes an increase in the plant layer thickness and an increase in forces in tension springs, as well as better compacting of plants between rolls. As a result of better compaction of thicker layer of plants, one can find better effectiveness of cutting and lower energy consumed by the chopping unit.

Key words: forage harvester, withdrawing-compacting rolls, chopping unit, energetic loading

INTRODUCTION

One of basic factors influencing the feed quality is chopping of the green forage into particles of uniform dimensional distribution, that meet technological and qualitative requirements. Length of chaff in ensilaging of grass and papilionaceous plants should amount to 20–30 mm, while of maize to 5–15 mm [Chlebowski 2011]. Minimal length of chaff available in currently produced forage harvesters amounts to 3.5 mm. It can be achieved by appropriate setting of working parameters: number of knives, rotational speed of chopping unit and feeding speed of plant material [Gach et al. 1991, Dmitrewski et al. 1998, 2000, Mójta et al. 2000]. There is a current trend in forage harvesters towards improvement of better plant shredding with simultaneous reduction of energy inputs [Kanafojski 1980, O'Dougherty 1982, Savoie et al. 1989, Pintara 1999, Mójta et al. 2000, Lisowski et al. 2001]. Energetic loading of the chopping unit is affected by setting of plant material cutting length [Savoie et al. 1989, Lisowski et al. 2001, 2005]. One can predict the energetic loadings basing on mathematical models that reflect energetic loads of the machine. Such simulations can be carried out for various conditions of machine operation.

This work aims at explanation of the effect of setting the plant material cutting length on effective power and specific energy related to a dry matter mass, needed to drive the withdrawing-compacting rolls and the chopping unit, on the base of developed mathematical models.

MATERIAL AND METHODS

To determine the effect of plant material cutting length on energetic loading of the withdrawing-compacting rolls and the chopping unit there were used the mathematical models positively verified by Chlebowski [2012a]:

$$P_w = \lambda_w \sqrt[3]{\frac{[F_m + F_0 + (h_p - h_z)iR]^4 \omega_w^2 (1-\delta_w)^2 q_m}{b_w^2 E_w \gamma_p}} \tag{1}$$

$$P_t = q_m \left[\frac{E_{ct}}{\varepsilon \gamma_p l_t} + \omega^2 r_t^2 (\mu_f \beta_t + \mu_d \beta_d) + \lambda_h \frac{\omega^2 r_t^2}{2} \right] \tag{2}$$

$$L_{wsm} = \frac{P_w}{q_{msm}} \tag{3}$$

$$L_{tsm} = \frac{P_t}{q_{msm}} \tag{4}$$

where:
P_w – effective power requirement to drive withdrawing-compacting rolls [W];
λ_w – dimensionless coefficient of rolls' operation [–];
F_m – force coming from weight of roll and its mounting elements [N];
F_0 – force of preliminary tension of springs [N];
h_p – thickness of plant layer in front of rolls [m];
h_z – compacting of plant layer by rolls [m];
i – number of springs [pcs];
R – index of spring rigidity [N·m^{-1}];
ω_w – angular speed of withdrawing-compacting rolls [s^{-1}];
δ_w – slip of plant material between rolls [–];
q_m – mass flow of moist plant material [kg·s^{-1}];
b_w – length of roll (assumed as equal to throat width of forage harvester $b_w = b_g$) [m];
E_w – elasticity coefficient of plants in layer [Pa];
γ_p – density of plant material in front of rolls [kg·m^{-3}],
P_t – effective power requirement to drive chopping unit [W];
E_{ct} – specific cutting energy [N·m^{-2}],
ε – degree of plant compacting;
l_t – theoretical length of cutting of plant material [m];
ω – angular speed of knife disk [rad·s^{-1}];
r_t – radius of knife disk [m];
μ_f – coefficient of friction between plant material and steel [–];
β_t – angular path of plant material motion on bottom of chopping unit [rad];
μ_d – coefficient of plant particle deformation [–];
β_d – angular path of plant material motion on bottom plate [rad];
λ_h – correction coefficient for chaff throw speed [–];
L_{wsm} – specific work of withdrawing-compacting rolls unit related to dry matter mass [kJ·kg^{-1}];

q_{msm} – mass flow of dry matter of plant material: $q_{msm} = q_m (1 – w_r)$ [kg·s$^{–1}$];
w_r – real relative humidity of plant material;
L_{tsm} – specific work of chopping unit related to dry matter mass [kJ·kg$^{–1}$].

TABLE 1. Specification of plant material used in simulation investigations

Item	Unit	Maize plants
Ripeness of maize grain	–	milk-wax, wax and full
Relative humidity of plants	%	66
Grain humidity	%	37
Grain mass fraction in plant	%	40
Length of harvested plants	m	2.3–2.5
Stem diameter at cutting height	mm	22–28

Source: Chlebowski [2012b].

The simulation investigations were carried out for maize plants specified in Table 1 and under working conditions presented in Table 2. Values of coefficients that occur in mathematical models (Table 3) were determined basing on results of stationary investigations on shredding of maize plants of San variety, carried out in Department of Agricultural and Forest Machinery WULS in Warsaw. Statistical variance analysis of the results of these investigations showed, that factors affecting theoretical length of plant cutting: specific mass of plants, moisture content of plants, speed of feeding, number of knives and rotational speed of knife disk diversified significantly (at significance level $\alpha = 0.05$) the effective power requirement to drive withdrawing-compacting rolls unit and chopping unit of forage harvester (Table 4).

TABLE 2. Specification of working conditions during simulation investigations

Parameter	Symbol	Unit	Value
Rotational speed of withdrawing-compacting rolls	n_w	rpm	50–300
Slip of plant material between rolls	δ_w	–	0.12
Density of plant material in front of rolls	γ_p	kg·m$^{–3}$	170
Yield of plants	Q	t·ha$^{–1}$	40
Plant elasticity coefficient in layer	E_w	Pa	153 900
Preliminary tension of springs	P_0	N	75
Diameter of withdrawing-compacting rolls	d_w	m	0.180
Mass of roll and its mounting elements	m_w	kg	20.0
Coefficient of spring rigidity	R	N·m$^{–1}$	15 962
Number of springs	i	pcs	3
Diameter of knife disk	d_t	m	0.910
Width of throat	b_g	m	0.340
Angular path of plant material motion on bottom plate	β_d	rad	0.636
Excentric setting of knife	p	m	0.075
Radius of knife disk	r_t	m	0.455
Vertical distance of stationary knife to axis of rotation	m	m	0.180
Horizontal distance of nearer side wall of throat to axis of rotation	a	m	0.095

Source: Chlebowski [2012b].

TABLE 3. Values of coefficients existing in mathematical models

Parameter	Symbol	Unit	Value
Specific cutting work of chopping unit	E_{ct}	J·m^{-2}	5057
Coefficient of friction between plant material and housing surface of chopping unit	μ_f	–	0.57
Coefficient of plant particle deformation	μ_d	–	0.66
Correction coefficient for chaff throw speed	λ_h	–	0.5
Dimensionless coefficient of rolls' operation	λ_w	–	1.05

Source: Chlebowski [2012a].

TABLE 4. Results of variance analysis on factors affecting effective power requirement for operation of basic forage harvester during maize shredding

Factor	Sum of squares	Degrees of freedom	Mean square	F_{emp}	Critical significance level
Specific mass of plants	4255.8	2	2127.9	338.4	<0.0001
Humidity of plants	780.4	2	390.2	62.0	<0.0001
Speed of feeding	55.2	2	27.6	4.4	<0.0132
Number of knives	196.8	2	98.4	15.6	<0.0001
Revolutions of knife disk	3476.1	4	869.0	138.1	<0.0001

The simulation investigations were carried out for moist plant flow intensity in the range 1.5–5.3 kg·s^{-1} (feeding of forage harvester working units), rotational speed of knife disk of 1000 rev, that assured appropriate course of plant cutting [Dmitrewski 1978, O'Dogherty 1982]. Various number of knives were used in investigations (5 and 10), while calculations were performed for theoretical cutting length amounted to 5 and 10 mm. The values of moist plant flow were simulated by changing the ground speed of forage harvester at the assumed plant yield and working width of the machine.

RESULTS AND DISCUSSION

The results of simulation investigations are presented on diagrams. A distinct effect of moist plant flow (feeding of forage harvester working units) on power requirement for driving both the withdrawing-compacting rolls (Fig. 1a) and the chopping unit (Fig. 1b). An increase in moist plant flow at certain rotational speed of withdrawing-compacting rolls and knife disk of chopping unit resulted in the increased thickness of plant layer and the increased density of plants between rolls. At rotational speed of disk equal to 1000 rpm, 5 cutting knives, and rotational speed of withdrawing-compacting rolls 51 rpm, that assured the theoretical cutting length equal to 5 mm, an increase in plant flow intensity from 1.5 to 5.3 kg·s^{-1} (3.5 times) caused an increase in power by 3 and 5 times, respectively to the drive of chopping unit and withdrawing-compacting rolls. The highest power requirement for driving chopping unit at theoretical length of cutting of mm

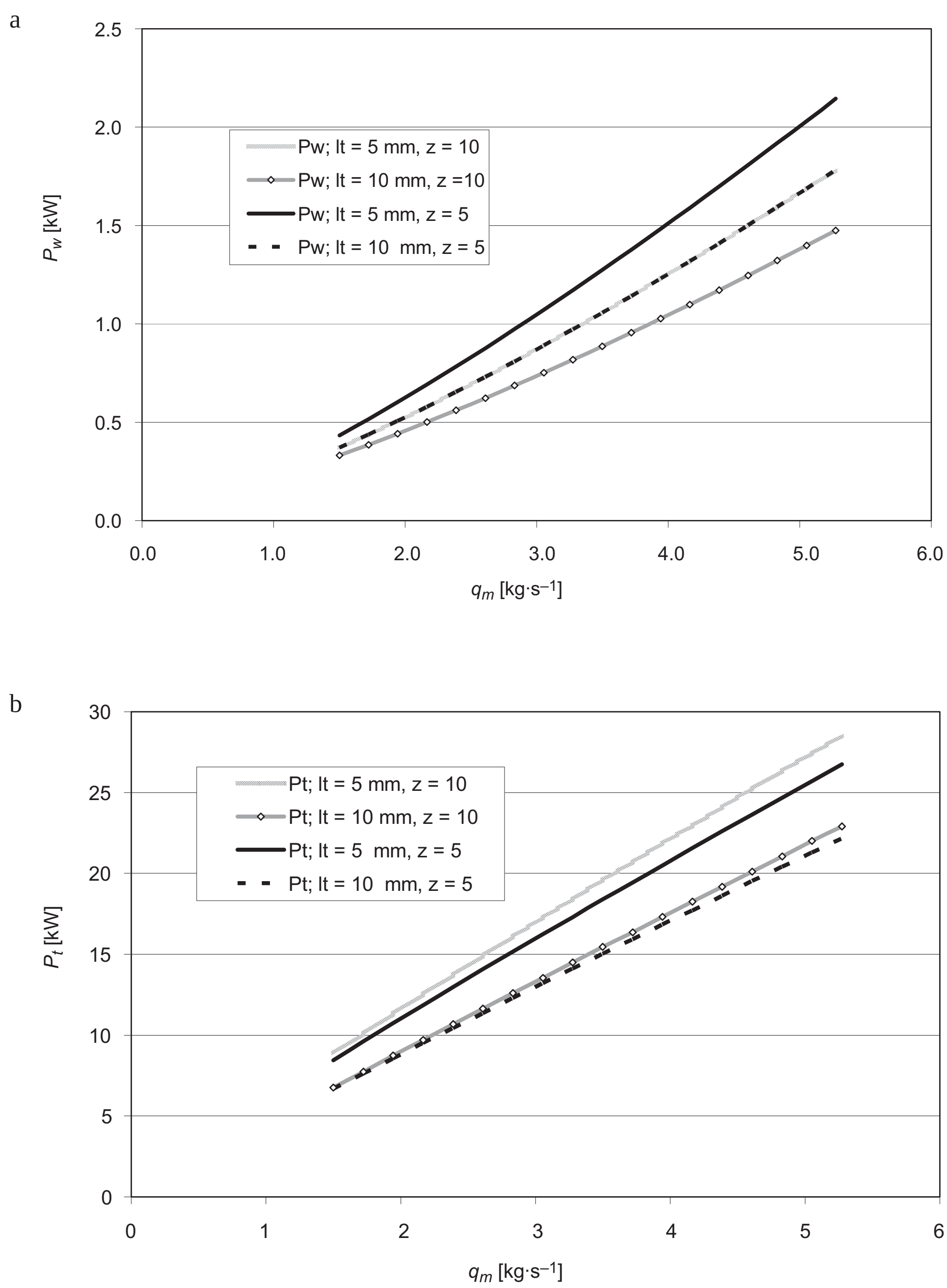

FIGURE 1. Effective power (P_t) requirement at different flow of maize plants (q_m), various theoretical cutting lengths and number of knives: a – withdrawing-compacting rolls, b – chopping unit

was obtained at application of 10 knives (Fig. 1b). Higher number of knives at the same rotational speed of disk caused an increase in the stem cutting frequency; it caused an increase in power requirement for driving the chopping unit. The obtained results were confirmed by reference data [O'Dogherty 1982, Lisowski Ed. 2009].

Interpreting the obtained simulation results one can find, that the dynamic of increase in power requirement for driving the withdrawing-compacting rolls is progressive. The increased power consumption by withdrawing-compacting rolls at higher feeding of forage harvester working units results from necessity of transporting the higher amount of plant material and its compacting in a thicker material layer between the rolls. In thicker layer of plant material, the pressure of tension springs acting on the rolls increases proportionally; this results in the increased friction resistance and deformation of material between rolls, that should be overcome.

Using rotational speed of withdrawing-compacting rolls (feeding the material to chopping unit) equal to 100 and 201 rpm, 10 knives and knife disk rotational speed of 1000 rpm, the theoretical lengths of cutting of 5 and 10 mm were obtained. At the moist plant material flow of 5 $kg \cdot s^{-1}$, a double increase in plant cutting length (from 5 to 10 m) by changing rotational speed of withdrawing-compacting rolls caused a decrease in effective power requirement of the chopping unit by 5.4 kW (20%). The similar effects were found at the change in cutting length from 5 to 10 mm with application of 5 cutting knives, while the speed of withdrawing-compacting rolls amounted to 50.6 and 100 rpm, respectively. In this case a decrease in effective power was lower and equal to about 17%. The main reason for reduction of power requirement for driving the chopping unit at constant flow and the increased plant cutting length is a decrease in layer thickness of plants directed to chopping unit at the higher rotational speed of withdrawing-compacting rolls.

At the same settings of feeding and knife disk rotational speed, an increase in theoretical cutting length from 5 to 10 mm by changing the rotational speed of withdrawing-compacting rolls, caused a decrease in effective power for their driving by 15 and 17%, respectively at 5 and 10 chopping knives.

A decrease in effective power requirement needed for driving the withdrawing-compacting rolls at higher values of cutting lengths results from the lower thickness of plant layer, that is less compacted by the rolls. Change in plant cutting length from 5 to 10 mm by changing number of knives from 10 to 5 at knife disk rotational speed of 1000 rpm calls for maintaining the same rotational speed of withdrawing-compacting rolls as in the case of achieving the cutting length of 5 mm with application of 10 cutting knives. In this case, the energetic loading of that working unit will be identical (Fig. 1a).

However, the effective power requirement for driving the chopping unit equipped with 5 knives instead of 10 knives, at the same speed of withdrawing-compacting rolls, decreases (Fig. 1b). For example, an increase in theoretical cutting length from 5 to 10 mm through the reduced number of knives, caused a decrease in effective power requirement by 6 kW (22%), at moist plant material flow of 5 kg·s^{-1}. Basing on simulation investigations one can find, that at moist plant flow of 5 kg·s^{-1}, knife disk speed of 1000 rpm and theoretical cutting lengths 5 and 10 mm, application of 5 knives instead of 10 caused a decrease in effective power consumed by the chopping unit by 1.7 and 0.7 kW, respectively.

Considering jointly specific energy consumption related to dry matter mass (Fig. 2) for the withdrawing-compacting rolls and the chopping unit one can find, that in order to obtain the cutting length of 5 mm it is better to use 5 knives instead of 10. The specific energy saving related to dry matter mass at knife disk rotational speed 1000 rpm and rotational speed of rolls 50.6 rpm can reach in this case 800 J·kg^{-1}; this results mainly from lower frequency of cutting plants. Lower differences were found also in theoretical length of cutting of 10 mm, where rotational speed of rolls should be increase to about 100 rpm. More distinct differences in energetic indices at small theoretical plant cutting length and the reduced number of knives results from lower speed of withdrawing-compacting rolls, that causes an increase in plant layer thickness between rolls and an increase in forces in tension springs, thus, better compacting of plants between rolls. As a result, in spite of thicker layer of plants chopped with the harvester's knives, the plant compacting by rolls improves as well as effectiveness of cutting [Haffert and Harms 2002, Chlebowski 2012b]; energy consumed by the chopping unit is lower.

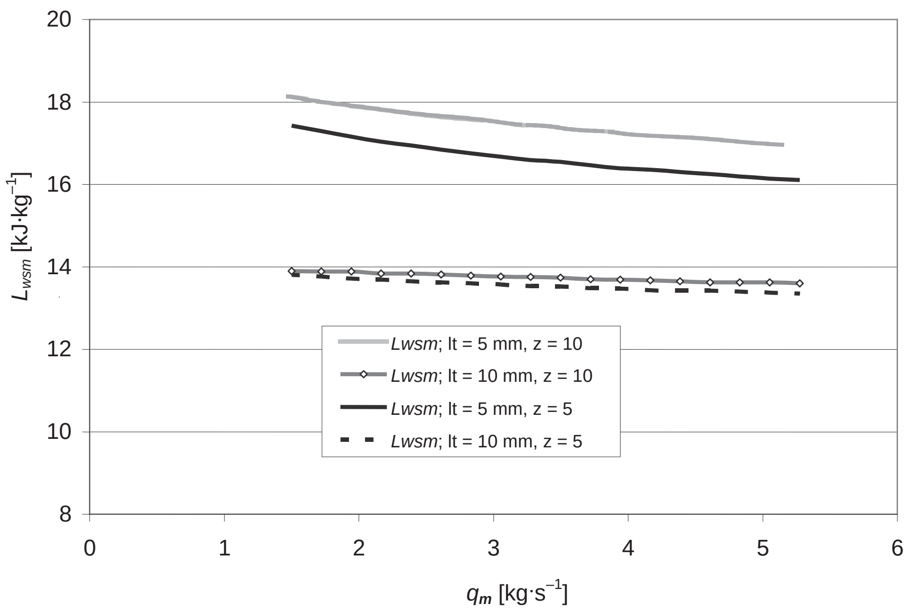

FIGURE 2. Sum of specific energy related to dry matter mass (L_{wsm}), for withdrawing-compacting rolls and chopping unit at various flow of maize plants (q_m)

SUMMARY

To maintain the same plant cutting length at certain knife disk rotational speed of forage harvester chopping unit and its constant feeding rate, reduction of number of knives calls for a decrease in rotational speed of withdrawing-compacting rolls. This results in the increased thickness of plant layer and its better compacting between the rolls. Under these conditions, in spite of a thicker layer cut by the chopping unit knives, the lower frequency and better effectiveness of plant cutting lead to reduction in energetic loading of this chopping unit. However, compacting of thicker layer of plants by withdrawing-compacting rolls unit causes an increase in its energetic loading, resulted from the need of overcoming higher resistance of material compacting and friction between the circumferential surfaces of rolls and plant material, at higher pressure of tension springs acting on the rolls. It is evident from energetic loading balance of the withdrawing-compacting rolls and the chopping unit, that at certain rotational speed of chopping unit, the reduction in number of cutting knives at the same theoretical cutting length causes a decrease in effective power requirement of the forage harvester, in spite of the increased loading of withdrawing-compacting rolls unit.

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Streszczenie: *Obciążenia energetyczne zespołów roboczych sieczkarni polowej w zależności od długości cięcia materiału roślinnego.* Na podstawie opracowanych i pozytywnie zweryfikowanych modeli matematycznych dla walców wciągająco-zagęszczających i zespołu rozdrabniającego przeprowadzono badania symulacyjne, na podstawie których wyjaśniono wpływ ustawienia długości cięcia materiału roślinnego na wskaźniki energetyczne tych zespołów podczas zbioru roślin kukurydzy. Badania przeprowadzono dla natężenia strumienia wilgotnych roślin w zakresie 1,5–5,3 kg·s^{-1}, prędkości obrotowej tarczy nożowej wynoszącej 1000 obr.·min^{-1} i teoretycznych długości cięcia wynoszących 5 i 10 mm. Z bilansu obciążeń energetycznych zespołu walców wciągająco-zagęszczających i zespołu rozdrabniającego wynika, że przy ustalonej prędkości obrotowej tarczy rozdrabniającej zmniejszenie liczby noży tnących przy zachowaniu tej samej teoretycznej długości cięcia powoduje redukcję zapotrzebowania na moc efektywną sieczkarni polowej pomimo zwiększonego obciążenia zespołu walców wciągająco-zagęszczających.

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