NEW DESIGN SOLUTIONS FOR WORKING UNITS OF MACHINES IN TERMS OF EFFICIENCY OF THEIR OPERATION

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Abstract
In this paper new design solutions of a drum cutting unit are presented, which can be applied in agricultural forage harvesters. The influence of the design features of the drum cutting unit on the performance characteristics in the biomass cutting process, which is one of the most important stages in the harvesting of plant material for energy, feed and food purposes, was determined. The tests described in the paper were carried out on a test stand developed by the authors of the paper. This test stand ensures the realisation of the process under the conditions reflecting the real cutting process. The tests were carried out for cross cutting, traditionally used in forage harvesters, but the tests were also extended to diagonal cutting, carried out for three different angles of plant material feeding. At the stage of experimental tests the influence of selected features and design parameters of the cutting drum on unit cutting resistance, cutting work, efficiency of the cutting unit and the degree of unevenness of the length of cut pieces was determined. It was found that the greatest influence on the energy consumption of the process of cutting stem plants has the cutting method, i.e. the material feeding angle, the cutting speed and the thickness of the blade.

Key words: *cutting of the material, biomass, drum cutting unit of the forage harvester, layer of plant material, cutting resistance, energy consumption, efficiency of the cutting process, degree of unevenness of the chopped material.*

INTRODUCTION

The cutting units are the basic working units of machines for harvesting biomass for consumption, feed or energy purposes. Among these machines we can distinguish choppers, where the basic working unit, cutting a layer of material into pieces of a specified length (chopped material), is a drum cutting unit. Due to the selectivity of the tests carried out so far, it is not possible to unambiguously determine which features and design parameters of the cutting unit in question have a decisive impact on the cutting efficiency, and the balance of power (Sankey) consumed by the forage harvester with a drum cutting unit shows that the power consumed by the cutting unit clearly dominates over the power consumed by the other working units and amounts to 75-80% (*Zastempowski & Bochat, 2020*). Currently operating versions of cutting units in forage harvesters are characterised by a high energy-consumption of the cutting process, and as a result, their drive systems are equipped with high-power engines. This indicates that the known design solutions have been developed largely on the basis of the designer's intuition. The problem of cutting plant material is a current topic and has been dealt with by many authors. However, publications often deal only with the mechanics of cutting selected plants without considering the design of cutting units (*Zhang et al., 2003; Zastempowski, Borowski & Kaszkowiak, 2013; Persson, 1987; Igathinathane et al., 2008, 2010*) or the researchers in their publications provide test results with respect to cutting different materials or layers of materials (*Igathinathane et al., 2009; Du &Wang, 2016; Abilzhanov et al.,2017*). However, these results are often not comparable due to differences in the testing programmes. At the same time, very often there is also a lack of precise information on the material tested in laboratory tests. Therefore, the aim of this study was to determine the influence of the selected features and design parameters of the drum cutting unit on its performance characteristics.

MATERIALS AND METHODS

The drum cutting unit is the basic working unit of a forage harvester. Its task is to cut plant material into pieces of a specific length (chopped material).

The use of this type of unit in forage harvesters makes it possible to achieve the required degree of material fragmentation. An exemplary design of a drum cutting unit is presented on fig. 1a.

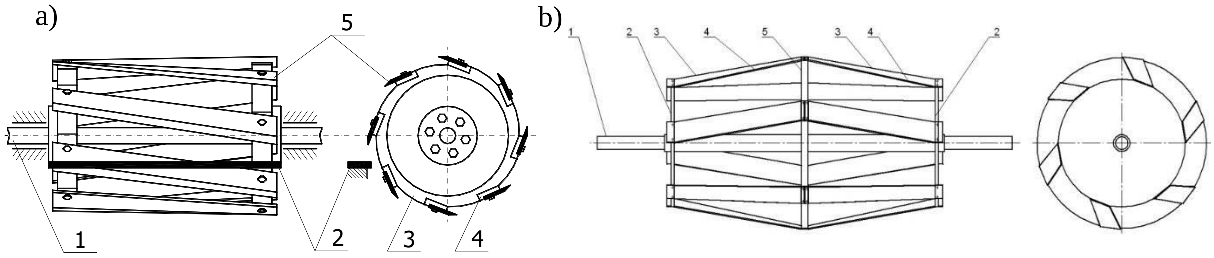


Fig. 1a Cutting drum of a forage harvester [Bochat, 2010]: 1- cutting drum shaft, 2 - counter cutting edge, called nib, 3 - cutting drum disc, 4 - knife vice, 5 - cutting knife
Fig. 1b New design of the cutting drum [own elaboration]: 1 - shaft, 2 - external discs, 3 - knives, 4 - knife cutting edges, 5 - central disc

Searching for more energy-efficient solutions for the construction of a drum cutting unit designed to cut plant material into chopped straw at the Department of Machinery and Technical Systems at the Faculty of Mechanical Engineering of Bydgoszcz University of Science and Technology, a new design of the cutting unit was developed, patented and manufactured. The essence of the new design of the cutting drum is that it consists of a driving shaft and three discs, of which the central one has a larger diameter than the side ones. Knives in V-shape with straight or curved blades along a helical line are bolted directly to the discs (Fig. 1b). Such a construction of the drum enables cutting the material in a slanting manner, which results in reduction of energy consumption of the cutting unit operation.
For the purposes of conducting experimental research, a test stand was designed and constructed to study the process of cutting a layer of plant material, including rye straw (Dańkowskie Złote winter rye). The test stand allows the process to be carried out with the use of interchangeable cutting drums, such as cylindrical or double conical drums with the possibility of changing the cutting angle.

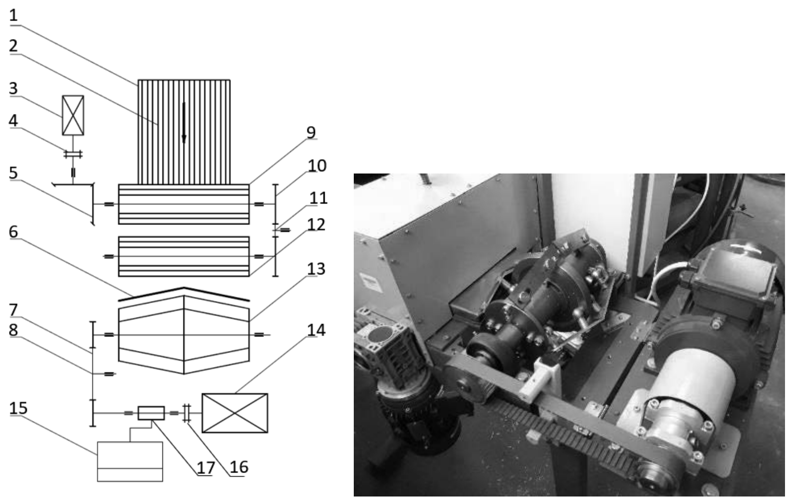


Fig. 2 Test stand: 1-trough of the forage harvester, 2-material to be cut, 3-electric motor, 4-coupling, 5-angle gear, 6-crosscutting edge, 7-gear belt transmission, 8-tension roller, 9-retracting-compacting roller upper, 10-gear belt transmission, 11-pinch roller, 12-retracting-compacting roller lower, 13-cutting drum, 14-electric motor, 15-computer (recorder of measuring system), 16-clutch, 17-torque and rotational speed measuring system on the drum shaft

In order to determine the influence of the selected features and design parameters of the drum cutting unit on its performance characteristics and to assess the possibility of applying an alternative design of the drum cutting unit for diagonal cutting, an experiment was planned according to the test scheme in Figure 3.

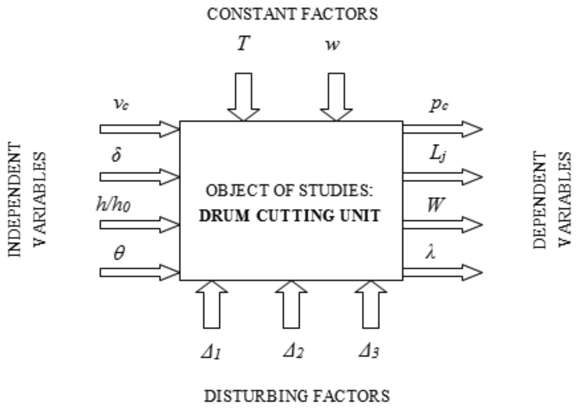


Fig. 3 Scheme of the experimental tests of the drum cutting unit (Błaszczyk, 2010): v_c - cutting speed, δ - thickness of knife blade, h/h_o - degree of plant material compaction, θ - angle of plant material feeding, pc - unit cutting resistance, L_j - unit cutting work, λ - degree of chaff length irregularity, W - efficiency of the cutting unit, Δ_1 - instrument setting error, Δ_2 - instrument inaccuracy, Δ_3 - reading error, T- air temperature, w - moisture content of the cut material.

RESULTS AND DISCUSSION

The selected results from the conducted tests are summarised in the table 1 and presented graphically in the form of a diagram of the impact of material feeding angle on the unit cutting resistance (fig. 4.)

Tab. 1 The selected experimental results for all the independent variables adopted in the research programme

Measurement no	θ [...°]	v_c [$m{\cdot}s^{-1}$]	h/ho	δ [μm]	p_c [$N{\cdot}m^{-1}$]	L_S [$J{\cdot}m^{-2}$]	W [$kg{\cdot}s^{-1}$]	L_m [$J{\cdot}kg^{-1}$]	λ [%]
1	2	3	4	5	6	7	8	9	10
1	90	3,85	0,65	40	4590	5354	0,078	6588	6,85
…	…	…	…	…	…	…	…	…	…
30	75	3,85	0,65	300	7013	8179	0,077	10609	7,39
…	…	…	…	…	…	…	…	…	…
60	60	3,85	0,54	300	7252	8458	0,077	10198	8,38
…	…	…	…	…	…	…	…	…	…
90	45	3,85	0,47	300	8317	9700	0,075	12838	9,26

In order to analyse the experimental results for all the independent variables included in the research programme, equations of a multivariate regression function were developed.
The general form of the regression function applicable in the presented analysis is presented in the following equation (1):

$$Y_E = a_1 + a_2\theta + a_3 v_c + a_4\frac{h}{h_o} + a_5\delta + a_6\theta^2 + a_7 v_c^2 + a_8\left(\frac{h}{h_o}\right)^2 + a_9\delta^2 \qquad (1)$$

where Y_E is the generalised dependent variable obtained as a result of the experimental tests, v_c is the cutting speed ($m{\cdot}s^{-1}$), δ is the blade thickness (μm), h/h_o is the degree of compaction of the cut material, θ is defined as the angle of the cut material feed (…°),and a_n are the regression coefficients.

Initially, for all the dependent variables, 9 regression coefficients were determined by solving a matrix equation. The significance of the regression coefficients was thus analysed at the significance level α_{pi} =0,05, for which t_{kr} =1,98. The value of t_{kr} was determined on the basis of Student's t-distribution for 108-9-1 degrees of freedom. The analysis of significance of regression coefficients was conducted in stages. In each stage, the least significant component, i.e. the one which met the inequality $t < t_{kr}$ was rejected from the overall regression function. If, in a given stage of the regression function study, the

significance test showed that the regression coefficients were significant, they were accepted for determining the function for a given variable.
In this way, the final formulas for:
- unit cutting resistance p_c,

$$p_c = 21128 - 65{,}898\theta - 209{,}3v_c - 45135\frac{h}{h_o} + 0{,}7399\theta^2 + 32684\left(\frac{h}{h_o}\right)^2 + 0{,}03692\delta^2 \tag{2}$$

- unit cutting work related to the surface area of the cut L_S,

$$L_S = 24321 - 75\theta - 244v_c - 51795\frac{h}{h_o} + 0{,}849\theta^2 + 37409\left(\frac{h}{h_o}\right)^2 + 0{,}0429\delta^2 \tag{3}$$

- unit cutting work related to the weight of the material to be cut L_m,

$$L_m = 27539 - 325{,}4\theta - 303{,}2v_c - 33512\frac{h}{h_o} + 2{,}3\theta^2 + 30583\left(\frac{h}{h_o}\right)^2 + 0{,}05135\delta^2 \tag{4}$$

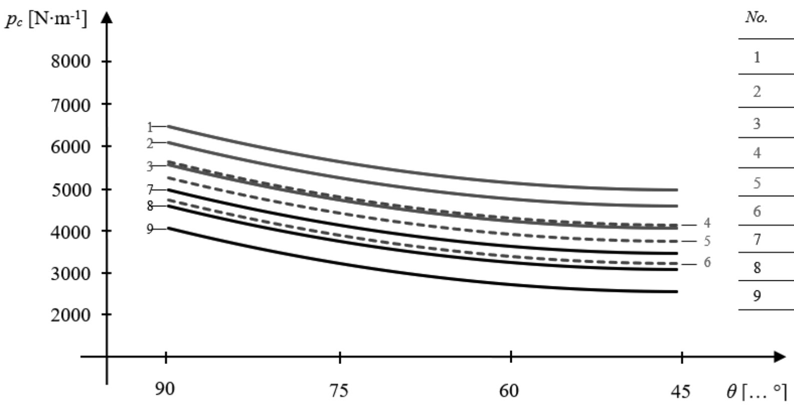
- capacity of the cutting unit W,

$$W = -0{,}0186 + 0{,}0217\theta + 0{,}0399v_c + 2{,}55\cdot 10^{-6}\frac{h}{h_o} + 2{,}16\cdot 10^{-7}\delta - 0{,}00011\theta^2 - 0{,}0293v_c^2 + 12{,}97\left(\frac{h}{h_o}\right) \tag{5}$$

- the degree of unevenness of the length of the cut material pieces λ,

$$\lambda = 18{,}61 - 0{,}058838\theta - 1{,}132v_c - 15{,}077\frac{h}{h_o} + 1{,}333\cdot 10^{-3}\delta + 2{,}181\cdot 10^{-4}\theta^2 + +0{,}06978\left(\frac{h}{h_o}\right)^2 + 12{,}97\delta^2 \tag{6}$$

Fig. 4 shows graphically the influence of the selected independent variables on the value of the unit cutting resistance p_c based on the equation (2).



No.	v_c [m·s-1]	h/h_o
1	3,85	
2	5,65	0,47
3	8,20	
4	3,85	
5	5,65	0,54
6	8,20	
7	3,85	
8	5,65	0,65
9	8,20	

Fig. 4 The effect of material feed angle θ on the unit cutting resistance of rye straw p_c for the values of cutting speed v_c and the degree of material compaction h/h_o contained in the table attached to the graph and a blade thickness $\delta=40\mu m$

From the diagram presented in fig. 4 it can be seen that as the material feed angle θ decreases, the unit cutting resistance p_c, decreases, assuming the highest value for a transverse cut (θ=90°), and the lowest value for a diagonal cut at an angle θ=45°.
From the tests carried out on the unit cutting resistance p_c it can be concluded that:

- for all the tested values of the angle θ the effect of the cutting speed v_c on the specific cutting resistance p_c is a linear function and the specific resistance decreases with the increase of the cutting speed.
- with increasing the degree of material compaction h/h_o the unit cutting resistance p_c, increases, and the dependence is a quadratic function and has the same course for all tested values of the angle θ.
- increasing the thickness of the knife blade δ also results in the increase of the unit cutting resistance p_c. The dependence is a quadratic function and takes a similar course for all the tested values of the angle θ.

On the basis of the conducted experimental tests and statistically elaborated mathematical models, a system of independent variables was established for the tested drum cutting unit, which corresponds to the minimum and maximum values of the dependent variables adopted in the testing programme, as shown in the table 2.

Tab. 2 An arrangement of independent variables for the highest and lowest values of the dependent variables

		Independent variable			
Dependent variable	The highest/lowest value of the dependent variable obtained from the experimental tests	Material feeding angleθ […°]	Cutting speed v_c [m·s^{-1}]	Degree of compaction of the material$h \cdot h_o^{-1}$	Thickness of bladeδ [μm]
p_c	11535 N·m^{-1} / 3212 N·m^{-1}	90 / 45	3,85 / 8,20	0,47 / 0,65	300 / 40
L_S	13454 N·m^{-2} / 3746 N·m^{-2}	90 / 45	3,85 / 8,20	0,47 / 0,65	300 / 40
L_m	12838 J·kg^{-1} / 4971 J·kg^{-1}	45 / 90	3,85 / 8,20	0,65 / 0,55	300 / 40
W	0,167 kg·s^{-1} / 0,075 kg·s^{-1}	90 / 45	8,20 / 3,85	0,65 / 0,55	40 / 300
λ	9,26 % / 6,04 %	45 / 90	3,85 / 8,20	0,47 / 0,58	300 / 40

The authors did not have the opportunity to directly compare their research results with those reported in the literature by other researchers. This is caused by the fact that the research results presented in this article mainly concern a new design of the drum cutting unit, which is covered by legal protection. In the specialist literature there is a lack of data describing the process of cutting rye straw into pieces of a specified length using a cutting drum of a forage harvester with a double-cut cone shape. The first proposal for the design of a cutting drum of this shape, which can realise a diagonal cut in two directions, was presented by Bochat (*Bochat, 2010*). Other authors in their works provide only data related to commonly functioning design solutions of cutting drums realizing transverse cutting. The results presented above by the authors, concerning the classical design of the cutting drum, are comparable with the data presented in the literature in this field (*Abilzhanov, 2017; Persson, 1987, Bochat & Zastempowski 2020*).

CONCLUSIONS

This work resulted in the following conclusions:

1. From the conducted experimental tests it results that the following factors have a significant influence on the unit cutting resistance p_c, unit cutting work L_j, efficiency of the cutting unit W efficiency of the cutting unit λ there have the following: the method of cutting (transverse or diagonal), the cutting speed, the thickness of the blade of the knife, the degree of density of the cut material;
2. In the design works on the drum cutting units it is necessary to take into account the possibility of performing a diagonal cut, which is a very important alternative to the traditional - transverse - way of cutting;
3. In order to assess the quality of cutting plant material by the drum cutting unit, the degree of unevenness of the length of the cut material was assumed. As a result of the experimental tests, the values of independent variables were determined for which this quantity takes the lowest values (θ=90°, v_c=8,20 m·s^{-1}, h/h_o=0,58, δ=40 μm);
4. On the basis of the results obtained for the diagonal cutting of the material layer, it can be concluded that it seems advisable to conduct works on the development of new designs of drum cutting units, implementing other than traditional ways of cutting;

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