Annals of Warsaw University of Life Sciences – SGGW
Agriculture No 67 (Agricultural and Forest Engineering) 2016: 63–70
(Ann. Warsaw Univ. Life Sci. – SGGW, Agricult. 67, 2016)

Empirical model of unit energy requirements for cutting giant miscanthus stalks depending on grinding process parameters

TOMASZ NOWAKOWSKI
Department of Agricultural and Forest Machinery, Warsaw University of Life Sciences – SGGW

Abstract: *Empirical model of unit energy requirements for cutting giant miscanthus stalks depending on grinding process parameters.* Unit energy of the plant cutting process is the key parameter used in the analysis of cutting units' loading. Knowing its value, one may obtain data useful for the design of the grinding unit, as well as in selection and analysis of optimum working parameters. The study presents an empirical model concerning changes in unit energy for cutting giant miscanthus stalks depending on position towards the edge of the cutting blade and depending on material humidity. The developed model allows evaluation of the relationships occurring during the process of cutting giant miscanthus stalks for the analysed parameters, and their quantitative analysis. Having analysed the obtained range of changes in the value of unit energy required for cutting miscanthus stalks depending on changes in material humidity and angle of the stalk towards the cutting blade, one may claim that – irrespective of humidity – increase of an angle causes reduction in the value of unit energy, with the lowest energy values recorded for the humidity below 20% and above 45%.

Key words: unit cutting energy, empirical model, giant miscanthus, cutting angle, humidity

INTRODUCTION

Acquisition of energy from renewable sources is being widely analysed worldwide. Particular attention is paid to energy plants, as they demonstrate high potential in terms of fuel value and mass production. The process involving obtaining of energy from such cultures involves transformation of biomass into a form easy to use at plants conducting thermal production of energy [Moiceanu et al. 2013, Lisowski et al. 2014]. Regardless of the biomass processing technology used, grinding of the plants is an indispensable element of the process. Consequently, scientists are paying particular attention to investigating the properties of energetic plants. The investigations are expected to help find such conditions in which the grinding process will be performed at minimum energy consumption [Kronbergs et al. 2012].

Familiarity with the mechanical properties of various kinds of energetic plants allows enhancements in machine designs. The scope of changes in resistance forces during bending, compression and cutting of energetic plant stalks contributes to discovery and explanation of phenomena taking place during those processes [Gendek et al. 2010, Lisowski et al. 2010a, Nowakowski 2010, Toledo et al. 2013, Bastian and Shridar 2014, Moiceanu et al. 2015]. Acquisition of such detailed information and its generalisation by developing models dependent on the analysed parameters allows modelling of the grinding process itself. The obtained data are necessary at the stage of designing the gridning units [Gach et al. 1989, 1991, Lisowski et al. 2010b, 2010c, 2012, Nowakowski 2012a, 2012b].

Consequently, the aim of the study was to explain the influence of the angle between the giant miscanthus stalk and the edge of the cutting blade, as well as material humidity onto the value of unit cutting energy. The results will allow development of a model covering cutting energy changes depending on the analysed parameters. The model will identify optimum conditions for performing the cutting process, while incurring the lowest possible energy outlays.

MATERIAL AND METHODS

Stalks of giant miscanthus (*Miscanthus giganteus*) falling into four humidity ranges 6.83 ±0.23, 21.85 ±0.63, 31.20 ±0.55 and 49.83 ±0.23% were used in the investigation [Nowakowski and Wróbel 2015]. Humidity of the vegetal material was determined using the moisture balance method. Sections of giant miscanthus stalks with undamaged internodes, picked at random from whole stalks obtained from the plantation, were used in the investigation. Biometric measurements were performed with respect to each of the stalks. Investigations of the giant miscanthus stalk cutting process were conducted on a TIRAtest universal testing machine, which allows determination of the relationship between the cutting strength and deformation. The determined relationship was used for determining the unit cutting force as the quotient of the total deformation energy and stalk section area [Chen et al. 2004, Lisowski et al. 2010a, Heidari and Chegini 2011, Taghinezhad et al. 2012, Sessis et al. 2013, Voicu et al. 2013]. A special grip was used for the measurements, allowing fixing of the tested stalks at a predefined angle towards the cutting knife. Measurements commenced from a setting whereby the longitudinal axis of the stalk was perpendicular to the blade edge. Subsequently, the angle was changed by 15° each time. The working element was a steel knife, 60 mm wide, 10 mm thick and with the blade angle of 30°. Cutting measurements were performed at 10 mm·min^{-1}.

RESULTS AND DISCUSSION

Exemplary courses of the cutting force-deformation relationships, obtained for four angles of placement of the stalk towards the cutting blade are presented in Figure 1. On the other hand, exemplary relationships for cutting samples of stalks characterised with varying humidity but constant stalk placement degree (45°) are presented in Figure 2. The determined courses are similar to those obtained while cutting hemp [Chen et al. 2004], corn [Lisowski et al. 2009], wheat [Tavakoli et al. 2009], caraway [Mahmoodi and Jafari 2010] and willow [Nowakowski 2012c]. Complex phenomena taking place during the cutting process are noticeable in the graphs (Figs 1 and 2), and may be divided into three distinguished areas. In the first area, immediately after commencement of cutting, stalk compression occurs. This is followed by cutting and compression, demonstrating significant force changes. The last area is only cutting of the vegetal material.

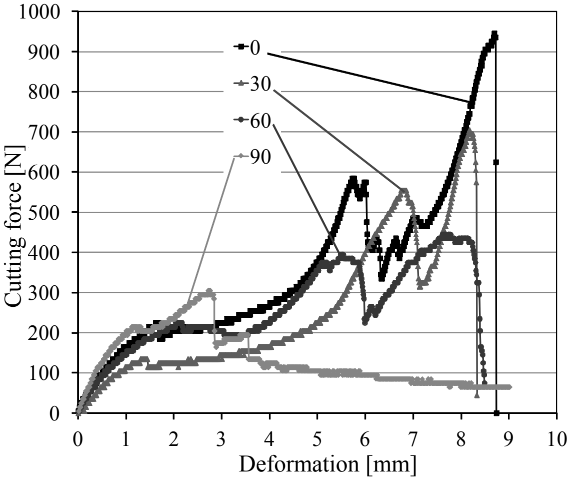

FIGURE 1. Exemplary courses of the cutting force-deformation relationships determined while cutting stalks characterised with constant humidity (21.63%) and varying stalk placement angles (0, 30, 60, 90°)

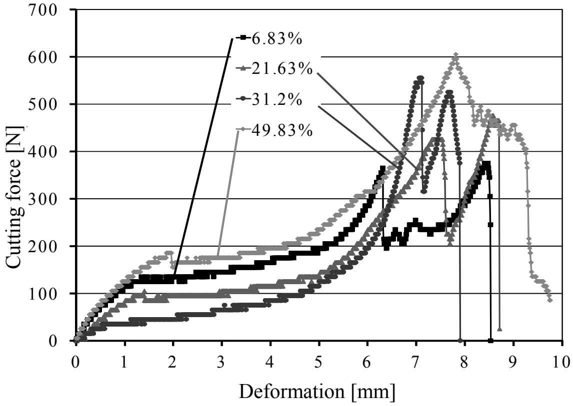

FIGURE 2. Exemplary courses of the cutting force-deformation relationships determined while cutting stalks characterised with constant stalk placement angle (45°) and varying plant humidity (6.83, 21.63, 31.20, 49.83%)

Results of cutting force investigation allowed identification of unit cutting energy. The variance analysis was performed for the values determined as above, which demonstrated significant differentiation in the value of unit cutting energy depending on changes in the angle of stalk placement towards the edge of the cutting blade and humidity of stalks of giant miscanthus. Fisher-Snedecor statistical values were, respectively: $F_{0.05,6,252} = 57.18$ and $F_{0.05,3,252} = 4.43$.

Multiple regression search was performed based on the resulting distribution of results. Parameters determining the final form of the equation included: value of the coefficient of determination and values of significant coefficients of regression [Kornacki and Wesołowska-

-Janczarek 2008]. Table presents the analysis of relevance of particular coefficients based on t-Student test and the relevance level. The empirical model of unit energy for cutting giant miscanthus stalks depending on the angle of stalk placement towards the edge of the cutting blade and plant humidity was obtained, in the form of the following polynomial:

$$E_{jt} = 0.1659k + 3.734w - 5.556 \cdot 10^{-2}w^2 - \\ - 5.483 \cdot 10^{-2}\, kw + 8.3004 \cdot 10^{-4}kw$$

for which the coefficient of determination was equal to 0.7933,

where:

E_{jt} – unit cutting energy [mJ·mm^{-2}];
k – angle of stalk placement towards the edge of the cutting blade [°];
w – humidity of giant miscanthus stalks [%].

The model may thus be used for describing the relationship of unit cutting energy with respect to changes in the angle of stalk placement towards the edge of the cutting blade $k \in$<0°–90°> and humidity $w \in$<6.83%–49.83%> for giant miscanthus stalks.

Analysis of the obtained range of changes in the values of unit cutting energy involved in cutting giant miscanthus stalks depending on changes in humidity and angle of stalk placement towards the cutting blade edge allows the conclusion that the lowest energy values were observed for humidity below 20 and above 45% (Fig. 3). Harvesting of miscanthus and its combustion in the conditions of high humidity requires auxiliary fuel. In such conditions, combustion is incomplete and may be accompanied by production of high amounts of carbon oxide. On the other hand, application of additional drying involves extra costs, which increase outlays incurred on the technology. Therefore, it is more beneficial to aim at harvesting the plants at low humidity. The other aspect analysed is the angle of stalk placement towards the cutting blade edge. Irrespective of humidity, angle increase causes reduction in the unit stalk cutting energy. Yet, the basic cutting system at chaff-cutters used in the harvesting of stalk plants is the system in which the stalk is fed perpendicularly to the cutting blade edge. Therefore, structural solutions allowing diagonal cutting of the materials are being analysed. This will allow significant reduction of energy consumption by the cutting unit [Bochat 2010].

TABLE. Analysis of relevance of regression coefficients for the empirical model of unit cutting energy

Independent variable	Coefficient of regression	Standard error	t-Student value	Relevance level
k	0.1659	0.056264	2.94813	0.0035
w	3.734	0.197158	18.9397	<0.0001
w^2	-5.556×10^{-2}	0.004587	–12.1115	<0.0001
$k \times w$	-5.483×10^{-2}	0.005490	–9.9862	<0.0001
$k \times w^2$	8.3004×10^{-4}	0.000101	7.9154	<0.0001

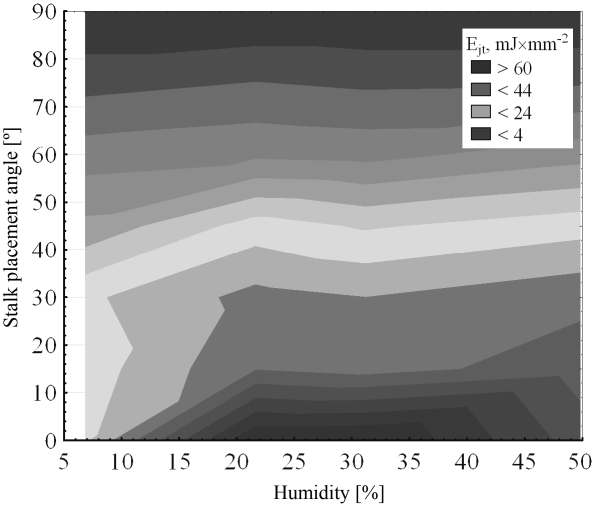

FIGURE 3. Change in unit cutting energy (E_{jt}) depending on the angle of stalk placement towards the cutting blade edge (k) and humidity of giant miscanthus stalks (w)

Theoretical analyses of stalk cutting, focused on predicting loads depending on parameters of the cutting element and kind of plant, are also being performed. The model proposed by Liu [2012] for cutting lychee (*Litchi chinensis* Sonn.) shoots may serve as an example. The theoretical model describes dependence of the cutting force on the blade angle and coefficient of friction of a wedge-shaped blade. Verification tests demonstrated that values calculated based on the model were very similar to the results of tests for stalks with the radius of 5–7 mm. What is more, the team of Zareiforoush [2012] proposed a model based on fuzzy logic, aimed at determining the cutting force of rice stalks. Experimental tests were conducted in order to validate the model, and demonstrated that the cutting energy value significantly fell from the bottom to the top of the stalk, within the range of 101.31–426.91 mJ. The developed fuzzy model had the acceptable programming ability on the levels of 86, 97 and 91%, respectively, for high, medium and low ranges of cutting energy. Mahdavian et al. [2012] conducted extensive investigations related to cutting energy required for canola stalks depending on variety, fertilisation scope, stalk humidity and the kind of cutting blade used. The scientists analysed regression models depending on the analysed parameters and concluded that an acceptable level of relationship between the cutting energy required for canola stalks and factors influencing the energy value was possible for two efficient parameters. Consequently, a model based on the MLP neuron network was proposed, which rendered the best forecast of unit cutting energy with the level of error of 0.00015 and coefficient of correlation for that model of 0.999.

Familiarity with changes in unit cutting energy allows proper designing of the cutting unit and predicting the power requirements.

CONCLUSIONS

1. The developed empirical model allows evaluation of the relationships occurring in the process of cutting giant miscanthus stalks.
2. Increase in the angle of stalk position towards the cutting blade, irrespective of the humidity value, resulted in decreased unit cutting energy requirements.
3. Knowing unit cutting energy required for giant miscanthus, calculated based on the proposed model, one may obtain data useful for designing the cutting unit and selecting optimum working parameters.

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Streszczenie: *Model empiryczny zapotrzebowania na energię jednostkową cięcia łodyg miskanta olbrzymiego w zależności od parametrów procesu rozdrabniania.* Energia jednostkowa cięcia roślin jest kluczowym parametrem wykorzystywanym w analizie obciążeń zespołów tnących. Znając jej wartość, można uzyskać dane przydatne w projektowaniu zespołu rozdrabniającego, a także w doborze i analizie optymalnych parametrów roboczych. W pracy przedstawiono model empiryczny zmian energii jednostkowej cięcia łodyg miskanta olbrzymiego względem krawędzi ostrza tnącego i wilgotności materiału. Opracowany model umożliwia ocenę związków występujących podczas cięcia łodyg miskanta olbrzymiego dla badanych parametrów i ich analizę ilościową. Analizując otrzymany obszar zmian wartości energii jednostkowej cięcia łodyg miskanta w zależności od zmian wilgotności i kąta ustawienia łodygi względem krawędzi ostrza tnącego, można stwierdzić, że zwiększenie wspomnianego kąta niezależnie od wilgotności materiału powoduje zmniejszanie wartości energii jednostkowej, a najmniejsze wartości energii wystąpiły dla wilgotności poniżej 20 i powyżej 45%.

Słowa kluczowe: energia jednostkowa cięcia, model empiryczny, miskant olbrzymi, kąt cięcia, wilgotność

MS received July 2015

Author's address:
Tomasz Nowakowski
Wydział Inżynierii Produkcji SGGW
Katedra Maszyn Rolniczych i Leśnych
02-787 Warszawa, ul. Nowoursynowska 164
Poland
e-mail: tomasz_nowakowski@sggw.pl