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MODELING OF DEMAND FOR ENERGY DURING SWEET CORN KERNEL CUTTING FROM THE COB

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Summary. In the paper the changes of demand for energy during the cutting of sweet corn kernel from the cob are discussed. Candle cv. was used for research. The measurements were realized in dependence on some technical and operating parameters of corn cutter: the shaft knife length (l), the speed of head knife (ω) and speed of cob feeder (v). The highest values of useful energy ($3.73 \cdot 10^{-4}$ kWh) were achieved at l = 0.013 m,ω = 194.5 rad·s^{-1} and v = 0.43 m·s^{-1}. However, the lowest values ($1.24 \cdot 10^{-4}$ kWh) were at ω = 301.2 rad·s^{-1}, v = 0.91 m·s^{-1} and l = 0.047 m.

Key words: sweet corn, cutting, kernel, energy.

Nomenclature:

R_t – shear strength of material [MPa],
M – elastic modulus of material [MPa],
φ_k – bearing angle of fibers in relation to shear edge [1°],
φ_s – bearing angle of plane of shear in relation to fibers[1°],
φ_r – bearing angle of resultant vector of shearing speed in relation to fibers [1°],
w – moisture of material [%],
Δ_s – degree of shearing edge blunt [1°],
β – angle of edge [1°],
γ – angle of attack [1°],
α – angle of affixture [1°],
l – length of knife shaft [m],
λ – angle of cutting slope [1°],
K_c – coefficient of slippage [-],
ω – angular speed of knife head [tad·s^{-1}],
v_p – linear speed of cob feeder [m·s^{-1}],
h – depth of cutting [m],
τ – temperature of material [°C],
E_u – useful energy [kWh],
E_c – consumption of total energy at cutting [kWh],
E_{bj} – consumption of energy at neutral gear [kWh],

i – number of cob [pcs.],
X_i – real variable,
$\bar{X}_i$ – code variable,
r – number of replication.

INTRODUCTION

The method of sweet corn kernel removing from the cob by mechanical cutting is characterized by comparatively large losses of kernels and high expenditure of energy [6, 7, 8, 9, 11]. It is related, among others, with the texture of the material and its moisture. Sweet corn kernels are cut from the cob at milk stage. The sweet corn moisture average out 70 – 78% [12, 13].

The cutting of biological material, even by means of elementary blade is a very complicated process. A tool makes a working movement which is getting to make a pressure to surface of tooled material. Under the pressure of knife edge there follows the crushing of material in the sphere of edge and next the cutting of fibril (in the case of fibril material), separation of the solid part, deviation from surface of the knife attack and deformation.. The knife hits on its way on the resistance resulting from the mechanical properties of tissue and friction between the material and knife [3, 10]. The significant influence on a resistance of cutting makes an angle of edge and cutting slope [2, 14]. The value of cutting resistance in the anisotropic material is dependent on the position to cutting area [1] and the edge thickness [15].

The objective of this article is the determination of an influence of the shift knife length, an angular speed of head knife and linear speed of cob feeder on demand for energy during sweet corn kernel cutting from the cob.

MATERIALS AND METHODS

The studies were carried out on sweet corn cob of Candle variety. The characteristics of sweet corn cob is presented in Table 1.

Table 1**.** Characteristics of sweet corn cob

Contests	Units	Results from – to mean
Weight of husked cob	g	296.31–328.14 320.57
Share of kernels in cob	%	71.42–72.54 72.22
Kernel moisture	%	71.86–74.97 72.41
Length of cob	cm	18.66–23.57 21.42
Max. diameter of cob	mm	47.55–52.71 50.48
Number of kernels per row	pcs.	27.15–31.45 28
Number of kernel rows	pcs.	12.66–16.24 14
Length of kernel	mm	7.24–10.58 10.23

The moisture content of the kernels was determined using the methods according to PN-90/A-75101.03.

The measurements of demand for energy were realized on the basis of mathematical model presented in Fig. 2 [4].

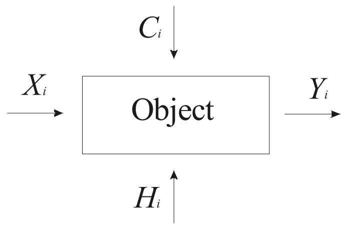

Fig. 2. Schema of model: X_i – input size, independent variable, Y_i – output size, dependent variable, C_i – constant variable, H_i – disturb factors

As a result of factorial analyses and identification study as well as the assumed presumption a variability interval of studied factors for the model is set: $Y_i = f(X_i)$:

X_i – independent variable;
a) structural parameters of cutter:
X_1 – l – length of knife shaft [m],
b) operating parameters:
X_2 – ϖ – angular speed of head knife [rad·s^{-1}],
X_3 – v – linear speed of cob feeder [m·s^{-1}],
Y_i – dependent variable,
Y_1 – E_u – useful energy [kWh],
C_i – constant factors,
$R_t, M, \varphi_k\ \varphi_s\ \varphi_r,\ \Delta_s,\ K_c,\ w = 74.3\%;\ \beta = 8^\circ;\alpha = 0^\circ;\gamma = 82^\circ;\lambda = 15^\circ, h = 10$ m; $\tau = 18^\circ C$,
H_i – disturb factors,
H_1 – heterogeneity of material (cob),
H_2 – uncontrolled wear of knife.

Mathematical model of cutting can be performed through the common mathematical record of the relation between sizes of biological material as well as structural and operating properties of object:

$$E_u = f(R_t, M, \varphi_k, \varphi_s, \varphi_r, w, \Delta_s, \beta, \gamma, \alpha, \lambda, l, K_c, \omega, v_p, h, \tau). \qquad (1)$$

After taking into account the presumption of study for continuation the following dependence was accepted:

$$E_u = f(\varpi, v, l). \qquad (2)$$

The variable interval of the studied factors was determined according to the initial study:

$$X_1 - l: 0.01 - 0.05 [\mathrm{m}], \qquad (3)$$

$$X_2 - \varpi: 167.50 - 301.20\ [\mathrm{rad \cdot s^{-1}}], \qquad (4)$$

$$X_3 - v - 0.31 - 0.92\ [\mathrm{m \cdot s^{-1}}]. \qquad (5)$$

Central value of factors $x_{i0}\ (i = 1,2,3)$ were counted according to:

$$x_{i0} = \frac{x_{i\min} + x_{i\max}}{2} \text{ dla } i = 1,2,3. \qquad (6)$$

hence: (7)

$$a)\ x_{10} = \frac{0.01 + 0.05}{2} = 0.03\ \ [m], \tag{8}$$

$$b)\ x_{20} = \frac{167.50 + 301.20}{2} = 234.31\ \ [rad \cdot s^{-1}], \tag{9}$$

$$c)\ x_{30} = \frac{0.31 + 0.92}{2} = 0.61\ \ [m \cdot s^{-1}]. \tag{10}$$

The unit of factors variability ΔX_i for i = 1,2,3, were counted according to:

$$\Delta X_i = \frac{X_{i\max} - X_{i0}}{\alpha} \text{ for } i = 1,2,3. \tag{11}$$

Assuming, that the study will be realized according to the determined five-level (compositive) rotary statistical plan [5], in which the value of star side for S = 3 is carried out as , the unit of variability for each factors are:

$$a)\ \Delta X_1 = \frac{0.05 - 0.03}{1.68} = 0.01\ \ [m], \tag{12}$$

$$b)\ \Delta X_2 = \frac{301.2 - 234.31}{1.68} = 39.82\ \ [rad \cdot s^{-1}], \tag{13}$$

$$c)\ \Delta X_3 = \frac{0.92 - 0.61}{1.68} = 0.18\ \ [m \cdot s^{-1}], \tag{14}$$

It allows for determination of the following code relations according to:

$$\bar{X}_i = \frac{X_i - X_{i0}}{\Delta X_i}, \text{ for } i = 1,2,3. \tag{15}$$

hence:

$$a)\ \bar{X}_1 = \frac{X_i - 0.03}{0.032}, \tag{16}$$

$$b)\ \bar{X}_2 = \frac{X_i - 234.31}{39.82}, \tag{17}$$

$$c)\ \bar{X}_3 = \frac{X_i - 0.61}{0.18}. \tag{18}$$

It means at the time for acceptance of code:

$$\bar{X}_i = +\alpha: \quad X_1(+\alpha) = X_{10} + \alpha \cdot \Delta X_{10} = 0.03 + 1.68 \cdot 0.01 = 0.047, \tag{19}$$

$$X_2(+\alpha) = X_{20} + \alpha \cdot \Delta X_{20} = 234.3 + 1.68 \cdot 39.82 = 301.20, \tag{20}$$

$$X_3(+\alpha) = X_{30} + \alpha \cdot \Delta X_{30} = 0.61 + 1.68 \cdot 0.18 = 0.91, \tag{21}$$

$$\bar{X}_i = +\alpha: \quad X_1(+\alpha) = X_{10} + \alpha \cdot \Delta X_{10} = 0.03 + 1.68 \cdot 0.01 = 0.047, \tag{19}$$

$$X_2(+\alpha) = X_{20} + \alpha \cdot \Delta X_{20} = 234.3 + 1.68 \cdot 39.82 = 301.20, \tag{20}$$

$$X_3(+\alpha) = X_{30} + \alpha \cdot \Delta X_{30} = 0.61 + 1.68 \cdot 0.18 = 0.91, \tag{21}$$

$$\bar{X}_i = +1: \quad X_1(+1) = X_{10} + \Delta X_{10} = 0.03 + 0.01 = 0.04, \tag{22}$$

$$X_2(+1) = X_{20} + \Delta X_{20} = 234.31 + 39.82 = 274.10, \tag{23}$$

$$X_3(+1) = X_{30} + \Delta X_{30} = 0.61 + 0.18 = 0.79, \tag{24}$$

$$\bar{X}_i = 0: \quad X_1(0) = X_{10} = 0.03, \tag{25}$$

$$X_2(0) = X_{20} = 234.31, \tag{26}$$

$$X_3(0) = X_{30} = 0.61, \tag{27}$$

$$\bar{X}_i = -1: \quad X_1(-1) = X_{10} - \Delta X_{10} = 0.03 - 0.01 = 0.02, \tag{28}$$

$$X_2(+1) = X_{20} + \Delta X_{20} = 234.31 - 39.82 = 194.50, \tag{29}$$

$$X_3(+1) = X_{30} + \Delta X_{30} = 0161 - 0.18 = 0.43, \tag{30}$$

$$\bar{X}_i = -\alpha: \quad X_1(-\alpha) = X_{10} + \alpha \cdot \Delta X_{10} = 0.03 - 1.68 \cdot 0.01 = 0.013, \tag{31}$$

$$X_2(-\alpha) = X_{20} - \alpha \cdot \Delta X_{20} = 234.3 - 1.68 \cdot 39.82 = 167.40, \tag{32}$$

$$X_3(-\alpha) = X_{30} - \alpha \cdot \Delta X_{30} = 0{,}61 - 1.68 \cdot 0.18 = 0.31. \tag{33}$$

The real and standardized values of the studied parameters are presented in Table 2.

Table 2**.** The real and standardized value of parameters

Level of parameter	Real value			Standardized value		
	$x_1 = l$	$x_2 = \omega$	$x_3 = v$	$\bar{x}_1$	$\bar{x}_2$	$\bar{x}_3$
„star” upper	0.047	301.2	0.91	+1.68	+1.68	+1.68
upper	0.040	274.1	0.79	+1	+1	+1
central	0.030	234.3	0.61	0	0	0
under	0.020	194.5	0.43	-1	-1	-1
„star” under	0.013	167.4	0.31	-1.68	-1.68	-1.68

The realization of determined five-level compositional program contains:
- eight layouts ($n_k = 2^s = 2^3 = 8$) in upper and under level,
- six layouts in „star point” ($n_\alpha = 2 \cdot S = 2 \cdot 3 = 6$),
- six parallel measurements in „centre” of program ($n_o = 6$).

All the required measurements:

$$N_c = N_r = (n_k + n_\alpha + n_o)r = (8 + 6 + 6) = 20r. \tag{34}$$

The measurement were realized for r = 6.
The layout of program is presented in Table 3.

Table 3. The layout of program

Number of measurement	No.	No. experiments	Factors					
			coded			real		
			x_1	x_2	x_3	$\bar{x}_1 = l$	$\bar{x}_2 = \omega$	$\bar{x}_3 = v$
Base of program No. measurements $n_k = 8$	1	1	-1	-1	-1	0.02	194.50	0.43
	2	2	+1	-1	-1	0.04	194.50	0.43
	3	3	-1	+1	-1	0.02	274.10	0.43
	4	4	-1	-1	+1	0.02	194.50	0.79
	5	5	+1	+1	-1	0.04	194.50	0.43
	6	6	+1	-1	+1	0.04	194.50	0.79
	7	7	-1	+1	+1	0.02	274.10	0.79
	8	8	+1	+1	+1	0.04	274.10	0.79
Star points No. measurements $n_\alpha = 6$	9	9	$-\alpha$	0	0	0.013	234.30	0.61
	10	10	$+\alpha$	0	0	0.047	234.30	0.61
	11	11	0	$-\alpha$	0	0.047	167.40	0.61
	12	12	0	$+\alpha$	0	0.047	301.20	0.61
	13	12	0	0	$-\alpha$	0.047	301.20	0.31
	14	14	0	0	$+\alpha$	0.047	301.20	0.91
Centre of program No. measurements $n_o = 6$	15	15	0	0	0	0.047	301.20	0.61
	16	16	0	0	0	0.047	301.20	0.61
	17	17	0	0	0	0.047	301.20	0.61
	18	18	0	0	0	0.047	301.20	0.61
	19	19	0	0	0	0.047	301.20	0.61
	20	20	0	0	0	0.047	301.20	0.61

The measurements of demand for energy of sweet corn kernel cutting from the cob were realized on the laboratory stand equipped with corn cutter, system of electric energy measurement and frequency transducers.

The useful consumption of energy was determined according to the formula:

$$E_u = E_c - E_{bj}. \tag{35}$$

An estimation of results was realized on the basis of analysis of variance and multiple regression. Comparison of means was conducted with the Fisher's least significant difference (LSD) test, at a significance level p = 0.05. In addition, the standard deviations for mean values were given.

RESULTS

The analysis of variance (Tab. 4) showed, that independent variable (length of shaft knife – l, angular speed of head knife – ω, linear speed of cob feeder – v) and their interaction had a statistically significant influence on the dependent variable (useful energy – E_u).

Table 4. Analysis of variance for $E_u = f(l, \omega, v)$

Source	Sum of square	Degree of freedom	Mean square	Test F	Significant level
l	96.67	3	32.22	289135	0.0001
n	5.92	3	1.70	17708	0.0002
v	0.38	3	0.12	1152	0.0001
$l \cdot \omega$	0.59	9	0.06	591	0.0001
$l \cdot v$	0.04	9	0.004	40	0.0002
$\omega \cdot v$	0.02	9	0.002	18	0.0002
$l \cdot \omega \cdot v$	0.03	27	0.001	9	0.0003
Error	0.01	128	0.0001		

The different values of F-test testify, that the largest influence on useful energy was exerted by the length of shaft knife. It accounts for about 94% of general variability of useful energy. While the speed of head knife is about 6% and speed of cob feeder about 0.5%, the interaction was interpreted about 0.02%.

The change of E_u in dependence of l, ω, v is presented in Fig. 3.

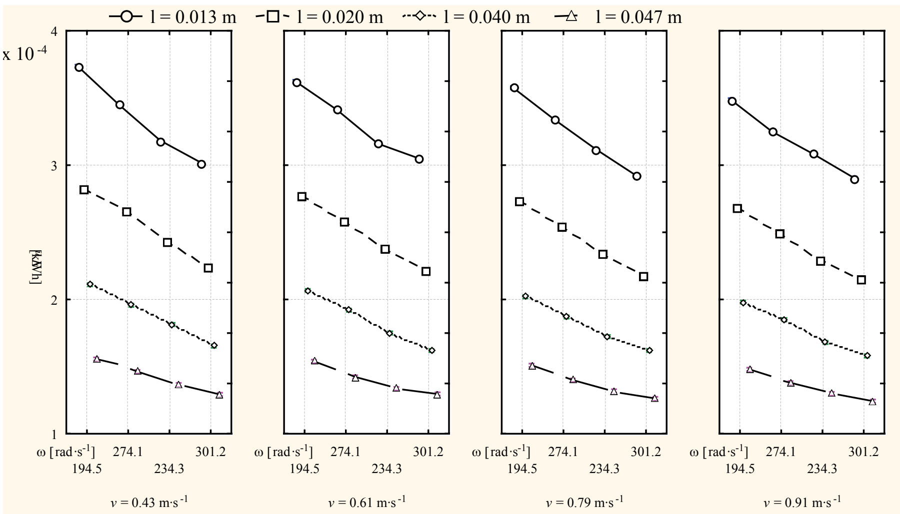

Fig. 3. Useful energy (E_u) in dependence of speed of head knife (ω), speed of cob feeder (v) and length of knife shaft (l)

In the range of angular speed of head knife from 274.1 to 301.2 rad·s^{-1} and speed of cob feeder from 0.43 do 0.91 m·s^{-1} useful energy decreased for the knife shaft length of l = 0.013 m from $3.73 \cdot 10^{-4}$ kWh to $2.90 \cdot 10^{-4}$ kWh, for $l = 0.020$ m from $3.82 \cdot 10^{-4}$ kWh to $2,15 \cdot 10^{-4}$ kWh, for $l = 0.040$ m from 2.11 to $1.58 \cdot 10^{-4}$ kWh, for $l = 0.047$ m from $1.55 \cdot 10^{-4}$ kWh to $1.24 \cdot 10^{-4}$ kWh.

However, in the range of speed of head knife from 274.1 to 301.2 rad·s^{-1} and the length of shaft knife from 0.013 to 0,047 m, useful energy (E_u) for speed of cob feeder for $v = 0.43$ m·s^{-1} carried out from $3.73 \cdot 10^{-4}$ kWh to $1.29 \cdot 10^{-4}$ kWh, for $v = 0.61$ m·s^{-1} from $3.62 \cdot 10^{-4}$ kWh to $1.29 \cdot 10^{-4}$ kWh, for $v = 0.79$ m·s^{-1} from $3.57 \cdot 10^{-4}$ kWh to $1.26 \cdot 10^{-4}$ kWh, for $v = 0.91$ m·s^{-1} from $3.48 \cdot 10^{-4}$ kWh to $1.24 \cdot 10^{-4}$ kWh.

Useful energy (E_u) decreases in the range of cob feeder speed from 0.43 to 0.91 m·s^{-1} and the length of shaft knife from 0.013 to 0.047 m in dependence of head knife speed change from $3.73 \cdot 10^{-4}$ kWh to $1.48 \cdot 10^{-4}$ kWh for $\omega = 194.5$ rad·s^{-1}, from $3.45 \cdot 10^{-4}$ kWh to $1.38 \cdot 10^{-4}$ kWh for $\omega = 274.1$ rad·s^{-1}, from $3.18 \cdot 10^{-4}$ kWh to $1.30 \cdot 10^{-4}$ kWh for $\omega = 234.3$ rad·s^{-1}, from $3.01 \cdot 10^{-4}$ kWh to $1.24 \cdot 10^{-4}$ kWh for $\omega = 301.2$ rad·s^{-1}.

Analyses of multiple regressions are presented in Table 5.

Table 5. Analyses of multiple regression for $E_u = f(l, \omega, v)$

Contests	Beta coefficient	SD for beta coefficient	Coefficient B	SD for B	t(188)	Significant level
Free word			4.72	0.118	40.00	0.0000
l	-0.94	0.020	-49.43	1.10	-44.73	0.0000
ω	-0.18	0.021	-0.003	0.00038	-8.68	0.0000
v	-0.06	0.021	-0.24	0.08	-2.89	0.0041

The dependence $E_u = f(l, \omega, v)$ were presented by means of the mathematical model:

$$E_u = - 49.42l - 0.0033\ \omega - 0.25v + 4.72\ (r = 96\%). \tag{36}$$

The analyses of variance showed that all independent variables are statistically significant at the level of $p \le 0.05$.

The comparison of measurements values with model are presented in Fig. 4.

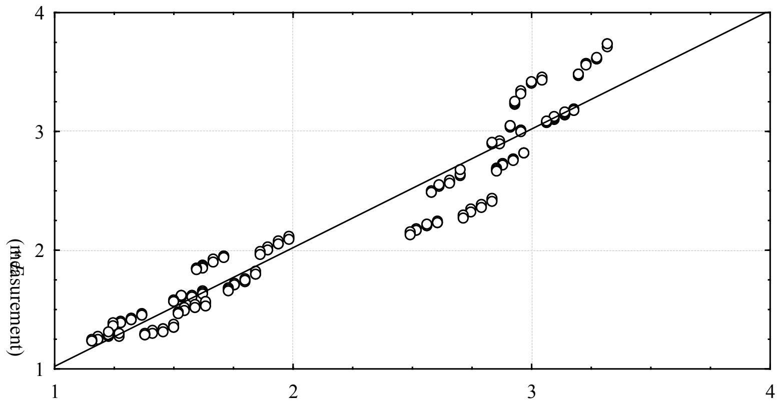

Fig. 4. The comparison of measurements values of useful energy (E_u) with model values

CONCLUSIONS

1. The statistical analyses showed the confirmation of dependence between parameters of the cutting process.

2. The mathematical model is characterized by the large quantitative and qualitative compatibility of influence of structural and operating parameters on useful energy of sweet corn kernel cutting. The dependence $E_u = f(l, \omega, v)$ is characterized by the high correlation coefficient (96%).

3. The highest values of useful energy ($3.73 \cdot 10^{-4}$ kWh) appeared at ω = 194.50 rad·s^{-1},v = 0.43 m·s^{-1} and l = 0.013 m. However, the lowest values of useful energy ($1.24 \cdot 10^{-4}$ kWh) at ω = 301.2 rad·s^{-1}, v = 0.91 m·s^{-1} and l = 0.047 m.

4. The highest decrease of useful energy appeared at l = var (ω = const, v = const) – about 64%, and the lowest at v = var (ω = const, l = const) – about 5%.

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