Modelling of Mechanical Peeling of Vegetables on the Basis of Energy Consumption

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ABSTRACT

Energy consumption model of peeling process is required to optimise main influenced factors as well as to limit peeling waste and consumed energy. Mechanical peeling process using an abrasive-cutter brush which applies both abrasive and cutting forces was modeled. Choosing the input and output variables which would be industrially applicable was attempted. Three variables, namely, angular velocities of abrasive-cutter brush (ωp), the degree of unevenness of produce surface (φ), and the shape of the abrasive-cutter brush (λ), were chosen as independent variables and the peel losses per unit time were chosen as the output of the model. The developed model was verified using the experimental results of peeling by abrasive-cutter brush for two varieties of pumpkin named Jarrahdale and Jap. The results showed correlation coefficients between predicted and experimental values of the Jap (0.98) and Jarrahdale (0.96) were statistically significant. It is concluded that the relationship among different parameters of the product and peeling tool and their effect on the peeling rate would be industrially applicable.

1. INTRODUCTION

Mechanical peeling of fruits and vegetables is the most common method compared to chemical and thermal methods. An understanding of the process of peeling is necessary for the optimal design and performance of mechanical peelers. A mathematical model of a peeling process could be an efficient tool for that purpose. Applying mathematical models in different aspects of agricultural engineering including tillage e.g. Fielke (1999), spraying machines e.g. Teske *et al.* (1991), crop handling machines e.g. Gorial & O'Callaghan (1991), harvesting e.g. Baruah and Panesar (2005*a*, *b*) and many versatile topics on post harvesting aspects have been successfully attempted. Although a few attempts have been made to model peeling process (Somsen *et al.*, 2004; Ferraz A C O *et al.*, 2007) but the authors could not find any published work on modeling of mechanical peeling. Development of energy model as one type of mathematical models for a peeler not only will enable to identify appropriate design parameters but also the optimization of these parameters will ensure energy saving. Achieving optimal peeling knowing the effective parameters of peeler and product will be more industrially operational if such parameters are identified and described in the model. This paper presents a developed energy model for mechanical peeling using abrasive-cutter brush. The model introduces effective operational parameters related to peeler and products which are industrially applicable and influential on energy requirement. The application of the model can be developed in wide range of mechanical peelers of fruits and vegetables.

Nomenclature

P_t	total expenditure power, N. mm/min	μ_d	the dynamic coefficient of friction between the brush's tooth and product
P_1	expenditure power for cutting, N. mm/min	K_2	the friction coefficient
P_2	expenditure power for fracture, N. mm/min	h	the length of removed peel, mm
η_c	total peeling efficiency	φ	the degree of unevenness of product's surface
n	the number of brushes on peeler head	R_v	the total normal reaction, N
ω_p	angular velocity of abrasive-cutter brush, rpm	F_{de}	deflection force of brush, N
E_p	penetration energy of brush, N. mm	N	the normal reaction force to the weight of brush, N
E_d	the deflection energy of brush, N. mm	W_1	the weight of one brush, g
K_1	average shearing resistance per unit length of stroke, N/mm	θ_2	the angle between direction of the weight and direction of the line passes through the gravity centre of brush and is perpendicular to the surface of product in contact point, degree
V_{ip}	linear penetration velocity of brush's teeth inside peel, mm/s	δ_4	the average deflection of brush in second stage of cutting, mm
t_1	time of stroke, s	l_3	the total projected lengths of protrusion's teeth engaged in cutting, mm
δ_1	deflection of product, mm	λ	actual protrusion of the brush
δ_2	the depth of average penetration, mm	K_3	the coefficient of elastic and plastic force
γ	the ratio of toughness of product (T_p) to toughness of tool (T_t)	E_2	the total required energy of peeling in second stage, N. mm
T_p	the toughness of product, N. mm	K_4	the coefficient of disintegration force
T_t	the toughness of abrasive-cutter brush, N. mm	K_5	scratching coefficient in second stage, number/min
α	the density of protrusions on a brush, number/mm^2	ω_v	angular velocity of vegetable holder, rpm
l_1	the effective length (covered by abrasive strip) of brush, mm	β	the number of scratches, number/min
d_1	the diameter of brush, mm	P. rate	peeling rate, g/min
τ	the shear strength of product, N/mm^2	LnP.rate:	the logarithmic transform of P. rate, g/min
d_2	the diameter of protrusion's hole, mm	K_6	transform coefficient of P_t to p. losses, g/N. mm
l_2	the length of each tooth on protrusion, mm	v. speed:	the angular velocity of vegetable holder, rpm
θ_1	the angle of teeth in protrusion, degree	p. speed:	the angular velocity of peeler head, rpm
E	the modulus of elasticity of the brush, $N.mm^{-2}$	peeling losses:	the substantial amount of usable vegetable flesh that is being
I	the geometrical moment of inertia of the brush, mm^4		
δ_3	the average deflection of the brush at fracture stage, mm		
L	the whole length of brush, mm		
δ_{3max}	the maximum deflection of brush in fracture stage, mm		
V_{op}	the linear velocity of brush's teeth in scratching stage, mm/s		

F_c total cutting force, N	discarded because of peeling, % of weight of whole produce before peeling
F_f friction force, N	peel losses: the ratio of the weight of removed peel to the weight of whole produce before peeling divided by time of peeling, %/min
F_d disintegration force on the structure of product, N	peeling efficiency: the percentage peel that is removed from the initial skin per unit time, %/min
F_e the spent force for elastic and plastic deformation, N	peeling rate: the weight of removed peel divided by peeling time, g/min
E_f the expended friction energy, N. mm	

2. MODEL DEVELOPMENT

Mechanical peeling is carried out mostly on the basis of applying abrasive and cutting forces. The peeling process can be split into two main stages including fracturing of the skin and scratching along removing the peel as formed chips. These operations are the main energy expenditures in mechanical peeling using abrasive-cutter brush. The supplied power from the power source and what are energy losses during transmission up to brush holder assumed to be independent from the main peeling process, and then only power requirement for conducting a mechanical peeling is modeled. The objective of this paper is to develop a model for mechanical peeling process using an abrasive-cutter brush which applies both cutting and abrasive forces. The physical laws which monitoring mechanical peeling functions in split processes and led to component models are discussed below.

2.1 Assumptions

The following assumptions were applied:

a. Removing peel is assumed to occur in layers and in the form of chips.
b. Peeling rate is in linear proportion to peeling energy.
c. The angular velocity of product is assumed to be zero.
d. The size and the weight of products for each variety are assumed to be the same and constant

2.2 Components Models

The total energy expenditure (P_t) during peeling process by abrasive-cutter brush is the sum total of the power required for cutting and scratching skin as given below:

$$P_t = \frac{1}{\eta_c}(P_1 + P_2), \qquad (1)$$

where, P_1 and P_2 are the required power for fracturing and scratching skin, respectively, in N. mm/min; and η_c is total peeling efficiency. The effective elements on the two above parameters are explained in details as below.

2.2.1 Fracture Stage

The energy consumed at the cutting stage itself is spent to penetrate the abrasive-cutter brush (teeth) inside the skin (Fig.1). The penetration depth depends on the stroke force developed by the rotational kinetic energy of the brush and neglecting the air resistance. The total penetration energy can be calculated as given below:

$$P_1 = n\omega_p(E_p + E_d), \qquad (2)$$

where, n is the installed number of brushes on the peeler head; ω_p is the rotastional velocity of the brush in rpm; E_p and E_d are the necessary penetration and deflection energy of one brush in N. mm respectively.

The energy required for penetration of one brush through the skin, E_p, is given below:

$$E_p = K_1(V_{ip}.t_1 - \delta_1) \times \delta_2, \qquad (3)$$

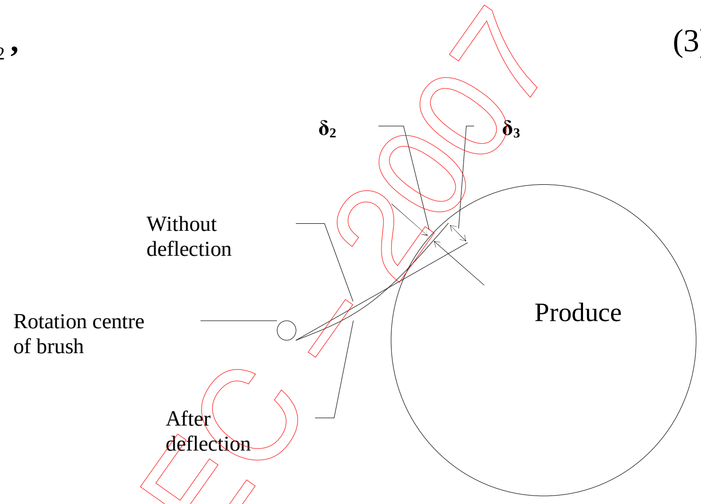

Figure 1.The view of abrasive-cutter brush after penetration into the skin

where, K_1 is the average shearing resistance per unit length of stroke in N.mm^{-1}; V_{ip} is the linear penetration velocity of brush teeth inside the skin in mm/s; t_1 is the time of stroke in s; δ_1 is the deflection of product in mm; and δ_2 is the average penetration depth of teeth inside the skin in mm. Each brush's stroke is accompanied by its deflection. In ideal conditions, the end of the brush will show a deflection of δ_3 because of reaction to the stroke. The average expenditure energy for this deflection (E_d) when considering a brush as a cantilever beam can be expressed as,

$$E_d = \frac{3EI\delta_3}{L^3}\delta_3, \qquad (4)$$

where, E is the modulus of elasticity of the brush in N.mm^{-2}; I is the geometric moment of inertia of the brush in mm^4; L is the whole length of the brush in mm; and δ_3 is the average deflection of the brush at the fracture stage in mm. Therefore, more splitting detailed parameters and coefficients and replacing them in Eq.2 leads to the final form of required power in the fracture stage of peeling as given below (Emadi, 2006):

$$P_1 = n\omega_p(4\pi\gamma\alpha l_1 l_2 d_1 d_2 \delta_2 \tau Sin\theta_1 + \frac{3EI\delta_3^2}{L^3}), \qquad (5)$$

2.2.2 Scratch Stage

Scratch is taking place as the second stage of energy consumption after cutting. This energy is required to scratch and remove the skin in chip form. The total power expenditure (P_2) at this stage can be written as follows:

$$P_2 = F_c \cdot V_{op}\,, \tag{6}$$

where, V_{op} is the linear velocity of scratching teeth inside the skin in mm/s; and F_c is the cutting force in N. The cutting force (F_c) of fibrous material such as fruits and vegetables is comprised of three effective forces (Dowgiallo, 2005) as given below:

$$F_c = F_f + F_e + F_d\,, \tag{7}$$

where, F_e is force spent for elastic and plastic deformation in N; and F_d is disintegration force exerted by brush teeth on the product structure in N. F_f and F_e as two important effective forces will be included in detail in the model. The expenditure energy due to F_d is released mostly as heat and depends significantly on some parameters such as the geometrical dimensions of teeth, the cutting speed, and resistance of product to cutting. F_d will be included in the model as part of the efficiency of cutting in this stage. The energy spent by F_f for one brush can be written using the law of friction as given below:

$$E_f = K_2 \times F_f \times h\,, \tag{8}$$

where, E_f is the energy spent on friction in N. mm; F_f is the friction force in N; h is the length of removed peel in mm; and K_2 is the friction coefficient related to the properties of the product and geometrical parameters of brush.

As fibrous materials are not less stiff than friable or crystalline materials (Dowgiallo, 2005), the force of F_e forms a considerable part of cutting force at the second stage. The elastic and plastic deformation force (F_e) can be determined as the equation given below:

$$F_e = K_3 \times \tau \times h \times l_3\,, \tag{9}$$

where, τ is the shear strength of product in N/mm^2; h is the length of removed peel in mm; and l_3 is the total projected lengths of the protrusion's teeth engaged in cutting in mm.

Therefore, the total elastic and plastic deformation energy can be given as follows:

$$E_e = 2\pi \cdot l_1 \cdot d_1 \cdot \alpha \cdot \tau \cdot h^2 \cdot l_2 \cos\theta_1 \tag{10}$$

With consideration of the disintegration force (F_d) as a coefficient (K_4) for both E_f and E_e and adding up Eqs.8 and 10, the total energy expenditure at the second stage could be calculated. The Eq.6 of required power for scratching and removing peel at the second stage can be rewritten as given below:

$$P_2 = K_5 E_2 \,, \tag{11}$$

where, K_5 is the scratching coefficient at the second stage of peeling. Therefore, the total required power of peeling at the second stage with more splitting detailed parameters and coefficients and replacing them on 6 will be given as follows (Emadi, 2006):

$$P_2 = K_4 \frac{\omega_v}{\omega_p} n\beta h\pi d_1 d_1 \alpha \left[\frac{\delta_2 \mu_d \varphi}{d_2} \left(W_1 \cos\theta_2 + \frac{3EI\delta_4}{L^3} \right) + 2 \cdot \tau \cdot hl_2 \cos\theta_1 \right] \tag{12}$$

2.2.3 Peeling Rate

As the cutting force of fibrous material is directly in relation to the resulted deformation during cutting (Dowgiallo, 2005), it can be assumed that the peeling rate also should be in direct relation to the required power of cutting. Assuming a linear relationship between the peeling rate and the required power of peeling leads to the following equation:

$$P.rate = K_6 \cdot P_t \,, \tag{13}$$

where, *P. rate* is the peeling rate during peeling in gr/min; and K_6 is the transform coefficient of P_t to *p. rate* in g/N. mm.

2.2.4. Final Model

As determination of all effective parameters is impossible at this stage, it was attempted to rewrite and arrange the above model using industrially applicable input and output variables. The review of effective parameters regarding the results of the experimental studies revealed three likely independent variables. They are the angular velocity of brush (ω_p), the unevenness of product surface (φ), and $cos\theta_1$ that represents the shape of the brush and actual protrusion of the brush and it is denoted as (λ). The output of model is kept as *p. rate* which is function of P_t and integrating all components using factorial technique on the basis of those three independent variables will show the general format of model as given below:

$$P.rate = C_0 + C_1\omega_p + C_2\varphi + C_3\lambda \,, \tag{14}$$

where, C_0 to C_3 are the model coefficients including detailed parameters and coefficients.

3. MATERIALS AND METHODS

3.1 Produce and Experimental Setup

Two different varieties of pumpkin including Jap and Jarrahdale, as the case studies, were used for experiments. The test rig with attachment, as described by Emadi et al. (2004), was used. Full factorial design was used for the design of experiments (DOE). The total number of runs was 128 which were divided equally for the two varieties. The experiments were conducted on three independent variables including coarseness of abrasive-cutter brush (coarseness: very coarse, coarse, mild, and fine), the rotational velocity of the peeler head (p. speed: 400, 550, 700, and 850 rpm), and the peeling location on the product (location: top, top-side, bottom-side, bottom) as shown in Figure 2. The rotational velocity of the produce was kept fixed at 5 rpm. Also the overlap of the brush and produce was considered fixed and equal to 10 mm for all runs. The running time of the experiments was 5 minutes and this was long enough to cover the necessary peeling time.

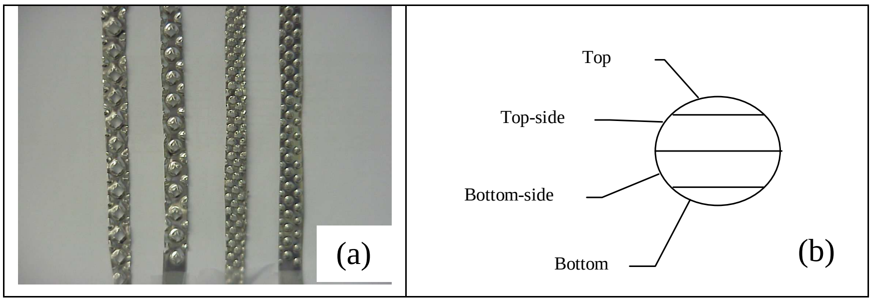

Figure 2. a. The strips with different type of coarseness used for fabrication of the abrasive-cutter brush (from left: very coarse, coarse, mild, fine), b. Different parts of produce's location

3.2 Determination of the Model Coefficients

Due to the impossibility of carrying out separate direct measurements, coefficients of the model were determined indirectly using experimental data and based on the multiple regression analysis technique. The obtained data from full experiments were used. Regarding the general linear function of the model, a multiple regression analysis was carried out for both varieties of pumpkin to determine four coefficients. The SPSS software package (version 13) was used for the analysis.

4. RESULTS AND DISCUSSION

4.1 Model Coefficients

The estimated values of model coefficients along with other results of multiple regression analysis are shown in Table 1. The results revealed that those three coefficients of the model for both varieties of pumpkin are highly significant ($p < 0.0001$). Despite the highly significant effect of these independent variables still they could explain 88% ($R^2 = 0.881$) of the variation in dependent variables for the Jarrahdale and about 89% ($R^2 = 0.894$) for the Jap. Regarding the relatively small number of variables (three independent variables), the R square is sufficiently satisfied.

Table1.The results of multiple regression analysis for coefficients of two models

Produce	Model coefficients				R^2	F	Sig.
	C_0	C_1	C_2	C_3			
Jarrahdale	-4.239	0.007	0.487	0.506	0.881	106.55	0.000
Jap	-3.088	0.005	0.405	0.410	0.894	123.86	0.000

The results also showed the significance of each independent variable in the model for both products. As all variables are highly significant ($p < 0.0001$), it means that all inserted parameters as coefficients to the model can significantly affect the peeling rate.

4.2 Model Validation

The validation of the model was assessed using scattered plots between experimental and predicted values (Fig.3).

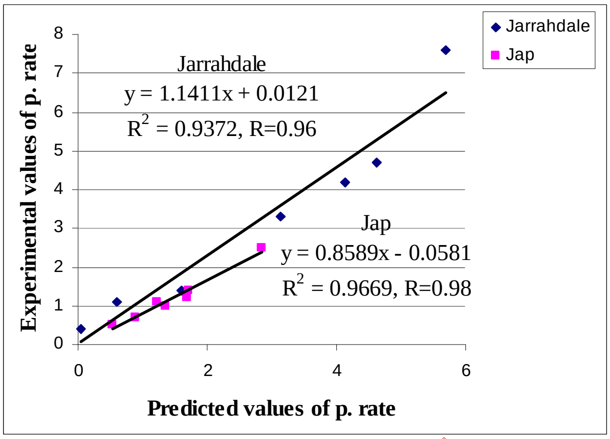

Figure 3. Experimental versus predicted values of p. rate (gr/min)

The values of the regression coefficients showed about ±0.14 difference with unity (not parallel trade lines). It was 0.85 for the Jap and 1.14 for the Jarrahdale. The intercepts of the regression lines were nearly close to zero. The values of -0.05 and 0.01 were obtained in this case for the Jap and Jarrahdale respectively. Also the correlation coefficients between predicted and experimental values of the Jap (0.98) and Jarrahdale (0.96) were revealed to be statistically significant. Therefore, all necessary criteria for meeting validity were satisfied.

5. CONCLUSIONS

Mechanical peeling using abrasive-cutter brush for two varieties of pumpkin (Jap and Jarrahdale) was simulated and results were shown as two mathematical models. The output of model was peeling rate (*p. rate*) and the input arranged with three main independent variables, namely, the angular velocity of brushes (ω_p), the degree of unevenness of product's surface (φ), and the shape of brush (λ). The results showed all three independent variables can significantly affect the peeling rate. The relationship was revealed as linear. The results revealed that the lower value of mechanical properties of the Jarrahdale such as shear strength, cutting force, rupture force and skin toughness, caused higher values of model coefficients involving C_1, C_2, and C_3 for the same conditions of experiments. The constant C_0 was unexpectedly higher for the Jap than for the Jarrahdale.

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