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Mathematical description of loading curves and deformation energy of bulk oil palm kernels

A. Kabutey[1,*], D. Herak[1], C. Mizera[1] and P. Hrabe[2]

[1]Czech University of Life Sciences Prague, Faculty of Engineering, Department of Mechanical Engineering, Kamycka 129, CZ16521 Prague, Czech Republic
[2]Czech University of Life Sciences Prague, Faculty of Engineering, Department of Material Sciences and Manufacturing Technology, Kamycka 129, CZ16521 Prague, Czech Republic
[*]Correspondence: kabutey@tf.czu.cz

Abstract. The study aimed at describing the experimental and theoretical relationships between the force and deformation curves as well as the deformation energy of bulk oil palm kernels under compression loading. Vessel diameters of 60, 80 and 100 mm with initial pressing heights of the bulk kernels measured at 40, 60 and 80 mm were examined by applying a maximum compressive force of 200 kN and a speed of 5 mm min^{-1}. For the theoretical description of the force and deformation curves, the tangent curve mathematical model was applied using the MathCAD 14 software where the force coefficient of mechanical behaviour, *A* (kN), the deformation coefficient of mechanical behaviour, *B* (mm^{-1}) and the fitting curve function exponent, *n* (-) were determined respectively. The determined coefficients in addition to the maximum deformation values obtained from the compression test were used for the estimation of the theoretical or analytical deformation energy. The determined regression models expressing the deformation, numerical energy and theoretical energy as well as the tangent model coefficients *A* and *B* dependent on the vessel diameter and pressing height were statistically significant ($P < 0.05$) or (F-ratio > F-critical). Improving the mechanical pressing of oil extraction for both domestic and industrial applications still remain a concern of researchers and engineers.

Key words: bulk oil palm kernels, vegetable oil, compression test, force-deformation curves, theoretical models.

INTRODUCTION

The oil palm fruit produces two types of oils namely palm oil and palm kernel oil. The palm oil is derived from the fibrous mesocarp while the palm kernel oil is obtained from the nut or seed of the palm fruit. The palm kernel oil is a triglyceride of a complex mixture of fatty acids with lauric and oleic acids as major fatty acids (Hadi et al., 2009; Septevani et al., 2015). The palm kernel oil contributes about 10% of the quantity of palm oil produced which is useful for both domestic and industrial purposes (Okoye et al., 2008; Vincent et al., 2014). The mechanical pressing which includes hydraulic press, screw press and the rolling press is the most common method for oil extraction due to several advantages including chemical-free and protein-rich meal, simple in construction and easy operation and maintenance (Mrema & McNulty, 1985; Okoye et al., 2008).

However, the process leaves about 8–14% of the residual oil in the seedcake compared to the solvent method which is able to extract over 98% of oil but it is a very complex process and high in cost (Bamgboye & Adejuno, 2007; Deli et al., 2011). As a result of the inefficiency associated with the mechanical pressing, there have been some considerable studies on its optimization in terms of the oil recovery efficiency and energy requirement (Tindale & Hill-Hass, 1976; Bredesson, 1993; Bargale et al., 1999). These studies focused on the process variables such as the pressure, temperature and moisture content as well as physical treatments such as size reduction, cracking, dehulling; thermal treatments such as preheating, dry extrusion; and hydrothermal treatment such as steaming, hot water soaking, blanching and flaking. Based on these processing steps, the oil recovery has improved from 50% to 80% (Singh & Bargale, 2000; Okoye et al., 2008).

In order to achieve suitable operation of the mechanical pressing for oil extraction, it is important also to examine the mechanical behaviour, the force and deformation curves and deformation energy of the bulk oilseeds, nuts or kernels in linear compression loading (Herak et al., 2012; Kabutey et al., 2013; Divišová et al., 2014; Akangbe & Herak, 2017; Kabutey et al., 2017). There is also the need to describe mathematically the linear compression process to predict the oil expression behaviour in mechanical pressing (Mrema & McNulty, 1985; Herak et al., 2013a; Sigalingging et al., 2014, Sigalingging et al., 2015). This knowledge, nevertheless, is very limited in the literature. Therefore, the study aimed at describing the experimental and theoretical relationships between the force and deformation curves and deformation energy of bulk oil palm kernels under compression loading.

MATERIALS AND METHOD

Sample and compression test

Bulk oil palm kernels purchased from Afosu/Abirim in the Birim North District in the Eastern Region of Southern Ghana were used for the compression test. The universal compression testing machine (ZDM 50, Czech Republic) and pressing vessels of diameters of 60, 80 and 100 mm with a plunger were used for the compression test. The initial pressing heights of the samples were measured at 40, 60 and 80 mm for all vessel diameters and loaded by applying a maximum compressive force of 200 kN and a speed of 5 mm min^{-1}.

Parameters determined

The moisture content of the samples was determined using the conventional method (ISI, 1996). From Eq. (1) (Blahovec, 2008), the moisture content was calculated to be 9% w.b.

$$M_C = \frac{m_a - m_b}{m_a} \cdot 100 \quad (1)$$

where M_C is the percentage moisture content in wet basis (% w.b.); m_a and m_b are the masses of samples before and after oven drying at a temperature of 105 °C and a drying time of 17 h.

The percentage kernel oil yield was determined as the ratio of the mass of kernel oil (the difference between the mass of initial height of bulk kernels and mass of bulk kernels cake) to that of the mass of initial pressing height multiplied by 100 as given by Eq. (2) (Deli et al., 2011).

$$O_Y = \frac{O_w}{O_m} \cdot 100 \tag{2}$$

where O_Y is the percentage kernel oil (%); O_w is the mass of bulk kernels oil (g) and O_m is the mass of initial pressing height of bulk kernels (g).

The numerical or experimental deformation energy, N_{de} of the bulk kernels was also calculated using Eq. (3) (Herak et al., 2013a; Akangbe & Herak, 2017).

$$N_{de} = \sum_{n=0}^{n=i-1} \left[\left(\frac{F_{n+1} + F_n}{2} \right) \cdot (x_{n+1} - x_n) \right] \tag{3}$$

where N_{de} is the numerical deformation energy (J); $F_{n+1} + F_n$ and $x_{n+1} - x_n$ are the values of the force (N) and deformation (mm), n is the number of data points and i is the number of subsections of the deformation axis (-).

The theoretical description of force and deformation curve was done by using the tangent curve mathematical model (Herak et al., 2013a; Sigalingging et al., 2014, Sigalingging et al., 2015) as given in Eq. (4) as follows:

$$F(x) = A \cdot (\tan(B \cdot x))^n \tag{4}$$

where F is the force (N); x is the deformation (mm); A is the force coefficient of mechanical behaviour (N); B is the deformation coefficient of mechanical behaviour (mm^{-1}), n is the fitting curve function exponent (-).

The theoretical or analytical deformation energy, T_{de} was determined by Eq. (5) which is the integral of Eq. (4) for $n = 1$ as follows:

$$\int F(x)dx \rightarrow -\frac{A \cdot ln(\cos(B \cdot x))}{B} \tag{5}$$

Statistical analysis

The calculated parameters were analysed using the STATISTICA 13 software (Statsoft, 2013) by employing the multiple regression procedure. The theoretical data analysis, that is, the determination of the coefficients A, B and n of the tangent curve mathematical model Eq. (4) and their statistical evaluation was done using the MathCAD 14 software (Marquardt, 1963; Pritchard, 1998; Mathsoft, 2014).

RESULTS AND DISCUSSION

The amounts of mass of kernel oil and percentage kernel oil of bulk oil palm kernels measured at pressing heights of 40, 60 and 80 mm in vessel diameters of 60, 80 and 100 mm are presented in Table 1. The increase in bulk kernels pressing heights and vessel diameters linearly increased the output kernel oil. The calculated percentage kernel oil at a maximum compressive force of 200 kN and a speed of 5 mm min^{-1}, however, showed both increasing and decreasing trends with the increase in bulk kernels pressing heights and vessel diameters. The literature indicates that pressure, temperature, pressing time, speed and moisture content are other processing factors influencing the percentage oil yield (Khan & Hanna, 1983; Mrema and McNulty, 1985; Deli et al., 2011). The varying combinations of these processing factors need to be studied extensively under compression loading to determine their optimum amounts.

Table 1. Calculated amounts of bulk kernels oil yield (Mean ± Standard Deviation)

Variables (mm)	Mass of bulk kernels* (g)	Mass of bulk kernel cake** (g)	Mass of kernel oil (g)	Kernel oil yield (%)
D = 60				
H = 40	65.7 ± 0.0	56.5 ± 0.3	9.2 ± 0.3	14.1 ± 0.4
H = 60	102.5 ± 0.7	86.4 ± 0.3	16.1 ± 0.4	15.7 ± 0.3
H = 80	135.4 ± 1.4	116.1 ± 0.0	19.4 ± 1.4	14.3 ± 0.9
D = 80				
H = 40	122.1 ± 2.3	110.6 ± 4.1	11.3 ± 1.7	9.3 ± 1.5
H = 60	180.3 ± 125	161.5 ± 0.2	18.8 ± 1.4	10.4 ± 0.7
H = 80	234.7 ± 1.7	210.7 ± 2.6	23.9 ± 1.1	10.2 ± 0.5
D =100				
H = 40	187.1 ± 4.2	171.9 ± 4.4	15.1 ± 0.2	8.1 ± 0.3
H = 60	281.5 ± 0.8	259.4 ± 1.1	22.1 ± 1.8	7.9 ± 0.6
H = 80	374.7 ± 2.7	329.7 ± 1.8	45.0 ± 4.5	12.0 ± 1.1

D is the pressing vessel diameter (mm); *H* is the pressing height of bulk kernels (mm); * is the mass of bulk kernels before pressing; ** is the mass of bulk kernels cake after pressing.

The values of the deformation, numerical energy and theoretical energy increased along with the increase in bulk kernels pressing heights and vessel diameters as shown in Table 2. The box plots of these relationships are shown in Figs 1 and 2.

The results were statistically significant where F-ratio > F-critical or P-value < 0.05 as presented in Table 3. The coefficients of determination (R^2) were 0.98, 0.96 and 0.94 respectively.The expressions of the deformation, D_{fm} (mm), numerical energy, N_{de} (J) and theoretical energy, T_{de} (J) dependent on the vessel diameter, D (mm) and pressing height, H (mm) are described in Eqs. 6, 7 and 8 as follows:

Table 2. Calculated amounts of bulk kernels deformation and deformation energy (Mean ± Standard Deviation)

Variables	Deformation	Deformation energy (J)	
(mm)	D_{fm} (mm)	Numerical, N_{de}	Theoretical, T_{de}
D = 60			
H = 40	25.6 ± 0.3	689.3 ± 10.9	780.4 ± 33.7
H = 60	38.1 ± 0.5	985.8 ± 25.1	950.8 ± 23.7
H = 80	50.1 ± 0.0	1,239.2 ± 42.0	1,241.0 ± 67.9
D = 80			
H = 40	23.2 ± 1.0	876.0 ± 2.3	874.9 ± 10.8
H = 60	35.3 ± 0.4	1,285.2 ± 8.8	1,266.0 ± 1.4
H = 80	45.5 ± 0.4	1,612.7 ± 16.2	1,595.5 ± 91.2
D =100			
H = 40	23.7 ± 0.4	1,073.9 ± 30.3	1,105.0 ± 18.4
H = 60	33.8 ± 0.2	1,561.4 ± 34.9	1,541.5 ± 7.8
H = 80	41.7 ± 0.4	2,045.5 ± 50.4	2,092.0 ± 33.9

D is the pressing vessel diameter (mm), *H* is the pressing height of bulk kernels (mm).

$$D_{fm} = 12.6 - 0.12 \cdot D + 0.54 \cdot H \quad (6)$$

$$N_{de} = -1{,}043.6 + 14.7 \cdot D + 18.8 \cdot H \quad (7)$$

$$T_{de} = -989.7 + 14.7 \cdot D + 18.1 \cdot H \quad (8)$$

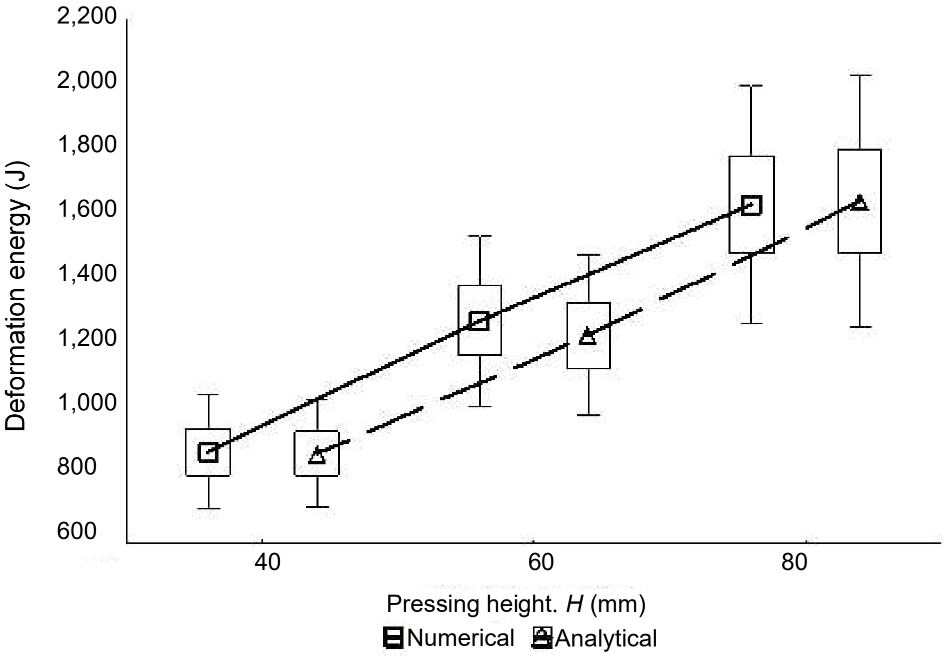

Figure 1. Comparison between numerical and analytical deformation energy based on the bulk samples pressing height.

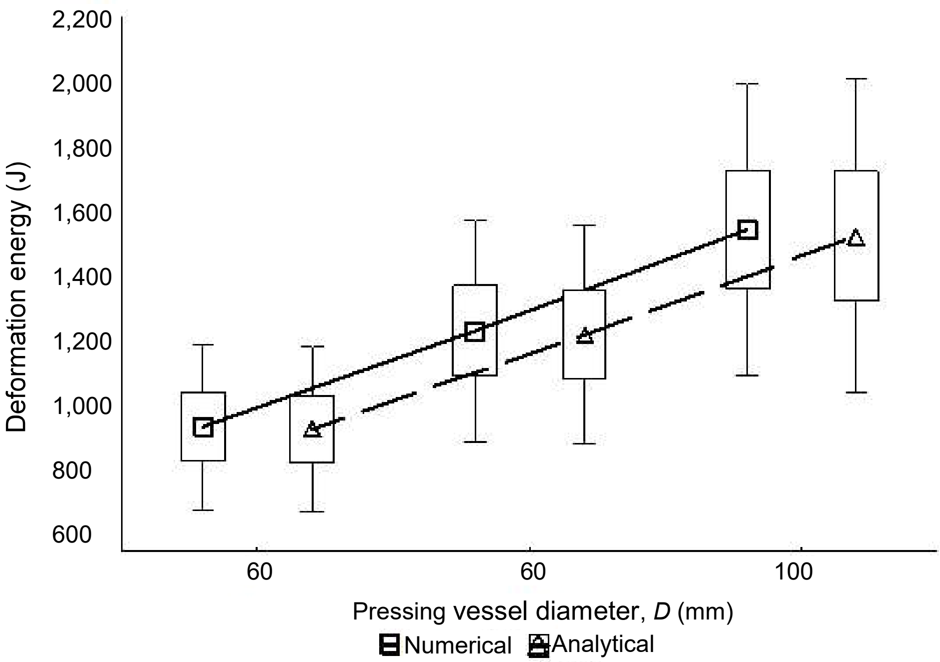

Figure 2. Comparison between numerical and analytical deformation energy based on the pressing vessel diameter.

The experimental and theoretical descriptions of the force and deformation curves of the bulk oil palm kernels for vessel diameters ($D = 60$, 80 and 100 mm) in relation to bulk kernels pressing heights ($H = 40$, 60 and 80 mm) are illustrated in Figs 3–5. All the curves showed a smooth curve characteristic which is important for analysing the deformation energy both experimentally and theoretically (Divišová et al., 2014; Kabutey et al., 2014; Sigalingging et al., 2014, Sigalingging et al., 2015). The smooth curve behaviour is also vital for understanding the required energy demand for the oil point and percentage oil yield (Faborade & Favier, 1996; Herak et al., 2010, 2013b).

Table 3. Statistical values of regression analysis of the calculated variables

Calculated parameters	F-ratio (-)	F-critical (-)	P-value (-)	R^2 (-)
D_{fm} (mm)	377.65	3.63	< 0.05	0.98
N_{de} (J)	205.67	3.63	< 0.05	0.96
T_{de} (J)	113.97	3.63	< 0.05	0.94

F-ratio > F-critical or P-value < 0.05 is significant (Statsoft, 2013). F-ratio is the value of the F test (-); F-critical is the critical value that compares a pair of models (-); P-value is the significance level used for testing a statistical hypothesis (-); R^2 is the coefficient of determination (-).

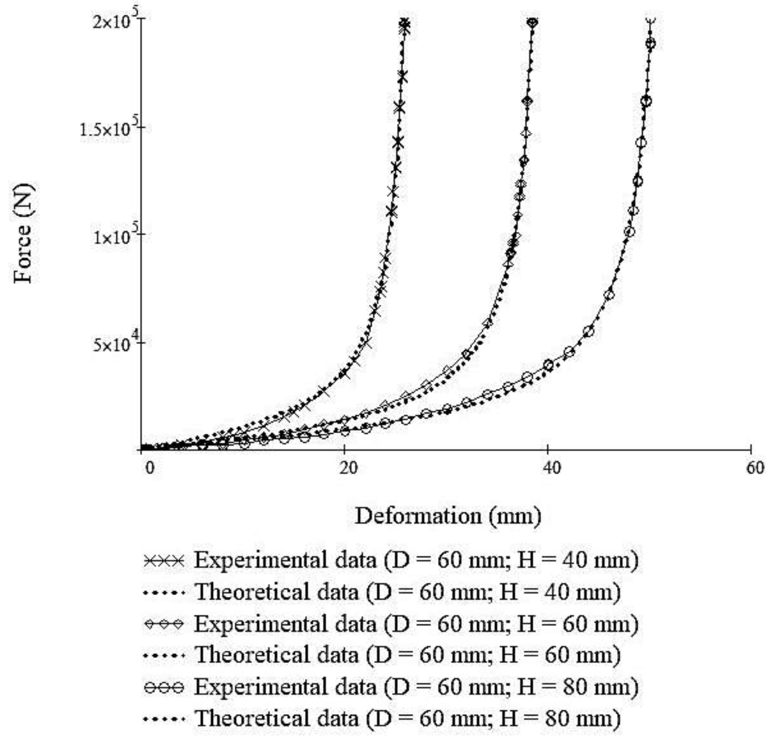

Figure 3. Experimental and theoretical descriptions of the force and deformation of bulk oil palm kernels for vessel diameter, ($D = 60$ mm) in relation to pressing heights, ($H = 40$, 60 and 80 mm).

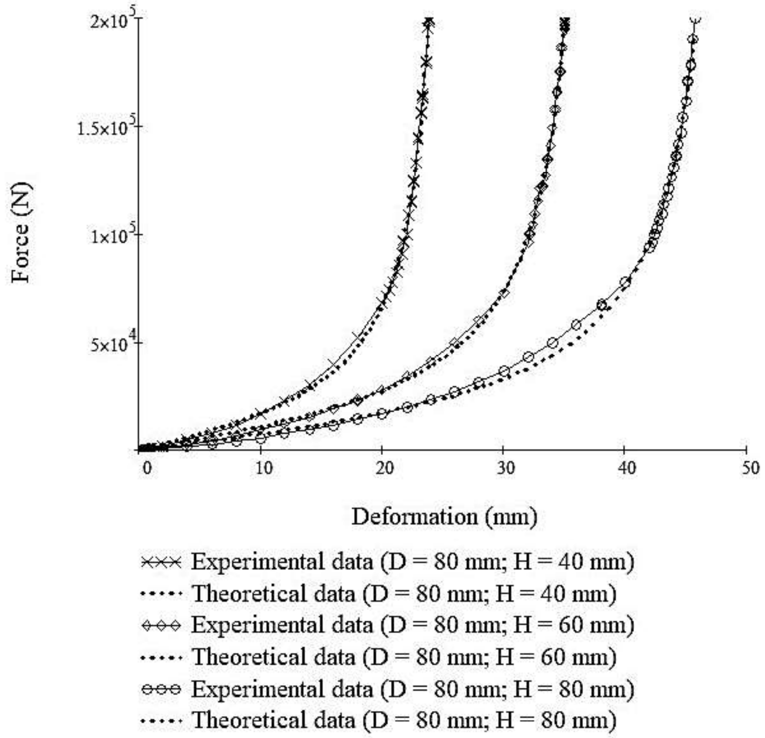

Figure 4. Experimental and theoretical descriptions of the force and deformation of bulk oil palm kernels for vessel diameter, (D = 80 mm) in relation to pressing heights, (H = 40, 60 and 80 mm).

The determined coefficients of the tangent curve mathematical model; A, B and n using Eq. 4 are given in Table 4. Their statistical values are also given in Table 5. The results were statistically significant ($P > 0.05$) or (F-ratio < F-critical) (Mathsoft, 2014). These determined coefficients together with the deformation values (Table 2) can be used to describe theoretically the experimental relationship between the force and deformation curves of bulk oil palm kernels compressed at a maximum compressive force of 200 kN and a speed of 5 min min^{-1}.

Table 4. Determined coefficients of the tangent curve model (Mean ± Standard Deviation)

Variables (mm)	A (N)	B (mm^{-1})	N (-)
D = 60			
H = 40	18,280.0 ± 2,262.7	0.058 ± 0.0	1
H = 60	15,030.0 ± 1,640.5	0.039 ± 0.0	1
H = 80	13,785.0 ± 685.9	0.030 ± 0.0	1
D = 80			
H = 40	26,175.0 ± 1,887.9	0.063 ± 0.0	1
H = 60	24,630.0 ± 1,513.2	0.041 ± 0.0	1
H = 80	23,540.0 ± 212.1	0.032 ± 0.0	1
D =100			
H = 40	39,485.0 ± 261.6	0.058 ± 0.0	1
H = 60	39,075.0 ± 1,364.7	0.041 ± 0.0	1
H = 80	44,140.0 ± 466.7	0.033 ± 0.0	1

A is the force coefficient of mechanical behaviour (N); B is the deformation coefficient of mechanical behaviour (mm^{-1}); n is the fitting curve function exponent (-).

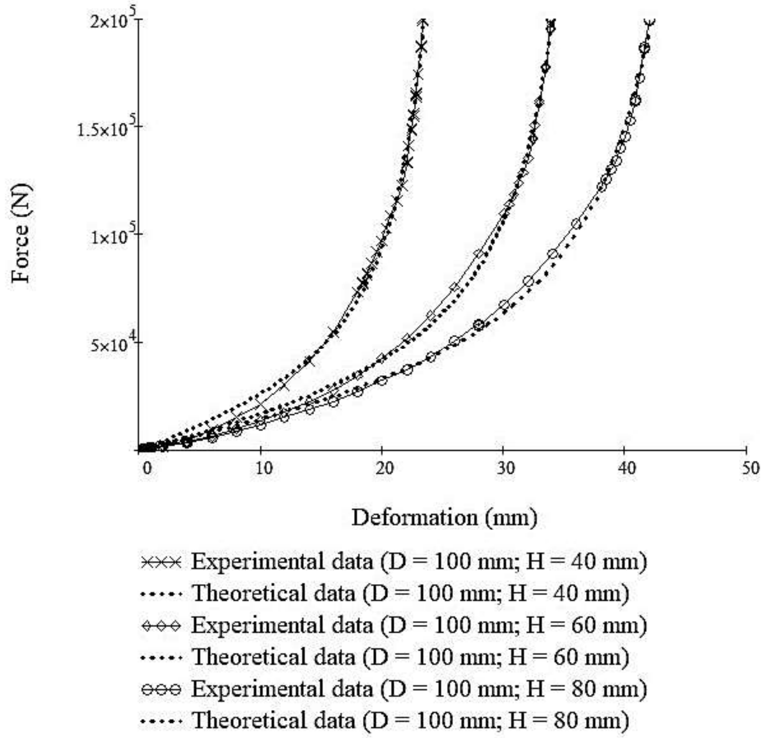

Figure 5. Experimental and theoretical descriptions of the force and deformation of bulk oil palm kernels for vessel diameter, (D = 100 mm) in relation to pressing heights, (H = 40, 60 and 80 mm).

Table 5. Statistical values of the ANOVA analysis of the tangent model coefficients (Mean ± Standard Deviation)

Tangent model coefficients	F-ratio (-)	F-critical (-)	P-value (-)	R^2 (-)
A, B, n (D = 60)				
H = 40	0.019 ± 0.006	3.858 ± 0.007	0.889 ± 0.019	0.998 ± 0.001
H = 60	0.003 ± 0.004	3.848 ± 0.000	0.964 ± 0.036	0.999 ± 0.001
H = 80	0.0001 ± 0.0001	3.862 ± 0.000	0.995 ± 0.003	0.999 ± 0.000
A, B, n (D = 80)				
H = 40	0.002 ± 0.00	3.848 ± 0.000	0.963 ± 0.001	0.999 ± 0.001
H = 60	0.002 ± 0.001	3.848 ± 0.001	0.964 ± 0.007	0.999 ± 0.001
H = 80	0.0001 ± 0.00	3.847 ± 0.000	0.991 ± 0.002	0.999 ± 0.000
A, B, n (D = 100)				
H = 40	0.028 ± 0.035	3.848 ± 0.000	0.886 ± 0.095	0.999 ± 0.001
H = 60	0.020 ± 0.006	3.848 ± 0.000	0.888 ± 0.169	0.999 ± 0.000
H = 80	0.018 ± 0.022	3.848 ± 0.000	0.906 ± 0.072	0.999 ± 0.000

F-ratio < F-critical or P-value > 0.05 is significant (Mathsoft, 2014).

The regression equations of the tangent model coefficients A (N) and B (mm^{-1}) of the tangent curve model for the fitting function exponent, $n = 1$ are described in Eqs. 9 and 10 dependent on the vessel diameter D and pressing height H. The whole models statistical values were significant ($P < 0.05$) or (F-ratio > F-critical). The coefficients of determination (R^2) of the determined models were 0.94 and 0.99 (Table 6).

$$A = -22{,}039.2 + 630 \cdot D - 20.6 \cdot H \quad (9)$$

$$B = 0.09428 + 0.0009 \cdot D - 0.0023 \cdot H - 0.000005 \cdot D^2 + 0.000013 \cdot H^2 \quad (10)$$

The force coefficient of mechanical behaviour, A (N) and the deformation coefficient of mechanical behaviour, B (mm^{-1}) dependency on the pressing vessel diameter in relation to the pressing height are displayed in Figs 6 and 7 respectively. It can be seen that the force coefficient of mechanical behaviour increased linearly with increasing pressing heights and vessel diameters while the deformation coefficient of mechanical behaviour was suitably fitted by a polynomial function.

Table 6. Statistical values of regression analysis of the tangent model coefficients A and B

Tangent model coefficients	F-ratio (-)	F-critical (-)	P-value (-)	R^2 (-)
A	115.37	3.63	< 0.05	0.94
B	372.53	3.63	< 0.05	0.99

A is the force coefficient of mechanical behaviour (N); B is the deformation coefficient of mechanical behaviour (mm^{-1}) (Statsoft, 2013).

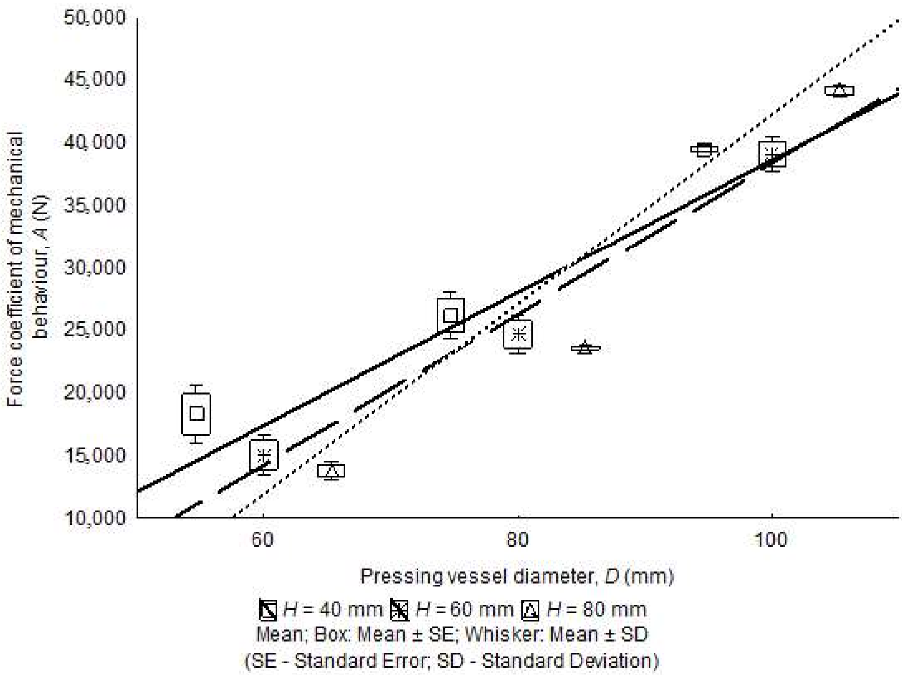

Figure 6. Force coefficient of mechanical behaviour, A (N) versus pressing vessel diameter, D (mm) in relation to bulk samples pressing heights, H (mm).

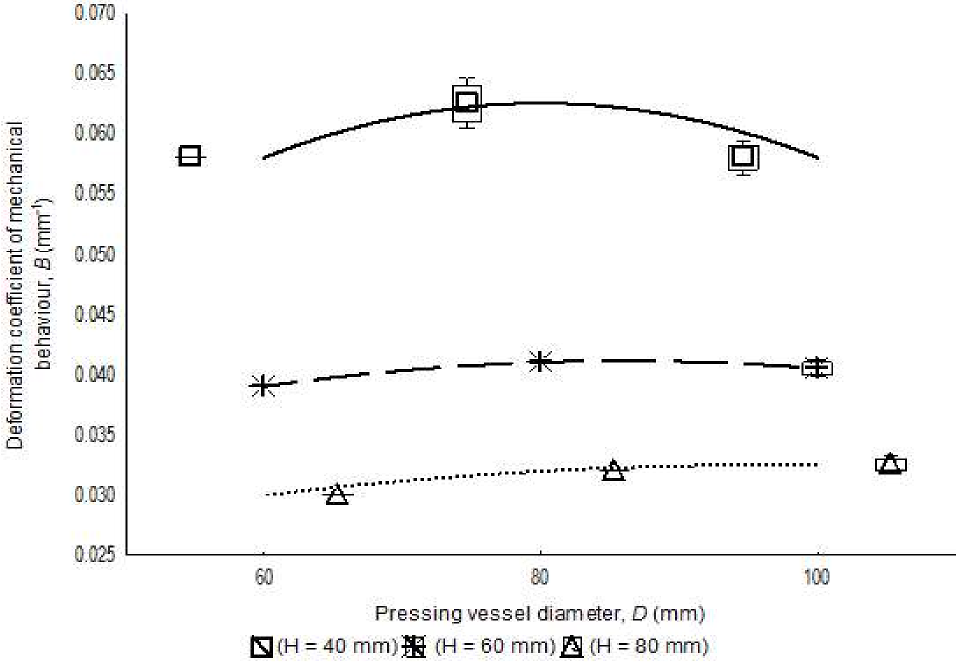

Figure 7. Deformation coefficient of mechanical behaviour, *B* (mm^{-1}) versus pressing vessel diameter, *D* (mm) in relation to bulk kernels pressing heights, *H* (mm).

CONCLUSIONS

The experimental dependency between the force and deformation curves of bulk oil palm kernels at pressing heights of 40, 60 and 80 mm and vessel diameters of 60, 80 and 100 mm were described theoretically using the tangent curve mathematical model. The statistical values of the ANOVA analysis of the tangent curve model coefficients namely the force coefficient of mechanical behaviour, *A* (N), the deformation coefficient of mechanical behaviour, *B* (mm^{-1}) and the fitting curve function exponent, *n* (-) were significant ($P > 0.05$) or (F-ratio < F-critical) based on the MathCAD 14 software. Regression equations of the deformation, numerical energy, theoretical energy, force coefficient of mechanical behaviour and deformation coefficient of mechanical behaviour dependent on the pressing height and vessel diameter were determined. Their statistical values from the regression analysis were also significant ($P < 0.05$) or (F-ratio > F-critical) based on the STATISTICA 13 software. At a maximum force of 200 kN and speed of 5 mm min^{-1}, the fitting curve function exponent, *n* of the tangent curve mathematical model for describing bulk oil palm kernels was found to be 1. This information is important for analyzing or predicting the oil expression behaviour involving the mechanical screw presses.

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