DEFORMATION CURVE CHARACTERISTICS OF RAPESEEDS AND SUNFLOWER SEEDS UNDER COMPRESSION LOADING

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The deformation curve characteristics of rapeseeds and sunflower seeds compressed using the equipment ZDM 50-2313/56/18 and varying vessel diameters (40, 60, 80, and 100 mm) were investigated. Maximum compressive force of 100 kN was applied on bulk oilseeds of rape and sunflower of measured height 20–80 mm and deformed at a speed of 60 mm·min–1. The compression test using the vessel diameters of 40 and 60 mm showed a serration effect while the vessel diameters of 80 and 100 mm indicated an increasing function effect on the force-deformation characteristic curves. Clearly, the increasing function effect described the region with oil flow and that of serration effect described the region without any oil flow. However, it was observed that the serration effect could be due to the higher compressive stress inside the smaller vessel diameters (40 and 60 mm) compared to those with bigger vessel diameters (80 and 100 mm). Parameters such as deformation, deformation energy, and energy density were determined from the force-deformation curves dependency showing both increasing function and serration effect. The findings of the study provide useful information for the determination of specific compressive force and energy requirements for extracting maximum oil from oilseed crops such as rape and sunflower.

oilseed crops; vessel diameters; increasing function; serration effect

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doi: 10.2478/sab-2014-0106

Received for publication on July 4, 2013

Accepted for publication on April 8, 2014

INTRODUCTION

Rape (*Brassica napus* L.) and Sunflower (*Helianthus annus* L.) are important oilseed crops with a large proportion of highly nutritious vegetable oil grown worldwide for human consumption, animal feed, and other potential uses (Gupta, Das, 2000; Izli et al., 2009). Recently, the oil from both crops has also gained a special recognition for biodiesel production (Pereyra-Irujo et al., 2009). Rape ranks the third while sunflower is the fourth in the world consumption of vegetable oils. The top five leading producers of rape are the European Union, Canada, the United States, Australia, and China; and of sunflower are Russia, the European Union, Ukraine, Argentina, and Turkey (www.marketreport.org; www.oilworld.org; www.opec.org).

Mechanical pressing involving the use of a screw press is the most common method of oil extraction worldwide (Mrema, McNulty, 1985). However, mechanical presses are capable of achieving 50–80% oil recovery efficiency compared to 98% efficiency reached by the solvent extraction method (Bargale et al., 2000). To improve the performance of mechanical presses for pressing maximum oil from oilseeds, there is the need to understand the mechanical characteristics of the oilseeds (Herak et al., 2010). In the literature, the mechanical properties such as compressive force, deformation, deformation energy, and hardness of sunflower seeds and rapeseeds have been discussed by few authors (Gupta, Das, 2000; Izli et al., 2009; Herák et al., 2012). However, in these studies, the deformation characteristic curve in relation to varying vessel diameters and seed height was not described as thoroughly as the mechanical properties. The lacking information of this kind poses a problem in the process of the design optimization of a new oil processing equipment. Most importantly, this information was insufficient as concerns the determination of the precise compressive force and energy requirement for achieving a higher oil recovery (Raji, Favier, 2004; Herak et al., 2010).

In addition, to develop mathematical models to describe the mechanical behaviour and deformation

* Supported by the Grant Agency of the Faculty of Engineering, Czech University of Life Sciences Prague (IGA), Project No.2014:31130/1312/3115..

characteristics of oilseeds, it is also necessary to describe the deformation characteristic curve accurately (H e r a k et al., 2013; K a b u t e y et al., 2013). In this respect, a mathematical model based on the tangent curve function (H e r á k et al., 2011) was developed to describe the mechanical behaviour and deformation characteristics of *Jatropha curcas* L. using different vessel diameters and seed heights under compression loading (H e r a k et al., 2013).

This model has to be further modified before using it for the description of the mechanical behaviour and deformation characteristics of other oilseed crops such as rape and sunflower because the required amount of compressive force and energy needed to produce a given deformation and deformation characteristic curve varies extensively among different oilseeds as reported by S t r o s h i n e, H a m m a n, 1994.

The objective of the study was to describe and compare the mechanical characteristics of rapeseeds and sunflower seeds using vessels of varying diameters in relation to seed heights under compression loading. The mechanical properties such as deformation, deformation energy, and energy density were also determined. This information is needed for understanding the actual amount of compressive force and energy requirement for extracting maximum oil from rapeseeds and sunflower seeds.

MATERIAL AND METHODS

Materials

Rapeseeds and sunflower seeds were procured from the Czech Republic. Compression device ZDM 50-2313/56/18 with a chart recorder (VEB, Dresden, Germany) and vessel diameters with plungers (Fig. 1) were employed for the compression test.

Moisture content determination

The initial moisture content of the samples (rapeseeds and sunflower seeds) was determined using the standard hot air oven method with a temperature setting of 105°C and a drying time of 17 h (I S I, 1966). The electronic balance Kern 440–35 (Kern & Sohn GmbH, Balingen, Germany) with an accuracy of 0.001 g was used for weighing the samples before and after oven drying. The mean moisture content (w.b.%) of rapeseeds (11.07 ± 0.33) and sunflower seeds (12.37 ± 0.38) was calculated using equation (Eq. 1) specified by (B l a h o v e c, 2008).

$$MC_{w.b.} = \left[\frac{Mi - Mc}{Mi}\right] \cdot 100 \qquad (1)$$

where:
$MC_{w.b.}$ = moisture content on wet basis (%)
M_i = weight of samples in the initial state (g)
Mc = weight of samples after oven drying (g)

Compression test of samples

The compression process using vessels of four diameters (40, 60, 80, and 100 mm) (Fig. 1) and seeds of various heights (20, 30, 40, 50, 60, 70, and 80 mm) was successively examined to determine the relationship between the compressive force and the deformation characteristic curve by applying maximum compressive force of 100 kN at the deformation rate of 60 mm·min^{-1}. The compression test was repeated twice for each seed height of rapeseeds and sunflower seeds. The force-deformation dependency curves obtained from the compression test were analyzed using Mark Mitchell Software Engauge Digitizer (Version 4.1., 2002) to determine the specific value of compressive force (N) and deformation (mm).

Seed volume

Using equation (Eq. 2) (H e r a k et al., 2010, 2011, 2012), the seed volume of rapeseeds and sunflower seeds was determined as follows:

$$V = \frac{\pi \cdot D^2}{4} \cdot H \qquad (2)$$

where:
V = seed volume (m^3)
D = diameter of the pressing vessel (mm)
H = seed height (mm)

Fig 1. Compressive device and vessel diameters 100, 80, 60 and 40 mm with plungers.

Table 1. Measured parameters under the force-deformation curve showing increasing function

Seed height (mm)	deformation ($\cdot 10^{-3}$m)	deformation energy (J)	seed volume ($\cdot 10^{-5}$ m^3)	energy density ($\cdot 10^6$ J$\cdot$m^{-3})
Vessel diameter 40 mm for rapeseeds and sunflower seeds				
20	^{R} 6.55±0.13 ^{S} 12.51±1.23	^{R} 71.32±4.89 ^{S} 133.18±3.13	^{R} 0.82±0.02 ^{S} 1.57±0.15	^{R} 8.65±0.42 ^{S} 8.50±0.63
30	11.55±0.80 19.47±0.12	132.06±30.67 173.26±10.52	1.45±0.100 2.44±0.02	9.04±1.48 7.08±0.38
40	16.59±0.20 24.59±0.54	197.82±12.54 214.36±25.54	2.08±0.03 3.09±0.06	9.48±0.48 6.92±0.67
50	21.12±1.42 29.08±0.83	248.54±79.93 238.05±50.01	2.65±0.18 3.65±0.01	9.28±2.38 6.49±1.18
60	26.10±1.02 37.42±2.45	254.40±54.24 275.15±95.09	3.28±0.13 4.70±0.31	7.72±1.35 5.79±1.64
70	30.74±0.12 44.29±3.50	296.76±2.97 326.07±73.91	3.86±0.02 5.56±0.43	7.68±0.10 5.82±8.67
80	33.73±0.76 50.91±1.32	316.45±42.41 387.62±71.38	4.23±0.10 6.39±0.16	7.45±0.83 6.04±0.95
Vessel diameter 60 mm for only rapeseeds				
20	6.80±0.08	127.94±6.77	1.92±0.02	6.65±0.26
30	11.23±0.08	175.42±9.55	3.17±0.02	5.52±0.26
40	13.81±0.22	222.79±14.62	3.90±0.06	5.70±0.28
50	18.27±1.47	264.86±19.21	5.16±0.41	5.12±0.04
60	23.30±0.10	318.59±7.06	6.58±0.02	4.83±0.08
70	29.61±0.10	400.64±6.37	8.37±0.02	4.78±0.06
80	31.97±0.06	442.95±5.60	9.04±0.01	4.89±0.53

^{R} = Rapeseeds; ^{S} = Sunflower seeds

Table 2. Measured parameters under the force-deformation curve showing both increasing function and serration effect

Seed height(mm)	deformation($\cdot 10^{-3}$m)	deformation energy(J)	seed volume($\cdot 10^{-5}$ m^3)	energy density ($\cdot 10^6$ J$\cdot$m^{-3})
Vessel diameter 40 mm for rapeseeds and sunflower seeds				
20	^{R} 16.94±0.25 ^{S} 17.74±1.32	^{R} 669.74±16.14 ^{S} 488.41±12.93	2.51	^{R} 26.64±0.64 ^{S} 19.43±0.51
30	26.99±0.52 27.30±0.56	1034.38±35.88 787.43±46.53	3.77	27.43±0.95 20.88±1.23
40	36.43±0.01 36.82±0.54	1416.47±2.04 1089.56±68.80	5.02	28.17±0.04 21.67±1.36
50	46.72±0.01 46.04±0.98	1791.92±2.73 1449.09±56.12	6.28	28.51±0.04 23.05±0.89
60	58.34±0.06 54.69±1.32	2245.49±8.19 1472.43±39.51	7.54	29.77±0.10 20.18±1.46
70	67.45±0.12 66.53±0.95	2564.30±12.38 1922.35±21.83	8.79	29.14±0.14 21.85±0.24
80	75.28±0.12 76.86±2.78	2964.02±17.44 2247.82±42.87	10.05	29.47±0.17 22.35±0.42
Vessel diameter 60 mm for only rapeseeds				
20	12.86±0.95	678.34±30.46	5.65	11.10±1.78
30	20.69±0.01	960.28±3.98	8.48	11.31±0.04
40	26.05±0.34	1279.55±26.22	11.31	11.31±0.20
50	30.82±1.41	1358.86±5.17	14.13	9.61±0.03
60	35.77±0.07	1433.73±9.26	16.96	8.45±0.05
70	39.59±1.96	1413.73±50.98	19.79	6.63±0.97
80	43.49±0.78	1478.48±54.49	22.62	6.53±0.24

^{R} = Rapeseeds; ^{S} = Sunflower seeds

Table 3. * Measured parameters under the force-deformation curve with vessel diameter 60 mm (without any serration effect)

Seed height (mm)	Deformation ($\cdot 10^{-3}$m)	Deformation energy (J)	Seed volume($\cdot 10^{-5}$ m^3)	Energy density ($\cdot 10^6$ J$\cdot$m^{-3})
20	12.13±0.75	206.37±18.14	5.65	3.64±0.32
30	18.58±0.80	329.82±24.56	8.48	3.88±0.28
40	24.46±1.18	364.29±9.50	11.31	3.22±0.08
50	28.95±0.87	420.45±14.69	14.13	2.97±0.10
60	36.78±0.84	488.20±3.31	16.96	2.87±0.19
70	42.21±0.01	564.79±4.19	19.79	2.85±0.02
80	48.41±0.70	655.64±5.11	22.62	2.89±0.02

* Sunflower seeds only

Table 4. Measured parameters under the force-deformation curve with vessel diameter 80 mm (without any serration effect)

Seed height (mm)	Deformation ($\cdot 10^{-3}$m)	Deformation energy (J)	Seed volume ($\cdot 10^{-5}$ m^3)	Energy density ($\cdot 10^6$ J$\cdot$m^{-3})
20	^{R} 6.53±0.04 ^{S} 11.53±1.35	^{R} 182.85±3.77 ^{S} 243.14±2.80	10.05	^{R} 1.81±0.03 ^{S} 2.41±0.51
30	10.12±0.06 18.61±0.43	224.78±6.03 346.39±12.40	15.08	1.49±0.03 2.29±1.23
40	14.73±0.11 22.82±0.55	326.66±8.81 413.45±13.79	20.10	1.62±0.04 2.05±1.36
50	18.42±0.11 29.47±0.33	386.33±9.35 591.13±27.02	25.13	1.53±0.03 2.35±0.89
60	23.07±0.15 34.58±1.26	468.43±12.35 637.71±27.46	30.16	1.55±0.04 2.11±1.46
70	27.97±0.08 39.59±0.84	829.37±1.82 705.37±11.15	35.19	2.35±0.005 1.86±0.24
80	32.64±0.01 46.36±0.14	939.51±22.77 843.36±30.84	40.21	2.43±0.08 1.96±0.42

^{R} = Rapeseeds; ^{S} = Sunflower seeds

Volumetric compaction

The volumetric compaction was calculated using equation (Eq. 3):

$$V = \frac{\pi \cdot D^2}{4} \cdot \delta \qquad (3)$$

where:
V = volumetric compaction (m^3)
D = diameter of the pressing vessel (mm)
δ = limit deformation (mm) on the force-deformation curve of both rapeseeds and sunflower seeds showing only the increasing function effect

Deformation energy

This is the energy required to deform a material under the influence of a specific for (force per area). It is represented as the area under the force-deformation curve (Grzegorz, 2007). The deformation energy was calculated using equation (Eq. 4) (Herak et al., 2010):

$$E = \sum_{n=0}^{n=i-1} \left[\left(\frac{F_{n+1} + F_n}{2} \right) \cdot \left(x_{n+1} - x_n \right) \right] \qquad (4)$$

where:
E = deformation energy (J)
$(F_{n+1} + F_n)$, $(X_{n+1} - X_n)$ = values of compressive force (N) and seed deformation (m), respectively

Energy density

The energy density (Eq. 5) is the ratio of the deformation energy to seed volume of rapeseeds and sunflower seeds:

$$e = \frac{E}{V} \qquad (5)$$

where:
e = energy density (J$\cdot$m^{-3})
V = seed volume (m^3)

Table 5 Measured parameters under the force-deformation curve with vessel diameter 100 mm (without any serration effect)

Seed height(mm)	Deformation ($\cdot10^{-3}$m)	Deformation energy (J)	Seed volume ($\cdot10^{-5}$ m^3)	Energy density ($\cdot10^6$ J$\cdot$m^{-3})
20	R 7.01±0.12 S 10.48±0.25	R 343.25±9.07 S 256.59±8.62	15.71	R 2.18±0.05 S 1.63±0.05
30	11.02±0.13 16.26±0.04	443.54±3.91 394.28±16.55	23.56	1.88±0.01 1.67±0.07
40	13.86±0.04 22.34±0.28	590.95±0.69 534.71±36.73	31.42	1.88±0.002 1.70±0.11
50	17.74±0.07 27.29±0.52	712.56±7.54 646.13±6.93	39.27	1.81±0.01 1.64±0.01
60	21.78±0.16 33.99±0.70	863.09±12.80 737.02±29.54	47.13	1.83±0.02 1.56±0.62
70	24.30±0.09 37.68±2.60	1071.23±11.66 816.15±75.75	54.98	1.94±0.02 1.48±0.13
80	28.96±0.04 45.19±0.91	1154.32±1.63 1004.81±2.94	62.84	1.83±0.002 1.59±0.004

R = Rapeseeds; S = Sunflower seeds

RESULTS AND DISCUSSION

Seed volume, volumetric compaction, deformation, energy, and energy density

The seed volume (Eq. 2), volumetric compaction (Eq. 3), deformation, energy (Eq. 4), and energy density (Eq. 5) for rapeseeds and sunflower seeds were respectively determined (Tables 1–5). Seed volume and volumetric compaction of rapeseeds and sunflower seeds varied as a result of different vessel diameters, seed height, and limit deformation (the deformation value on the force-deformation curve showing only the increasing function). The deformation values were obtained directly from the force-deformation curve (Mark Mitchell Software Engauge Digitizer, Version 4.1, 2002). Sunflower seeds exhibited greater deformation than rapeseeds due to the seed size. However, the energy demand required for the rapeseeds compression was greater than in the case of the sunflower seeds suggesting that the energy requirement of a particular oilseed crop cannot be estimated by the visual observation of the seed size but that it depends solely on the inherent seed mechanical properties (Stroshine, Hamman, 1994; Kabutey et al., 2012a, b). The energy density explains the work required for the deformation of both rapeseeds and sunflower seeds per unit volume.

Increasing function effect on the force-deformation curve

The compression test with the vessel diameter of 60 mm for sunflower seeds only and vessel diameters of 80 and 100 mm for both rapeseeds and sunflower seeds showed an increasing function effect (Fig. 2).

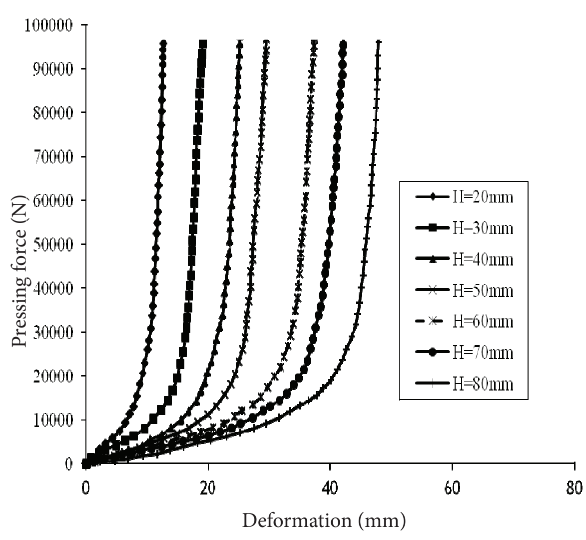

Fig. 2. Force-deformation characteristic curves in relation to seed height for vessel diameter 60 mm similar to vessel diameters 80 and 100 mm for both sunflower seeds and rapeseeds

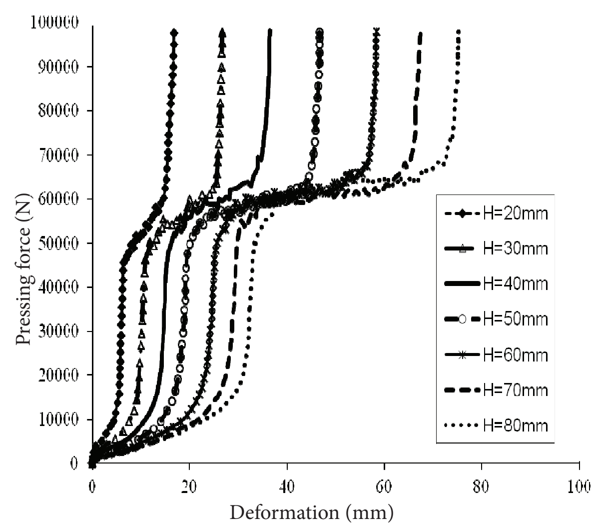

Fig. 3. Force-deformation characteristic curves of rapeseeds in relation to seed height for vessel diameter 40 mm

The increasing function effect is the limit point on the force deformation curve before or without the display of the serration effect. Oil flow was observed here and this effect is very important for the determination of the exact compressive force and energy utilization for extracting maximum oil from oilseeds such as rapeseeds and sunflower seeds (H e r a k et al., 2010). The present result compared to previously published information on *Jatropha curcas* L seeds using similar vessel diameters in relation to seed height indicated only the increasing function characteristics (H e r a k et al., 2013, K a b u t e y et al., 2013). The present findings correspond to the statement reported by S t r o s h i n e, H a m m a n, 1994 that mechanical and deformation characteristics vary extensively among different oilseeds. Additionally, based on the study conducted by H e r a k et al., 2010 on *Jatropha curcas* L. seeds, the increasing function on the force and deformation curve dependency can be divided into three distinct phases. The author explained that phase (I) illustrates the magnitude between the pressing force and deformation which is a linear function and this is the area where oil separation starts. Phase (II) is the area under the curve in which maximum oil can be achieved, while phase (III) denotes energy utilization efficiency in relation to oil recovery.

Serration effect on the force-deformation curve

Rapeseeds showed the serration effect during the pressing process in vessels with 40 and 60 mm in diameter (Figs. 3, 4), while for sunflower seeds this effect was observed only in 40 mm vessel diameter (Fig. 5). The serration effect was reflected in the change of the function character from increasing to trigonometric (H e r á k et al., 2012). The projection of this effect onto the force-deformation curve could be due to the higher compressive stress inside the smaller vessel diameters (40 and 60 mm) compared to those of bigger diameters (80 and 100 mm).

The hypothetical higher compressive stress stated here, however, engineered the kernel cake ejection through the 0.2 mm diameter holes around the bottom of the smaller vessel diameters. Generally, there was no oil flow during the ejection process which suggests inefficient energy utilization; therefore it would be economically viable to stop the pressing process whenever this effect occurs in any oilseed compression test. Furthermore, in the literature, it has been also reported that with high seed moisture content the serration effect could be pronounced leading to vibration of the compression equipment which can automatically stop the pressing process (K a b u t e y et al., 2011, K a b u t e y et al., 2014).

CONCLUSION

The compression test using smaller vessel diameters 40 and 60 mm caused a change in the mechanical behaviour (serration effect) of rapeseeds and sunflower seeds compared to bigger vessel diameters (80 and 100 mm) which indicated increasing function behaviour (smooth deformation curve). More energy was utilized for the deformation of the rapeseeds than the sunflower seeds. It was observed that maximum oil can be achieved under the force-deformation curve dependency with the increasing function compared to that of serration effect. The results of this study provide essential information for the determination of specific compressive force and energy requirements for extracting maximum oil from oilseed crops such

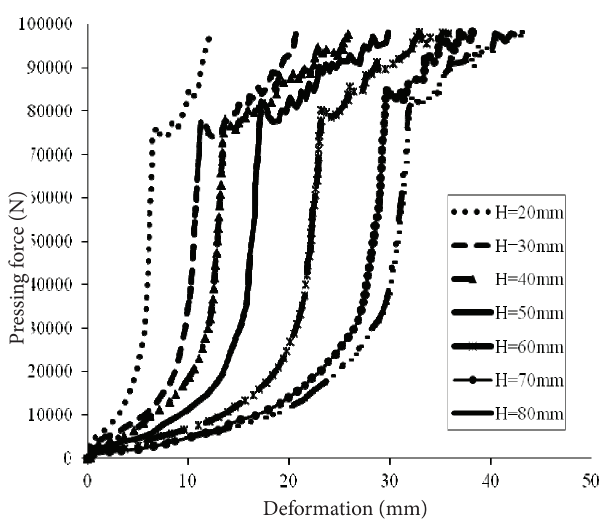

Fig. 4. Force-deformation characteristic curves of rapeseeds in relation to seed height for vessel diameter 60 mm

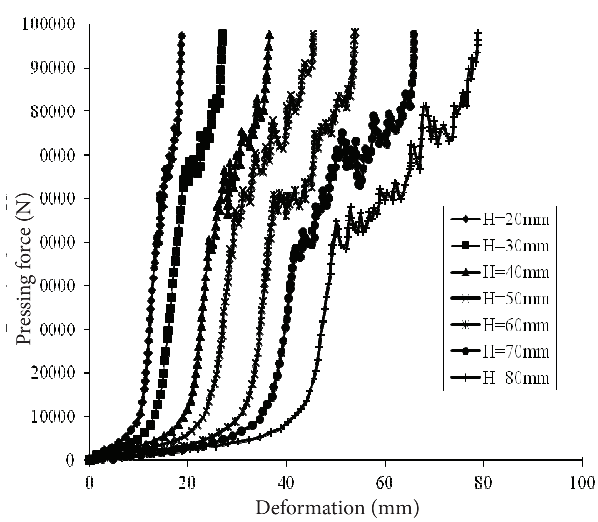

Fig. 5. Force-deformation characteristic curves of sunflower seeds in relation to seed height for vessel diameter 40 mm

as rape and sunflower. The present results could also be used for the development of mathematical models (Herak et al., 2013, 2014) for the description of mechanical behaviour and deformation characteristics of rapeseeds and sunflower seeds under compression loading as well as for the optimization of mechanical screw presses.

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