PREDICTION OF PRESSURE AND ENERGY REQUIREMENT OF *JATROPHA CURCAS* L BULK SEEDS UNDER NON-LINEAR PRESSING

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Abstract
This article presents the theoretical evaluation of pressure and energy requirement of screw press FL 200 (Farmet Model, Czech Republic) for oil processing of *Jatropha curcas* L. bulk oilseeds. Both the linear and non-linear compression information were analysed. The tangent curve mathematical model was applied which is appropriate for fitting of linear experimental data as the dependency between compressive force and deformation in relation to bulk seeds pressing height and vessel diameter. The integral of the tangent model represents energy. The non-linear pressing involving a mechanical screw press FL 200 geometric parameters namely screw shaft diameter (mm), inner and outer diameters (mm), screw thickness (mm) and screw pitch diameter (mm) were incorporated into the tangent curve mathematical model. The press designed with 44 lamellas at the oil outlet were divided into seven pressing sections or chambers. The determined amounts of pressure and energy substantially increased along the pressing sections. The results require validation to confirm the suitability of the tangent curve mathematical model for optimising the performance of screw press FL 200.

Key words: compression, screw press configuration, mathematical model, optimization.

INTRODUCTION

Despite the considerable studies on the optimization of mechanical screw presses for oil extraction of oilseed crops such as jatropha, further research is still necessary to improve the mechanical process regarding pressure and energy demand for oil recovery efficiency as stated by DELI ET AL. (2011), HARMANTO ET AL. (2009) and SINGH AND BARGALE (2000). The general hypothesis is that higher pressure produces higher temperature and oil percentage as described in the studies of KARAJ AND MULLER (2011) and WILLEMS ET AL. (2008, 2009). BEERENS (2007), however, indicated that increasing temperature thus affects the quality of the oil by increasing the amount of phospholipids contained in the oil. Determining the specific pressure and energy along the screw pressing sections could reduce temperature increment during oil extraction. To achieve this objective, it is important to understand the linear compression of bulk oilseeds, where considerable studies have been described by the authors DIVISOVA ET AL. (2014), STUART AND MUNSON-MCGEE (2014), HERAK ET AL. (2013, 2014, 2015) and KABUTEY ET AL. (2012, 2013).

HERAK ET AL. (2012, 2013A) and SIGALINGGING ET AL. (2014A) have drawn the attention to the applicability of the tangent curve mathematical model for describing the mechanical behaviour and deformation curve characteristics of jatropha, rape, sunflower and other bulk oilseeds under compression loading. The Mathcad 14 software with Levenberg-Marquardt algorithm for data fitting is optimal for the tangent curve approximation according to PRITCHARD (1998). The advantage of the Mathcad software is that it does not require high memory computer for more rigorous algorithm compared to other simulation programmes like finite element method as reported by PETRU ET AL. (2012). Furthermore, as stated by HERAK ET AL. (2013) and SIGALINGGING ET AL. (2014) the use of the tangent curve mathematical model takes into account the boundary conditions of the linear compression test which are: when the compressive force is approaching infinity the deformation reaches a maximum limit, zero compressive force relates to zero deformation and the integral of the tangent curve function describes the energy.

HERAK ET AL. (2013A) and SIGALINGGING ET AL. (2014, 2015) described the tangent model as given by equation (Eq. 1):

$$F(x, D, H) = C \cdot D^2 \cdot \left[\tan\left(G \cdot \frac{x}{H} \right) \right]^2 \tag{1}$$

Where: $F(x, D, H)$ is the compressive force (N) as a function of deformation, x (mm),the vessel diameter, D (mm) and pressing height, H (mm), C is the stress coefficient of mechanical behaviour (N·mm^{-2}), G is the compression coefficient (-), $\frac{x}{H}$ is the strain or compression ratio (-). The stress and compression coefficients have been in detail discussed in the study published by HERAK ET AL. (2013A). The objective of the study was to determine theoretically the amounts of pressure and energy in each of the screw pressing chambers for oil extraction of *Jatropha curcas* L. bulk oilseeds by combining both the tangent curve mathematical model and screw press FL 200 geometric characteristics.

MATERIALS AND METHODS

Sample and compression test

The results of jatropha bulk seeds of moisture content 10 % (w. b.) published by HERAK ET AL. (2013A) and KABUTEY ET AL. (2013) were further processed. In those studies, varying pressing heights of 30, 40 50, 60, 70 and 80 mm and vessel diameters of 60, 80 and 100 mm (Fig. 2) at maximum force 100 kN and speed 1 mm·s^{-1} were investigated. In linear pressing, the bulk material is compressed in a pressing vessel by applying a specific compressive force and speed using a Universal Testing Machine. The pressing vessel contains holes beneath which allow the oil leakage whiles the pressed solids are retained as indicated by HERAK ET AL. (2013), KABUTEY ET AL. (2013) and MUNSON-MCGEE (2014). The increasing force results in the deformation of the bulk material which can be described as the dependency between the pressing force and deformation (Fig. 1) where the area under the curve is denoted as the deformation energy as defined by DIVIŠOVÁ ET AL. (2014), HERAK ET AL. (2013A) AND KABUTEY (2014).

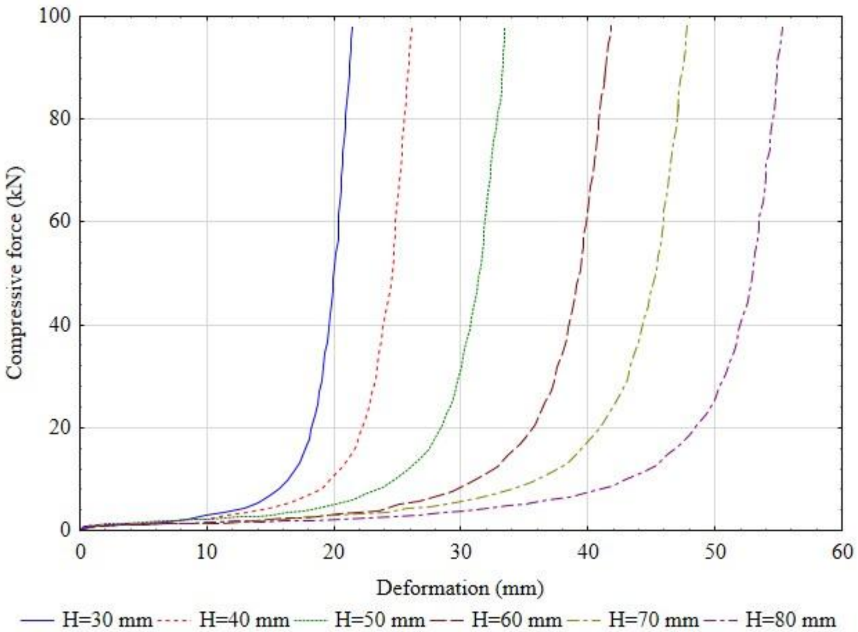

Fig. 1. – Dependency between compressive force and deformation curves for different pressing heights of jatropha bulk seeds for vessel diameter 60 mm similar to diameters 80 and 100 mm given by HERAK ET AL. (2013A) AND KABUTEY ET AL. (2013)

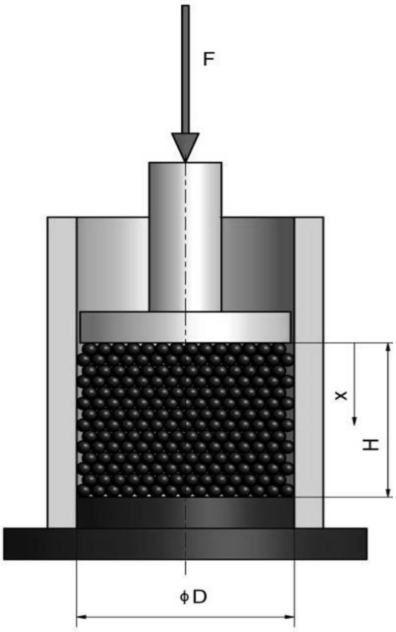

Fig. 2. – Schematic of pressing vessel diameter

Screw press FL 200 and principles of operation

The mechanical screw press FL 200 (Farmet model, Czech Republic) was examined. The press designed with 44 lamellas at the oil outlet were divided into seven pressing sections as shown in Fig. 3. The press parameters include throughput 180 kg·hr^{-1}, input power 16 kW, length 2120 mm, width 640 mm, height 840 mm and weight 930 kg. The press speed can be controlled between 25 and 40 min^{-1}. Specific parameters of press FL 200 namely the screw pitch diameter P_T (mm), screw thickness T_K (mm) and screw shaft inner and outer diameters (mm) were used for the theoretical calculations of pressure. The screw pitch diameters are represented here as screw pressing sections as 0, 1, 2, 3, 4, 5, 6 and 7 respectively. Screw pitch is the distance from a point of one thread to the corresponding point of the next measured parallel to the axis as described by the authors HERAK ET AL. (2010) AND KHURMI AND GUPTA (2005). Mathematically, the screw pitch for the screw shaft (Fig 4) is given by equation (Eq. 2).

$$P = \pi \cdot D \cdot tg\alpha \qquad (2)$$

where P is the screw pitch (mm), D is the diameter of the screw pitch (mm) and α is the pitch angle (∘).

Accurate dimensions of the screw press during the design phase are relevant for optimal performance according to KHURMI AND GUPTA (2005), DELI ET AL. (2011) AND BARYEH (2001). Operationally, the screw rotates around a nut with corresponding helical grooves on the internal surface. When the nut remains stationary the screw rotates and translates axially; and vice versa. The contact surfaces will eventually produce friction which requires power to be overcome. However, the power demand of the the screw and nut connection will be lower than the actual power utilization. The screw thread and nut groove contact surfaces are perpendicular to the outside and inside cylindrical surfaces which keep coefficient of friction at a lower rate. SINGH AND BARGALE (2000) AND KARAJ AND MULLER (2011) indicated that during the mechanical oil extraction, bulk oilseeds are fed through the hopper continuously into the screw press where they are compressed under high pressure, for instance, at 35 MPa which ruptures the cell walls causing the oil globules to escape allowing the oil through the slits provided along the screw. The compressed solids are continuously discharged through a choke given at the end of the press.

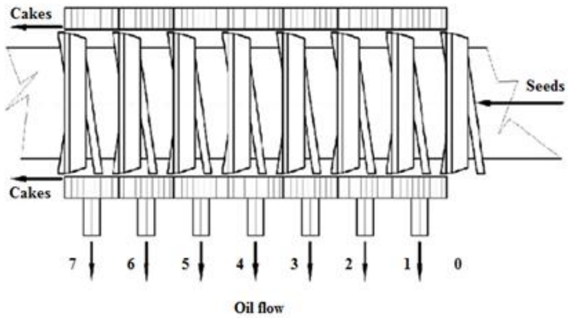

Fig. 3. – Schematic of screw press FL 200 (KABUTEY ET AL., 2010)

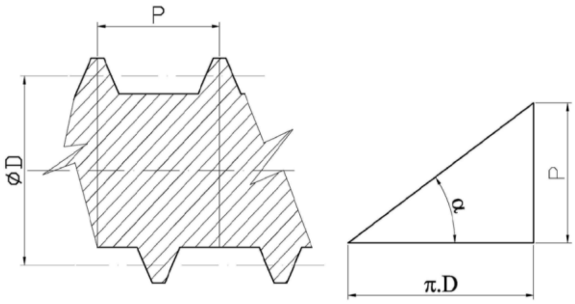

Fig. 4. – Schematic of screw shaft (HERAK ET AL., 2010)

Theoretical calculations

Screw press volume of material

The volume expression of bulk jatropha seeds in the screw press was calculated using (Eq. 3):

$$V_T = \left[\frac{\pi}{4} \cdot D_O^2 - \left[\left(\frac{D_1 + D_2}{2} \right)^2 \right] - \left(P_T - T_K \right) \right] \qquad (3)$$

Where V_T is the theoretical volume of bulk seeds (m^3), P_T is the screw pitch diameter (mm), T_K is the screw thickness (mm), D_O is the screw shaft diameter (mm), D_1 is the screw inner diameter (mm), D_2 is the screw outer diameter (mm).

Initial bulk seeds height

Using (Eq. 4) the initial height of bulk seeds was determined.

$$H_{BK_i} = \left[\frac{V_T \cdot 4}{\pi \cdot D^2}\right] \tag{4}$$

Where H_{BK} is the bulk seeds height (mm), D is the pressing vessel diameter (mm) (Fig. 2).

Bulk seeds deformation

This was determined as the difference between bulk seeds initial and final pressing height(Eq. 5).

$$D_T = \left[H_{BK_i} - H_{BK_f}\right] \tag{5}$$

Where D_T is the theoretical deformation (mm), H_{BK_i} is the initial height of bulk seeds (mm) and H_{BK_f} is the final height of bulk seeds (mm).

Compression ratio

This was determined as the ratio of deformation (Eq. 5) to initial bulk seeds height (Eq. 4).

$$C_R = \left[\frac{D_T}{H_{BK_i}}\right] \tag{6}$$

Where C_R is the compression ratio (-).

Compressive force

The compressive force was determined using the modified form of (Eq. 1) as described in (Eq. 7).

$$F(x, D, H) = C \cdot D^2 \cdot \left[\tan\left(G \cdot \frac{C_R}{f}\right)\right]^2 \tag{7}$$

Where f expresses the coefficient of pressing factors and/or screw press configuration (-).

Pressure

The pressure (Eq. 8) was determined combining Eq. 7 and 9 respectively.

$$P_T = \left[\frac{F}{A_S}\right] \tag{8}$$

$$A_S = \left[\frac{\pi}{4} \cdot D_O^2 - \left[\left(\frac{D_1 + D_2}{2}\right)\right]^2\right] \tag{9}$$

Where P_T is the theoretical pressure, F is the compressive force (N) (Eq. 1 or Eq. 7) and A_S is the cross-sectional area of the screw press (m^2).

Energy

The integral of the tangent curve model (Eq. 1 or Eq. 7) represents energy (Eq. 10)

$$E_T = \int C \cdot D^2 \cdot \tan\left(G \cdot \frac{x}{H}\right)^2 dx \rightarrow \frac{C \cdot D^2 \cdot H \cdot \left(\tan\left(\frac{G \cdot C_R}{f}\right) - \frac{G \cdot C_R}{f}\right)}{G} \tag{10}$$

Where E_T is the theoretical energy (J).

RESULTS AND DISCUSSION

The initial height (mm), deformation (mm), compression ratio (-) and volume (mm^3) of bulk jatropha seeds are given in Tab. 1, 2 and 3 respectively. These parameters were considered for the theoretical analysis of pressure and energy requirements using the tangent curve mathematical models (Eqs. 1, 7 and 10). The ratio of deformation to initial bulk seeds pressing height describing the strain is related to the compression ratio. The compression ratio influences the performance of the screw press as reported by SINGH AND BARGALE (2000). It is defined as the ratio of volume of material displaced per revolution of the shaft at the feed section to the volume displaced at the choke section. SINGH AND BARGALE (2000) again stated that compression ratios higher than the theoretical values of high oil content seeds are used to compensate for slip and rotation of meal with respect to the screw shaft. The volume of material that is processed through the pressing sections or screw length is related to the throughput within a given time which should be largest at the beginning of the pressing and smallest at the end.

Tab. 1. – Determined amounts of Jatropha bulk seeds using vessel diameter 60 mm

*Pressingsections (-)	Initalheight (mm)	Deformation (mm)	Compression ratio (-)	Volume ($\cdot 10^3$ mm^3)
0	144.18	144.18	0.00	408
1	85.75	58.43	0.41	242
2	44.39	99.79	0.69	126
3	41.96	102.22	0.71	119
4	37.02	107.16	0.74	105
5	34.52	109.66	0.76	98
6	28.17	116.01	0.80	80
7	19.06	125.12	0.87	54

Tab. 2. – Determined amounts of Jatropha bulk seeds using vessel diameter 80 mm

Pressing-sections (-)	Initalheight (mm)	Deformation (mm)	Compression ratio (-)	Volume ($\cdot 10^3$ mm^3)
0	81.10	81.10	0.00	408
1	48.23	32.87	0.41	242
2	24.97	56.13	0.69	126
3	23.60	57.50	0.71	119
4	20.82	60.28	0.74	105
5	19.42	61.68	0.76	98
6	15.85	65.25	0.80	80
7	10.72	70.38	0.87	54

Tab. 3. – Determined amounts of Jatropha bulk seeds using vessel diameter

Pressing-sections (-)	Initalheight (mm)	Deformation (mm)	Compression ratio (-)	Volume ($\cdot 10^3$ mm^3)
0	51.91	51.91	0.00	408
1	30.87	21.04	0.41	242
2	15.98	35.93	0.69	126
3	15.10	36.80	0.71	119
4	13.33	38.58	0.74	105
5	12.43	39.48	0.76	98
6	10.14	41.75	0.80	80
7	6.86	45.05	0.87	54

* Each screw pressing section has a specific pitch diameter (mm)

The theoretical amounts of pressure and energy are shown in Tab. 4 and illustrated in Fig. 5 and 6.Clearly, the pressing vessel diameter has great influence on the tangent curve model, that is, the change of the vessel diameter directly affects the other coefficients of the model. However, this change does not influence the compression ratio or strain. Therefore, using the tangent curve model for each pressing vessel diameter of 60, 80 and 100; pressure increased from 0.34 to 51.74 MPa, 0.42 to 50.71 MPa and 0.58 to 48.53 MPa along the pressing chambers.Similarly, energy increased from 12.22 to 330.47 J, 7.76 to 191.68 J and 6.32 to 132.55 J. Since oil yield in screw press is directly related to higher pressure and higher energy then the vessel diameter 60 mm becomes a constant variable of the tangent curve model for the evaluation of pressure and energy in a screw press. The lowest amount of energy obtained by the vessel diameter 100 mm suggests lower oil recovery efficiency, higher oil residue in press cake and higher material throughput as published by KARAJ AND MULLER (2011).

In the screw press, DELI, ET AL. (2011), HARMANTO ET AL. (2009) and KARAJ AND MULLER (2011) observed that the increasing pressure thus produces the output oil. However, higher pressure thus increase the friction and temperature between the bulk material and the press which adversely affects the cake and quality of the oil as noticed by BEERENS (2007) and SINGH AND BARGALE (2000). The screw press FL 200 design or configuration characteristics might have also contributed to the pressure or energy increment along the pressing chambers. This can be related to the results of DELI ET AL. (2011) who compared both the smaller and bigger screw shaft diameters in terms of pressure, rotational speed and percentage oil yield. They observed that the smaller screw shaft provided much smaller space for the compression of the seeds resulting in higher pressure compared to the bigger screw shaft diameter which required bigger space for the seeds to be filled hence lower pressure towards the bulk seeds which subsequently affected speed and oil yield.

Tab. 4. – Theorectical amounts of *Jatropha curcas* L. bulk seeds of screw press FL 200

Screw-sections (-)	Force (kN)	Pressure (MPa)	Energy (J)	*Cumulative amounts*		
				Force (kN)	***Pressure (MPa)***	***Energy (J)***
Vessel diameter 60 mm (*f* =1.42)						
0	0.00	0.00	0.00	0.00	0.00	0.00
1	1.65	0.34	12.22	1.65	0.34	12.22
2	8.97	2.86	45.10	10.62	3.20	57.32
3	9.99	3.37	47.38	20.61	6.57	104.70
4	12.51	4.78	51.81	33.12	11.35	156.51
5	14.11	5.78	53.95	47.23	17.13	210.46
6	19.50	9.79	58.58	66.73	26.92	269.04
7	33.43	24.82	61.44	**100.16**	**51.74**	**330.48**
Vessel diameter 80 mm (*f* =1.55)						
0	0.00	0.00	0.00	0.00	0.00	0.00
1	2.01	0.42	7.76	2.01	0.42	7.76
2	9.91	3.16	27.08	11.92	3.58	34.84
3	10.91	3.68	28.27	22.83	7.26	63.12
4	13.32	5.09	30.49	36.15	12.35	93.60
5	14.79	6.06	31.50	50.94	18.41	125.01
6	19.50	9.79	33.36	70.44	28.20	158.46
7	30.32	22.51	33.22	**100.76**	**50.71**	**191.68**
Vessel diameter 100 mm (*f* =1.74)						
0	0.00	0.00	0.00	0.00	0.00	0.00
1	2.79	0.58	6.32	2.79	0.58	6.32
2	11.33	3.61	19.76	14.12	4.19	26.08
3	12.23	4.12	20.39	26.35	8.31	46.47
4	14.27	5.46	21.47	40.62	13.77	67.94
5	15.45	6.33	21.87	56.07	20.10	89.81
6	18.91	9.49	22.23	74.98	29.59	112.03
7	25.51	18.94	20.52	**100.49**	**48.53**	**132.55**

f is the coefficient of pressing factors (determined by considering the maximum force applied in Eq. 1)

The pressing factors function described in equations (Eq. 7 and Eq. 10) also explain but not limited to the following; the friction between the pressing vessel and bulk seeds, applied compressive force, speed, temperature, biological status of the bulk material in terms of quality of bulk seeds and moisture content and screw press design or configuration. These parameters could also influence the tangent curve mathematical model coefficients for accurate evaluation of pressure or compressive force and energy needs in both linear and non-linear pressing. For example, KARAJ AND MULLER (2011) mentioned that higher screw speed requires higher material throughput and higher oil content residue in press cake since less time is available for the oil to drain from the solids. In addition, the viscosity at higher speed reamins lower resulting in lower pressure build-up hence more oil content in press cake as established by BEERENS (2007), KARAJ AND MULLER (2011) and WILLEMS ET AL. (2008, 2009). FABORADE AND FAVIER (1996) as well as DELI ET AL. (2011) referred that the increase of temperature might reduce the moisture content of the seeds causing reduction of oil yield. On the other hand, BARYEH (2001) stated that the quality of bulk seeds, moisture content and screw press configuration could contribute to lower oil yield.

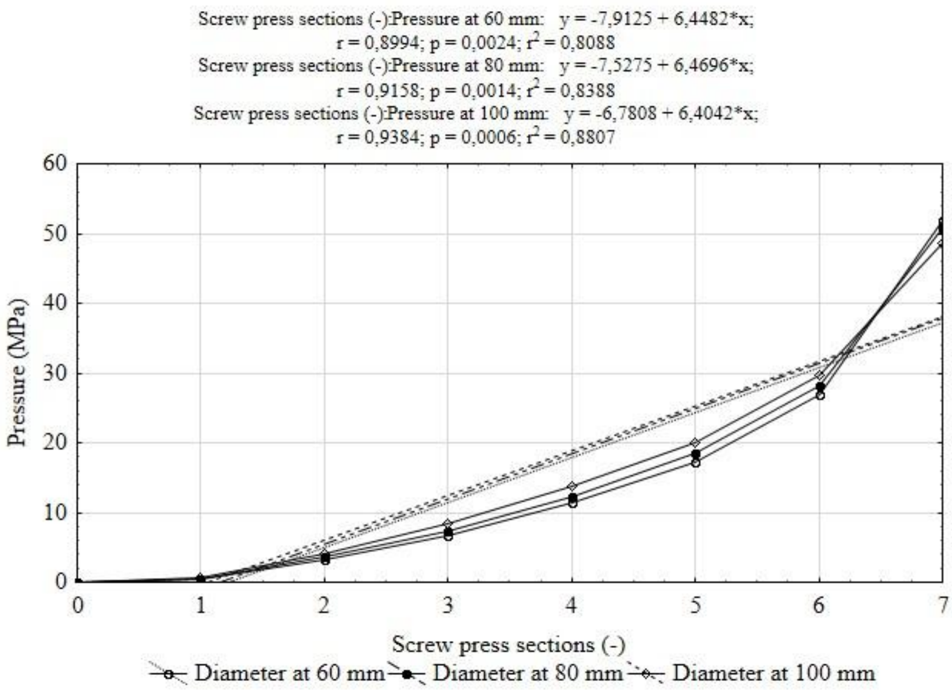

Fig. 5. – Pressure requirement at screw pressing sections of varying vessel diameters applying the tangent model (Eq. 8 and 9)

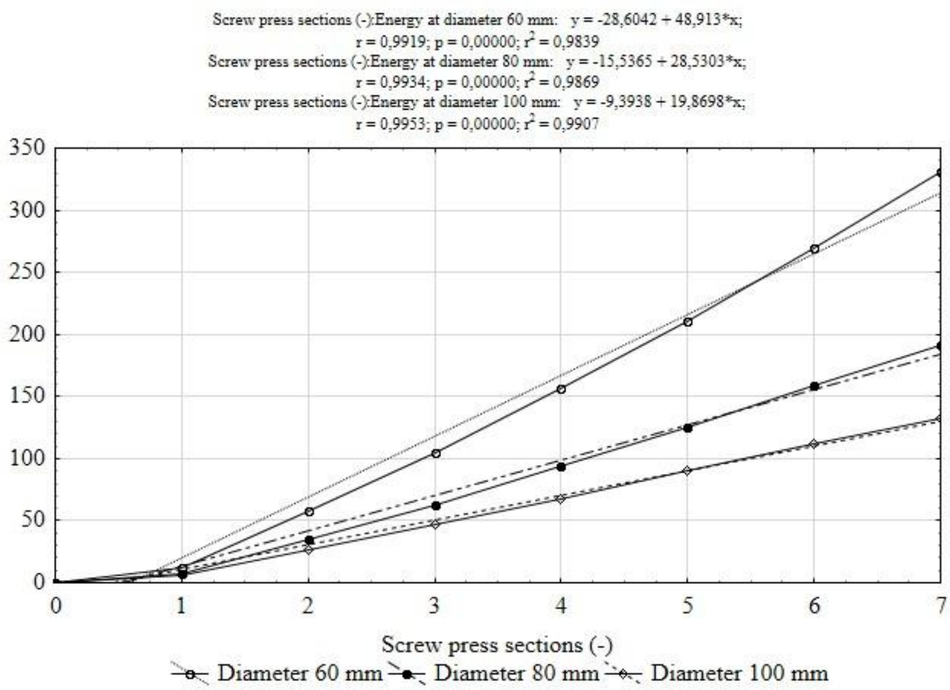

Fig. 6. – Energy requirement at screw pressing sections of varying vessel diameters applying the tangent model (Eq. 10)

CONCLUSIONS

Determining the specific pressure and energy would improve the press performance in terms of oil recovery efficiency. The findings provided herein can be useful for engineers and scientists in design and development of mechanical oil presses. However, the results require validation to establish the suitability of the tangent curve mathematical model for optimising pressure and energy utilization. The pressing factors should be incorporated into further mathematical models.

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