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EVALUATION OF A MATHEMATICAL MODEL FOR OIL EXTRACTION FROM OLEAGINOUS SEEDS

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1. Introduction

The process of extraction of oil from sunflower seeds may be carried out mechanically by pressing, or chemically using solvent extraction methods. On the whole the pressing system is a simpler process than solvent extraction although it is less efficient owing to the amount of residual oil in the solid cake [5].

Numerous attempts have been made to improve the efficiency of oil extraction through pressing [7]. In general three types of intervention have been studied: optimization of the operating parameters of the process, improvement of the geometric configuration of the press; pre-treatment of the seed.

However many of these studies are the result of criteria based on experience and intuition rather than on a rigorous theoretical analysis of the physical principles involved in the process [2].

Over the last 15 years the first studies based on the development of simulation models of the extraction process for different types of seeds have been published [4, 5, 6, 7, 8]. The common starting point of some of these models is the result of a combination of Terzaghi's theory (1943), regarding the theory of consolidation for saturated soils, and Darcy's law for flow of fluids through a porous medium [5, 7, 8].

However some of the basic assumptions of these models diverge from the real behaviour of the process studied. On the basis of Terzaghi's theory, Bargale *et al*. developed a mathematical model which attempts to overcome these differences, implementing some mathematical functions which are aimed at making the simulation model more similar to the phenomena which occur during the extraction of vegetable oil using mechanical pressing of the seeds. The model proposed by Bargale was applied and assessed by the author himself using experimental testing on a discontinuous type press using soy and sunflower seeds.

The aim of our work was to follow the experimentation proposed by Bargale for sunflower seeds using a discontinuous mechanical press. Having implemented the mathematical model for oil extraction the results of the simulation were transferred to a continuous press, similar to larger machines. The possibility to apply a mathematical model to continuous extraction plants may lead to design improvements and consequently to an optimization of press performance.

Oil extraction was carried out using a high-fat variety of sunflower seeds. The choice of this oleaginous species was dictated by the general field and purpose of the research project which this study is part of. In fact this study is an important stage in a wider field of research which is aimed at assessing the possibility of developing a sunflower oil energy chain in the agricultural sector. In this field the process of mechanical extraction has a key role in the production of sunflower oil which can be subsequently destined for directly feeding electricity generators or for the production of biodiesel.

It should be underlined that the economic convenience of the whole chain greatly depends also on the performance of the extraction plant in terms of productivity and efficiency.

2. Theory and model development

The hypothesis at the basis of this experimentation is that during extraction by pressing the oil-seed consolidation process is analogous with homogeneous saturated soils subjected to the same mechanical stress. In some experimental works (1,2) Bargale has provided interesting results, applying this theory to the discontinuous extraction process on oleaginous seeds. The behaviour which controls this system has been described in Terzaghi's theory. According to this theory, when a saturated medium, characterised by a low coefficient of permeability, is subject to a compressive force, the pressure of the fluid present in the pores of the medium rapidly increases and then de-

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creases, after a certain period of time, as a result of the extrusion of fluid through the pores [3]. The variation in the pressure of the fluid present in the pores, according to Terzaghi's theory, is proportional to the variation in the hydraulic gradient [1,2,10]:

$$\frac{\partial u}{\partial t} = c\frac{\partial^2 u}{\partial z^2} \tag{1}$$

in which u is the pressure of the fluid inside the compressed medium, z is the depth of the medium, t is the compression time, c is the coefficient of consolidation of the compressed medium defined as:

$$c = \frac{k}{m_v \rho_f} \tag{2}$$

where ρ_f is the oil unit density, m_v is the coefficient of volume change, k is the coefficient of permeability calculated as:

$$k = \frac{QH}{\Delta h A_d} \tag{3}$$

where Q is the fluid infiltration rate or flow in the medium, H is the height of the medium, Δh is the loss of pressure through the medium, A_d is the area of drainage of the fluid; while m_v is defined as:

$$m_v = -\frac{1}{V}\frac{dV}{dU} = -\frac{1}{H}\frac{dH}{dU} = \frac{d\varepsilon_z}{d\sigma_z} \tag{4}$$

where V is the volume of the sample, dU is the change in applied pressure, $d\varepsilon_z$ is the increment of vertical strain under uniaxial compression $d\sigma_z$ is the increment of applied vertical stress under uniaxial compression.

Some of the assumptions of Terzaghi's theory of soil consolidation can only be partially respected. In particular, when a sample of seed is subjected to compression, the initial deformation following this stress is mainly due to the rearrangement of the solid structure and the expulsion of air from the inter-granular voids [1].

Therefore the hypothesis of the saturated system, that is to say characterised by the presence of only one fluid phase, may occur only after an initial compression stage during which the oil fills all the voids which remain after the air has been expelled.

The flow of fluid through the porous medium and, therefore, the process of extracting oil from the seeds, is described by Darcy's law:

$$q = \frac{Q}{A_d} = \frac{k}{\rho_f}\frac{\partial u}{\partial z} \tag{5}$$

where q is the fluid flow flux and $\delta u/\delta z$ is the hydraulic gradient [2, 9].

On the basis of a series of considerations and mathematical steps [2], a relation is found which allows a forecast to be made of the amount of oil obtained (V_{es}) during extraction in a system made up of a cylindrical chamber containing a piston which applies a pressure U on the seeds:

$$V_{es}(t) = B_0\left(\int_0^t k(t)e^{-B_1 c(t)t}\,dt\right) \tag{6}$$

in which:

$$B_0 = \frac{2A_d U}{\rho_f H} \quad (7) \tag{7}$$

$$B_1 = \left(\frac{\pi}{2H}\right)^2 \tag{8}$$

where B_0 and B_1 are the constants. It must be specified that during his applications Bargale uses an arbitrary and variable lowest integration time limit value (t_{int}).

An estimate of the amount of oil extracted, with reference to (6), requires the definition of the change in the value of k and c with time. During the oil extraction phase, these changes can be attributed to modifications in the structure of the solid matrix of the medium owing to compression.

3. Materials and Methods

The experimental activity was carried out on two types of mechanical presses for oil extraction from oleaginous seeds. In the first type, which is discontinuous, measurements were made to determine the characteristic parameters of the material subjected to extraction, k, c, m_v and ρ_f considered in the mathematical model. Subsequently the model was verified on the second press used in the experimental trials which was a continuous press. The seed used for all the extraction trials was a variety of high-fat sunflower seed, with a 41.3% oil content. The whole product had humidity values in a range of between 5% and 6%.

3.1 *Discontinuous mechanical press*

The discontinuous extraction system is made up of a mechanical press with a horizontal cylindrical chamber inside which two opposing pistons slide (Fig. 1). Both the pistons are activated by the oil under pressure in the hydraulic circuit. This is regulated by an instrument panel which controls a piston pump driven by a 3kW motor.

The compression chamber, where the oil is extracted, has a diameter of 120mm and is 60 mm long; on its external surface there are numerous oil drainage openings arranged in straight lines and the overall A_d is 22608 mm^2. However, during compression the real drainage surface becomes smaller, according to the distance between the two pistons. In order to make calculations with the model an average surface is considered between the initial surface, when the pistons are at the greatest distance from each other, and the final surface where there is the least distance between the pistons. The maximum pressure exerted by the pistons on the seeds present in the compression chamber may arrive at 45 MPa.

Fig. 1 - Lateral section of the discontinuous mechanical press.

The pressure is measured using a precision pressure meter inserted in the hydraulic circuit of the press. A vernier (precision 0.1 mm), fixed to the side of the press parallel to the piston rods allows the changes in position to be recorded.

The seeds are poured into the compression chamber through a funnel and fall between the two pistons. The pistons are driven, independently, by means of the instrument panel. Under the compression chamber there is a sloped surface for the recovery of the extracted oil, which is then conveyed to a container for weighing.

3.2 *Continuous mechanical press*

The continuous press used reproduces, on a small scale, the structure and the functions of larger machines. The structure is made up of a 4 kW motor, of a transmission system with belt and pulley, of a machine body which surrounds a compression chamber and systems for collecting the solid cake and the extracted oil. The productivity in processed seed (p_{rs}) of the continuous press for sunflower seeds is on average about 46.2 kg/h. The seed is loaded in a small hopper under which there is a screw conveyor with a pitch (*f*) of 30 mm.

Around and parallel to the screw there are 8 steel staves, each with a length of 200 mm, which are arranged so as to form a cylinder and are contained in a cast iron body.

At one end of the screw there is a crank handle and at the other a steel ogive shaped press head which turns inside a body with a cylindrical chamber. The gap between the press head and the inner walls of the cylindrical chamber form the compression chamber with an internal diameter of 70 mm and a length of 120 mm. Rotation of the crank causes the movement of the screw along the horizontal axis, and consequently also modifies the position of the press head inside the compression chamber. This allows the modification of the volume of the compression chamber due to the presence at the end of the chamber of a fixed ring paste pusher, which, as the press head progressively moves forward, generates a reduction in the overall volume with a relative increase in the pressure exerted on the seed (Fig. 2).

Compression of the seed starts when the space between the press head and the inner wall of the compression chamber is smaller than the average thickness of the sunflower seeds. The solid matrix, moving forward along the head, is further compressed, reaching a final thickness of 1.5 mm.

Knowing that the length of the part of the compression chamber in which seed compression really takes place (l_c) is 28.2 mm, and knowing that the rotation speed of the screw (v_{rc}) is 2 rps, it is possible to estimate the average compression time (t_{cp}) of the seed:

$$t_{cp} = \frac{l_c}{v_{lc}} = \frac{l_c}{v_{rc} \cdot f} \quad (9)$$

in which v_{lc} is the linear speed of the screw and, therefore the flow rate of seed through the press. On the basis of the values indicated for each of these parameters it is possible to calculate a t_{cp} value of about 0.47 s.

The extracted oil drains through the end drainage openings of the compression chamber and is subsequently filtered through a series of overlapping metal grids, flows into a container and is weighed. The residual cake is expelled at the opposite end, slides along a metal slope and is collected in a container.

The press has a heating system, made up of electrical resistances and regulated by a thermostat, which surrounds the screw and the compression chamber. The level of pressure on the seed increases as the press head moves along the inside of the extraction chamber. This condition leads to real difficulties in the reading of this parameter. Therefore, the estimate of the extraction pressure is found on the basis of the comparison between the efficiency extraction of the discontinuous press in which the pressure is measured with a precision pressure meter and that of the continuous press.

In other words, it is assumed that in correspondence with the same amount of efficiency extraction (η_e), defined by the ratio between the mass of oil extracted and the mass of seed introduced, the average pressure condition exerted by the two machines is, on the whole, the same. This pressure is defined as the equivalent extraction pressure (U_{eq}).

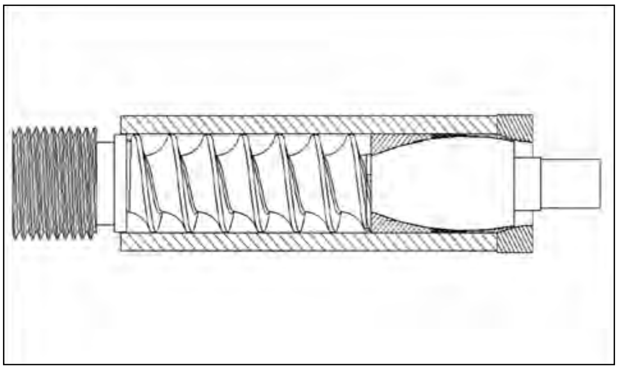

Fig. 2 - Lateral section of the mechanical continuous press.

3.3 *Extraction trials on the discontinuous mechanical press*

The determination of the physical parameters which are characteristic of the material considered in the simulation model for oil extraction, (k, c, m_v e ρ_f), was obtained using specific measurements made during extraction trials with the discontinuous press. The tests were carried out by combining two different extraction temperature conditions (T_1 = 30° C and T_2 = 60 °C) and three levels of pressure (U_1 = 250 bar, U_2 = 350 bar and U_3 = 450 bar). In total 6 different extraction conditions were trialled.

For each test a seed mass (S_m) of 300g was used, which was adequate for the volume of the compression chamber. After loading the seeds the initial height (H_i) of the layer of seeds was measured using a vernier. The extraction tests were carried out using t_{cp} of 5,10, and 20 seconds with 5 replications made for each time. At the end of the given t_{cp} the piston was released and the extracted oil flowed for several minutes through the drainage part of the machine and into the underlying container.

Before each testing session, the press was set to full operating capacity by means of a certain number of starting extractions. Moreover, by means of some preliminary tests, the optimum rate of oil drainage from the press (beyond which the amount of oil collected is not significant) was identified. This time was adopted in all the extraction trials for the recovery of the extracted oil. The value of k with time, as reported by Bargale (1), was determined in each replication on the basis of (10), defined in accordance with (3):

$$k(t) = \frac{V_o}{t_{cp}} \frac{H_i}{\Delta h A_d} \tag{10}$$

in which Δh is identified with the extraction pressure (U_e) related to the density of the oil and V_o is the volume of the oil extracted from the discontinuous press in the period of time t_{cp}.

Subsequently, for each extraction trial the average values of k, read during the various replications, were calculated. Likewise, during the same extraction tests the parameters for the determination of the average values of m_v were found, as set down in (11) and defined in accordance with (4):

$$m_v = \frac{H_i - H_f}{H_i \cdot U_e} \tag{11}$$

in which H_f is the final thickness of the residual sunflower seed cake.

Finally, using a pycnometer the value of ρ_f was found. The value of this parameter, required by the mathematical model, was calculated as the average of the ρ_f values, measured on samples extracted during each replication.

3.4 *Extraction trials on the continuous mechanical press*

The most important parameter that characterizes the trials on the continuous press is extraction yield (η_e) defined as the ratio between the mass of oil extracted (O_e) and the mass of seed used for the extraction (S_m):

$$\eta_e = \frac{O_e}{S_m} \tag{12}$$

In order to determine the value of η_e, 5 extraction trials were carried out using, for each trial, 100 kg of sunflower seeds with an oil content of 41.3%. During the trials measurements of the mass of the processed seed, the oil extracted and the residual cake were made using a 0.5g precision balance. The extraction times were also measured and the temperature of the oil leaving the extraction chamber was constantly read using a thermocouple. Associating the O_e values with the respective t_e the levels of oil productivity (p_{ro}) of the press throughout the trial were calculated:

$$p_{ro} = \frac{O_e}{t_e} \tag{13}$$

3.5 *Model application*

The mathematical solution of (6), which estimates the V_{es} obtained during compression, is obtained through the definition of equations which measure the change, with time, of the physical parameters of the material subjected to extraction *k(t)* and *c(t)*. The determination of *k(t)*, for the different conditions of temperature and pressure, was obtained through the non-linear regression of the average value of k found during the extraction trials with the discontinuous press with different t_{cp}. The analysis was carried out using Tablecurve™ 2D Windows software (Jandel Scientific, San Rafael, CA, USA), bearing in mind the models previously applied by other authors [1.2]. In particular, *k(t)* is defined by the following function:

$$\left(\frac{1}{k}\right) = k_0 + k_1 t^2 \tag{14}$$

For the determination of *c(t)*, (2) was used, with known values of ρ_f and m_v, the latter being hypothesised as constant [1]. In particular, *c(t)* is represented by:

$$\frac{1}{c} = c_0 + c_1 t^2$$

in which

$$c_0 = k_0 \rho_f m_v$$
$$c_1 = k_1 \rho_f m_v$$

Finally, the values of B_0 and B_1 were calculated using (7) and (8) which were then substituted in (6). The numerical solution of (6) was found through integration using the Fourth Order Runge-Kutta method implemented in the MATLAB (The Math Works Inc., Natick, MA, USA) software.

The simulation allows us to predict the volume of oil which can be extracted, according to the model (V_{es}), from a known mass of sunflower seeds subjected to extraction in the compression chamber under the conditions specified in paragraph 2. The calculation of the extraction efficiency obtained through the simulation (η_{es}) is determined by (15) where g is the value of acceleration of gravity.

$$\eta_{es} = \frac{V_{es} \cdot \rho_f}{g \cdot S_m} = \frac{O_{es}}{S_m} \quad (15)$$

In order to assess the differences between real values and those obtained with the simulation, the average of O_e values was compared with the value of O_{es}, that is to say, the amount of oil calculated by the simulation and defined by compression times of t_{cp}. In particular, the percentage of error of prediction (E_p) was defined using (16):

$$E_p = \frac{(O_{es} - O_e)}{O_{es}} \cdot 100 \quad (16)$$

On the basis of the E_p values it is possible to measure the capacity of the mathematical model to produce results regarding the performance of the discontinuous press which are compatible with real behaviour.

3.6 *Prediction of continuous press performance*

By adopting equation (9) for the mathematical model (6) it is possible to predict the rate of extraction and the oil productivity of the continuous press according to the rotation speed of the screw and the operating capacity of the machine. For the application of the mathematical model to the continuous press a value of A_d = 6200 mm^2 was considered, corresponding to the part of the inner wall of the compression chamber where the gap between this wall and the press head is in a range of between 3.2 mm and 1.5 mm, H_i and H_f respectively.

To find U_{eq}, the equivalent extraction pressure, a ratio was defined between the values of extraction pressure (U_e), compression time (t_{cp}) and η_e obtained from the trials on the discontinuous press. The values used for this type of analysis concern the extraction trials at temperature T2, which represents the average operating condition of the continuous press.

The mathematical analysis was carried out by regression using Tablecurve3D Copyright SYSTAT software Inc, 1993-2002, considering among the simple type mathematical relations, the one with the highest regression coefficient.

After establishing the mathematical relation between the abovementioned parameters and substituting in it the values of t_{cp} and η_e, which are characteristic of the continuous press, the value of U_{eq} can be determined.

In order to determine the *k(t)* inU_{eq} the previously mentioned method was used, with non-linear regression of the average values of *k* for the different values of t_{cp}. However, since it was not possible to carry out extractions on the discontinuous press for pressure values equal to U_{eq}, it was necessary to find the values of *k* indirectly using $k(U_e)$ type functions. The latter were defined singly for each of the t_{cp} considered during the trial with the aid of Tablecurve 2D, using the values of *k* obtained at pressures U1,U2 and U3. The curve chosen to define the function is the one with the highest R^2 of the group of simple type equations. Through the functions $k(U_e)$, for each value of t_{cp}, the values of k in the U_{eq} were found, and using these the curve, *k(t)* in U_{eq},was built adopting the same criteria of analysis as described in paragraph 3.5.

Introducing U_{eq} in the model (6), implementing the *k(t)* and the *c(t)* and considering the remaining parameters required as described in paragraph 3.2 it was possible to calculate the amount of oil extracted by the continuous press (O_{es}) in the extraction time t_{cp}. The determination of O_{es} was carried out adopting two different initial integration times t_{int}.

As in the case of the extraction trials with the discontinuous press, in order to assess the reliability of the model, the error of prediction (E_p) was calculated as shown in (16) for extraction time t_{cp}.

The value of t_{cp} is defined by the rate of rotation of the screw conveyor (9). This parameter conditions the p_{ro} of the press. In particular:

$$p_{ro} = v_{rc} \cdot f \cdot m_s \cdot \eta_e \quad (17)$$

in which m_s is the mass of the sunflower seed processed per unit of length of the screw. The value of m_s was found by relating p_{rs} with v_{lc} and is considered a characteristic parameter of the machine.

In particular:

$$m_s = \frac{p_{rs}}{v_{lc}} = \frac{46200 g \cdot h^{-1}}{3600 s \cdot h^{-1} \cdot 60 mm \cdot s^{-1}} = 0.21 g \cdot mm^{-1} \quad (18)$$

The combination of 17 with 18 allows us to determine the performance of the p_{ro} with variations in the speed of the screw. Therefore, on the basis of these relations, a prediction was developed for the performance of the press, considering the t_{int} which reduces the E_p value to zero as the value to be adopted in the mathematical model.

4. Results

4.1 *Determination of the physical parameters of the material*

The measurements obtained using the continuous press are fundamental for the application of the prediction model for oil extraction from seeds. The parameters identified during the first part of the experimentation describe specific physical characteristics of the material under certain compression conditions during extraction.

On the basis of the methodology described in paragraph 3.3, Table 1 shows the average values of *k* obtained for the different extraction conditions used.

t_{cp}	T1			T2		
	P1	P2	P3	P1	P2	P3
(s)	*k* (m/s)			*k* (m/s)		
5	3.2E-09	1.2E-09	2E-09	5.7E-09	3.5E-09	3.8E-09
10	1.7E-09	9.6E-10	1.2E-09	3.8E-09	2.4E-09	2.4E-09
20	1.5E-09	8.3E-10	9.2E-10	2.1E-09	1.4E-09	1.4E-09

TABLE 1 - Average values of k related to compression time, pressure and temperature.

The results show the change in k as the t_{cp} increases. In particular, by increasing t_{cp} from 5 to 10 seconds, the reductions in k are of up to 40-45% and, in some cases, are greater than 60% with t_{cp} of 20 seconds. The reduction in permeability following the increase in t_{cp} is clearly shown by the progressive reduction in the rate of oil recovered from the mechanical presses. In fact, the extraction trials show that most oil is extracted during the first few seconds of compression. In particular, considering 20 seconds of compression, about 60%-70% of the extracted oil is released during the first 5 seconds.

The analysis of k also illustrates the role of other parameters during the extraction process. In particular, extractions carried out at higher temperatures have greater permeability values. This trend is particularly noticeable in correspondence with low t_{cp} . In these conditions the k found at T2 may reach values which are three times larger than those found at T1. The opposite trend is seen with extraction pressure: on average a reduction in k can be seen with an increase in the extraction pressure. This characteristic seems to be more noticeable at higher temperatures. However, it also appears to be limited to within certain pressure ranges, beyond which the changes in k corresponding with changes in pressure become negligible or uncertain.

The measurements carried out during the trials on the continuous press also allowed us to determine, using (11), the values of m_v. Table 2 shows the average values of this parameter obtained for each extraction condition.

In general the values of m_v are higher, even if only slightly, in the T2 trials compared with those performed at T1, and tend to decline as the pressure increases. The results of the analysis of both parameters partially confirm the results of Bargale's tests on soy and sunflower seeds.

t_{cp}	T1			T2		
	P1	P2	P3	P1	P2	P3
(s)	m_v (m^2/kN)			m_v (m^2/kN)		
5	1.23E-06	1.13E-06	1.08E-06	1.26E-06	1.23E-06	1.15E-06
10	1.12E-06	1.14E-06	1.09E-06	1.27E-06	1.20E-06	1.18E-06
20	1.15E-06	1.15E-06	1.10E-06	1.17E-06	1.15E-06	1.13E-06

TABLE 2 - Average values of m_v related to compression time, pressure and temperature.

4.2 *Extraction trial on the continuous press*

Table 3 shows the results obtained from the trials on the continuous press. In particular the table indicates the values of O_e, of η_e, of the average temperatures of the oil draining from the press, of the extraction time and of the p_{ro}, obtained during each extraction trial with the continuous press.

Trial	O_e (kg)	η_e (%)	Oil Temperature (°C)	p_{ro} (kg/h)
1	32.5	32,5	61.2	14.7
2	33.8	33.8	63.5	14.2
3	31.9	31.9	60.8	14.5
4	34.3	34.3	60.9	14.8
5	33.5	33.5	64.1	14.3

TABLE 3 - Results for trials using the continuous press.

The general indication that is made clear by the trials is that the average value of η_e is about 33.2%. The temperature throughout the various extraction trials proved to be sufficiently stable at about 62.1°C (S.D. 1.6°C). With this type of performance the machine has an average p_{ro} of about 14.5kg/h of oil (S.D.0.2kg/h).

4.3 *Comparison between real and simulation values*

Following the methodology described in paragraph 3.5 and on the basis of the results obtained with the discontinuous press (using the methodology shown in paragraph 3.3) it was possible to determine, for each extraction condition, the k_0 and k_1 coefficients of equation (14) which expresses the *k(t)* (Table 4).

Pressure (bar)	Temperature (°C)	k_0 (m/s)	k_1 (m/s)	R^2	p
P1	T1	2.9E+08	1.4E+06	0.60	0.22
P2		8.2E+08	8.7E+05	0.78	0.11
P3		4.8E+08	1.8E+06	0.84	0.08
P1	T2	1.6E+08	8.7E+05	0.98	0.01
P2		2.6E+08	1.0E+06	0.97	0.02
P3		2.4E+08	1.4E+06	0.96	0.02

TABLE 4 - Values of coefficients k_0 and k_1 in different extraction condition.

In general the values of R^2 obtained, for each operating condition, may be considered satisfactory since they are always greater than 0.6, and in several cases are much higher. However, only with the extractions carried out at T2 is the p value lower than the limit of 0.05. A typical example of the *k(t)* trend is shown in Figure 3. As can be seen, the permeability has greater values in the first seconds of extraction, followed by a rapid decline in correspondence with the increase in t_{cp}.

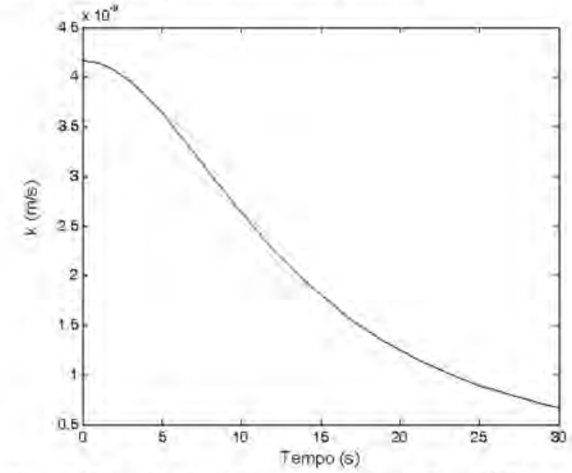

Fig. 3 - Trend in k(t) for extraction at U3 and T2.

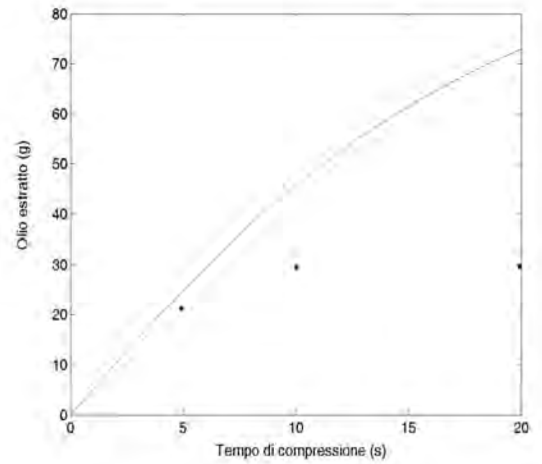

Fig. 4 - Example of comparison between real values (points) and values obtaining using the model (line) for T2 and U3.

This trend is coherent with what happens to the solid matrix of the seed. In the first stages of compression the matrix has high porosity and the oil is extracted through the voids in the tissue which are still empty.

As the compression continues, the porosity tends to become less and the intracellular and intercellular voids become blocked, preventing the extraction of oil from the solid cake [1]. The comparison between the real values of the quantity of oil extracted and the values obtained from the prediction model are shown in Tables 5 and 6, for T1 and T2 respectively. With reference to E_p, the differences between real data and those found with the model are immediately clear.

In general, the value of E_p varies between 8.9% and 63.9% and tends to be higher as t_{cp} increases (Figure 4).

t_{cp}	T1								
	U1			U2			U3		
	O_e	O_{es}	E_p	O_e	O_{es}	E_p	O_e	O_{es}	E_p
(s)	(g)	(g)	(%)	(g)	(g)	(%)	(g)	(g)	(%)
5	7.2	7.9	8.9	11.7	15.5	24.5	12.3	17.1	28.1
10	10.6	15.4	31.2	10.7	28.2	62.1	14.7	31.6	53.5
20	17.4	28.2	38.3	18.4	44.2	58.4	18.4	51.1	63.9

TABLE 5 - Comparison between O_e and O_{es} for different extraction trials at 30°C.

t_{cp}	T2								
	U1			U2			U3		
	O_e	O_{es}	E_p	O_e	O_{es}	E_p	O_e	O_{es}	E_p
(s)	(g)	(g)	(%)	(g)	(g)	(%)	(g)	(g)	(%)
5	21.2	28.1	24.6	21.5	24.9	13.7	24.4	34.3	28.9
10	28.1	51.6	45.5	26.9	45.0	40.2	30.5	61.2	50,1
20	29.7	78,8	62.3	31,8	73,2	56,6	35.3	92,8	62,0

TABLE 6 - Comparison between O_e and O_{es} for different extraction trials at 60°C.

In the first 5 seconds E_p reaches maximum values of 29% and tends to increase as the exerted pressure increases.

In order to transfer the model onto the continuous press it is necessary to determine the U_{eq}. For this reason, on the basis of what was established in paragraph 3.6, the following equation was identified:

$$\ln \eta_e = a + b \cdot U_e^{\,3} + c \cdot t_{cp}^{\,1.5} \tag{19}$$

in which a= 2.12, b= 3.56 * 10^{-9} and c = 7.55 * 10^{-3} with a correlation coefficient R^2 equal to 0.87.

Resolving the equation with t_{cp} = 0.47 s and η_e equal to 33.2%, which correspond respectively to the compression time and the average rate of extraction found with the continuous press, a value of U_{eq} equal to 880 bar is obtained.

Table 7 shows the terms of $k(U_e)$ functions for the different values of t_{cp}. The function which best interprets the relationship between the parameters is of the type $k = d + e \cdot U_e^{-2}$.

Table 7 also shows the values of k at 880 bar with which the $k(t)$ for this pressure was determined. The latter, with expressions of the same type as (14), showed the following terms: $k_0 = 4.34 \cdot 10^8$ and $k_1 = 1.35 \cdot 10^7$ with R^2 equal to 0.99.

The result of the simulation, which considers the $k(t)$ for U_e values of 880 bar and m_v of $6.04 \cdot 10^{-9}$ is represented by the curve in Figure 5 which shows the trend in the quantity of oil extracted related to t_{cp}.

t_{cp} (s)	d	e	R^2	k (880 bar) (m/s)
5	2.5E-09	2.0E-04	0.84	2.7E-09
10	1.5E-09	1.4E-04	0.93	1.7E-09
20	9.7E-09	7.1E-05	0,93	1.1E-09

TABLE 7 - Coefficients of functions $k(U_e)$ and values of k at 880 bar and different t_{cp}.

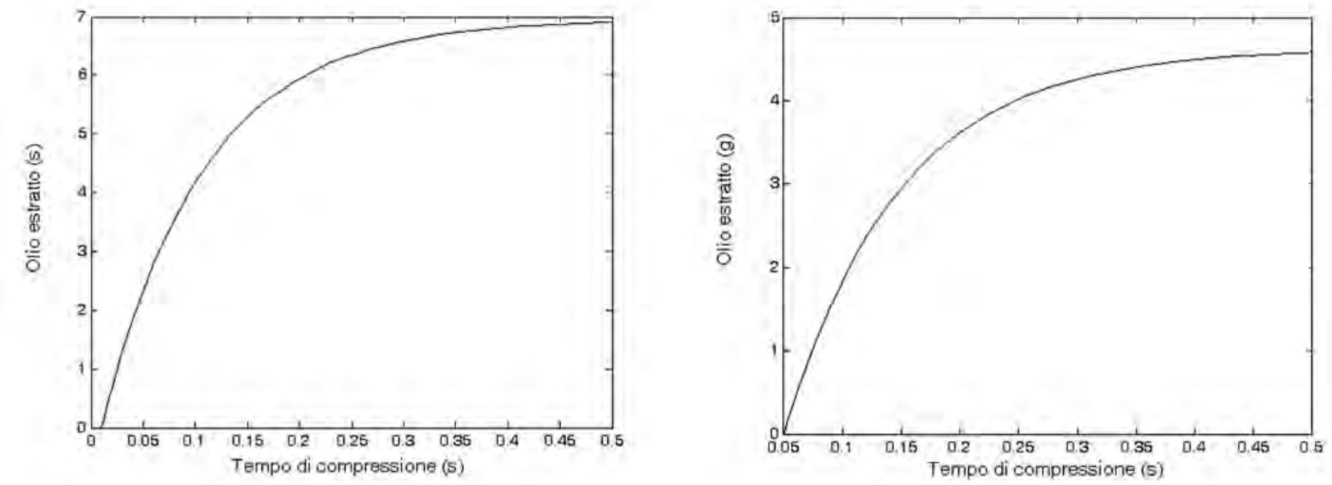

Fig. 5 - Trend in extraction efficiency related to t_{cp} using different t_{int} (0.01 s left graph and 0.05 s right graph).

t_{int} (s)	O_{es} (g)	O_e (g)	E_p (%)
0.01	6.89	1.89	72.6
0.05	4.56	1.89	58.6
0.08	3.34	1.89	43.4
0.1	2.71	1.89	30.3

TABLE 8 - Values of E_p in relation to the t_{int}.

Knowing the value of p_{ro} (1.89 g/s), the E_p calculated is in the range of between 30.3% and 72.6% in relation to the t_{int} (Table 8).

By analysing the E_p in relation to the t_{int} (initial integration time) it was found that in correspondence with an t_{int} of 0.125s the E_p is reduced to zero.

4.4 *Prediction of continuous press performance*

Using the methodology indicated in paragraph 3.6 a prediction model was obtained which links the productivity of the machine to the extraction efficiency in relation to v_{rc} (Figure 6). As can be seen, with the change in v_{rc}, the p_{ro} and the η_{es} have inverse trends. In general, as the v_{rc} increases, the η_{es} goes down, while the p_{ro} tends to rise.

In correspondence with a v_{rc} of 2 rps (speed held during the experimental trials with the continuous press), a p_{ro} of about 4 g/s (14.4 kg/h) of oil extracted is found.

The exact correspondence with the experimental values is a consequence of taking $t_{int} = 0.125$ s in the mathematical model used for the prediction.

The prediction model trend shows that as the speed of screw rotation increases, the extraction efficiency tends to go down while the oil productivity increases (Figure 6). The increase in the latter parameter occurs within a limited screw rotation speed range beyond which (at about 4 rps) an inverse tendency is observed, with a reduction in the oil productivity.

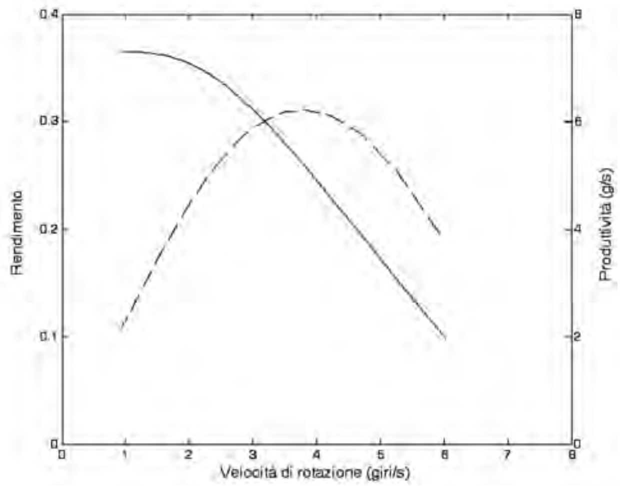

Fig. 6 - Prediction of p_{ro} (dashed line) and η_{es} related to the v_{rc}.

5. Conclusions

The change in the characteristics of the material during the mechanical compression of oleaginous seeds is of key importance for understanding the mechanisms related to the oil extraction process.

One of the most important physical parameters is believed to be the permeability of the solid matrix of the seed which may contribute significantly to the capacity to extract oil from the seeds during compression. The pressure, the temperature and the t_{cp} are the main operating factors which condition the permeability of the solid matrix of the seeds.

The experimental trials showed that k has high values at high temperatures. In practical terms, by increasing the temperature of the material during the extraction process it is possible to accelerate the drainage of oil during compression and, with the same t_{cp}, the yield is increased. This behaviour is presumably connected with the reduction in viscosity of the oil.

This is particularly evident in the first seconds of compression of the seeds, and therefore for values of t_{cp}

which are typical, in general, of normal continuous presses. Considering the t_{cp} of 5 seconds, in which more than 60% of the mass of extractable oil is extracted, with a t_{cp} of 20 seconds, the quantity of oil extracted at a higher temperature may be 2 or 3 times greater than that extracted at a lower temperature. The variability in this behaviour is connected with the extraction pressure which, with the same t_{cp} tends to reduce the value of k. However, in the range of t_{cp} considered, this does not appear to have a great influence on the quantity of oil extracted. Presumably, the effects of this parameter are more visible at lower compression times.

As regards the application of the mathematical model developed by Bargale, the results lead us to suppose that the lowest t_{cp} range analysed in the experimental trials may influence the response and the validity of the model in the event of simulation extractions with higher $t_{cp.}$ However, it is interesting to notice that the differences between real and simulated data, calculated with t_{cp} of 5 seconds, are limited and less than 30%. The best adaptation of the mathematical model to the behaviour of the press studied can be obtained by working on the t_{int}. In other words, it is possible to consider a way of adjusting the mathematical model based on the identification of the t_{int} in which the differences between the simulated and real values are as low as possible.

Perfecting the calculation algorithm allows us to analyse the changes in efficiency and productivity of the press in different operating conditions. It therefore becomes an interesting tool for optimising the machine in order to attain the production targets required.

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Summary

Mechanical extraction from seeds represents an important process in the production of vegetable oils. The efficiency of this step can have an effect on the economic convenience of the entire production chain of vegetable oils. However, the mechanical presses used for extraction are designed following criteria based more on the experience and intuition of the operators than on rigorous analyses of the physical principles involved in the process. In this study we have tested the possibility of applying a mathematical model that reproduces oil extraction from seeds, on a laboratory type of continuous press. In other words, we have compared the results of our mathematical model with those obtained from real extractions with mechanical presses on sunflower seeds. Our model is based on determining the main operating parameters of mechanical extraction, such as temperature, pressure and compression time, and on the knowledge of some physical characteristics of the solid matrix of the seeds. The results obtained are interesting because they include the role of operating parameters involved in extraction while the application of the mathematical model studied here allows, although with potential for improvement, a mathematical instrument to be developed for optimising the sizing and the operating conditions of mechanical presses.

Key words:
Oil extraction, vegetable oil, mathematical model, mechanical press

NOTATION

A_d area of drainage of the fluid (m^2)
B_0 constant (m^2)
B_1 constant (m^2)
c coefficient of consolidation of the medium (m^2/s)
Δh loss of pressure through the medium(m)
$d\varepsilon_z$ increment of vertical strain under uniaxial compression (m/m)
$d\sigma_z$ incremental applied vertical stress under uniaxial compression (kPa)
dU differential of applied pressure (kPa)

$\delta u/\delta z$ hydraulic gradient (Pa/m)
E_p percentage prediction error (%)
f pitch of the screw (mm)
g acceleration of gravity (m/s^2)
H height of the medium(m)
H_f final height of the cake (m)
H_i initial height of the cake (m)
k coefficient of permeability (m/s)
l_c length of the compression chamber (mm)
m_s mass per unit of screw length (g/mm)
m_v coefficient of volume change (m^2/kN)
O_e mass of oil extracted (g)
O_{es} oil extracted calculated by the model (g)
p_{ro} oil productivity (g/s)
p_{rs} productivity in processed seeds (kg/h)
Q fluid infiltration flow (m^3/s)
q fluid flow rate (m/s)
S_m seed mass (g)
t time (s)
t_{cp} compression time (s)
t_e extraction times (s)
t_{int} initial integration time (s)
U applied pressure (Pa)
u pressure of the fluid in the compressed medium (Pa)
U_e extraction pressure(bar)
U_{eq} equivalent extraction pressure (bar)
V sample volume (m^3)
V_{es} volume of extractable oil according to the model (cm^3)
V_o volume of oil extracted by the discontinuous press (m^3)
v_{lc} linear speed of the screw (mm/s)
v_{rc} rotational speed of the screw (rps)
z depth of the medium (m)
η_e extraction efficiency (%)
η_{es} extraction efficiency according to the model (%)
ρ_f unit weight (N/m^3)