Continuously pulsed electric field treatment chamber modelling and design

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Abstract. The perspectives of pulsed electric field (PEF) application for rheological changes in plant materials and treatment chamber design are considered in current paper. By using some mathematical tools and experiments data, viscosity of transporting plant materials confirms proposed Bingham rheological model assumption. Experimental studies have shown the presence of structure formation in material supplied to the treatment chamber channel. An effect of PEF treatment, with changes of material structure and increasing of material plastic viscosity from 0.117 to 0.159 Pa·s for samples after treatment by a field strength of E = 8 kV/cm and the number of pulses n = 300 was found. Obtained results of pulsed electric fields application in continuously material flow can be used in pulsed electric fields technologies, equipment design and help to determine cost efficiency of treatment in industrial application.

1. Introduction

Plant raw material processing in the agricultural sector has a number of features associated with the predominant share of the cost of raw materials in the cost of finished products. Therefore, the development of promising directions of effective food production associated with the successive processes of multistage fractionation with the release of food components. The most interesting in this case are such fractionation processes like common heat transfer and mass transfer with novel assisted methods. Assisted methods includes: microwave assisted processing, ultrasonic treatment, high voltage electric discharge in liquids and pulsed electric field (PEF) [1-3]. PEF has already been mentioned as a promising technology for mild oil cell disintegration in literature [4]. By applying short electrical pulses the cell membrane can be charged sufficiently to cause a rearrangement of the membrane, resulting in pore formation [5]. Numerical analysis of these processes shows a significant influence on the consistency of the material speed of the target component transfer process. Given the limitations of mathematical modeling, related parametrization transfer equations of particular relevance acquire physical-chemical methods of analysis of raw materials of components [6], basic and auxiliary materials involved in these processes. In order to expand the scope of application of the PEF treatment on an industrial scale, a clear understanding of the changes in the internal material structure, processing efficiency, and material rheological properties changes are necessary.

In a number of cases, mathematical modeling makes it possible to obtain indirect characteristics of the process [7] that are not directly observable. In this case, the decisive factor can determine the adequacy of the model to the real process is the experimental determination of these characteristics [8]. In current paper, particular interest to the oilseed mesh material flow in the channel, which are necessary for oil seed processing assisted by a pulsed electric field in a continuous flow is given.
The purpose of this work is to investigate the efficiency of continuously PEF pre-treatment usage to sunflower oil mesh with rheological parameters changes. Obtained results can be used to modify oil press configuration for better extraction process.

2. Materials and methods

2.1. Pulsed electric field treatment

Heated and crashed sunflower mesh was used as objects of this study. In short, sunflower seed mesh was transported at room temperature (20 °C) with a flowrate of 10 mL min⁻¹ through co-linear treatment zones with a gap distance of 3 mm, resulting in a total residence time of 10.5 ms in the treatment chamber. The material was transported by a piston connected with step motor through a shaft and a worm gear.

From the previously treatment modes data [7,10] the electric field strength was set in range from 7 to 10 kV/cm. Electrode gap in treatment chamber was set at 3 cm. Square electric pulses were generated by a function generator (Agilent 33220A, Agilent Technologies, Loveland, Colorado 80537, USA) and amplified for 2500 times by a high-voltage amplifier Matsusada (Matsusada Precision Inc, Japan) in range up to 20 kV. The main advantage of using Matsusada amplifier is the output amplitude growth rate 1200 V/μs. This condition is necessary for generation of qualitative rectangular shape pulses. The characteristics of the applied electric pulses such as electric field, frequency and pulse width were monitored, using a digital oscilloscope (Tektronix TBS 2072) with P6015A oscilloscope probe (400 MHz, X1000). The laboratory setup presented at figure 1. Directly after leaving the treatment chambers, samples rheological characteristics was measured. Treated and untreated samples were compared.

2.2. Rheology measurements

The identification of the viscous-plastic material flow in the conveyor channel based on determination of the effective viscosity. Taking into account the influence of the pressure developed in the zone of the interelectrode space the chamber of the viscometer was equipped with a hydraulic system of controlled pressure on the viscometer rotor (figure 1).

![Figure 1](https://example.com/image1)

**Figure 1.** Rotational viscometer with a hydraulic load system (left) and continuous PEF treatment dielectric chamber scheme

Choice of the rotational measuring method is based on the possibility of viscosity measuring, both for Newtonian and non-Newtonian [9] (structured or rheological) media. The structure of rheological flows in a screw conveyor is largely determined by the choice of a rheological flow equation that affects the volumetric efficiency of the processing unit. Therefore, the experimental study was aimed for determining dependence of viscosity to stress and shear rate, as well as the hydraulic pressure on the material under study for samples before and after PEF treatment.

Taking into account that the measured viscosity is connected with the processes of structure formation with increasing shear rate, the measured viscosity tends to Newtonian viscosity. Fungilab One S rotary viscometer at an excess hydrostatic pressure of 981 Pa was used for all measurement experiments. Material layer high in chamber was 38 mm. The shear rate during the measurement was
set at 10, 20, 30, 50 and 100 rpm, which are 1.05, 2.09, 3.14, 5.24 and 10.47 rad/sec subsequently. All experiments were repeated twice.

3. Results and discussion

3.1. Material rheology

Experimentally revealed that PEF treatment process leads to electroporation of plant cells and, as a result, destroys the oilseed cells. This contributes to the release of oil on the surface of the material and reduces material plastic viscosity. A typical graph of effective viscosity is shown in axes $\mu$ (effective viscosity) - $\gamma$ (shear rate) (Figure 2).

![Figure 2. Effective viscosity on shear rate dependence of for a material without and after treatment](image)

As can be seen from figure 2, when the shear rate increases, material viscosity decreases monotonically, which confirms the proposed assumption of the sunflower seed cake structure formation, which is also retained for samples after PEF treatment at $E = 8$ kV/cm. With number of pulses increasing from $n = 100$ to 300, the viscosity of the seed cake increases. Further, for rheological characteristics comparison, data for $n = 300$ are used. Considering that the effective viscosity recorded on the rotational viscometer is the ratio of stress to the shear rate $\mu_{eff} = \tau \cdot \gamma^{-1}$ the primary rheological data were processed (Table 1).

Table 1. Rheology parameters of untreated sunflower mash

| Shear rate $\dot{\gamma}$, rad / sec | Shear stress $\tau$, Pa | Engineering model $\tau_R$, Pa | Bingham model $\tau_{lin}$ Pa | Discrepancy engineering model $(\tau - \tau_R) / \tau$ | Discrepancy Bingham model $(\tau - \tau_{lin}) / \tau$ |
|--------------------------------------|------------------------|-----------------------------|-----------------------------|--------------------------------|--------------------------------|
| 10.47                                | 25.48                  | 25.49                       | 25.48                       | 0%                            | 0%                            |
| 5.24                                 | 25.00                  | 24.88                       | 25.00                       | 0.5%                          | 0%                            |
| 3.14                                 | 24.09                  | 24.11                       | 24.81                       | 0.1%                          | 3.0%                          |
| 2.09                                 | 23.09                  | 23.21                       | 24.71                       | 0.5%                          | 7.0%                          |
| 1.05                                 | 20.92                  | 20.88                       | 24.62                       | 0.2%                          | 17.7%                         |

To approximate data from Table 1, the linearization of the initial rheological indices in inverse quantities was used: $\dot{\gamma}^{-1}$; $\tau^{-1}$. In this case, the model dependence of the material flow curve in the oil press can be represented in the following form:

$$\tau^R(\dot{\gamma}) = 1/(b_0 + b_1 \dot{\gamma})$$  \hspace{1cm} (1)

where $b_0, b_1$ - coefficients of linear approximation of reciprocals of the material flow curve (figure 3) ($b_0 = 0.03826$ Pa$^{-1}$) and ($b_1 = 0.01009$ Hz/Pa). To estimate the form of this structure formation, the consistency of this viscoplastic material in the axes of shear rate-shear stress was plotted (Figure 3).
Figure 3. Consistency plot of viscoplastic material before (left) and after PEF treatment with n = 300.

To determine PEF treatment effect on the rheological parameters of the oilseed cake, a graph of the consistency of the viscoplastic material was constructed after processing by a pulsed electric field (Figure 3). The engineering model of oilseed cake, represented by equation (1), allows to determine the limiting values of rheological properties by constructing the asymptote of the shear stress $\tau_\infty$, defined by the following relation:

$$\tau_\infty = \lim_{\dot{\gamma} \to \infty} \left[ R(\dot{\gamma}) \right] = \frac{1}{b_0}$$  \hspace{1cm} (2)

To clarify the engineering rheological model parameters (9), a smooth functional dependence is required in the form of an approximation spline of the curve at the points of the graph (Figure 3) on the interval $[a=1.05; b=10.47]$ Hz, divided into parts of $\gamma_i$ (Table 1). For the approximation a cubic spline of defect 1 used, which is a function that:

- on each segment is a polynomial of degree at most three;
- has continuous first and second derivatives on the entire interval $[a, b]$;
- at the experimental points, the spline of the interpolating function is equal. In order to uniquely specify the spline, we impose additional requirements on the spline boundaries: $\tau''(a) = \tau''(b) = 0$. In this case, according to the Schoenberg-Whitney condition [11], there is only one spline $\tau_s(\gamma)$ for the existence of an interpolating spline, satisfying the conditions listed above. In this case, the integral relative discrepancy of the trial engineering rheological function can be represented as the objective function $Z(b_0, b_1)$:

$$Z(b_0, b_1) = \int_a^b \left[ \frac{\tau_R(\gamma) - \tau_s(\gamma)}{\tau_R(\gamma)} \right]^2 d\gamma$$  \hspace{1cm} (3)

Minimization of the functional (11) made it possible to refine the parameters of the engineering model in comparison with their quasilinear approximation ($b_0 = 0.03817$ Pa$^{-1}$) and ($b_1 = 0.01052$ Hz/Pa) for non-treated and ($b_0 = 0.0399$ Pa$^{-1}$) with ($b_1 = 0.0156$ Hz/Pa) for samples after PEF treatment. The rheological equation of flow characteristic for PEF treatment during the extraction of oil from oilseed cake is determined by an interval of shear rates: from 5 rad/sec to 11 rad/sec. In this case, to determine the rheological parameters of the flow of pulp in the channel of the pulp conveyor, the most realistic flow equation is the ideally plastic Bingham model [12]:

$$\tau(\dot{\gamma}) = \tau_0 + \mu_{pl} \cdot \dot{\gamma}$$  \hspace{1cm} (4)

where $\tau_0$ - yield strength, Pa; $\mu_{pl}$ - plastic viscosity. The parameters of equation (4) can be determined on the basis of linear approximation in the indicated interval of shear rates, taking into account the asymptote (2) found from the parameters of the engineering model (1). From the plots of linear approximations (Figure 3) it follows that $\tau_0 = 24.522$ Pa; $\mu_{pl} = 0.0917$ Pa·s and $\tau_0 = 22.413$ Pa; $\mu_{pl} = 0.159$ Pa·s for samples after PEF treatment, respectively. Specifying the initial approximation of these parameters for the shear rates used in the transportation of oilseeds in a screw conveyor used the integral relative discrepancy of the ideal-plastic Bingham model (4) with respect to the engineering rheological function:

$$Z_B(\tau_0, \mu_{pl}) = \int_{5.2}^{10.5} \left[ \frac{\tau_R(\dot{\gamma}) - \tau(\dot{\gamma})}{\tau_R(\dot{\gamma})} \right]^2 d\dot{\gamma}$$  \hspace{1cm} (5)
Minimization of the functional (5) made it possible to refine the parameters of the ideal-plastic Bingham model with respect to the engineering rheological function ($\tau_0 = 24.3617$ Pa, $\mu_{pl} = 0.1118$ Pa·s).

3.2. Treatment chamber design
The calculation of the main characteristics of the working pulse chamber is carried out taking into account the electrical and obtained rheological characteristics. Treatment chamber head plays an important role in achieving the desired physical properties of the product, such as density, volume expansion, and degree of cell disintegration of the material being processed.

When determining the coefficient of the geometric shape of the treatment unit, its profile should be considered as consisting of the channels of the simplest forms.

$$K = K_1 + K_2 + K_3$$ (6)

where $K_1$ is the coefficient of the geometric shape for a cylindrical channel, m$^3$; $K_2$ - geometrical form coefficient for a slotted channel, m$^3$; $K_3$ - coefficient of geometric shape for a conical channel, m$^3$.

The calculation for each geometric shape is determined by [13]:

$$K_1 = \frac{\pi \cdot d_1^4}{128 \cdot L_1} = 5 \cdot 10^{-5} m^3$$ (7)

where $d_1$ is the channel diameter, m; $L_1$ - channel length, m;

$$K_2 = \frac{\pi \cdot (r_1 \cdot \delta_2 - r_1 \cdot \delta_1)}{6 \cdot L_2 \cdot m} = 1.8 \cdot 10^{-4} m^3$$ (8)

where $r_1$-slotted channel, m; $L_2$ - channel length, m; $\delta_1$ - width at the entrance of the slotted channel, m; $\delta_2$-width at the exit of the slotted channel, m.

$$m = \left(2.3 \cdot \frac{(R_1 - R_2)^2}{(R_1 \cdot \delta_2 - R_2 \cdot \delta_1)^2}\right) \cdot \log \left(\frac{R_1 \cdot \delta_1}{R_2 \cdot \delta_2}\right) - \left(\frac{R_1 - R_2}{(R_1 \cdot \delta_2 - R_2 \cdot \delta_1) \cdot \delta_1 \cdot \delta_2}\right) - \frac{\delta_1^2 - \delta_2^2}{2 \cdot \delta_1^2 \cdot \delta_2^2}$$ (9)

where $R_1$ is the larger average radius of the slotted channel, m; $R_2$ is the smaller average radius of the slotted channel, m; $\delta_1$ - width at the entrance of the slotted channel, m; $\delta_2$-width at the exit of the slotted channel, m.

For a conical channel [13]:

$$K_3 = \frac{3 \cdot \pi \cdot D_3^3 \cdot d_3^2}{128 \cdot L_3 \cdot (D_3^2 + D_3 \cdot d_3 + d_3^2)} = 1.04 \cdot 10^{-4} m^3$$ (10)

where $D_3$ is the diameter at the inlet of the conical part of the channel, m; $d_3$ - diameter at the exit of the conical part of the channel, m; $L_3$ - channel length, m.

Thus, the pressure drop in the extruder head is determined by the equation [13]:

![Figure 4. Treatment unit](image)
\[ \Delta P = \frac{Q \cdot \mu_{ef}}{K} = 0.83 \cdot 10^4 \text{Pa} \]  \hspace{1cm} (11)

where \( Q \) is the volumetric capacity, \( m^3/s \); \( \mu_{ef} \) is the effective viscosity of the material, \( \text{Pa}\cdot\text{s} \); \( K \) - the total coefficient of the geometric shape of the head, \( m^3 \).

4. Conclusion

Considering the fact that the plastic viscosity of the sunflower crop corresponds to the viscosity of the vegetable oil that is part of this viscous-plastic material, confirmation of the proposed assumption of the Bingham rheology of this material before and after PEF treatment. As can be seen from the presented data, the consistency plot present a Bingham viscoplastic fluid.

The carried out experimental researches have shown presence arriving in a treatment unit material structuration. As the shear rate increases, the effective viscosity decreases. The consistency of the material corresponds to Bingham rheology. The influence of PEF treatment on the rheological parameters of the material is present and confirms the effect of a change in the structure of the material after preliminary treatment with an increase in the plastic viscosity of the test material from 0.117 to 0.159 \( \text{Pa}\cdot\text{sec} \) for samples after processing with a field strength \( E = 8 \text{ kV/cm} \) and a number of pulses \( n = 300 \).

The obtained parameters of the engineering model make it possible to predict the rheology of viscoplastic flow over a wide range of shear rates, including PEF treatment. On the basis of the obtained results, it can be concluded that PEF treatment is a promising direction in improving cold pressing process. It is noted that the technology of processing by a pulsed electric field can be extended to other oilseeds as a preparation stage before the main extraction processes.

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References

[1] Moubark A, El-Belghiti K and Vorobiev E 2011 Food Bioprod. Proc. 89 356
[2] Sarkis J R, Boussetta N, Tessario I C, Marczak L D F and Vorobiev E 2015 J. of Food Eng. 153 20
[3] Guderjan M, Elez-Martinez P and Knorr D 2007 Innov. Food Sci. & Emerging Tech. 8 55
[4] Eing C, Bonnet S, Pacher M, Puchta H and Frey W 2009 IEEE Trans. Dielectr. Electr. Insul. 16 1322
[5] Kotnik T, Frey W, Sack M, Meglič S H, Peterka M and Miklavčič D 2015 Trends Biotech. 33 480
[6] Shorstkii I, Koh X Q and Koshevoi E 2015 J Food Proc. and Preservation 39 3092
[7] Shorstkii I, Mirshekarloo M S, and Koshevoi E 2017 J. of Food Proc. Eng. 40 1
[8] Akbulut M and Coklar H 2008 J.1 of Food Proc. Engineering 31 488
[9] Heso H, Garnier C, Loisé C, Chevalier S, Bouchet B and Le-Bail A 2015 Food Struct. 5 31
[10] Shorstkii I and Koshevoi E 2018 Iranian J.1 of Sci. and Techn. Trans. A: Sci. 5 1
[11] Sommer M and Strauss H 1996 Adv. in Comp. Mat. 5 381-97
[12] Tichy J A 1991 J. of Rheo. 35 477-496.
[13] Koshevoi E P 2001 Technological equipment of plant oil processing (Saint Petersburg: GIORD Press) 368