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Abstract

The effects of preliminary vacuum drying (VD) and pulsed electric field (PEF) treatment on characteristics of fried potatoes were studied. The samples were preliminary dehydrated to a different levels (with moisture ratio of $MR \geq 0.2$) using VD at sub-atmospheric pressure of p=30 kPa, and two different drying temperatures, T_v=40°C and 70 °C. After dehydration the samples were fried for different frying time at 130 °C. The effects of PEF included significant shortening the VD time and absence of starch gelatinizing during the VD. Both application of PEF treatment and increase of temperature allowed shortening the drying time. For example, the drying time for the untreated sample dried at 40°C was by ≈2.45 times higher than for the PEF treated sample dried at 70°C. Increase in level of preliminary VD dehydration resulted in decrease of moisture content and oil uptake in fried samples. For PEF treated samples the moisture contents were significantly smaller than for untreated ones and the PEF treatment also resulted in significant decrease in oil contents. For example, at T_v=40°C and MR_v <0.2 the oil uptakes were O_f=0.26±0.02 and O_f=0.17±0.01 for untreated and PEF treated samples, respectively. Preliminary VD dehydration allowed preservation the starch granules in fried potato.

Keywords: pulsed electric fields; vacuum drying; frying; texture; potato

Nomenclature

d_c	cutting distance, mm
E	electric field strength, V/cm
F_c	maximum cutting force, N
m	mass of a sample, g
MR	moisture ratio
n	number of pulses
N	number of trains
O_f	oil uptake after frying, db
t	time, s
t_f	time of frying, s
t_i	pulse duration, μs
t_{PEF}	time of PEF treatment, s
T	temperature inside sample, °C
T_v	temperature in vacuum chamber, °C
Δt	interval between pulses, ms
W_i	initial moisture content, db
W_f	moisture contents after frying, db
τ_v	characteristic vacuum drying time, s
τ_f	characteristic frying time, s

Abbreviations

db	dry basis (g water/g solid)
PEF	pulsed electric fields
SEM	scanning electron microscopy
U	untreated
VD	vacuum drying
wb	wet basis (g water/g sample)

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Introduction

The frying in hot oil is very popular method for potato processing (Oke et al., 2018; Zeb, 2019). However, health considerations require strong control of the quality of fried potatoes, reduced oil absorption, and low contents of carcinogens and acrylamide in fried potato (Furrer et al., 2018; Zeb, 2019). The existing methods to improve the quality of fried potato include reducing cooking time, temperature and application of different preliminary treatments. For example, preliminary blanching and convective hot air drying, freezing, superheated steam drying, osmotic dehydration, microwaves, ultrasound and pulsed electric fields (PEF) were applied (Cruz et al., 2018; Oladejo et al., 2018).

The effects of PEF prior frying of potatoes have been discussed and reviewed in several works (Botero-Uribe et al., 2017; Fauster et al., 2018; Ignat et al., 2015; Janositz et al., 2011; Liu et al., 2018a, 2017). The reduction of oil uptake with PEF treatment was more effective than with hot water blanching (Janositz et al., 2011). The PEF treatment also resulted in lower browning tendency during frying (Ignat et al., 2015). It was also demonstrated that PEF treatment could improve cutting of potatoes (Ignat et al., 2015; Janositz et al., 2011; Liu et al., 2017). An industrial scale application of PEF for French fries production was also demonstrated (Fauster et al., 2018).

Recently, it was shown that combined PEF-treatment and convective air drying can significantly decrease the frying time and reduce oil absorption in fried potato (Liu et al., 2018a). It was demonstrated that dehydration efficiency of potato can be significantly improved by application of PEF treatment and vacuum drying (VD) at sub-atmospheric pressure (Liu et al., 2018b). At all drying temperatures within the interval 40-70 °C the most significant part of free water was evaporated at relatively low temperatures inside samples (18–27 °C) and the effects of starch gelatinisation were excluded. However, combined effects of PEF treatment and VD on frying behavior were never studied before.

This work evaluates the effects of preliminary PEF treatment and VD on frying of potato disks. After preliminary PEF treatment, the samples were dehydrated to different humidity levels using VD at sub-atmospheric pressure, p=30 kPa with two different drying temperatures, 40°C and 70 °C, and then fried. The effects of preliminary dehydration on different characteristics of fried potatoes were evaluated.

Materials and methods

Materials

Commercial potatoes (*Agata*) were purchased in a local supermarket (Compiegne, France) and placed in a refrigerator at ≈7 °C. All experimental data were collected within 10 days of the purchase. The studied samples had disk shape (25 mm in diameter and 2.5 mm in thickness). An initial moisture content of potatoes (W_i =5.18±0.1 db or 0.84±0.1 wb) was determined by drying of samples at 105 °C in the convection oven (UL50, Memmert, Germany).

Treatments

The samples were preliminary treated by PEF and dehydrated by using VD. Then the samples were fried. In all experiments the temperature changes were recorded inside the centre of the samples using a teflon-coated thermocouple Thermocoax (type 2, AB 25 NN).

PEF treatment

A PEF generator delivering monopolar pulses (1500V-20A, Service Electronique UTC, France) was used. A sample was placed between bottom and upper electrodes in a Teflon cylindrical tube (Atelier Genie des procédés industriels, UTC, Compiegne, France). The PEF treatment was applied using the electric field strength of E=600 V/cm and the series of N=10 trains. Each train consisted of n (= 100) pulses with pulse duration of t_i=100 μs, and time interval between pulses of Δt = 10 ms. The temperature elevation inside the samples never exceeded several °C (1-2 °C). The applied protocol allowed obtaining the high level of electroporation of potato tissue (e.g., see the data presented in (Ben Ammar et al., 2011; Boussetta et al., 2013)).

Preliminary vacuum drying

The VD of potato was done in a vacuum oven (Cole-Parmer, 2.3cuft, 120 VAC, USA) connected with a vacuum pump (30 kPa, Werie, Rietschle, RTV1, Germany). Untreated (U) and PEF treated samples were dried at two selected temperatures inside VD chamber, T_v=40° and 70° C. These samples were designated as 40U, 70U (untreated samples), and 40PEF, 70PEF (PEF treated samples). The total time of the preliminary VD was up to 7200 s.

Running mass of the sample, $m(t)$, during the drying was recorded at 5s intervals using digital balance (GF-600, A & D, Japan). The moisture ratio of the sample during the drying was calculated as

$$MR = (m(t) - m_d)/(m_i - m_d), \quad (1)$$

where m_i and m_d are the initial (t=0 s), and final (completely dried) masses of the samples, respectively.

Frying

The preliminary dried potato was then deep-fried in hot vegetable oil (Isio 4) contained in a beaker at the potato/oil mass ratio of 1/30. The mixture was heated and stirred on a ceramic heating plate C-MAG HS 7 S000 (IKA, France). The temperature of frying (130±1°C) was stabilized using heating system EST-D6 (IKA, France). The mass of the samples, m_f, during the frying was periodically controlled. After the frying the samples were drained, blotted using adsorbent paper and their terminal mass, m_f, was determined after drying for 24h at 105 °C in the convection oven (UL50, MEMMERT, Germany). The oil uptake, m_o, was determined using Soxhlet extraction with hexane according to AOAC methods (Anonymous, 2016). The dry basis moisture contents, W_f, and oil uptake, O_f, were determined as:

$$W_f = (m_f - m_o - m_d)/m_d, \quad (2a)$$

$$O_f = m_o/m_d, \quad (2b)$$

where $m_d = m_t - m_o$ is the dry matter content.

Analysis of the samples

Texture

To examine the firmness of the samples the textural cutting tests were performed using a texture analyzer TA-XT plus (Rhéo, Champlan, France). A TA-42 knife blade (3 mm thick and 68 mm wide) with a 45° chisel edge was used to cut a sample at a pre-test speed of 1.0 mm/s. The cutting distance (depth), d_c, was 1.25 mm (a half of initial thickness of a sample). The maximum (peak) force, F_c, was determined from force-displacement curve. The measured values of F_c were used as the firmness indicator.

Microstructure

Scanning electron microscopy (SEM, Quanta FEG 250, FEI, Holland) were used to observe the changes in the cell microstructure of U and PEF-treated samples. The mode of Low Vacuum (LowVac) at a voltage of 20 kV was applied.

Statistical analysis

All experiments were replicated 5 times. The mean values and the standard errors were calculated. The error bars in all figures correspond to the standard errors.

Results and discussion

Figure 1 presents the moisture ratio, *MR,* (a) and temperature inside the sample, *T*, (b) versus the drying time, *t*, for different samples 40U, 70U, 40PEF, and 70PEF. The preliminary analysis of VD curves *MR(t)* has shown that they can be satisfactory fitted with the extended exponential function (Gradshteyn et al., 1980):

$$MR = \exp(-(at/\tau_v)^{\beta}, \quad (3)$$

where τ_v is the characteristic VD time, β is the shape parameter, $a = \Gamma(1/\beta)/\beta$, and Γ is the Euler gamma function.

The lines (solid and dashed) in Fig.1a correspond to the fittings obtained with Eq. (3).

Table 1. Shape parameter, β, characteristic VD time, τ_v, and coefficient of determination, R^2, for U and PEF treated samples at two VD temperatures, T_v=40 °C (samples 40U, 40PEF) and T_v=70°C (samples 70U, 70PEF)

	Samples			
Parameters	40U	40PEF	70U	70PEF
β	1.127±0.005	1.198±0.006	1.220±0.002	1.221±0.004
τ_v, s	3128±10	2298±10	1827±3	1277±10
R^2	0.995	0.992	0.999	0.998

Table 1 presents the evaluated parameters β, τ_v, and R^2 for different samples 40U, 70U, 40PEF, and 70PEF. The estimated values of β were slightly higher than one (1.13-1.22) that evidences for the compressed (log-concave) shape of extended exponential functions. The PEF treatment resulted in acceleration of VD that evidently reflected effects of electroporation. Both application of PEF treatment and increase of temperature allowed shortening the drying time. For example the value of τ_v for the 40U sample was by ≈2.45 times higher than for the 70PEF sample.

The similar effects of PEF treatment on convective air drying of potatoes have been previously reported (Angersbach and Knorr, 1997; Arevalo et al., 2004; Lebovka et al., 2007). For example, PEF treatment with

optimum parameters allowed reducing the drying time to up to 20-25% (Angersbach and Knorr, 1997). The different mode of the PEF treatment were applied before and in the course of the drying (Lebovka et al., 2007). The acceleration of the drying rate was explained the electroporation and disintegration of cell membranes.

The changes of temperature inside the sample during VD are related with removal of water from potato (Liu et al., 2018b). During the rather long initial period the temperature inside the sample remained nearly constant at the level that is close to the room temperature. At this initial stage the free water intensively evaporates and most the cell membranes could be disrupted. In the potato tissue such disruption can be observed at the moisture content of about W=2-4 db (MR=0.39-0.78) (Khan et al., 2017). The duration of the initial stage decreased with increasing of the drying temperature. The progression of the temperature inside samples at the final drying stages can reflect removal the different forms of bound water (Hatakeyama et al., 2016; Wong, 2017).

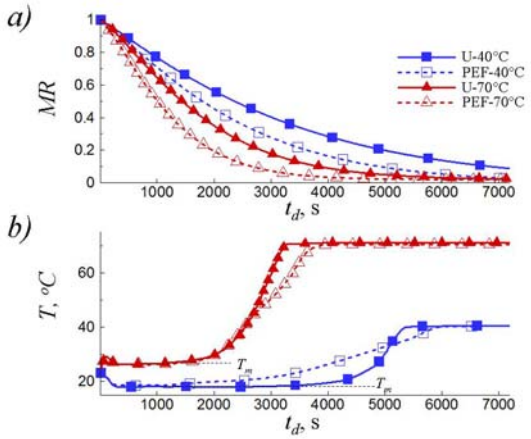

Fig. 1. Moisture ratio, *MR,* (a) and temperature inside geometrical centre of the sample, *T*, (b) versus the drying time, t_d, for U (solid lines, filled symbols) and PEF treated (dashed lines, open symbols) samples at two VD temperatures, T_v=40 °C (40U and 40PEF samples) and T_v=70°C (70U and 70PEF samples).

Vacuum drying is accompanied with different complex heat and mass transfer processes. The various transformations and redistributions of moisture and temperature can occur during the drying (shrinkage, changes in colour, texture, odour or other properties). It is widely accepted that mechanism of drying is dominatingly controlled by moisture diffusion, but for porous food materials it can also include surface diffusion, capillary flow actions, and other mechanisms (Onwude et al., 2016). Therefore, the structure of the VD sample can be rather heterogeneous and quite different at the surface (more dried) and inside central region (saturated with water) in dependence of the final moisture ratio, MR_v, and presence of PEF treatment.

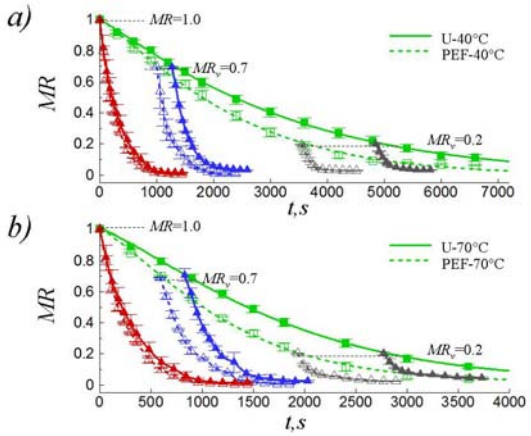

Fig. 2. Moisture ratio, *MR,* versus the time, *t*, for U (solid lines, filled symbols) and PEF treated (dashed lines, open symbols) samples. The samples were preliminary dehydrated by VD to different levels (MR_v= 0.2 and 0.7) and then they were fried. The VD temperatures were T_v=40 °C (a, 40U and 40PEF samples) and T_v=70°C (b, 70U and 70PEF samples). The curves for undehydrated samples (*MR*=1) are also presented.

Figure 2 shows the moisture ratio, *MR,* versus the time, *t*, for U and PEF treated samples pre-dried by vacuum to the different levels, MR_v. The samples were initially dehydrated by VD and then they were fried. The data are presented for two drying temperatures 40 °C (Fig. 2a) and 70°C (Fig. 2b).

For better understanding the effects of the PEF treatment and VD on frying kinetics the changes of the behaviour of a reduced moisture ratio, $MR^* = (MR - MR_f)/(MR_v - MR_f)$, were analyzed (Fig. 3). Here, MR_f is the moisture ratio after long time of frying (t_f=1200 s), respectively. Analysis has shown that all frying curves $MR^*(t_f)$ can be satisfactory fitted (with coefficients of determination, R^2>0.984) using a simple exponential first order kinetic law:

$$MR^* = \exp(-t_f / \tau_f), \quad (4)$$

where τ_f is a characteristic frying time. The value of effective moisture diffusion coefficient is inversely proportional to the characteristic frying time, i.e., $D_{eff} \propto t_f$.

The exponential model was frequently used for description the moisture ratio, *MR*, behaviour during frying (Pedreschi and Zúñiga, 2009). However, the mechanism of moisture loss is rather complex, and it include the transport processes governed by molecular diffusion, as well as capillary and pressure driven flows (Bouchon and Dueik, 2018). In general, kinetics of frying evolve four different stages (Farkas et al., 1996a, 1996b) related with (i) initial heating in absence of moisture evaporation; (ii) surface boiling with intensive removal of free water from the surface; (iii) falling rate with loss of the water and thickening of the crust region, and (iv) bubble end point with cessation of moisture evacuation. The more complex models of drying include also the crust and core regions separated by a moving boundary.

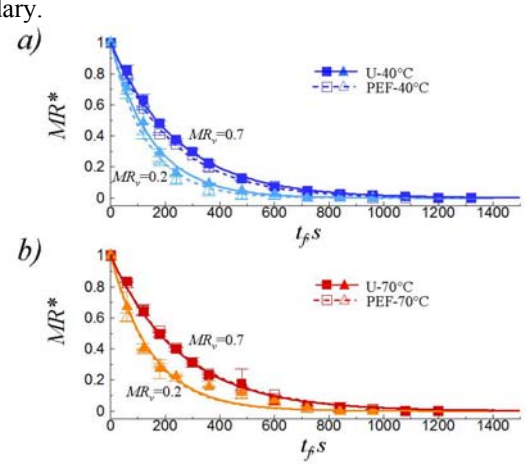

Fig. 3. Reduced moisture ratio, $MR^* = (MR - MR_f)/(MR_v - MR_f)$, versus the time of the frying, t_f, for U (solid lines, filled symbols) and PEF treated (dashed lines, open symbols) samples. The samples were preliminary dehydrated by VD to different levels (MR_v= 0.2 and 0.7) and then they were fried. The VD temperatures were T_v=40 °C (a, 40U and 40PEF samples) and T_v=70°C (b, 70U and 70PEF samples). Here, MR_v and MR_f are the moisture ratios after VD and after long time of frying ($t_f \geq 1200$ s), respectively.

Figure 4 presents the characteristic frying time, τ_f, versus the moisture ratio after preliminary VD, MR_v, at two VD temperatures, T_v=40 °C (a) and 70°C (b). The values of τ_f significantly decreased with decreasing of MR_v. In absence of preliminary VD (*MR*=1) the PEF treatment resulted in noticeable decrease of τ_f. However, for dehydrated samples the effects of PEF on τ_f were noticeable at T_v=40 °C and practically absent at T_v=70 °C. The similar effects of preliminary convective air (CA) drying and the PEF treatment on the frying times were recently reported (Liu et al., 2018a). For PEF treated samples the frying time was significantly smaller than for untreated ones and the synergetic effect of combined preliminary PEF-treatment and CA-assisted dehydration on decreasing of frying time was noted.

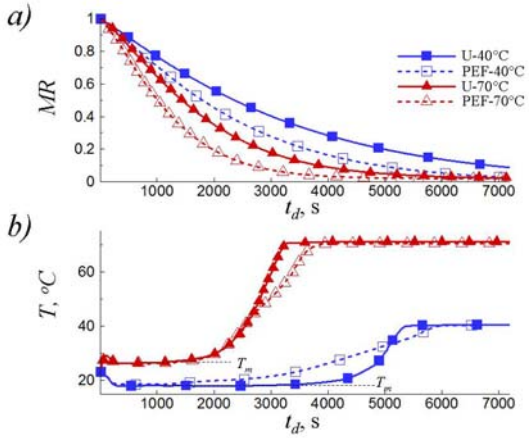

Fig. 4. Characteristic frying time, τ_f, versus the moisture ratio after VD, MR_v, for U (solid lines, filled symbols) and PEF treated (dashed lines, open symbols) samples. The samples were preliminary dehydrated by VD and then they were fried for t_f=600 s. The VD temperatures were T_v=40 °C (a, 40U and 40PEF samples) and T_v=70°C (b, 70U and 70PEF samples)

Figure 5 presents dry basis moisture content, W_f(a,b) and oil uptake, O_f, (c,d) versus the moisture ratio after VD, MR_v, for U (solid lines, filled symbols) and PEF treated (dashed lines, open symbols) samples. The samples were preliminary dehydrated by VD and then they were fried for t_f=600 s. Increase in preliminary dehydration (decrease in MR_v) resulted in decrease of moisture content (Fig. 5a,b). For PEF treated samples (40PEF and 70PEF)

the water contents were significantly smaller than for U ones (40U and 70U). The most significant changes in the moisture content, W_f, were observed at relatively high dehydration (MR_v<0.6).

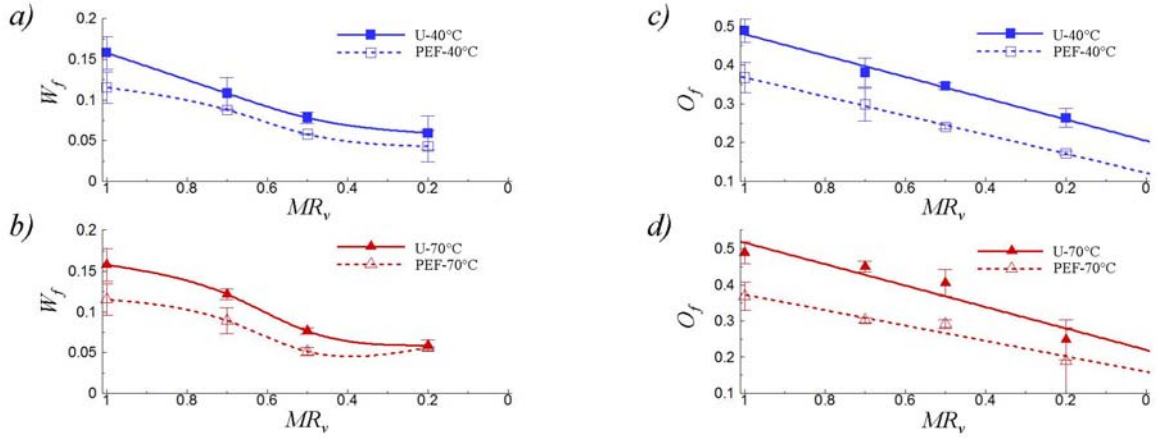

Fig. 5. Dry basis moisture content, W_f (a,b) and oil uptake, O_f, (c,d) versus the moisture ratio after VD, MR_v, for U (solid lines, filled symbols) and PEF treated (dashed lines, open symbols) samples. The samples were preliminary dehydrated by VD and then they were fried for t_f=600 s. The VD temperatures were T_v=40 °C (a,c, 40U and 40PEF samples) and T_v=70°C (b,d, 70U and 70PEF samples).

The oil uptake, O_f (Fig. 5c,d), decreased with increasing the dehydration for both the U and PEF treated samples. Moreover, the PEF treatment resulted in significant decrease of the oil contents. For example, at T_v=40°C and MR_v <0.2 the oil uptakes were O_f=0.26±0.02 and O_f=0.17±0.01 for untreated and PEF treated samples, respectively. The effects of VD temperature on behaviors of the oil uptake $O_f(MR_v)$ for U and PEF treated samples were insignificant.

In fried potato, three main oil fractions were identified (Bouchon et al., 2003): (i) structural oil (the oil absorbed during frying); (ii) penetrated surface oil (oil suctioned into the food during cooling after removal from the fryer); (iii) surface oil, which is the oil that remains on the surface. It is generally accepted that most of the oil is related with the penetrated surface oil trapped during the cooling period (Ufheil and Escher, 1996). So, the oil uptake is a surface phenomenon (Zeb, 2019) and it can be significantly affected by the sample thickness (Ziaiifar et al., 2008), development of surface porosity (Moreira et al., 1997; Pinthus and Saguy, 1994), and surface roughness (Dana and Saguy, 2006), etc.

The obtained data on PEF effects on frying behaviour and oil uptake reduction are in good agreement with previously reported results for potatoes (Fauster et al., 2018; Ignat et al., 2015; Janositz et al., 2011). The PEF effects on oil uptakes can be attributed to the different structural modification of potato tissue and its surface permeability owing to the electroporation (Botero-Uribe et al., 2017; Ignat et al., 2015) and complex effects of vacuum drying.

Textural changes during frying can also reflect development of heat and mass transfer processes (Pedreschi and Zúñiga, 2009). Figure 6 presents maximum (peak) force, F_c, versus the frying time, t_f, for non-dehydrated samples (MR =1.0) and preliminary dehydrated samples with water content ratio MR_v=0.2 at two VD temperatures.

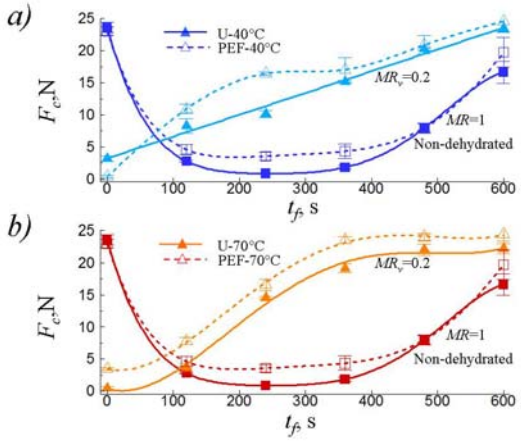

Fig. 6. Maximum (peak) force, F_c, versus the frying time, t_f, for U (solid lines, filled symbols) and PEF treated (dashed lines, open symbols) samples. The examples of $F_c(t_f)$ curves for non-dehydrated samples (MR =1.0) and preliminary dehydrated samples with the water moisture ratio of MR_v =0.2. The samples were preliminary dehydrated by VD and then they were fried. The VD temperatures were T_v=40 °C (a, 40U and 40PEF samples) and T_v=70°C (b, 70U and 70PEF samples).

For non-dehydrated samples the values of F_c initially decreased with increase of the frying time, t_f, and at long time of frying (t_f>350 s) the values of F_c increased. The observed softening and hardening stages are in full

correspondence with previously reported data on textural properties of the fried potato (Pedreschi and Moyano, 2005; Pedreschi and Zúñiga, 2009). Initial softening is originated by lamella media solubilization and starch gelatinization (Andersson, 1995) and final hardering reflects the formation of surface crust. The $F_c(t_f)$ dependencies were qualitatively similar for U (40U,70U) and PEF (40PEF,70PEF) treated samples, but the PEF treatment resulted in enhancing of the firmness at the intermediate frying times (t_f=100-400 s).

The dehydration owing to VD (MR_v=0.2) resulted in significant decrease the value of F_c (Fig. 6). These changes in texture for the potato tissue can reflect a softening of cell wall owing to dehydration (Krokida et al., 2000). Here, the effects of starch gelatinization were insignificant, because in our experimental conditions the temperature increase inside samples during VD was relatively low (<60^{o}C at MR_v=0.2) (Fig. 1). The irreversible dissolution of the starch granules in water typically occurs at >60^{o}C (Carlstedt et al., 2015). For the preliminary VD samples (MR_v=0.2) the values of F_c significantly increased in the course of the frying (Fig.6) and the firmness was higher for PEF treated samples. The VD temperature also affected the shape of $F_c(t_f)$ dependencies. It can reflect numerous processes associated with changes in micro and macro structures during the drying (Ramos et al., 2003).

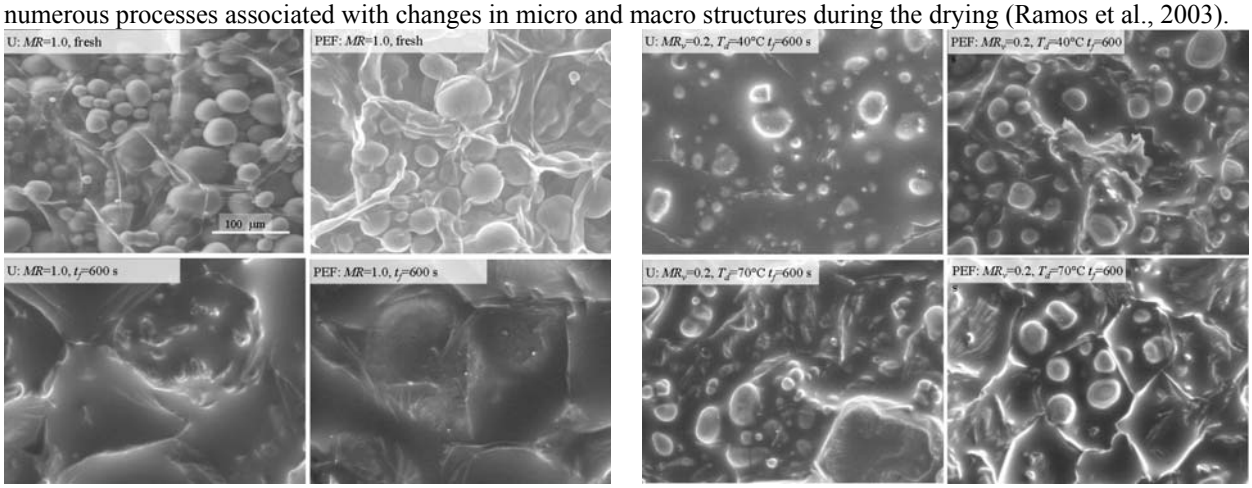

Fig. 7. SEM images of U and PEF treated fresh samples and samples fried for t_f=600 s without preliminary VD dehydration (MR=1.0).

The microstructure of fried potato can reflect the different alterations in the outer and core parts of the tissue (Bouchon and Aguilera, 2001). The alterations in the outer part are more significant due to the cutting (slicing), gelatinization of starch granules, formation of vapour bubbles etc. The changes in the core are much milder. In this work the SEM images of core parts of the samples were also analyzed. Figure 7 compares SEM images of U and PEF treated fresh potatoes samples, and samples fried for 600 s without preliminary dehydration by VD. SEM images did not revealed noticeable difference in structure of fresh U and PEF treated samples. However, the starch granules were not observed in fried potatoes without preliminary VD (MR=1.0) for both the U and PEF treated samples. It reflects the presence of strong gelatinization in fried potatoes. The smaller oil uptake for PEF treated samples can reflect the stronger surface starch gelatinization and formation of protective layer against oil absorption (Zeb, 2019) as compared with untreated samples.

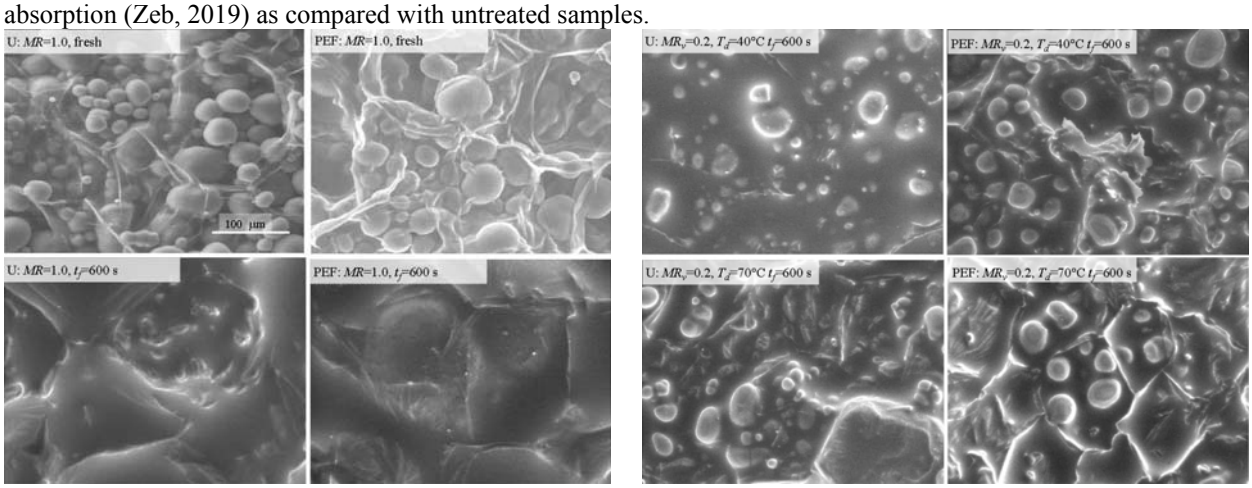

Fig. 8. SEM images of fried samples. The U and PEF treated samples were preliminary dehydrated by VD to the same moisture ratio of MR_v =0.2 and then they were fried for t_f=600 s. The VD temperatures were T_v=40 °C (40U and 40PEF samples) and T_v=70°C (70U and 70PEF samples).

Figure 8 presents the SEM images of fried samples (for t_f=600 s) with preliminary VD (MR_v =0.2) at two temperatures, T_v=40 °C (40U and 40PEF samples) and T_v=70°C (70U and 70PEF samples). The differences between U and PEF-treated samples can not be clearly detected from SEM images and the starch granules were present in all cases. The texture properties were also rather similar for the 40U, 40PEF, 70U and 70PEF samples (Fig. 6).

However, accounting for the significant differences in moisture contents and oil uptakes (Fig. 5) we can assume existence of differences in more fine structures for these samples (e.g., changes in starch granules and cell wall architecture (Botero-Uribe et al., 2017)).

Conclusions

The preliminary VD was applied before frying of U and PEF treated potatoes. The acceleration of VD for PEF treated potatoes reflected the effects of disintegration of cell membranes (electroporation). The electroporation effects in potatoes were intensively discussed in previous works (Janositz et al., 2011; Lebovka et al., 2007, 2006; Liu et al., 2018a, 2018b). Application of PEF treatment and increase of temperature allowed significant shortening the VD time. Moreover, the VD even at 70°C allowed avoiding of starch gelatinizing during the drying. The characteristic frying time, τ_f, significantly decreased with increase the level of preliminary VD dehydration and it was affected by PEF treatment. Moreover, increase the level of preliminary VD dehydration also resulted in decrease of moisture content and oil uptake. For PEF treated samples (40PEF and 70PEF) the water contents were significantly smaller than for U ones (40U and 70U). The most significant changes were observed at relatively high dehydration (MR_v <0.6). The PEF treatment also resulted in significant decrease of oil contents. The firmness tests also revealed impact of preliminary VD dehydration on the sample texture. SEM images did not revealed noticeable difference in structure of fresh U and PEF treated samples, but strong gelatinization in fried U and PEF treated samples was observed. Preliminary VD dehydration allowed preservation the starch granules in fried potato. However, the SEM images did not revealed any differences in structure of fried tissues for studied 40U, 40PEF, 70U and 70PEF samples.

Acknowledgements

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