Effect of Carbonic Maceration Pre-treatment on Quality Characteristics of French Fries and a Numerical Approach for Prediction of Moisture and Temperature Distribution

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***Abstract*—The effect of carbonic maceration (CM) pre-treatment on some quality characteristics of fried potato strips were evaluated and changes in the moisture and temperature distribution under the effect of CM treatment were figured out by a numerical approach. Parameters (temperature of 25-35 ℃, pressure of 1-2 bar and time of 7-14 hours) of CM treatment were examined in a full factorial experimental design. CM pre-treatment was found to be effective on shortening the frying time up to 30% and considerably limited oil absorption. Total colour change and alteration of *a** value were inhibited to some extent with CM, and any negative change was observed with respect to *b** value. On the other hand, CM treated samples had lower textural values (elasticity, firmness and skin strength) compared to those of control sample (with no pre-treatment). Finite difference method was used for numerical calculations. An explicit, capacitance method was employed. In order to verify predicted data, they were compared with the corresponding experimental results and good agreement was found between them.**

***Index Terms*—carbon dioxide, frying, potato, numerical prediction**

I. INTRODUCTION

Frying is one of the oldest cooking techniques. Especially deep-fat-frying of potato slices is popular and commonly preferred due to its unique taste and ease of preparation.

Frying may be briefly defined as a procedure for food cooking in a faster way by immersing them in a hot edible oil usually at 150-200⁰C [1]. During frying, simultaneous mass and heat transfer take place between food and frying oil in both directions. Heat is transferred from oil to food material and causes temperature raise. As a mass transfer, water is removed throughout solid matrix and oil is absorbed by food to some extent. These transport mechanisms are under the control of thermal and physicochemical properties of the food and the oil, temperature, food geometry and also the pre-treatments that applied before frying [2].

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Although the oil and frying dependent minor components contribute to the taste and flavour, high fat content may cause serious problems in economic view point for manufacturers and more notably some health problems for consumers. Thus, great effort has been made in order to reduce the oil absorption of foods during frying such as edible coating [3], [4], blanching and using some food ingredients [5], [6], pre-frying or pre-drying [5], [7]-[10]. Among these approaches the pre-drying method is come through as a leading most probably due to its efficiency, ease of application and economic advantages. To sum up, it is clearly declared in the literature that the lower initial moisture content, the lower fat absorption is attained.

The Carbonic Maceration (CM) technique was invented by Flanzy, Flanzy [11] to enhance the body and aroma of final product in wine processing. The CM has also been used in cabernet, grape juice and sugar production [12], [13]. And recently, the technique was studied as a pre-treatment before drying of raisins [14], chili peppers [15], tomatoes [16] and potatoes [17] in order to reduce the drying time. The studies demonstrated that time required for drying can easily be shortened using CM as a result of an array of biochemical changes occurred in the plant tissue [12]. Briefly, CM decreases the pH of cytoplasm, cell structure is decomposed (cell wall collapsed, capillary ruptured, vacuole ruptured), cell wall and membrane permeability are increased, high polymers are broken down into smaller ones and bound water is decreased and transformed into free water [15]. And these alterations help to enhance the characteristics of final products while leading a notable reduction in drying time [15]-[17]. Thus, it was thought that the faster removal of water from the sample may result in reduction of final fat content since it may most probably shorten the time for frying.

Hence the objective of the study is to investigate the effects of the CM pre-treatment on total frying time, colour, texture and final fat content of French fries, and to visualize the temperature and moisture distribution as a result of CM pre-treatment using a numerical approach.

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II. Materials and Methods

A. Material and Frying Procedure

Potatoes and sunflower oil, used as a frying medium, were purchased from a local market in Isparta, Turkey and stored at room temperature until the experiments. Special care was taken to pick disease free, uniform coloured potatoes, and they were washed under tap water, peeled and sliced to be French fry strips (1x1x6 cm). Potato strips were kindly washed and dried with paper tissue just before frying (for control) or done pre-treat. Frying process was performed for optimal cooking time for every sampling groups in vegetable oil pre-heated to 180^{0}C using an industrial type fryer (Remta, İstanbul, Turkey). The optimal cooking time for CM pre-treated and control (no pre-treatment) samples were previously determined employing the method suggested by Edwards, Izydorczyk [18].

B. Carbonic Maceration Pretreatment

Carbonic maceration pre-treatment was carried out as a full-factorial experimental set up at different conditions that is specified in Table I. For CM pre-treatment, potato strips were placed in a pressure vessel in which pressure (bar) and temperature (^{0}C) were controlled. After the samples were let in the chamber and then the desired conditions were attained, treatment was applied for desired time period.

TABLE I. Parameters For Different Carbonic Maceration Pre-Treatments

Treatment	Temperature (℃)	Pressure (bar)	Time (hour)
A	25	1	14
B	25	1	7
C	25	2	14
D	25	2	7
E	35	1	7
F	35	1	14
G	35	2	7
H	35	2	14

C. Analyses

In order to determine the dry matter content, samples were ground and 3-5 g were dried in an oven at 105±5^{0}C, until no weight change was attained (n=2).

Fat content of the fried potatoes were determined by hexane extraction of 5 g previously grounded and dried samples. Results were expressed in % (wb).

Colour parameters ($L*$, $a*$, $b*$) of fried sample were measured (n=18) using a portable colour meter (NH310, Shenzhen 3NH technology Co. Ltd., China) and the total colour change (ΔE) was calculated as follows (1).

$$\Delta E = \sqrt{(\Delta L^{*})^2 + (\Delta a^{*})^2 + (\Delta b^{*})^2} \tag{1}$$

Firmness (F), skin strength (SS) and elasticity (E) of fried strips were determined (n=5) using a texture analyser (TA.XTPlus; Stable Micro Systems Co. Ltd, Godalming, UK) as detailed in [16]. The F and SS were expressed in g-force and E was expressed in mm.

D. Staytistical Analysis

All the results were compared using Minitab Statistical Software (version 16.2.3.0) (Minitab Inc., State College, PA, USA). Tukey pairwise comparison test was performed to determine significance of mean values for comparison at (p<0.05). The results were given as “mean ± standard error of means”.

E. Numerical Approach

In order to reveal an idea about how CM treatment changes the moisture and temperature distribution in potato strips during deep-fat-frying, an explicit, capacitance finite difference method [19] was applied with a self-written algorithm using MATLAB (2016b, Mathworks Inc., Natick, MA, USA). The mesh was set up to 53361 nodes and 48000 elements for a better stability after preliminary computational experiments. Since the Courant number must be less than or equal to 1, two different time step size (0.1 and 0.01 s) were used to ensure the accuracy of the solutions [20]. In order to simplify calculations following assumptions were employed [21], [22]: 1. The sample is composed by liquid water and solid material, and a negligible amount of gas; 2. As it is significantly limited due to shrinkage [23], density of sample is constant and accepted as 1528 kg m^{-3} [24]; 3. The sample is accepted as homogenous and isotropic; 4. The initial temperature (20^{0}C) and moisture (0.79 kg kg^{-1}, db) are uniform; 5. Internal heat generation and the effect of oil-uptake on temperature and moisture distribution are negligible. That is, energy flux into the sample due to oil uptake is much more less than convection and conduction; 6. The mass fraction of oil in the sample is negligible and has negligible effects on heat and mass transfer; and also on other physical and thermal properties; 7. Alleviation in heat and mass transfer due to bubbling and a decrease in temperature of oil at the beginning of frying are neglected. Thus; heat and mass transfer coefficients are accepted constant and as 227 (W m^{-2} ^{0}C^{-1}) and 1.58e-05 (m s^{-1}) [25], respectively; 8. All heat and mass transfer fluxes are orthogonal to the surface of the strips; 9. Heat required for chemical changes is negligible. In order to reflect the effect of evaporation, the calculations are manipulated to remain the temperature at boiling point at where the moisture content is above the critical point; 10. The only transport mechanism of heat and mass transfer are conduction at inner area and convection at external boundary of sample.

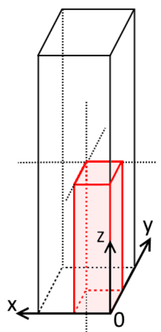

Figure 1. The sketch that reflects a potato strip (black) and the control volume (red)

The geometry given as in Fig. 1, representing the 1/8 part of a potato strip, was employed in numerical calculations and remaining 7 parts of potato strip were assumed to have same moisture and temperature properties since they were symmetric with control volume along neighbour axis. The side lengths of the control volume are 5x5x3 mm for x, y and z direction, respectively.

Eq. (2) and (3) show the equation of continuity and conversation of energy in Cartesian coordinates, respectively [26]; where ω_A, t, ρ, D_A, q, c_p, k are mass fraction of water (kg kg^{-1}), time (s), density of potato strip (kg m^{-3}), diffusivity of water in potato (m^2 s^{-1}), energy transported by conduction , specific heat (J kg^{-1} ^{0}C^{-1}) and thermal conductivity (W m^{-1} ^{0}C^{-1}), respectively.

$$\rho \frac{\partial \omega_A}{\partial t} = \rho D_A \left[\frac{\partial^2 \omega_A}{\partial x^2} + \frac{\partial^2 \omega_A}{\partial y^2} + \frac{\partial^2 \omega_A}{\partial z^2} \right] \tag{2}$$

$$\rho c_p \frac{\partial T}{\partial t} = - \left[\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} + \frac{\partial q_z}{\partial z} \right] \tag{3}$$

$$q_i = -k \frac{\partial T}{\partial i} \tag{4}$$

Diffusivity of water throughout solid matrix is used as a function of time [27] (5);

$$D_A = D_0 \ (\ 1 + D_0 \ t \ / \ l^2 \ )^{3.07} \tag{5}$$

where D_0 is 7.14e-09 m^2 s^{-1} for control sample and thermal conductivity (W m^{-1} ^{0}C^{-1}) [28] and specific heat (kJ kg^{-1} ^{0}C^{-1}) [29] is used as a function of mass fraction of water (6, 7). In previous studies, effective diffusivity of CM pre-treated samples was found to be 1.7 times for tomatoes [16], 1.25-1.90 times for apples slices [30] and almost 2 times for potatoes [17] compared to that of corresponding control samples. Thus, D_0 value is used a 1.7 times of control for CM pre-treated sample.

$$k = 0.148 + 0.493 \ \omega_A \tag{6}$$

$$cp = 0.837 + 3.349 \ \omega_A \tag{7}$$

The data obtained from mathematical models were compared to experimental results to verify the accuracy of predicted results.

III. Results and Discussion

Total time requirement for cooking, reduction in cooking time for CM treated samples compared to control sample, dry matter and lipid content of samples were presented in Table II. As it is clearly seen, the longest cooking time was found for control sample being 3.30 minutes. On the other hand, CM pre-treated samples had lower values in between 2.30-3.00 minutes, meaning a decrease in a process time up to 30%. It is obvious that the longer CM treatment caused higher rate of reduction in frying time, however any temperature and pressure related clear trend could not be observed. It has been previously reported that various chemical changes occurring during CM led to an increment in moisture diffusivity up to 1.7 times in drying tomatoes [16], and also similar alteration was observed in microwave dying of potato slices, as well [17]. CM maceration has briefly shown three major effects on biological materials that were well documented in previous reports [12], [15]. Although there are missing points, it has been accepted that CM, mainly has three acting points (cell wall, membrane and vacuoles) and two mechanistic approaches (hydrolysis and anaerobic fermentation) causing acceleration in mass transfer [15]. As a result of CM pre-treatment, pH of cytoplasm and activation of key enzymes decrease, explosive cell rupture and modification of cell membrane come through resulting extraction of intracellular substances [12]. Additionally, a reduction in degree of polymerization as well as in degree of methyl and acetate esterification in solid matrix releases some bound water into free water and enhances the moisture permeability in the plant tissue [15].

TABLE II. Cooking Time, Reduction of Cooking Time, Dry Matter and Lipid Content of Potato Samples

Treatment	Cooking time (min)	Reduction of cooking time (%)	Dry matter (%db)	Lipid content (%wb)
NP	3.30	-	48.68 ±1.97^a	11.53 ±0.45^a
A	2.30	30.30	36.62 ±0.88^a	9.94 ±0.11^{ab}
B	3.00	9.09	49.02 ±3.39^a	6.41 ±0.75^c
C	2.50	24.24	35.30 ±2.46^a	8.85 ±0.36^{abc}
D	2.50	24.24	35.17 ±4.38^a	9.61 ±1.08^{abc}
E	3.00	9.09	35.60 ±3.44^a	9.34 ±0.39^{abc}
F	2.30	30.30	45.17 ±0.74^a	7.10 ±0.10^{bc}
G	2.30	30.30	38.45 ±3.87^a	9.40 ±0.17^{abc}
H	3.00	9.09	47.80 ±3.79^a	11.36 ±0.14^a

$^{a-c}$ means in the same column with different superscripts are significantly different (p<0.05).
NP: no pre-treatment (control)

As previously noted, frying is a process in which simultaneous heat and mass transfer take place and some chemical (protein denaturation, starch gelatinization and following local retrogradation at crust region, lipid hydrolyses and Maillard reaction etc.) and physical (colour and textural changes, alterations in porosity etc.) changes occur at the same time leading the unique sensorial properties of French fries. It is declared, especially for thick food materials such as French fry strips, that the technological objective of frying is to achieve a final product with an intermediate moisture content [23]. Although any significant difference could be observed in the dry matter content of potato samples (p>0.05), the tendency is apparent for CM treated samples commonly have lower dry matter, namely higher moisture compared to control one with some exceptions.

But nonetheless, just the opposite would have been expected due to hypothesis describing the faster moisture removal after CM treatment. The reason for these deceptive result may be associated with the liberation of bound water from damaged plant tissue and an increase in water activity [15], which was previously observed [16]. On the other hand, except H, CM pre-treated potato samples had lower lipid content than control sample. The reduction observed in total time required for cooking was decrease the direct contact of material with oil, thus this might limit the penetration of sunflower oil into potato strips. But as it is well known the majority amount of oil is absorbed by material during the post-frying. During frying, the high inertial pressure due to vaporization of water hinders the oil penetration into food. On the other hand, cooling period following frying, inertial pressure begins to drop to the equilibrium point with atmospheric pressure due to condensation of water vapour; as a result the partial vacuum effect taking place promotes the penetration of excess surface oil into potato slice. Thus, more pressure elevation during frying, may affect the final lipid content of product and the elevation of pressure is depended on apparent density and porosity of the material [23]. At this point, CM may be effective on limiting the lipid content as a result of two possible reasons related to faster water removal. Firstly, the deteriorations appeared CM treated samples led to enhancement of the rate of water diffusion through the material at the beginning of the frying and consequently the inertial pressure could have stayed at lower degree as vapour could not be trapped in solid matrix. The mentioned deteriorative effect of CM on plant tissue could be easily seen by texture analysis result (Table III). Secondly, rapid removal of water due to CM likely cause early crust formation on the surface layer of potato than control one resulting in inhibition of oil absorption due to its barrier effect against oil transfer.

TABLE III. Textural Properties of Control and Carbonic Maceration Pre-treated Potato Strips

Treatment	Elasticity (mm)	Skin strength (g force)	Firmness (g force)
NP	8.55 ± 0.75^{a}	686.40 ± 331.54^{a}	1267.02 ± 556.82^{a}
A	6.25 ± 1.45^{ab}	98.51 ± 13.01^{b}	308.12 ± 24.68^{ab}
B	6.67 ± 1.24^{ab}	177.68 ± 42.7^{b}	318.04 ± 66.68^{ab}
C	5.38 ± 1.14^{ab}	89.00 ± 17.56^{b}	286.97 ± 22.62^{ab}
D	4.92 ± 1.24^{ab}	96.14 ± 13.71^{b}	352.32 ± 35.57^{ab}
E	5.47 ± 0.92^{ab}	76.17 ± 10.00^{b}	249.66 ± 32.17^{ab}
F	6.22 ± 0.73^{ab}	137.01 ± 25.74^{b}	357.11 ± 16.70^{ab}
G	3.72 ± 0.46^{b}	81.62 ± 10.23^{b}	247.29 ± 31.51^{b}
H	5.19 ± 0.66^{ab}	176.47 ± 22.94^{b}	395.40 ± 22.14^{ab}

$^{a-b}$ means in the same column with different superscripts are significantly different ($p<0.05$).
NP: no pre-treatment (control)

Elasticity (mm), skin strength (g force) and firmness (g force) results belonging to control and CM pre-treated samples after frying were shown in Table III. The corresponding results for control samples were found to be higher compared to that of other's. As a result of CM treatment, high molecular weight substances present in cell wall (pectin, cellulose, hemicellulose) were broken into smaller carbohydrates (beta galactronic acid, glucose and arabinose) [31]. The fragmentation of high polymers and break down of cell wall may have reduced the integrity of plant structure and consequently resistance against deformation.

TABLE IV. Colour Properties of Control and Carbonic Maceration Pre-Treated Potato Strips

Treatment	L^*	a^*	b^*	ΔE
NP	53.72 ± 0.76^{ab}	7.85 ± 0.52^{a}	21.08 ± 1.04^{a}	13.73 ± 0.91^{ab}
A	52.97 ± 0.61^{ab}	3.76 ± 0.32^{d}	12.65 ± 0.97^{c}	8.42 ± 0.61^{d}
B	48.77 ± 0.90^{c}	6.01 ± 0.38^{b}	21.14 ± 1.15^{a}	8.37 ± 0.92^{d}
C	49.18 ± 0.50^{c}	4.03 ± 0.26^{cd}	21.09 ± 0.83^{a}	4.52 ± 0.61^{e}
D	50.69 ± 0.87^{bc}	1.87 ± 0.11^{e}	21.44 ± 0.49^{a}	10.83 ± 0.49^{bcd}
E	48.03 ± 0.91^{c}	3.35 ± 0.19^{d}	16.83 ± 0.97^{b}	8.95 ± 0.97^{cd}
F	50.62 ± 0.60^{bc}	4.62 ± 0.14^{cd}	21.81 ± 0.90^{a}	16.88 ± 0.93^{a}
G	54.78 ± 1.16^{a}	3.51 ± 0.38^{d}	16.83 ± 0.77^{b}	13.68 ± 0.97^{ab}
H	50.94 ± 0.64^{bc}	5.24 ± 0.22^{bc}	20.58 ± 0.91^{ab}	12.62 ± 0.92^{bc}

$^{a-d}$ means in the same column with different superscripts are significantly different ($p<0.05$).
NP: no pre-treatment (control)

Among the other physical properties, colour may be considered as the most important one since it directly influences the consumer perception about food quality. Colour properties of control and CM pre-treated samples were presented in Table IV. The lowest lightness (L^*) values were determined for CM treated samples. On the contrary, the highest redness (a^*) belonged to the control sample. A similar observation has been previously sound and noted that there is a strong negative correlation between L^* and a^* parameters [32]. Both of the colour attributes induce the presence of non-enzymatic browning reactions, namely Maillard, and L^* decreases with frying time and temperature and just the opposite is valid for a^* value [23], [32]. As aforementioned, the L^* value is an indicator of browning. Although the frying time was shorter than control one, CM treated samples was seem to have darker appearance. As it is well known, the reason for Maillard reaction is the chemical reactions between proteins and reducing sugars at higher temperatures. Thus, after CM pre-treatment, the rate of browning could have been altered most probably because of higher concentration of reducing sugars which may possibly be formed from complicated carbohydrates [31]. However, another browning indicator, a^* value was found lower than control one for all CM treated groups and that may be resulted by shorter frying time. The parameter b^* is genuinely important for fried potato quality, because French fries is characterized with their yellow colour for many times. In general, a higher b^* value give more yellow products, which is desirable for fried potatoes [2]. In spite of sample A, CM pre-treatment did not cause a considerable change in yellowness (b^*). The total colour change (ΔE) gave promising results for CM treated samples especially that applied at low temperature (25 °C). So it may be concluded that, CM pre-treatment can inhibit the colour change to some extent due to short frying time and the solute of CO_2 that can reduce the degradation of colouring compounds [17]. However, the degradation of high polymer carbohydrates may be considered as a disadvantage of CM treatment for light coloured raw materials such as potato.

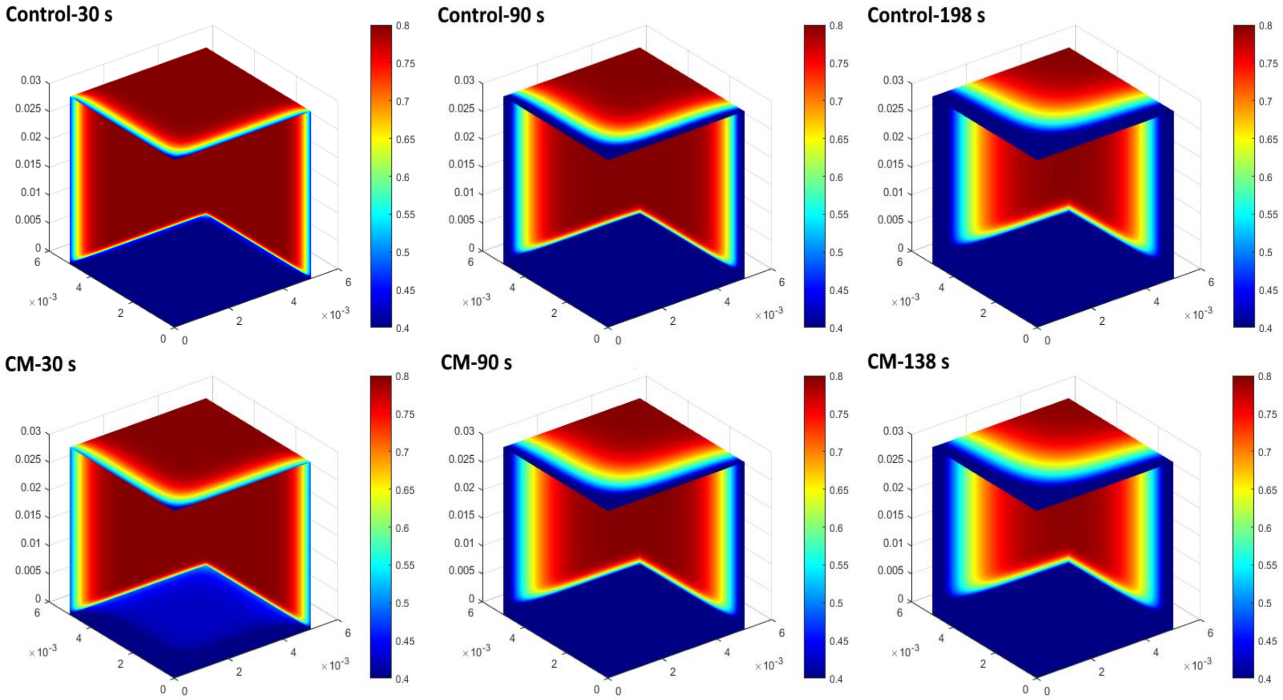

Figure 2. Moisture profiles (mass fraction of water) of control and carbonic maceration pretreated samples at three different times

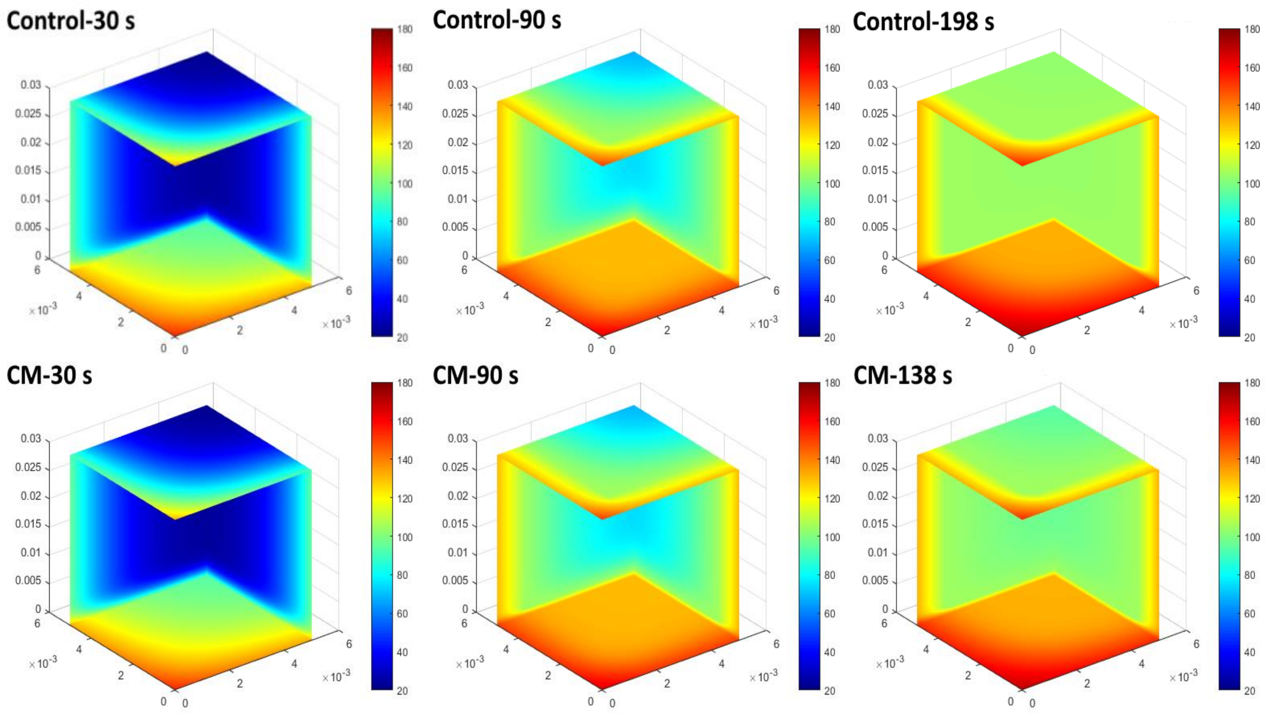

Figure 3. Temperature profiles (°C) of control and carbonic maceration pretreated samples at three different times

Moisture (mass fraction of water) and temperature contours for control and CM treated samples were given in Fig. 2 and 3 at different frying times (at 30, 60 s and end of frying). The mentioned times were arbitrarily chosen from the results. In order to check the prediction ability of mathematical model, experimental values were compared with predicted ones. Mean of the experimental mass fraction of water belonging to control sample (0.5132±0.0197) is in a good agreement with predicted result (0.5015) with 2.28% divergence. On the other hand, same property was calculated as 0.5234 for CM treated sample by increasing initial moisture diffusivity for 1.7 times than control samples. The reason for this approximation is that the effective moisture diffusivity for CM pre-treated dried tomatoes was previously found 1.7 times higher than that of control sample [16]. Moreover, approximate results were reported previously [17], [30]. As a result, moisture content was found to be pretty similar to sample F (0.5483±0.0074) which was cooked for 138 s. However, it is obvious that different levels of CM treatments have considerable impact on diffusion ability of water in solid matrix, and it is no doubt that this affects the final moisture content of potatoes. Moreover, liberation of bound water found in plant tissue after CM treatment was found to be misleadingly deflect the results, thus it was thought that the moisture content of CM treated samples were considered to vary so much [16].

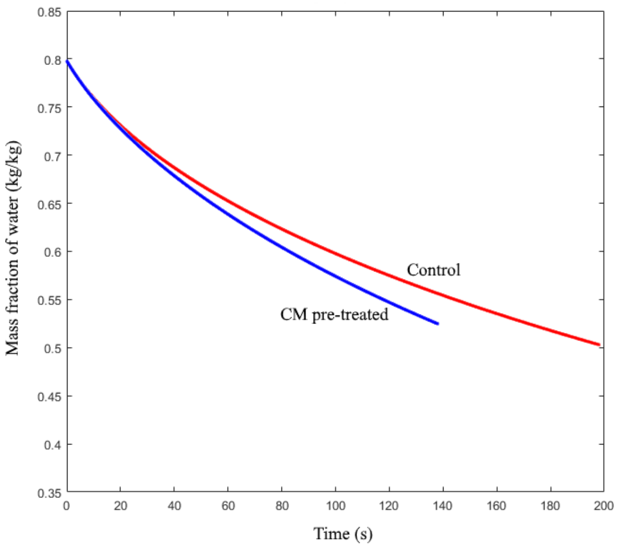

Figure 4. Change of mean water concentration of control and carbonic maceration pre-treated potato strips according to mathematical model.

As presented in the Fig. 2, the moisture profile of control and CM samples at 30th s of frying are almost same, but the figures representing 90th s indicating that CM maceration is considerably effective on increasing drying rate (Fig. 4), and at the end of the frying both control and CM treated samples has almost similar moisture distribution (Fig. 2). Farkas, Singh [24] reported that crust thickness was between 0.08-0.09 cm for fried potato at 180℃. Thus, it was thought that at the end of the frying, the 0.40-0.45 (as a mass fraction) water containing region in Fig. 2 may represent the dry crust region for both control and CM pre-treated samples as it corresponds to about 0.08 cm. In order to validate the hypothesis, reading taken from cross sectional area of potato strips (Fig. 5) were compared and the results support the idea because the mean thickness of the crust region (A+B in Fig. 5) was calculated as 0.083±0.004 cm.

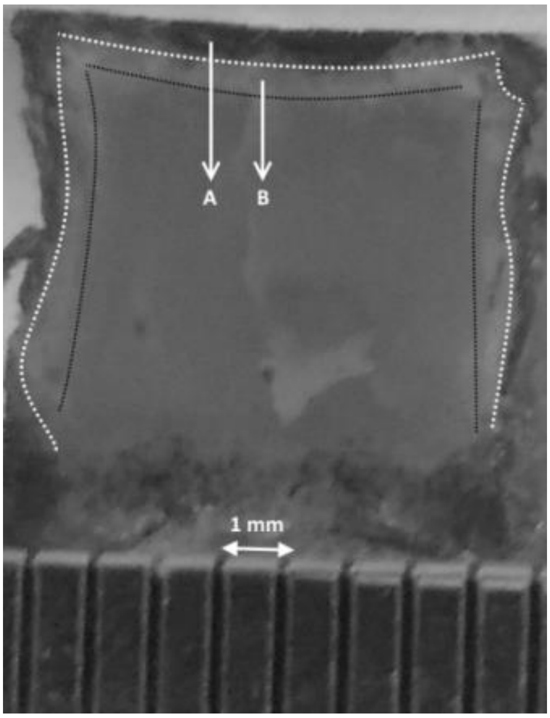

Figure 5. Cross sectional area of a potato strip (A: dark coloured outer crust and B: light coloured inner crust)

During frying procedure, heat is primarily transferred by conduction in the crust and core region. The core temperature increased up to boiling point and remained stable at that level until the end of the frying and at the core/crust interface where the water was being vaporized, temperature was constant at its boiling point until the moisture content reduced under the critical point. After critical moisture is achieved, the temperature of crust began to increase up to oil temperature [22]-[24]. In the experimental studies, the central temperature of potato strips was found to be constant at around 105℃. Thus, 105℃ was accepted as the boiling point of water in our model system. That is slightly higher than boiling point of distilled water, presumably due to two possible reasons. One is the boiling point elevation of water as a result of dissolving substances [33], and second is the effect of inertial pressure over atmospheric one favours the elevation of boiling point [23]. Thus, the numerical calculations is manipulated to make remain the local temperature at 105℃, if the water fraction is higher than 0.4 (arbitrarily chosen approximate final moisture content of crust region as dry basis [34], [35]). According to experimental results, the time required to heat up the central point of potato strips to boiling point was almost 130 s for both control and CM treated samples. On the other hand, based on mathematical modelling, change of the central temperature followed almost same trend for both control and pre-treated one (Fig. 3), and reached the boiling point at almost 140 s of frying. Thus, prediction ability of the model was also found to be sufficient for central temperature. Moreover, it was also predicted that if frying were not ended at optimal cooking times, the central temperature will begin to exceed the boiling point after 720.9 and 1128.65 s, and will reach to 180 °C after 975 and 1345 s of frying for CM treated and control samples, respectively.

So, all in all, the model has some limitations, as well. Firstly potato was considered as a homogenous material. However it has been previously reported that potato is in fact a non-homogenous material such as most of other composite foods [24]. Secondly, heat and mass transport due to capillary action on water and penetration of oil was not taken into account. There is no doubt that they play some important roles on heat and moisture distribution. On the other hand, omitting the temperature reduction of surrounding oil layer and bubbling effect, that occur just after the raw potato get in touch with hot oil, would have some influences on predicted results.

IV. Conclusion

The CM pre-treatment was studied in order to minimize the time required for French fries and its effects on some quality characteristics of final product were investigated. The CM conditions were ranged between 25-35 °C, 1-2 bar and 7-14 hours for temperature, pressure and time, respectively. Potato strips (10x10x60 mm) were fried at 180 °C in sunflower oil for experimentally determined optimal time. After CM treatment, up to 30% reduction in frying time has been achieved and the lipid absorption of potato strips was reduced. The total colour change and alteration of a^* value was inhibited for CM sample and also b^* value was successfully protected. The textural analyses (firmness, skin strength and elasticity) showed that the CM treatment caused formation of vulnerable plant tissue against deformation. On the other hand, a predictive model was developed and solved for prediction of moisture and temperature distribution in sample. These predicted results were compared to experimental data and it was found that the model was able to predict final moisture content, the time for central temperature to reach at boiling point, and crust thickness were in satisfying agreement with experimental data. Briefly, the model developed using finite difference numerical approach was in good agreement with experimental results, CM pre-treatment was considerably shortened frying time, and a consequence the CM positively affected quality characteristics of fried potato strips.

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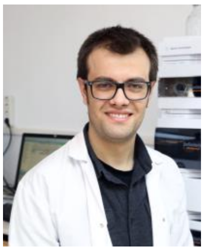

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