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A novel drying system – simultaneous use of ohmic heating with convectional air drying: system design and detailed examination using CFD

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Abstract

This paper introduces a novel drying system called ohmic assisted drying (OAD) – the simultaneous combination of ohmic heating and convective air drying. The OAD system improved the drying characteristics of potato slices. Depending on the process conditions, drying time was shortened by 20-60% by OAD compared to conventional air-drying system. The level of applied voltage and air temperature were effective on drying time reduction. To achieve a better understanding of the changes in potato slices during OAD, a 3D mechanistic model was developed and validated with experimental moisture and temperature results. The model involves coupled heat, mass, momentum transfer as well as heat generation due to electrical current through the porous media. A non-conjugate, macroscopic, non-equilibrium modelling approach helps to define OAD process. Drying material (potato) consists of solid matrix, water, and gas phases, where pressure-driven flow, binary diffusion and phase change in drying volume were considered. The model predicts the spatial distribution of temperature, moisture, and pressure in the drying material. The prediction performance of the model is satisfactory especially in terms of moisture content since the standard
error of estimate changes between 0.05-0.23. A deeper understanding is presented about the mechanisms of OAD highlighting strengths and weaknesses of the model and the drying system.

**Keywords**

volumetric heating, COMSOL, porous media, Joule heating, finite element method, electric

1. **Introduction**

Drying is a common preservation method used to extend the shelf-life of foods such as vegetables, fruits etc. Moreover, drying reduces costs related to transportation and storage operations. However, drying uses about 12–20% of total energy in the industrial sector, and it is considered as one of the highest energy-intensive operations in food processing (Moses, Norton, Alagusundaram, & Tiwari, 2014; Raghavan, Rennie, Sunjka, Orsat, Phaemsang, & Terdtoon, 2005; Ratti, 2001).

For food drying, manufacturers use different methods. One of them is drying under sunlight (DSL). Although DSL is preferred by some local producers throughout the world due to its low capital/equipment cost and ease of application, climate conditions should be suitable for this method. So, it is not preferable for professionals in their industrial applications. Additionally, DSL has some drawbacks like low quality and product standardization problems (Ceylan, Aktaş, & Doğan, 2006). With the use of conventional methods (CD), it is possible to deal with these drawbacks. More than 85% of the industrial systems are CD or similar hot air-drying methods (Mujumdar & Beke, 2003). However, these methods are not only time and/or energy intensive, but also lead to losses in nutritional values and the quality of foods (Canizares & Mauro, 2015; Liu, Wang, Zhao, An, Ding, & Wang, 2014; Turgut, Küçüköner, & Karacabey, 2018). To improve performance of drying systems, it is necessary to find alternative ways to overcome these problems. Some of the efforts towards to this mostly focus on developing novel, energy-saving and time-effective heating technologies (Borda-Yepes, Chejne, Granados, Rojano, & Raghavan, 2019; Cokgezme, Sabanci, Cevik, Yildiz, & Icier, 2017; Thijs Defraeye & Martynenko, 2018; C. Kumar, Joardder, Farrell, Millar, & Karim, 2016). Ohmic
heating is an example of these novel heating methods and it is in the class of the volumetric heating techniques like microwave.

Ohmic heating is based on the passage of electric current through the material (food matrix). The magnitude of resistance of food against the electrical current generates heat in matrix volume. Advantages of ohmic heating include (1) rapid heating and uniform temperature profile, (2) instant shut down and no residual heat transfer, (3) reduced fouling problems, (4) being environmentally friendly and (5) low maintenance cost and high efficiency for energy conversion (Sakr & Liu, 2014). Ohmic heating has been used for different food operations such as thawing (Icier, Cokgezme, & Sabanci, 2017), cooking (Farahnaky, Kamali, Golmakani, Gavahan, Mesbahi, & Majzoobi, 2018), pasteurisation/sterilisation (Crattelet, et al., 2013; Halden, Alwis, & Fryer, 1990), pre-treatment (Icier, 2010) etc. As a pre-treatment, ohmic heating was used before different drying methods (air, vacuum, osmotic drying etc.) and evaluated in drying different solid foodstuffs (carrot, potato, yam fruit, apple, artichoke, strawberry etc.) (Icier, 2010; Moreno, Espinoza, Simpson, Petzold, Nuñez, & Gianelli, 2016; Moreno, et al., 2012; Wang & Sastry, 2000; Zhong & Lima, 2003). In general, ohmic heating pre-treatment positively affects the drying performance of solid food materials and helps to retain high levels of nutrients, vitamins, and bioactive compounds in the final dried product. Another alternative use of ohmic heating is dehydration of liquid foods. For example, Hosainpour, Darvishi, Narges, and Fadavi (2014) reported that the moisture content of tomato puree was reduced from 90% to 70% using ohmic heating. Moreover, the combination of ohmic heating and vacuum application for various fruit juices (cherry, pomegranate and tomato) has been studied before (Cokgezme, et al., 2017; Darvishi, Hosainpour, Narges, & Fadavi, 2015; Hosainpour, et al., 2014; Sabanci & Icier, 2017). Although ohmic heating was previously adapted for simultaneous use with vacuum drying of liquid foods, to the best of our knowledge, there is no available study on developing a hybrid of ohmic heating and convectional (hot air) drying for solid food materials (briefly ohmic assisted drying, OAD) in literature.
Therefore the purpose of the current study is to introduce the applicability of OAD for solid food materials; to evaluate the efficacy of OAD in terms of experimental drying results and to develop and validate a unified numerical model for coupled electric, heat and mass transport during OAD to understand in-depth how this hybrid system affects drying characteristics.

2. Experimental Methodology

2.1. Sample and sample preparation

Potatoes (*Solanum tuberosum* cv. Agria) were used as a model product in the experiments and potato tubers were purchased from a local market in Isparta, Turkey. Special care was taken to select potatoes that were defect-free, uniform in colour, shape, and size. Potatoes were kept at room temperature (25-30 °C) until the experiments. Potato tubers were sliced to form rectangular prisms (40x40x5 mm) before drying trials. To be affected as little as possible from the regional variations in potato tubers, slices were obtained perpendicular to pith keeping the corners of slices at least 5 mm inside of periderm (approximately no outer than vascular ring) as shown in Figure 2-c.

2.2. Drying equipment and drying protocol

Experiments were performed in a tunnel type hot air dryer (Eraktek Innovation, Konya, Turkey) (Figure 1a). The dryer is equipped with a lab-scale electrode apparatus (ohmic cell). The developed ohmic cell is seen in Figure 1-b, c, and d. It has six stainless steel needle-shaped electrodes (3 mm in diameter) attached to a cylindrical polyethylene base to ensure electrical isolation and high temperature resistance (approximately until 150-180 °C). The ohmic cell is powered by an AC power supply (max operation 400V-10A AC at 50-60 Hz) (Eraktek Innovation, Konya, Turkey).

Before starting the experiments, the oven with ohmic cell was left self-working for almost 30 min to reach the specified conditions (temperature and flow rate) in the drying chamber ((i) 0.74 m/s at 50 °C, (ii) 1.55 m/s at 50 °C, (iii) 2.15 m/s at 50 °C and (iv) 2.15 m/s at 60 °C) (for details please see Table 1). Next, a freshly cut potato slice was immediately attached to the electrodes as shown in Figure 2. The ohmic cell was placed on an in-situ weighed drying tray (using a precision balance (KB 3600-2N,
Kern & Sohn GmbH, Germany) to monitor the real-time weight change of the sample. As soon as the ohmic cell was placed in the dryer, power supply was turned on and alternating electric current was supplied at constant voltage (75, 100 and 125 V) without any interruption during drying. The constant voltage level was set using a device with a manual variac equipped with a digital multimeter (volt and ampere measurement) (Eraktek Innovation, Konya, Turkey). The initial moisture content of potato tubers was determined before each trial using a moisture analyser Kern DBS (Kern & Sohn GmbH, Germany). The sample weight was recorded at one-minute intervals to monitor the change in moisture content during drying. The moisture content of the sample was calculated on dry basis (g moisture/g dry matter). In addition, the tunnel dryer is equipped with an IR thermal camera (FLIR TG167, FLIR Systems, Inc., USA) placed on the dryer in a position targeting potato surface. The temperature change of the sample (temperature of the pale area (10x10 mm) in Figure 2-b) was also recorded at one-minute intervals.

3. Modelling of transport phenomena

3.1. Model description and assumptions

The schematic diagram of the ohmic cell and the modelled potato slice are presented in Figure 2-a. The proposed model’s equations for multiphase porous media dried with OAD system requires solving a combination of different physics which includes heat, mass, momentum transfer in the media and electrical current. Because in an ohmic heating system, product heating is mainly controlled by electrical energy rather than conduction and convection (Goullieux & Pain, 2005; Jun & Sastry, 2005). The model developed in this study considers the transport of liquid water, vapour, and air inside a potato slice as a porous material. The convection, conduction, diffusion, evaporation, and heat generation due to electrical current are included in conservation equations of mass and heat. Darcy’s equation was considered to describe the momentum conservation. Non-equilibrium evaporation formula was used to describe phase change and distribution of water throughout the domain (Zhang & Datta, 2004).
To reduce the computational requirements, a quarter (one-fourth) of the potato slice was taken into consideration (Figure 2-c). All transfer equations were applied to all domains except on the symmetry boundaries. Moreover, the following assumptions were made to simplify the mathematical expressions:

- The potato is a porous medium and the pores are filled with liquid water, air, and water vapour.
- All phases (solid, liquid and gases) are continuous and local thermal equilibrium is valid for all phases at a location.
- Transport of liquid water in the domain arises from capillary flow and/or pressure gradient of gases. Binary diffusion and pressure-driven movement are considered for gases. Gases are assumed to behave as ideal. Gravitational effects are ignored.
- All water can be removed so there is no bound water.
- There is a non-equilibrium between water in liquid and vapour in the gas phase.
- The structure of the food does not change (shrinkage or expansion) during the heating process.
- Voltage is only applied between electrodes, so other surfaces are considered isolated.
- The effect of starch gelatinisation on electrical properties are assumed to be insignificant (Palaniappan & Sastry, 1991).
- Relative electrical permittivity of material for current is insignificant (Wu, Kolbe, Flugstad, Park, & Yongsawatdigul, 1998).

3.2. Governing equations

The following mathematical expressions were adopted from previous papers focusing on heat and mass transfer in porous food materials (Halder, Dhall, & Datta, 2007; Rakesh, Datta, Walton, McCarthy, & McCarthy, 2012). First, a base model was developed and validated for convectional drying without ohmic heating. Then, electric current physics were added to the base model to define the heating effect of ohmic heating.

3.2.1. Mass and momentum transfer
The representative elementary volume (ΔV) for the domain consists of the volume of different phases which are gas (ΔVg), water in liquid state (ΔVw) and solid (ΔVs).

\[ \Delta V = \Delta V_g + \Delta V_w + \Delta V_s \]  

(1)

The apparent porosity (\( \phi \)) is defined as the volume fraction of pores (water and all gases) to total volume (Eq. 2). The water saturation (\( S_w \)) and the gas saturation (\( S_g \)) are defined as the fraction of pore volume corresponding to these phases (Eq. 3 and Eq. 4).

\[ \phi = \frac{\Delta V_g + \Delta V_w}{\Delta V} \]  

(2)

\[ S_w = \frac{\Delta V_w}{\Delta V_g + \Delta V_w} = \frac{\Delta V_w}{\phi \Delta V} \]  

(3)

\[ S_w + S_g = 1 \]  

(4)

The concentration of liquid water (\( c_w \)), water vapour (\( c_v \)), and air (\( c_a \)) are described by the mass conservation equation given by Bird, Stewart, and Lightfoot (2002) (Eq. 5).

\[ \frac{\partial c_i}{\partial t} + \nabla \cdot (-D_i \cdot \nabla c_i + u_i \cdot c_i) = \pm R_i \]  

(5)

where \( c_i \) is the concentration of related phase (mol/m\(^3\)), \( D_i \) is the diffusion coefficient (m\(^2\)/s), \( u_i \) is the velocity of the phase in the porous domain (m/s) and \( R_i \) is the reaction term describing the evaporation/condensation of water in liquid/vapour form (mol/m\(^3\)s) where “-” is used for liquid water and “+” is used for vapour. Regarding air, \( R_i \) is equal to 0 (Eq. 6).

\[ R_i = K(a_w c_{v, sat} - c_v) \]  

(6)

The \( K \) is evaporation rate constant (s\(^{-1}\)), \( a_w \) describes water activity according to desorption isotherms of potato as a function of moisture content (\( m_{db} \), g water/g solid matter) (Eq. 7) (Kaymak-Ertekin & Gedik, 2004), and \( c_{v, sat} \) is saturated vapour concentration (mol/m\(^3\)). The saturated vapour concentration was calculated from saturated vapour pressure (\( P_{v, sat} \), Pa) (Eq. 8), which was previously presented by Vega-Mercado, Góngora-Nieto, and Barbosa-Cánovas (2001), using ideal gas law.

\[ a_w = \exp \left( -\frac{0.033}{m_{db}^{1.497}} \right) \]  

(7)
\[ P_{\text{v, sat}} = \exp[-580.2206/T + 1.3915 - 0.04867T + 0.4176 \times 10^{-4}T^2 - 0.01445 \times 10^{-7}T^3 + 6.546 \ln(T)] \]  

\[ m_{db} = \frac{c_w M_w}{(1 - \phi) \rho_s} \]  

The velocity component of each moving phase in the domain is calculated using Darcy’s law where the total gas pressure, \( P \) (Pa) is the sum of partial pressures of vapour, \( p_v \) (Pa) and air, \( p_a \) (Pa) based on the ideal gas law. The actual velocity of pressure-driven flow was defined using the related phase volume, so the related expression is described as in Eq. 10 (Rakesh, et al., 2012).

\[ \mathbf{u}_i = -\frac{k_{\text{in}, i} \cdot k_{r, i}}{\phi S_i \mu_i} \nabla P \]  

\[ P = p_a + p_v \]  

where \( \mu_i \) is the dynamic viscosity of each phase (Pa.s), \( \phi \) is saturation, \( k_{\text{in}, i} \) (m\(^2\)) and \( k_{r, i} \) are intrinsic and relative permeability of phases, respectively.

Liquid water in the pores experiences the capillary pressure, \( p_c \), in addition to the gas pressure.

\[ p_w = P - p_c \]  

The effective velocity (\( u_{\text{eff, w}} \)) of the liquid phase is therefore given by Eq. 13 and the effect of capillary pressure (\( p_c \)) is described by capillary diffusivity (Halder, et al., 2007).

\[ u_{\text{eff, w}} = u_w + D_{\text{cap}} \nabla c_w \]  

where \( u_{\text{eff, w}} \) is the effective velocity of liquid water (m/s), \( u_w \) is Darcy velocity of liquid water (m/s) and \( D_{\text{cap}} \) is capillary diffusion coefficient (m\(^2\)/s).

For gas phases, bulk flow and binary diffusion are considered (Eq. 14).

\[ u_{\text{eff, g}} = u_g + D_{\text{eff, g}} \nabla c_g \]  

where \( u_{\text{eff, g}} \) is the effective velocity of gas (m/s), \( u_g \) is Darcy velocity of gas (m/s) and \( D_{\text{eff, g}} \) is diffusion coefficient for gas (m\(^2\)/s).

### 3.2.2. Heat transfer

The conservation of energy in the domain is described using Eq. 15 (Bird, et al., 2002).
\[ \rho_{\text{eff}} c_{\text{p,eff}} \frac{\partial T}{\partial t} + \nabla \cdot \left( -k_{\text{eff}} \nabla T + \rho_{\text{eff}} c_{\text{p,eff}} u_{\text{eff}} \cdot T \right) = \pm R_i M_w \lambda + Q \tag{15} \]

where \( c_{\text{p,eff}} \) is specific heat capacity \((J/kg.K)\), \( k_{\text{eff}} \) is thermal conductivity \((W/m.K)\), \( \rho_{\text{eff}} \) is density \((kg/m^3)\) of the porous domain, \( \lambda \) is the latent heat of evaporation \((2.26 \times 10^6 J/kg)\) and \( Q \) represents the heat generated by electricity \((J/m^3 s)\). The effective thermal conductivity, density and specific heat capacity of the porous material were calculated using the following mathematical expressions based on volume or mass fractions of different phases were used for this calculation (Eq. 16-18) (Halder, et al., 2007).

\[
\rho_{\text{eff}} = \phi(S_g \rho_g + S_w \rho_w) + (1 - \phi) \rho_s \tag{16}
\]

\[
c_{\text{p,eff}} = x_g(\omega_o c_{p,v} + \omega_a c_{p,a}) + x_w c_{p,w} + x_s c_{p,s} \tag{17}
\]

\[
k_{\text{eff}} = \phi[S_g(\omega_v k_v + \omega_a k_a) + S_w k_w] + (1 - \phi) k_s \tag{18}
\]

where \( c_p \) is specific heat capacity \((J/kg.K)\), \( k \) is thermal conductivity \((W/m.K)\), \( \rho \) is density \((kg/m^3)\) and the subscripts \( g, v, a, w \) and \( s \) correspond to gas, water vapour, air, water and solid fractions in potato slice, respectively. Density \((\rho)\) of the phases was calculated using ideal gas law (Eq. 19),

\[
\rho_i = \frac{p_i}{RT} M_i \tag{19}
\]

where \( p_i \) is the partial pressure \((Pa)\), \( R \) is the ideal gas constant \((8.314 J/K.mol)\), \( T \) is the temperature \((K)\), and \( M_i \) is the molar mass of the related phase \((kg/mol)\).

For the case of constant voltage, the heat generated by electric current \((Q)\) is described by Eq. 20 (De Alwis & Fryer, 1990; Sastry & Palaniappan, 1992).

\[
Q = \sigma |\nabla v|^2 \tag{20}
\]

\[
\sigma = 0.25(1 + 0.030(T - 298.15)) \tag{21}
\]

where \( \sigma \) is electrical conductivity of materials \((S/m)\) from Palaniappan, et al. (1991) (Eq. 21) and "v" represents the voltage \((V)\) applied to the system. A strong relation between the electrical conductivity of material and its moisture content has been previously reported (Icier & Ilicali, 2004).

Thus, it is required to express change of electrical conductivity of potato slices as a function of moisture content. However, no available data about the electrical conductivity of potatoes at very
low moisture content is in the literature. But Lewicki (2004) reported that electrical conductivity of solid foods is considerably low for water activities below 0.75-0.80. This water activity level corresponds to 0.15-0.30 dry basis moisture content at around room temperature according to the sorption isotherms (Kaymak-Ertekin, et al., 2004). This range of moisture contents is glass transition levels for potato (Benczédi, Tomka, & Escher, 1998). So, we consider glass transition moisture levels for potatoes to find the moisture effect on electrical conductivity. To define moisture dependence of electrical conductivity, a moisture correction factor ($\mathcal{K}$) was added into Eq. 20.

$$Q = \mathcal{K}\sigma|\nabla v|^2 \tag{22}$$

The $\mathcal{K}$ describes moisture dependency of sample’s electrical conductivity (Eq. 23). It was derived by making an analogy to the expression for $\kappa_{r,w}$ which is used to formulate the moisture dependence of $\kappa_{m,w}$ (Bear, 1972). Benczédi, et al. (1998) denotes that glass transition moisture ranges between 0-0.30 depending on the temperature of starchy tissue (potato). But Gulati and Datta (2015) say full transition at sample surface can be observed at 0.25 moisture ratio (about 1.13 dry basis moisture content) depending on the process conditions. Thus, it was decided to use glass transition moisture content as a limit moisture content ($m_{db,\text{lim}}$) for available electrical conductivity (Eq. 23). As a result, there is no electrical current at regions where moisture content was lower than $m_{db,\text{lim}}$. In the present study, a series of simulation was performed for $m_{db,\text{lim}}$ ranging from 0.20 to 1.0.

$$\mathcal{K} = \begin{cases} \left[\left(\frac{m_{db}-m_{db,\text{lim}}}{m_{db,0}-m_{db,\text{lim}}}\right)^3, m_{db} > m_{db,\text{lim}} \right] \left[0, m_{db} < m_{db,\text{lim}}\right] \end{cases} \tag{23}$$

where $m_{db,0}$ is the initial moisture concentration of sample (dry basis).

The electrical potential distribution can be computed using the Laplace equation (Eq. 24) (De Alwis, et al., 1990).

$$\nabla \cdot \sigma \nabla v = 0 \tag{24}$$

Figure 3 shows a brief list of the equations used in the developed model.

3.3. Initial and boundary conditions
The initial moisture contents \((m_{db0})\) of the potato slices are in Table 1. Since different potato tubers were used to prepare potato slices, there are three different \(m_{db0}\) values (3.21, 3.91, 4.05 g moisture/g dry matter) in Table 1. This variation in the initial moisture content due to tuber differences was considered and introduced in the model where it was necessary (Figure 4-5). Total pressure at all surfaces was set to ambient pressure \((P_{amb}=1 \text{ atm})\) for Darcy’s flow. In the model, Darcy’s pressure was calculated by the ideal gas law based on concentrations of vapour and air. So, as suggested by Chen, Pitchai, Birla, Negahban, Jones, and Subbiah (2014), air concentration was defined on the boundary according to the water vapour pressure to make the total boundary pressure to be atmospheric pressure instead of defining pressure at the boundaries.

\[
P_{sur} = P_{amb}
\]  
(25)

The initial temperature of potato \((T_0)\) slice was assumed to be uniform and equal to the environmental temperature given in Table 1. These \(T_0\) values were obtained by measuring the room temperature just before each trial and introduced to the model.

The vapour and liquid water flux from the food surface to the ambient air can be calculated as follows (Eq. 26 and Eq. 27). In volumetric heating techniques, some drip loss can also be experienced when the liquid water saturation becomes high \((S_w=1, \text{ Eq. } 27)\) (Rakesh, et al., 2012).

\[
n_{v, sur} = c_v u_n, uv + h_m \phi S_w (c_v - c_{v, oven}) \quad \text{Removal of vapour from boundaries due to internal pressure and diffusion}
\]  
(26)

\[
n_{w, sur} = h_m \phi S_w (c_v - c_{v, oven}) \quad \text{Evaporation of liquid water from sample boundaries}
\]  
(27)

\[
n_{w, sur} = h_m \phi S_w (c_v - c_{v, oven}) + \left( c_w u_n, w \right)_{S_w=1} \quad \text{Loss of liquid water due to drip loss}
\]

where \(h_m\) is the mass transfer coefficient \((m/s)\) and calculated using Lewis number from heat transfer coefficient \((h_t)\) (Çengel & Ghajar, 2014), \(c_{v, oven}\) is the vapour concentration in the oven. It is calculated from the relative humidity \((RH\%_{oven})\) of air in the oven at set temperature. The \(RH\%_{oven}\) is determined by conversion of the relative humidity \((RH\%_{ambient-air})\) of ambient air at the date of experiments using the psychrometric chart from Singh and Heldman (2001) (Eq. 28).
\[ c_{v,\text{oven}} = \left( \frac{R \times H\%_{\text{oven}} \times P_{\text{sat}} \times T_{\text{oven}}}{R 	imes T_{\text{oven}}} \right) \]  

(28)

To calculate heat transfer from the surfaces Eq. 29 is applied.

\[ q_{\text{sur}} = \frac{h_T(T - T_{\text{oven}})}{\text{Heat transfer due to external air flow}} - \frac{n_{\text{v,SW}} M_w c_{p,v} T}{\text{Heat loss due to removal of vapour}} \]

\[ - h_m \phi S_w M_w (c_v - c_{v,\text{oven}})(\lambda + c_{p,v} T) - \left( c_w u_{n,w} \right) M_w c_{p,v} T \bigg|_{S_w=1} \]

Heat loss due to evaporation and removal of liquid water

Heat loss due to drip loss

where \( h_T \) is average heat transfer coefficient (W/m\(^2\)K) which is calculated as a function of oven temperature and hot air velocity, (i) 0.74 m/s at 50 °C, (ii) 1.55 m/s at 50 °C, (iii) 2.15 m/s at 50 °C and (iv) 2.15 m/s at 60 °C (for details please see Table 1) using Eq. 30 from Çengel, et al. (2014) for Reynolds number (\( RE \)) < 5 x 10\(^5\) and Prandtl number (Pr) > 0.6.

\[ Nu = \frac{h_T L}{\kappa_a} = 0.0664 \times R e^{1/2} \times P r^{1/3} \]  

(30)

where \( Nu \) indicates dimensionless Nusselt number (Çengel, et al., 2014). The approach velocity used to calculate heat and mass transfer coefficients and it was measured using an anemometer (AN100, Extech Instruments, Melrose, MA) at different fan powers and given in Table 1. All boundary conditions given above are applied for all surfaces except the symmetry boundaries and electrode surfaces. For boundaries where the potato is in contact with electrodes, the following boundary conditions are used.

\[ v = \begin{cases} 
0 & \text{at neutral electrode} \\
75, 100 \text{ and } 125 \text{ V where appropriate} & \text{at phase electrode}
\end{cases} \]  

(31)

and for other boundaries, there is no electrical current (i.e., insulation boundary).

\[ \nabla v = 0 \]  

(32)

### 3.4. Model solution and validation

The model describing CD was firstly developed and it was used as the base model for OAD modelling studies, as well. Electrical current physics was built on the base model to describe the effect of ohmic heating. The partial differential equations for OAD and CD of potato were solved using finite
elements method with commercial software COMSOL Multiphysics® (5.3a, Burlington, USA). The model parameters used are presented in Table 1. The 3D geometry was created and meshed with COMSOL software. Mesh sensitivity analysis was performed by a number of series of mesh refinement until no longer mesh density has an impact on the simulation result (in terms of the change of moisture content) (A. Kumar & Dilber, 2006). For mesh sensitivity, seven simulations were conducted with changing number of elements between 1071 and 27875. The mean absolute error between the results of following simulations were calculated until it was reduced under 0.05 (which is the linearity level of the used weight balance). The mean absolute error was calculated as 0.023 between the two high dense meshes (Figure 4). Therefore, the highest mesh density was preferred to increase solution accuracy. The model was validated against the experimental data. To evaluate the goodness-of-fit between experimental data and predictions, the standard error of estimate (SEE) was calculated using Eq. 33.

\[ SEE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (x_p - x_e)^2} \]  

(33)

where \( n \) is the total number of the data, \( x_p \) and \( x_e \) are predicted and measured results. A fully coupled time dependent solver (with the direct linear PARDISO solver and 1 min of time stepping) was used to solve the partial differential equations. The relative tolerance of the time dependent solver was 0.001.

4. Results and discussion

4.1. Effect of ohmic heating

The combined ohmic heating and hot air drying system (OAD) showed a high performance in drying potato slices in terms of drying time. It was around 155 to 200 min for convective drying (CD) to attain the desired final moisture content \( (m_{db}=0.1) \) at different drying parameters. OAD reduced drying time by 20-60% under the same conditions.
The typical drying curves for CD of potato samples can be seen in Figure 5. The curve starts with rapid dehydration and continues with decreasing rate. Although similar trends have been observed for different drying processes, they differ from each other depending on process conditions such as air velocity and temperature (Akpinar, Midilli, & Bicer, 2003). In addition to the effects of air velocity and temperature, the effect of hybrid ohmic heating on drying was also investigated in the present study (Figure 5). With the inclusion of ohmic heating, drying process achieved higher rates compared to CD. This increase in drying rate is clearly seen in Figure 5. Similarly, process times were shortened in previous studies using ohmic heating as a potato drying pre-treatment (Lebovka, Shynkaryk, & Vorobiev, 2006). The positive effect (time reduction) of ohmic heating on drying can be attributed to different reasons. The most common one is the structural changes in potato sample, also referred to as “tissue damage”. The tissue damage as a result of the electrical field is caused by electroporation (Lebovka, et al., 2006; Lebovka, Shynkaryk, & Vorobiev, 2007). Some structural changes in potato tissue caused by electroporation have been reported even for very low voltage levels. For electrical field values ≥20 V/cm, a considerable increase in conductivity disintegration index (an indicator of electrically induced tissue damage) was observed for potatoes during ohmic heating using alternating current (Lebovka, Praporscic, Ghnimi, & Vorobiev, 2005). Moreover, as the applied voltage and medium temperature (between 20-50 °C) increased more robust tissue damage were reported (Lebovka, et al., 2005; Lebovka, et al., 2006). When the distance between mutual electrodes (which was about 35 mm giving approximately 21-36 V/cm electrical field for 75-125 V) and higher sample temperatures far above 50 °C (Figure 11) is considered when ohmic heating is active, electrically induced tissue damage during OAD treatment seems to be inevitable. During processing, tissue damage stimulates water release from the cell wall, and this enhances the transport phenomena. As a result, the drying rate increases. Indeed, changes such as density, porosity and textural properties of samples that improve drying performance were detected after application of ohmic heating (Bastías, Moreno, Pia, Reyes, Quevedo, & Muñoz, 2015; Icier, et al., 2017; Kamali & Farahnaky, 2015; Lebovka, et al., 2007). The enhanced diffusivity of water through the tissue is associated with these
structural changes (Lebovka, et al., 2006). However, for simultaneous use of ohmic heating with CD, the major contributing factor is not the structural changes in potato tissue. It is rather due to very rapid heating of drying material by ohmic heating. As known, ohmic heating is a volumetric heating method like microwave application. In volumetric heating methods, temperature of the all heating domain increases too fast (Rakesh, et al., 2012). In our study, this very fast heating promoted the water removal from the sample and decreased drying time. The deeper understanding of how simultaneous ohmic heating affects drying is given in the following sections.

4.2. Model validation

Experimental validation of a mathematical model is critical since it is a successful indicator of the viability and reliability of the model predictions. So, in the present study, validation was done by comparing the experimental results (average moisture content ($m_{ab}$) and surface temperature (belong to pale area as shown in Figure 2-b)) with model predictions. Figure 6 shows experimental validation for two different drying systems (i.e. CD and OAD).

Determining the right value for $m_{ab,lim}$ is a part of model validation in our study. Since the most suitable value for $m_{ab,lim}$ is not available in reported studies, we made a series of simulation to determine it. In those preliminary simulations, $m_{ab,lim}$ was changed in the range of 0.20 to 1.0 (The reason for this range was previously explained under section “3.2.2. Heat transfer”). The most suitable $m_{ab,lim}$ value was determined according to $SEE$ values. Figure 6 shows the results of these simulations (the change of moisture content and temperature of potato slices according to $m_{ab,lim}$ value of 0.3, 0.5, and 1.0) (all results were not given for figure readability and clarity). Among all trials, the most suitable choice for $m_{ab,lim}$ value is 0.3, since it gives the smallest $SEE$ values almost for every simulation corresponding to moisture data (Figure 6). Thus, all results in Figure 5-b and Figures 10-13 were plotted using $m_{ab,lim}$ value of 0.3. As it can be seen from Figure 5 and Figure 6, drying curves for OAD consists of two regions. The first region is observed due to high product temperature as a result of ohmic heating. This region will be referred to as “accelerated drying step” in the
remainder of the paper. The accelerated drying step roughly corresponds to the combination of heating, streaming and enthalpic periods of drying (Perré & Turner, 1997). The second region relates to the period in which OAD starts losing its activity and system behaves as CD, during which the sample’s temperature drops to a level around oven temperature. The characteristics of this region are very similar to convection drying, so it will be called the “regular drying step”.

Temperature change of potato’s top surface was predicted by the developed models for CD and OAD systems (Figure 6). Similarly, average moisture content of whole potato slice was also predicted, and the results were properly overlapped with their experimental measurements. However, the predicted temperature values were not in a good agreement with experimental ones for the regular drying step (Figure 6). This problem is most probably due to the difference between empirically calculated \( h_T \) values (it calculates mean for all surfaces of potato slice) and its real values (it varies according to different drying surfaces of potato slice). Due to the electrodes, fasteners and the polyethylene base plate, the air flow rate is lower on the potato bottom and leeward surfaces than the potato top and windward surfaces. Undoubtedly, this leads to rapid drying and rapid temperature increases on surfaces where air flow is faster. So, in real life, both \( h_T \) and \( h_M \) should be higher for top and windward surfaces. But in the mathematical model, an average \( h_T \) and \( h_M \) are calculated from empirical correlations, in which approach velocity of air flow in the drying tunnel is used, and the results are applied to all potato’s surfaces. The use of an average \( h_M \) is not a problem when moisture content is followed, since experimental moisture data expresses the whole sample. However, the calculated \( h_T \) value is not able to adequately represent the upper surface where temperature measurements are taken using a thermal camera like in our study. Thus, \( h_T \) value remained lower than that achieved in laboratory experiments. As a result, model predictions for temperature are always lower than the experimental values and it becomes more apparent at higher velocities where \( h_T \) is higher and more effective (Figure 6). For OAD experiments, the deviation between experimental measurements and model predictions is smaller. This deviation only appears for the regular drying step, not for the accelerated drying step. This can be attributed to the
dominant characteristics of ohmic heating which suppresses other heat transfer mechanisms such as convection and conduction. In the OAD system, when ohmic heating is effective, the convective heat transfer effect on the potato surface remains relatively weak (Figure 7). As previously described, temperature of the product is mainly controlled by electrical energy rather than conduction and convection during the ohmic heating active periods (Goullieux, et al., 2005; Jun, et al., 2005). That is why temperature outputs of the model are more prophetic at the accelerated drying step. On the other hand, according to measurements carried at lower voltage levels (75 V, 100 V) than 125 V in the experiments, slice’s surface temperature reaches its local maximum later than model prediction’s. In other words, in experiments carried at voltage levels less than 125 V, heat generation by ohmic heating is slow and the related temperature rise is also slow. Thus, most of the produced energy is consumed by evaporation. As seen from Figure 8-a, only for OAD at 125 V, at the beginning of the process, the heat generated by electric current is not consumed by evaporation. On the contrary, vapour condensation is superior to evaporation. This is because of very high-pressure levels observed (Figure 8-b) in potato following rapid temperature increase. On the other hand, at lower voltage levels, heat generation is slower than that observed for 125 V and the generated heat is mainly consumed by evaporation compared to condensation. Slow heat generation is more apparent for 2.15 m/s, 50 °C, 100 V and 2.15 m/s, 60 °C, 75 V. This is attributed to the structural/spatial differences (such as moisture, ion content) between and/or within potato tubers/slices. The images in Figure 10 support the effect of these structural/spatial changes on temperature profile. Thermal images show the different temperature regions on the measuring surface (lower on the regions close to sides and higher on the middle region) and these differences disappear with time progress (Figure 10).

4.3. Spatial variation of temperature during drying

Temperature profile in the products during ohmic heating is an important challenge for a process design, especially in the case of non-homogeneous electrical field distribution depending on sample
properties or system geometry. Because variations in the electric field on different regions may result in local over or lower-heating. Over-heating causes quality loss. Similarly, due to over-heating and the related rapid temperature rises between electrodes (especially at the locations close to electrode surfaces), rapid drying and the related burned surfaces were clearly observed in our experiments (Figure 9). When the moisture level is sufficiently low, material transforms from rubbery state to glassy state. This change significantly decreases the water permeability through the domain (Gulati, et al., 2015), and it also decreases electrical conductivity. Considering these challenges, the electrode geometry is usually adapted to the product properties to achieve the best possible uniformity for heating (Jaeger, et al., 2016). Moreover, overshoot at electrode contact surfaces arises especially at 125 V (Figure 9-b). This overshoot causes burned regions around electrodes and results in a rapid decrease in conductivity. So, voltage levels lower than 100 V is preferable to use at OAD.

To better understand the spatial temperature change of the samples, temperature maps for top surface (both experimental and predicted) and interface (only predicted, since in-situ monitoring is not possible for ohmic system.) were presented in Figure 10 and Figure 11, respectively. For clarity, temperature maps for all computations are not presented. They are given up to 5 min since spatial variations of temperature become insignificant for times longer than 5 min. A similar case is also valid for pressure and moisture maps which are presented in the following sections (Figure 12 and Figure 13). To compare top surface temperature maps created for the experimental and predicted results, Figure 10 and Figure 11 are used. Both figures present temperature change of the top surface of potato slice for 5-min period in 1-min intervals. Regional warming paths for the same period during the process are similar for temperature maps corresponding to experimental and predicted ones. For example, in the first minute of the process, temperature rise starts, and heating regions are seen as bands, but they do not cover a wide surface (Figure 10). Similar heating behaviour for the predicted potato surface is observed (Figure 11). At the following second minute, heating regions are clear and wider (Figure 10), which is also valid for predictions given in Figure 11. At the end of the 5-min heating period, cooling started and the temperature decreased on the surface (Figure 10). This
cooling period can be easily seen in Figure 11. Heating and cooling behaviours were monitored experimentally. Although the model estimates are similar, there are still some differences in the time shifting and regional temperature profiles between Figure 10 and Figure 11. Since ohmic heating is a volumetric heating method, a potato volume between electrodes (the areas where the electric current passes) is heated almost simultaneously, except for some delays between the electrodes. These delays are thought to be due to changes in spatial humidity and electrolyte concentration in potato slices. Because the non-homogeneous nature of foodstuffs affects the electrical conductivity and temperature profile (Içler, 2014).

Figure 10 and Figure 11 also show the effects of voltage on drying. With higher voltage gradients, the heating rate increases. For both experimental measurements and model predictions, temperatures are higher at 125 V than at 100 V, regardless of drying air characteristics (flow rate and temperature). On the other hand, as seen in Figure 8-a, the condensation rate is higher at 125 V than at 100 V at the beginning of the OAD process. This can be attributed to the rapid pressure increase in the potato slice due to the sudden temperature rise (Figure 8). The excessive pressure causes an increase in the condensation rate of the vapour and a decrease in the evaporation rate of water in the potato slice. As the evaporation rate decreases, more of the energy is used to increase the slice’s temperature.

When electric energy was applied, there was a considerable rise in temperature not only at the surface but also in the interior locations. It is the most important difference between OAD and CD systems. This difference (between convection and volumetric heating methods) is due to the phenomena of volumetric or bulk heating (Constant, Moyne, & Perré, 1996; Perré, et al., 1997; Rakesh, et al., 2012; Turner & Jolly, 1991). In convective heating, higher temperatures are first observed in regions close to the boundaries and the heating rate increases when the moisture content falls below saturation (T. Defraeye & Radu, 2017). However, as seen in Figure 11, in OAD heating starts in the volume, especially between the electrodes. On the other hand, when volumetric heating methods are used, internal temperature may exceed the boiling point of water (Rakesh, et
It has been reported that in microwave combined drying, porous materials’ temperature can reach levels above 150 °C (Perré, et al., 1997), which is similar to our study, particularly for higher voltage levels (>100 V) (Figure 11). If such high temperature values are a problem for the product quality, lower voltages and/or intermittent current regimes can be applied in the case of ohmic heating.

According to the simulation results, OAD has significant effects not only on the internal heat transfer of potato slices but also on the heat transfer or loss at product boundaries. At the beginning of OAD (when ohmic heating is active), heat transfer from surrounding air to the potato surface is redeemed by ohmic heating. It is because of the higher temperatures attained on the product surface than the drying air’s temperature. In the process at 125 V, convectional heat transfer from the potato surface to the drying air was observed for a limited time. As time progressed, ohmic heating effect decreased due to the reduced moisture content and external heat transfer became important.

4.4. Spatial variation of moisture during drying

Moisture distribution in material and its level are two critical factors for food manufacturers. Because moisture directly affects the microbial/chemical safety and product quality as well as the process design. Furthermore, during the following storage period, environmental conditions are determined mostly in accordance with the product’s moisture content. The overall moisture loss from samples during OAD and CD were previously presented in Figure 6. For CD, the moisture loss mainly occurs from the surfaces, as interior locations remain wet during the drying. In this type of drying, the dominant mode of water transport is related to the capillarity that takes liquid water to surfaces. The effect of pressure-driven flow and binary diffusion of the vapour is practically insignificant since interior spaces are not sufficiently heated (Rakesh, et al., 2012). This explains why reaching the target moisture content in CD is longer than the required one in the OAD system. During OAD, higher amounts of moisture were removed from the samples in a short time. This is due to improved water evaporation as a result of higher energy generation in drying material. Therefore, the mechanisms
related to OAD are different from CD. As a result of interior heating, most of the liquid water evaporates in the potato (not on the surfaces). Then, water vapour is transported throughout the pores to the borders from the inside. This transport is accomplished by pressure-driven flow and binary diffusion. During accelerated evaporation, a significant overpressure builds up around the material’s core. Similar results have been reported for volumetric heating methods in previous studies (C. Kumar, Joardder, Farrell, & Karim, 2016; Perré, et al., 1997; Rakesh, et al., 2012; Salagnac, Glouannec, & Lecharpentier, 2004). The overpressure promotes the water transfer from the core region of the porous sample to the surface (Salagnac, et al., 2004). As seen in Figure 12, as the applied voltage increases from 100 V to 125 V, the evaporation of water is significantly accelerated at the locations between electrodes where there is a rapid temperature increase as well as overpressure (Figure 8 and Figure 13). These phenomena are seen in Figure 7, as well. The ratio of the energy consumed to remove the liquid water from the slice’s surface (ERW, corresponds to the energy consumed for evaporation of water on the surface in liquid state then removal of it) to the energy required to remove the water vapour (RV, corresponds to the energy consumed for removal of water in vapour state) from the surface varies depending on the process conditions. As the applied voltage increases, the ERW ratio decreases and the RV ratio increases simultaneously. This behaviour shows us that at lower voltages, more energy is used for ERW and less energy is used for RV. Because, as the voltage increases, more liquid water evaporates inside the potato slices and moves towards the surface as vapour. This is undoubtedly due to the higher internal heat generation and temperature-dependent pressure increase. Therefore, the amount of water vapour on the sample surface increases as the voltage increases. However, the amount of liquid water on the surface decreases over time with drying. As a result, the energy consumed for ERW decreases (since the water in liquid state decreases at surfaces) till the end of drying. At the same time, the energy consumed for RV increases (since the water in vapour state increases at surfaces) For CD (Figure 7-a), heat transfer mechanisms are completely different at surfaces compared to OAD. External convectional heat transfer is the only dominant mechanism for CD (as previously explained, pressure-
driven flow and binary diffusion are superior during accelerated drying step in OAD). During CD, the energy which is taken by the potato from the surrounding hot air is used for ERW at the beginning of drying (constant rate period). However, as the liquid water content on the potato surface decreases in time, the energy required for ERW decreases (since the water in the liquid state decreases at surfaces) and the energy required for RV increases (since the water in the vapour state increases at surfaces), relatively.

In the regions where the ohmic heating is not effective, temperature and pressure increases remain limited (Figure 10, Figure 11, and Figure 13). As a result, the rate of moisture removal is lower. The moisture transfer from the surface of these regions is not equivalent to water transfer from inner regions where ohmic heating is superior. Thus, water accumulation occurs on potato surfaces, resulting in higher moisture content in these regions (even higher than the initial level). It has been previously reported that this is undesirable during food processing. Because it can lead to the formation of soggy surfaces which is characteristic for microwave combined drying (Rakesh, et al., 2012). Apart from applied voltage, air velocity and temperature have noticeable impacts on the water accumulation at sample’s boundaries (surfaces). In our study, when their levels were increased from 0.74 m/s and 50 °C to 2.15 m/s and 60 °C, moisture content at the soggy regions compatibly decreased. This is due to more elution of water from surfaces when $h_f$ and $h_m$ were changed depending on process conditions.

The enormous water transfer from sample’s core to the surfaces also affects the electrical properties of the foodstuff. Because immediately after the ohmic heating is applied, the liquid water content decreases rapidly, electrical conductivity of fast drying regions decreases and ohmic heating efficiency is lost. Then, especially when the medium temperature drops, the drying characteristics become similar to those of CD.

In volumetric heating techniques, some drip loss may also be experienced when the liquid water saturation becomes high ($S_w=1$) (Rakesh, et al., 2012). However, according to the simulations results,
no energy consumption is observed for drip loss (Figure 7). Because $S_w$ never reaches full saturation at the sample’s boundaries. So, this term can be neglected for the current system. However, if the materials to be dried have (i) higher initial moisture content, (ii) higher water permeability and (iii) lower air velocity, the drip loss term may gain importance. Thus, it is beneficial to be considered for future studies.

4.5. **Spatial variation of pressure during drying**

Figure 13 presents pressure distribution for the top surface and the interface of the potato slices during OAD. Briefly, pressure distribution follows an almost similar pattern to temperature distribution. This is because these two parameters (pressure and temperature) are strongly dependent on each other. In other words, temperature increases when ohmic heating is active which causes accelerated evaporation. Higher evaporation in the inner region of the sample causes overpressure. This situation is induced by a high electrical heating rate. Due to evaporation, the internal pressure of the product is higher than at boundaries. Near the electrodes where the effect of ohmic heating is strong, the internal pressure reaches up to 2.37 atm (gauge). Such a high pressure level (up to 4 atm gauge pressure) was previously reported during combined microwave-convection drying of softwood materials (Perré, et al., 1997). For foodstuffs, comparably lower overpressures have been reported for microwave drying (C. Kumar, Joardder, Farrell, & Karim, 2016; Rakesh, et al., 2012; Salagnac, et al., 2004). This difference between the pressure levels found in the literature and ours may be attributed to different heating rates due to varying powers and structural behaviour of materials such as texture. Porous tissue is getting harder with simultaneous water loss. Thus, water transport gets weaker and results in higher interior pressure levels (Gulati, et al., 2015; Perré, et al., 1997). However, at relatively colder regions, e.g. sample edges where electrical current is relatively low, the pressure is close to the atmospheric pressure or slightly higher. This case is due to the vapour transport from core region in addition to the limited evaporation.

4.6. **Perspective**
In the present study, the system based on the simultaneous use of ohmic heating with convectional drying was developed and its effect was assessed in terms of process performance. According to the results, OAD system has a positive impact on the reduction in drying time. It is thought that, this achievement in drying process of plant material is originated not only from the electrically induced structural changes in plant tissue but also from the changes in the transfer mechanisms that occurred as a result of internal temperature and pressure increase. In addition to the reduction in drying time, simultaneous use of ohmic heating with convectional drying may have some advantages compared to its use as a pre-treatment. For instance, the hybrid system of ohmic heating-convectional drying can omit the requirement of blanching the plant materials for enzyme inactivation. As known, blanching is a common pre-treatment method that is applied to ensure the desired colour, texture and flavour of potatoes during further processes like drying, frying, canning, storage. It also improves drying performance (Leeratanarak, Devahastin, & Chiewchan, 2006; Moreno-Perez, Gasson-Lara, & Ortega-Rivas, 1996; Pimpaporn, Devahastin, & Chiewchan, 2007; Reis, 2017). The use of ohmic heating and its positive effects on products was previously reported and it was suggested as an alternative to blanching (Icier, 2010; Lebovka, et al., 2006; Zhong, et al., 2003). However, most of the ohmic heating pre-treatments are conducted in water/juice which is then discarded and not used (Icier, 2010; Icier, et al., 2017; Jaeger, et al., 2016). This environmental problem can be avoided with the use of ohmic heating simultaneously with convectional drying. Besides, due to the increase in temperature of the majority part of the sample volume over the level for starch gelatinisation, pre-gelatinised materials can be achieved at the end of the OAD without any additional treatment. This may also be beneficial for the convenience food industry (soup powders, dough mixtures etc.) since it supplies pre-gelatinisation for starchy foods which need to be dried.

5. Conclusion

In the present study, the combination of simultaneous ohmic heating with convectional drying (OAD) was introduced. Efficacy of the OAD system was assessed experimentally. A deeper understating of
the system was achieved by means of the developed mathematical model. The three-dimensional mathematical model consists of coupled heat, mass, momentum transfer and heat generation due to ohmic heating in the porous media. A non-conjugate, macroscopic, non-equilibrium modelling approach was followed. The key conclusions from the work are summarised as follows. (1) OAD is a promising technique to increase the drying rate of food materials. Drying time was shortened by 20-60% compared to CD. However, its efficiency disappears in the regions where the moisture content drops under a certain level. This is due to the reduction in the electrical conductivity of the material depending on moisture content. (2) There are two distinct stages appeared during OAD, which are named “accelerated drying step” and “regular drying step” in the present study. Because of the volumetric heating during the accelerated drying step, drying curve differs from that is observed in CD. (3) According to the validation results, the prediction ability of the model is satisfying. Thus, simulated temperature, moisture and pressure distributions can serve researchers a deeper understanding of OAD system and its improvement and optimization. (4) Due to the high evaporation rate during ohmic heating (which is the dominant heat source), different mass transfer mechanisms take place. During OAD, pressure-driven flow and binary diffusion are rather dominant instead of capillary flow of water. The former one is superior for CD. (5) Ohmic heating also causes overpressurised regions. This leads to the water movement to the colder regions where pressure is also lower. However, simultaneous convective mass transfer of water from the surface cannot compensate for this accumulation. This may cause the formation of unfavourable soggy locations. Overall, with some promising improvements, the OAD system can be used to increase the effectiveness of the drying process.

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**Author Contribution Statement**

**Sebahattin Serhat Turgut:** Conceptualization, Methodology, Writing - Original Draft  
**Erdoğan Küçüköner:** Funding acquisition  
**Abraham Hailu Feyissa:** Supervision, Writing - Review & Editing  
**Erkan Karacabey:** Supervision, Writing - Original Draft, Funding acquisition

**Declaration of interests**

☐ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☒ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

- “The Scientific and Technical Research Council of Turkey (TÜBİTAK)”, Turkey (post graduate scholarship (2211-C))  
- “European Cooperation in Science & Technology (COST)” (Short Term Scientific Mission under action number: CA15118)

**References**


**Figure and Table Captions**

Figure 1 Schematic illustration of (a) the drying tunnel and the ohmic heating apparatus from (b) top view, (c) and (d) side views where red and black lines are phase/neutral power supply cables, respectively.

Figure 2 (a) Schematic illustration of ohmic cell and transport mechanisms for different phases, (b) installation and orientation of potato slice, (c) approximate slicing region of a tuber and (d) the computational domain for the drying simulations.

Figure 3 A summary of the model showing the governing equations, boundary and initial conditions and input data.

Figure 4 Sensitivity of moisture content against mesh density during drying where operating temperature, air velocity and applied voltage were 60 °C, 2.15 m/s and 100 V, respectively.

Figure 5 Drying curves for CD and OAD drying experiments (a) and model predictions (b) \((m_{db,lim}=0.30)\) for different air velocities [m/s], temperatures [°C] and voltage levels [V].

Figure 6 Comparison of experimental moisture and temperature data to model predictions for different processing conditions of (a) CD and (b-g) OAD (Exp.: experimental, Pred.: Prediction and SEE: standard error of estimate (Eq. 33); moisture content is given as g moisture/g dry matter).

Figure 7 Comparison of heat transfer or loss over external surface of potato the potato slice during drying at 2.15 m/s and 60 °C for (a) 0 V (convectional drying), (b) 75 V, (c) 100 V and (d) 125 V.

Figure 8 Comparison of (a) ratio of heat generated by ohmic heating in potato to change of heat with phase change of water and (b) average pressure in potato slice during the first 30 min of OAD.

Figure 9 Image of potato slice dried using OAD at (a) 100 V and (b) 125 V. The black spots are the regions (or close) of electrodes.

Figure 10 Experimental temperature maps of the top surface of potato slices for the first five minutes of OAD at different processing conditions (The average temperatures of the target measurement area (see Figure 2-c) are given on images).

Figure 11 Predicted temperature maps of top surface and interface of potato slices for the first five minutes of OAD at different processing conditions \((m_{db,lim}=0.30)\).

Figure 12 Predicted moisture contents (dry basis) of potato quarters for the first ten minutes of OAD at different processing conditions \((m_{db,lim}=0.30)\).

Figure 13 Predicted pressure maps of top surface and interface of potato slices for the first five minutes of OAD at 2.15 m/s, 60 °C and 100 V \((m_{db,lim}=0.30)\) (the gauge pressures are given in atm. To ensure scale consistency between interface and top maps, corresponding max and min pressure values were given for each interface map).

Table 1 Input parameters, symbols, and corresponding values with units.
### Table 1 Input parameters, symbols, and corresponding values with units

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<td>J/kg.K</td>
<td>(Choi &amp; Okos, 1986)</td>
</tr>
<tr>
<td>Water</td>
<td>$c_{p,w}$</td>
<td>4178</td>
<td>J/kg.K</td>
<td>(Choi, et al., 1986)</td>
</tr>
<tr>
<td>Vapour</td>
<td>$c_{p,v}$</td>
<td>2068</td>
<td>J/kg.K</td>
<td>(Choi, et al., 1986)</td>
</tr>
<tr>
<td>Air</td>
<td>$c_{p,a}$</td>
<td>1006</td>
<td>J/kg.K</td>
<td>(Choi, et al., 1986)</td>
</tr>
<tr>
<td><strong>Thermal conductivity</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solid</td>
<td>$k_s$</td>
<td>0.21</td>
<td>W/m.K</td>
<td>(Choi, et al., 1986)</td>
</tr>
<tr>
<td>Water</td>
<td>$k_w$</td>
<td>0.57</td>
<td>W/m.K</td>
<td>(Choi, et al., 1986)</td>
</tr>
<tr>
<td>Vapour</td>
<td>$k_v$</td>
<td>0.026</td>
<td>W/m.K</td>
<td>(Choi, et al., 1986)</td>
</tr>
<tr>
<td>Air</td>
<td>$k_a$</td>
<td>0.026</td>
<td>W/m.K</td>
<td>(Choi, et al., 1986)</td>
</tr>
<tr>
<td><strong>Intrinsic permeability</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water</td>
<td>$k_{in,w}$</td>
<td>$1\times10^{-16}$</td>
<td>m$^2$</td>
<td>(Datta, 2006) or our study</td>
</tr>
<tr>
<td>Gas</td>
<td>$k_{in,g}$</td>
<td>$1\times10^{-15}$</td>
<td>m$^2$</td>
<td>(Chen, et al., 2014)</td>
</tr>
<tr>
<td><strong>Relative permeability</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water (Eq. 34)</td>
<td>$k_{rw}$</td>
<td>$[(S_w-0.09)/0.91]^3$, $S_w &gt; 0.09$</td>
<td>W/m.K</td>
<td>(Bear, 1972)</td>
</tr>
<tr>
<td>Gas (Eq. 35)</td>
<td>$k_{rg}$</td>
<td>$1-1.1S_w$, $S_w &gt; 1/1.1$</td>
<td>W/m.K</td>
<td>(Bear, 1972)</td>
</tr>
<tr>
<td><strong>Diffusion coefficient</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water</td>
<td>$D_{cap}$</td>
<td>$1\times10^{-8} e^{(2.8+2m_{db})}$</td>
<td>m$^2$/s</td>
<td>(Ni, et al., 1999)</td>
</tr>
<tr>
<td>Gas</td>
<td>$D_{eff,g}$</td>
<td>$2.6\times10^6$</td>
<td>m$^2$/s</td>
<td>(Halder, et al., 2007)</td>
</tr>
<tr>
<td><strong>Viscosity</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Property</td>
<td>Symbol</td>
<td>Value</td>
<td>Unit</td>
<td>Source</td>
</tr>
<tr>
<td>-----------------------------------------------</td>
<td>--------</td>
<td>------------------</td>
<td>---------------</td>
<td>---------------------------------------------</td>
</tr>
<tr>
<td>Water viscosity</td>
<td>$\mu_w$</td>
<td>$0.988 \times 10^{-3}$</td>
<td>Pa.s</td>
<td>(Rakesh, et al., 2012)</td>
</tr>
<tr>
<td>Gas viscosity</td>
<td>$\mu_g$</td>
<td>$1.8 \times 10^{-5}$</td>
<td>Pa.s</td>
<td>(Rakesh, et al., 2012)</td>
</tr>
<tr>
<td>Latent heat of evaporation</td>
<td>$\lambda$</td>
<td>$2.26 \times 10^6$</td>
<td>J/kg</td>
<td>(Rakesh, et al., 2012)</td>
</tr>
<tr>
<td>Evaporation rate constant</td>
<td>$K$</td>
<td>10</td>
<td>$s^{-1}$</td>
<td>Model assumption</td>
</tr>
<tr>
<td>Water activity</td>
<td>$a_{w}$</td>
<td>Eq. 7</td>
<td></td>
<td>(Kaymak-Ertekin, et al., 2004)</td>
</tr>
<tr>
<td>Electrical conductivity</td>
<td>$\sigma$</td>
<td>Eq. 22</td>
<td>S/m</td>
<td>(Palaniappan, et al., 1991)</td>
</tr>
<tr>
<td>Volt</td>
<td>$v$</td>
<td>75, 100, 125</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>Heat transfer coefficient</td>
<td>$h_T$</td>
<td>Eq. 30</td>
<td>W/m$^2$K</td>
<td>(Çengel, et al., 2014)</td>
</tr>
<tr>
<td>Mass transfer coefficient</td>
<td>$h_m$</td>
<td>Calculated using Lewis number from $h_T$ (Eq. 30)</td>
<td>m/s</td>
<td>(Çengel, et al., 2014)</td>
</tr>
<tr>
<td>Final moisture for electrical conductivity</td>
<td>$m_{db,lim}$</td>
<td>0.3, 0.5, 1.0</td>
<td></td>
<td>Model assumption</td>
</tr>
</tbody>
</table>
Highlights

- A novel drying method, namely simultaneous use of ohmic heating with convectional drying, is introduced.
- Ohmic heating can accelerate drying by 20-60%, when combined with convective heating.
- A mathematical model consisting of heat, mass, momentum transfer with electric current physics was developed for drying of porous materials.
- The model can predict moisture and temperature changes during drying.
- A good agreement between the experimental and predicted results were obtained.
Figure 1C
Figure 2A
Figure 2B

Direction of drying air
Figure 2D
Drying Process

Governing Equations

Mass Transfer (Eq. 5)
- Water $c_w$

Momentum Transfer $u_i$ (Eq. 10)
- Gas $c_g$

Heat Transfer $T$ (Eq. 15)
- Vapour $c_v$
- Air $c_a$

Boundary Conditions
- $P$ (Eq. 25)
- $c_v$ (Eq. 26)
- $c_w$ (Eq. 27)
- $T$ (Eq. 29)
- $v$ (Eq. 31-32)

Initial conditions and Input data (Table 1)
Convectional drying
(0.74 m/s, 50°C and 2.15 m/s, 60°C)

Figure 5A
Figure 5B

Predicted (b)

Moisture content (g moisture/g dry matter)

Time (min)

- 2.15m/s, 60°C, 0V
- 0.74m/s, 50°C, 0V
- 0.74m/s, 50°C, 125V
- 1.55m/s, 50°C, 125V
- 2.15m/s, 50°C, 100V
- 2.15m/s, 60°C, 100V
- 2.15m/s, 60°C, 75V
- 2.15m/s, 60°C, 125V
Figure 6B

2.15 m/s, 60°C, 75V

Moisture content (dry basis)

- Exp.
- Pred. ($m_{db,lim}=1.0$, $SEE=0.18$)
- Pred. ($m_{db,lim}=0.5$, $SEE=0.13$)
- Pred. ($m_{db,lim}=0.3$, $SEE=0.13$)

Temperature (°C)

Time (min)
Figure 6C
Figure 6D

2.15 m/s, 60°C, 100V

- Exp.
- Pred. ($m_{db,lim}=1.0$, $SEE=0.23$)
- Pred. ($m_{db,lim}=0.5$, $SEE=0.16$)
- Pred. ($m_{db,lim}=0.3$, $SEE=0.15$)

Moisture content (dry basis)

Temperature (°C)

Time (min)
Figure 6E

0.74 m/s, 50°C, 125V

Moisture content (dry basis)

Exp.
Pred. ($m_{db,lim}=1.0, SEE=0.05$)
Pred. ($m_{db,lim}=0.5, SEE=0.06$)
Pred. ($m_{db,lim}=0.3, SEE=0.07$)

Temperature (°C)

0 20 40 60 80 100 120 140

Time (min)

Exp.
Pred. ($m_{db,lim}=1.0, SEE=6.98$)
Pred. ($m_{db,lim}=0.5, SEE=8.97$)
Pred. ($m_{db,lim}=0.3, SEE=11.99$)
Figure 6F

1.55 m/s, 50°C, 125V

Moisture content (dry basis)

- Exp.
- Pred. ($m_{db,lim}=1.0, \ SEE=0.20$)
- Pred. ($m_{db,lim}=0.5, \ SEE=0.11$)
- Pred. ($m_{db,lim}=0.3, \ SEE=0.09$)

Temperature (°C)

- Exp.
- Pred. ($m_{db,lim}=1.0, \ SEE=8.52$)
- Pred. ($m_{db,lim}=0.5, \ SEE=8.52$)
- Pred. ($m_{db,lim}=0.3, \ SEE=8.72$)

Time (min)
Figure 6G

2.15 m/s, 60°C, 125V

Moisture content (dry basis)

- Exp.
- Pred. ($m_{db,lim}=1.0$, $SEE=0.18$)
- Pred. ($m_{db,lim}=0.5$, $SEE=0.12$)
- Pred. ($m_{db,lim}=0.3$, $SEE=0.11$)

Temperature (°C)

- Exp.
- Pred. ($m_{db,lim}=1.0$, $SEE=7.69$)
- Pred. ($m_{db,lim}=0.5$, $SEE=7.55$)
- Pred. ($m_{db,lim}=0.3$, $SEE=7.83$)

Time (min)
Figure 7

Heat transfer/loss (W) over external sample surfaces due to:
- **External air flow**
- **Evaporation and removal of liquid water**
- **Drip loss**
- **Removal of vapour**

(+ values for \( q/q_{\text{total}} \) correspond to heat gained by potato slice
(-) values for \( q/q_{\text{total}} \) correspond to heat lost by potato slice

---

**External sample surfaces**
Figure 8A

- $Q$: Heat generated by electricity in model geometry (W)
- $(R_i M_W \lambda)$: Change of heat with phase change of water (W)

$(+) \text{ values for } \left[ \frac{Q}{(R_i M_W \lambda)} \right] \text{ correspond to evaporation dominates condensation}$

$(-) \text{ values for } \left[ \frac{Q}{(R_i M_W \lambda)} \right] \text{ correspond to condensation dominates evaporation}$
Figure 8B

Average pressure in model geometry (gauge, atm)

- 2.15m/s, 60°C and 125V
- 2.15m/s, 60°C and 100V
- 2.15m/s, 60°C and 75V
Figure 9A
Figure 11