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RESEARCH ARTICLE

Mathematical Modelling and Determination of Mass Transfer Characteristics of Celeriac Slices under Vacuum Drying

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Abstract
This study aimed at mathematical modelling and determination of mass transfer parameters of celeriac slices during vacuum drying at different temperatures and vacuum pressures. The usefulness of eight mathematical thin layer models to simulate the drying kinetics was examined and the Midilli-Kucuk model best described the drying curves with the minimum values of root mean square error and some of squares error. The effective diffusivity of the samples was obtained in the range of $2.1908 \times 10^{-10} - 8.9304 \times 10^{-10}$ (m^2/s). Diffusivity increased with increasing drying temperature and decreasing vacuum pressure. The obtained results showed that the convective mass transfer coefficient had ascendant trend during the drying process. Any increment in the drying temperature and vacuum pressure led to an increment and decrement in the convective mass transfer coefficient, respectively.

Keywords
vacuum drying, temperature, pressure, mass transfer, mathematical modelling

1 Introduction

Drying is an essential unit operation in a variety of industries e.g., food, pharmaceutical, chemical, plastic, timber and paper. The industries use drying equipments to eliminate moisture from the products for one or several of the reasons such as easy handling, safe preservation and longer storage, reduction in cost of transportation, desired quality, usage diversity and improved economical value [1]. Depending on the specific product attributes required, different industry sectors require different types of drying technology. Improper drying may lead to quality deterioration of product, high energy consumption, high process duration, unseasonable charges, etc. Hence, drying of high value and heat sensitive products such as food, pharmaceuticals and biological products demands special attention [2].

Most dryers can be classified as direct dryers and vacuum dryers. In direct dryers, hot air at atmospheric pressure is used to supply the heat to evaporate water or other solvents from the product whereas, vacuum dryers use a reduced-pressure atmosphere to surround the product. In comparison with conventional atmospheric dryers, vacuum dryers have some unique advantages e.g., higher drying rate, lower drying temperature, higher energy efficiency and oxygen deficient processing environment [3]. Some researchers have applied vacuum dryers to dry various food materials and investigated dehydration kinetic and quality attributes of dried products [4-7].

To predict drying behaviour of materials being dried, design new dryers, and control the process, mathematical modelling is widely used to simulate the drying process. The main proposed mathematical models used to describe the drying behaviour of agricultural materials are categorised as theoretical, semi-theoretical and empirical models. Theoretical models are built based on the understanding the fundamental phenomena and mechanisms involved during drying process whereas the two other models are built by fitting model parameters to experimental data using multiple linear regressions. Theoretical simulations can give an explanation for phenomena occurring during the process but, they are more difficult and require substantial amount of computing time. The empirical models are derived from a direct correlation between moisture content and drying

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time, and neglect fundamentals of drying process. The semi-theoretical models offer a compromise between theory and ease of application and generally are derived from direct solution of Fick's second law by assuming some simplifications [8].

Knowledge of effective moisture diffusivity and convective mass transfer coefficient is necessary for modelling and prediction of mass-transfer processes such as dehydration. In the literature, various complex models have been developed for foodstuffs. However, among the proposed models, simple analytical models are useful to offer optimal solutions for the operating process without undertaking experiments on the actual system [9]. To develop a drying model, at first, it is necessary to specify the main mechanism of water removing and governing resistance. In thermal drying, simultaneous heat and mass transfer phenomena are occurred. In this process, moisture transfer occurs in two forms of internal vapour evaporation and surface evaporation. Moisture is transferred from inside of the object to its surface by diffusion and from the surface to surrounding by convection. Therefore, effective moisture diffusivity and convective moisture transfer coefficient (CMTC) are the two important parameters of mass transfer required to be study. Some factors including drying method, drying conditions, physico-chemical properties of material, and initial moisture content of object affect these parameters [10]. Several researchers have determined the mass transfer parameters during drying process for different agricultural products. Tiwari et al. (2004) evaluated convective mass transfer coefficient of jiggery during greenhouse drying process [11]. Babalis and Belessios (2004) studied the influence of drying air temperature and velocity on the drying constants and moisture diffusivity of figs during thin layer drying [12]. Wu et al. (2007) investigated vacuum drying characteristics of eggplant slices at different chamber vacuum pressures and temperatures [3]. Dak and Pareek (2014) dried pomegranate arils using microwave-vacuum method and studied the effect of sample mass, vacuum pressure and microwave power on the moisture diffusivity [13].

The main objectives of this study were to 1) fit the experimental vacuum drying curves of celeriac slices to eight most used thin layer models available in the literature and find the best model, 2) determine moisture diffusivity and convective mass transfer coefficient of the samples and 3) investigate the effect of drying temperature and pressure on the mass transfer characteristics of the celeriac slices.

2 Materials and methods

2.1 Experimental data

In this study, the experimental data reported by Alibas (2012) for moisture content variation of celeriac slices during vacuum drying process was used. The researcher dried celeriac slices (57 mm in diameter and 3mm in height), with initial moisture content of 14.39 (kg $_{water}$/kg $_{dry\ matter}$) until leaf moisture content to 0.1 (kg $_{water}$/kg $_{dry\ matter}$), using a vacuum dryer at pressures of 0.1, 3, 7, 10, 13 and 17 kPa and temperatures of 55, 65, 75 °C [6]. For details of the celeriac slices drying in vacuum dehydration process, see Alibas (2012) [6].

Using Eq. (1), the moisture content data of the celeriac slices was converted to dimensionless moisture ratio (*MR*):

$$MR = \frac{M}{M_0} \tag{1}$$

where M and M_0 are instantaneous moisture content at each time (kg $_{water}$/kg $_{dry\ matter}$) and initial moisture content (kg $_{water}$/kg $_{dry\ matter}$) of the samples.

2.2 Mathematical modelling

To describe drying curves of the samples, the eight widely used mathematical models were selected (Table 1). Curve fitting tool of MATLAB 7.10 (MathWorks, Inc., Natick, MA) and nonlinear regression technique were applied to fit the models to experimental moisture ratio data. The fit goodness of the mathematical models was evaluated and compared in terms of root mean square error (*RMSE*) and sum of squares error (*SSE*). Among the models, a model having minimum *RMSE* and *SSE* was selected as the best model to describe the drying curves [14]. These parameters are defined as:

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}\left(MR_{pre,i} - MR_{\exp,i}\right)^2\right]^{\frac{1}{2}} \tag{2}$$

$$SSE = \frac{1}{N}\sum_{i=1}^{N}\left(MR_{pre,i} - MR_{\exp,i}\right)^2 \tag{3}$$

where $MR_{exp,i}$ is the *i-th* experimental moisture ratio, $MR_{pre,i}$ is the *i-th* predicted moisture ratio, and N is the number of the observations.

2.3 Determination of effective diffusivity and activation energy

The moisture removing in fruits and vegetables drying is mainly controlled by liquid and/or vapour diffusion mechanism. To simple analyses of the only diffusion-based thin layer drying equation, one dimensional diffusion is considered and Fick's diffusion equation is used. To define the mass transfer process, by assuming isotropic behaviour of the samples with regards to the water diffusivity, Fick's second law of unsteady state diffusion can be written as follow:

$$\frac{\partial M}{\partial \mathrm{t}} = Div\left(D\left(gradM\right)\right) \tag{4}$$

Supposing uniform moisture distribution, negligible external resistance, constant diffusivity and negligible shrinkage through the drying process, the solution of Eq. (4) can be carried out by using the separation of variables. Crank (1975) has given an analytically solution for Eq. (4) for different solid geometries which for an infinite slab is written as [15]:

$$MR = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left(-\frac{(2n+1)^2\pi^2 Dt}{L^2}\right) \tag{5}$$

D, L, and t are the effective diffusivity (m^2/s), thickness of the slab (m), and the drying time (s), respectively.

For long drying periods, Eq. (5) can be simplified to only the first term of the series and written in logarithmic form as [16]:

$$\ln MR = \ln\frac{8}{\pi^2} - \left(\frac{\pi^2 Dt}{L^2}\right) \tag{6}$$

By plotting experimental data in term of $\ln(MR)$ against drying time, a straight line is obtained and the effective moisture diffusivity calculated as:

$$D = -\left(\frac{L^2}{\pi^2}\right)\times(\text{slope of line}) \tag{7}$$

To determine the activation energy, the effective moisture diffusivity is related with drying temperature as follow:

$$D = D_0\exp\left(-\frac{E_a}{RT_{abs}}\right) \tag{8}$$

where D_0 is Arrhenius constant or the constant equivalent to the diffusivity at infinitely high temperature (m^2/s), R is the universal gas constant (8.314×10^{-3} kJ/mol °k), T_{abs} is the absolute temperature (°k), and E_a is the activation energy (kJ/mol).

The graph of $\ln(D)$ against $1/T_{abs}$ is plotted and its slope used to determine the activation energy as follow [1]:

$$-(\text{slope of line})\times R = E_a \tag{9}$$

2.4 Determination of convective mass transfer coefficient (*CMTC*)

The transient moisture diffusion process is exactly in the Fourier equation form of heat transfer, where temperature and thermal diffusivity are replaced with concentration and moisture diffusivity, respectively. The one-dimensional time-dependent moisture diffusivity equation for slab shaped moist materials is written as [17]:

$$\left(\frac{\partial}{\partial y}\right)\left(\frac{\partial M}{\partial y}\right) = \left(\frac{1}{D}\right)\left(\frac{\partial M}{\partial t}\right) \tag{10}$$

Initial and boundary conditions are as the follows:

$$M(y,t) = M_o, \quad t = 0, \quad -\frac{L}{2} \le y \le \frac{L}{2} \tag{11}$$

$$\frac{\partial M}{\partial y}(y,t) = 0, \quad t > 0, \quad y = 0 \tag{12}$$

$$-D\frac{\partial M}{\partial y}(y,t) = k(M_s - M_e), \quad t > 0, \quad y = \pm\frac{L}{2} \tag{13}$$

where k is the convective mass transfer coefficient (m/s) and M_s is the moisture content of the samples surface (kg $_{\text{water}}$/kg $_{\text{dry matter}}$).

The convective mass transfer coefficient (k) in the surface of the celeriac slices was determined by using the procedure described by Kaya et al. (2007) [18]:

$$k = -\frac{V}{A\cdot \mathrm{t}}\ln(MR) \tag{14}$$

where V and A are the samples volume (m^3) and sample surface area (m^2), respectively.

3 Results and discussion

3.1 Modelling of drying curves

Statistical analyses results obtained through fitting experimental moisture ratio data with the mathematical models are shown in Table 1. As the results show, the Midilli-Kucuk model with average values of *RMSE*=0.008289 and *SSE*=0.0002 was found as the best model to describe the drying kinetics of the celeriac slices. Similarly, the Midilli-Kucuk model has been introduced as the best mathematical model to describe microwave drying of white mulberry [19], intermittent drying of rough rice [20], convective solar drying of prickly pear peel [21], convective drying of potato pulp waste [22] and hot air drying of apple slices [1].

Furthermore, in order to evaluate the Midilli-Kucuk model, the moisture ratios estimated by the model was compared with experimental data and the results for some randomly selected drying curves are shown in Fig. 1. As the results show, the points were generally located on the 45° straight line, indicating the suitability of the Midilli-Kucuk model to describe the drying curves of the celeriac slices. For the other drying conditions, the same trends were also obtained.

3.2 Effective moisture diffusivity and activation energy

The graph of experimental values of ln(*MR*) of the celeriac slices against drying time were plotted and the effective moisture diffusivity values (D) of the samples were determined by using Eq. (7) (Table 2). As the results show, the effective diffusivity values varied from 2.1908×10^{-10} (m^2/s) to 8.9304×10^{-10} (m^2/s). The obtained diffusivity values are within the range reported for moisture diffusion of food materials (10^{-11} to 10^{-6} m^2/s) [23]. In addition, the obtained diffusivities are comparable with reported values in the literature for biological products e.g., 7.026×10^{-10}-3.326×10^{-9} (m^2/s) for coconut presscake [5], 1.72×10^{-11}-3.31×10^{-11} (m^2/s) for rapeseed [24], 5.683×10^{-10}-1.544×10^{-9} (m^2/s) for sweet cherry [25], and 1.809×10^{-9}-11.055×10^{-8} (m^2/s) for peppermint leaves [8].

Table 1 Statistical results obtained from the applied thin layer drying models for prediction of moisture content of the celeriac slices.

		55 °C		65 °C		75 °C	
Model name	Pressure (kPa)	SSE	RMSE	SSE	RMSE	SSE	RMSE
Newton	0.1	0.003032	0.012980	0.000677	0.007511	0.001122	0.012660
	3	0.004919	0.015300	0.000417	0.005459	0.002575	0.016920
	7	0.006610	0.016950	0.004104	0.016020	0.008154	0.027230
	10	0.019690	0.027520	0.007739	0.019670	0.003799	0.015410
	13	0.030350	0.032350	0.031490	0.037830	0.007010	0.019730
	17	0.030990	0.032140	0.032870	0.037800	0.014620	0.027740
Two-term exponential	0.1	0.000314	0.004295	0.000424	0.006206	0.000199	0.005759
	3	0.000111	0.002350	0.000130	0.003167	0.000119	0.003859
	7	0.001098	0.007066	0.000414	0.005253	0.000622	0.007888
	10	0.000429	0.004141	0.000420	0.004704	0.000481	0.005660
	13	0.000628	0.004736	0.001935	0.009599	0.000213	0.003538
	17	0.000421	0.003811	0.001205	0.007401	0.000228	0.003557
Logarithmic	0.1	0.000360	0.004745	0.000146	0.003825	0.000089	0.004231
	3	0.001150	0.007778	0.000077	0.002539	0.001360	0.013940
	7	0.002603	0.011130	0.001408	0.010030	0.003148	0.018700
	10	0.008019	0.018280	0.002400	0.011550	0.002006	0.011970
	13	0.007918	0.017200	0.008778	0.020950	0.002398	0.012240
	17	0.008443	0.017370	0.010310	0.022150	0.005899	0.018630
Henderson and Pabis	0.1	0.002198	0.011370	0.000648	0.007677	0.001051	0.013230
	3	0.003310	0.012870	0.000359	0.005252	0.002234	0.016710
	7	0.004010	0.013510	0.002891	0.013880	0.006847	0.026217
	10	0.011590	0.021530	0.004615	0.015590	0.002717	0.013460
	13	0.018810	0.025920	0.021940	0.032320	0.005187	0.017470
	17	0.018770	0.025440	0.021890	0.031540	0.010160	0.023760
Middili-Kucuk	0.1	0.000048	0.001797	0.000120	0.003658	0.000032	0.002834
	3	0.000050	0.001664	0.000057	0.002277	0.000127	0.004599
	7	0.000873	0.006605	0.000320	0.004959	0.000426	0.007292
	10	0.000336	0.003820	0.000223	0.003624	0.000359	0.005253
	13	0.000387	0.003859	0.000892	0.006850	0.000286	0.004369
	17	0.000336	0.003529	0.000710	0.005955	0.000305	0.004366
Two-term	0.1	0.000396	0.005139	0.000461	0.007160	0.000174	0.006593
	3	0.000089	0.002220	0.000365	0.005760	0.000116	0.004405
	7	0.000607	0.005509	0.000323	0.004988	0.000528	0.008122
	10	0.000300	0.003613	0.000204	0.003460	0.000279	0.004632
	13	0.000338	0.003606	0.001526	0.008963	0.000157	0.003232
	17	0.000234	0.002944	0.000910	0.006747	0.000190	0.003447
Diffusion approach	0.1	0.003790	0.015390	0.002876	0.016960	0.000165	0.005738
	3	0.004555	0.015480	0.000251	0.004570	0.002427	0.018620
	7	0.004629	0.014580	0.000324	0.004807	0.012130	0.036710
	10	0.000303	0.003554	0.007498	0.020410	0.002988	0.014610
	13	0.029130	0.032850	0.031110	0.039440	0.002449	0.012370
	17	0.030520	0.033020	0.032280	0.039200	0.000198	0.003414
Wang and Singh	0.1	0.034790	0.045240	0.036970	0.057980	0.016460	0.052370
	3	0.042790	0.046250	0.054040	0.064470	0.025270	0.056200
	7	0.047870	0.046640	0.036380	0.049250	0.016380	0.040480
	10	0.040940	0.040470	0.034520	0.042630	0.044120	0.054240
	13	0.018800	0.025910	0.008573	0.020210	0.032850	0.043960
	17	0.021820	0.027430	0.012290	0.023630	0.030040	0.040850

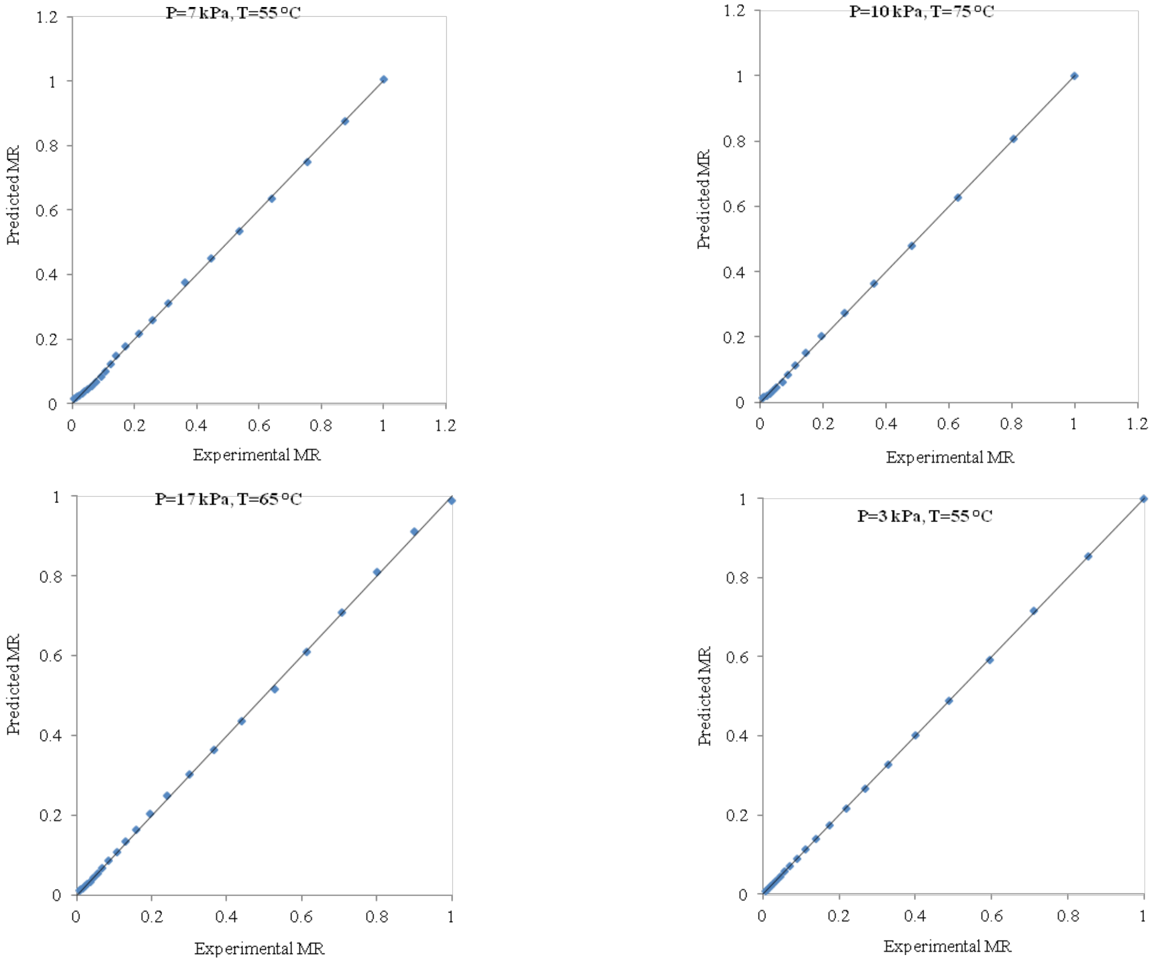

Fig. 1 Experimental moisture ratio values versus Midilli-Kucuk model predicted ones for the celeriac slices.

The effect of drying temperature on the moisture diffusivity can be discussed by using the Table 2. The results show that the moisture diffusivity increases with increasing drying temperature. In fact, an increase in temperature causes a decrease in water viscosity and increases the activity of water molecules. These phenomena facilitate water molecules diffusion in object capillaries and consequently, increase the moisture diffusivity [26]. This observation is in agreement with the reported results in the literature [27].

From Table 2, it is can be seen that any increment in vacuum pressure in drying chamber decreases the moisture diffusivity. This is due the fact that at vacuum pressures, surrounding air is expanded and water vapour present in food creates a puffed structure. The expanded structure provides large area to volume ratio for good heat and mass transfer whivh leads to facilitate the water transport and consequently increases drying velocity and diffusivity [28]. Similar results have been reported in the literature. Arévalo-Pinedo and Murr (2006) dried pumpkin slabs using vacuum drying method at different pressures (5, 15 and 25 kPa) and temperatures (50, 60 and 70 °C), and found that moisture diffusivity decreased with increasing vacuum pressure at all of the applied temperatures [29].

Table 2 Effective moisture diffusivity of the celeriac slices.

Pressure (kPa)	Temperature (°C)	D ($\times 10^{10}$, m^2/s)	R^2
0.1	55	3.3166	0.9982
	65	5.1270	0.9999
	75	8.9304	0.9981
3	55	3.0579	0.9978
	65	4.8836	0.9996
	75	7.7894	0.9961
7	55	2.7993	0.9952
	65	4.0468	0.9973
	75	6.4201	0.9912
10	55	2.6472	0.9915
	65	3.2253	0.9955
	75	4.2294	0.9970
13	55	2.2364	0.9696
	65	2.9667	0.9669
	75	3.8490	0.9877
17	55	2.1908	0.9730
	65	2.8449	0.9702
	75	3.7578	0.9895

Furthermore, the relationship between moisture diffusivity, drying temperature and vacuum pressure, and respective R^2 and *RMSE* were obtained to be as follow:

$$D = 10^{-10} \times \left(0.007273P^2 + 0.004196T^2 + 0.5597P - 0.2778T - 0.01337PT + 6.014\right)$$

$$R^2 = 0.9667 \qquad RMSE = 4.096 \times 10^{-11}$$

Using the equation, diffusivity can be calculated for the celeriac slides during drying.

For each vacuum pressure, the activation energy (E_a) were calculated by plotting the graph of ln(D) against $1/T_{abs}$ and using Eq. (9). The obtained E_a values are presented in Table 3. As the results show, the activation energy varied from 2.22 kJ/mol to 4.70 kJ/mol. The obtained activation energy values are in the range reported for food materials (1.27-110 kJ/mol) [30]. Activation energy is defined as the energy needed to initiate the moisture diffusion from the internal regions of the material [26]. Therefore, based on the results, it is clear that relatively little energy is required to initiate moisture diffusion during vacuum drying of celeriac slices.

Table 3 Activation energy of the celeriac slices.

Pressure (kPa)	E_a (k/mol)	R^2
0.1	4.70	0.9925
3	4.44	0.9997
7	3.94	0.9934
10	2.22	0.9885
13	2.58	1
17	2.56	0.9988

3.3 Convective mass transfer coefficient

Mass transfer between the interface of a liquid or solid and a gas is an important phenomenon and often is described by convective mass transfer coefficient (CMTC). The convective mass transfer coefficient of the celeriac slices was calculated by using Eq. (14) and via linear regression analysis. Figure 2 presents variation of CMTC versus drying time for some randomly selected experimental drying data. As the results show, the CMTC had ascendant trend during the drying process duration. The same trends were also obtained for the other drying conditions. Similar observations have been reported for CMTC changes with drying time for papaya slices under hot air drying [31]. Also, variations of CMTC values with drying time for the applied drying conditions were formulated based on the regression analysis and the results are shown in Table 4.

The values of CMTC are in the range from 4.1268×10^{-7} (m/s) to 2.9931×10^{-6} (m/s) for the vacuum drying conditions that agree well with the reported results in the literature for different fruits and drying conditions e.g., hot air drying of papaya slices (3.10×10^{-7} to 6.05×10^{-6} m/s) [31]. Furthermore, average values of the CMTC were calculated and presented in Table 4. From the table, the average convective mass transfer coefficient values ranged from 6.3127×10^{-7} (m/s) to 2.8358×10^{-6} (m/s) that are comparable with the reported values for apple slices (1.46×10^{-7}-3.39×10^{-7} m/s) [1], slab eggplant (6.478×10^{-7}-2.190×10^{-6} m/s) [32] and sliced lemons (3.677×10^{-8}-5.007×10^{-6} m/s) [33].

From Table 4, the effects of drying temperature and vacuum pressure on the average values of CMTC can be discussed.

Table 4 Convective mass transfer coefficient of the celeriac slices.

Pressure (kPa)	Temperature (°C)	K (t)	$k_{average}$ (m/s)
0.1	55	$6\times10^{-14}t^3-2\times10^{-11}t^2+3\times10^{-9}t+9\times10^{-7}$	1.0521×10^{-6}
	65	$6\times10^{-14}t^3-1\times10^{-11}t^2+1\times10^{-9}t+2\times10^{-6}$	1.6738×10^{-6}
	75	$2\times10^{-12}t^3-2\times10^{-10}t^2+2\times10^{-8}t+3\times10^{-6}$	2.8358×10^{-6}
3	55	$4\times10^{-14}t^3-2\times10^{-11}t^2+3\times10^{-9}t+8\times10^{-7}$	9.6123×10^{-7}
	65	$9\times10^{-14}t^3-3\times10^{-11}t^2+3\times10^{-9}t+1\times10^{-6}$	1.5742×10^{-6}
	75	$1\times10^{-12}t^3-2\times10^{-10}t^2+2\times10^{-8}t+2\times10^{-6}$	2.4306×10^{-6}
7	55	$4\times10^{-14}t^3-2\times10^{-11}t^2+4\times10^{-9}t+7\times10^{-7}$	8.6265×10^{-7}
	65	$1\times10^{-13}t^3-4\times10^{-11}t^2+5\times10^{-9}t+1\times10^{-6}$	1.2685×10^{-6}
	75	$8\times10^{-13}t^3-2\times10^{-11}t^2+2\times10^{-8}t+1\times10^{-6}$	1.9441×10^{-6}
10	55	$4\times10^{-14}t^3-2\times10^{-11}t^2+4\times10^{-9}t+6\times10^{-7}$	7.9701×10^{-7}
	65	$7\times10^{-14}t^3-3\times10^{-11}t^2+4\times10^{-9}t+8\times10^{-7}$	9.9483×10^{-7}
	75	$1\times10^{-13}t^3-4\times10^{-11}t^2+6\times10^{-9}t+1\times10^{-6}$	1.3228×10^{-6}
13	55	$4\times10^{-14}t^3-2\times10^{-11}t^2+3\times10^{-9}t+4\times10^{-7}$	6.4537×10^{-7}
	65	$3\times10^{-14}t^3-1\times10^{-11}t^2+4\times10^{-9}t+5\times10^{-7}$	8.4243×10^{-7}
	75	$1\times10^{-13}t^3-4\times10^{-11}t^2+5\times10^{-9}t+9\times10^{-7}$	1.1679×10^{-6}
17	55	$3\times10^{-14}t^3-2\times10^{-11}t^2+3\times10^{-9}t+4\times10^{-7}$	6.3127×10^{-7}
	65	$7\times10^{-14}t^3-3\times10^{-11}t^2+5\times10^{-9}t+5\times10^{-7}$	8.1403×10^{-7}
	75	$1\times10^{-13}t^3-5\times10^{-11}t^2+8\times10^{-9}t+8\times10^{-7}$	1.1236×10^{-6}

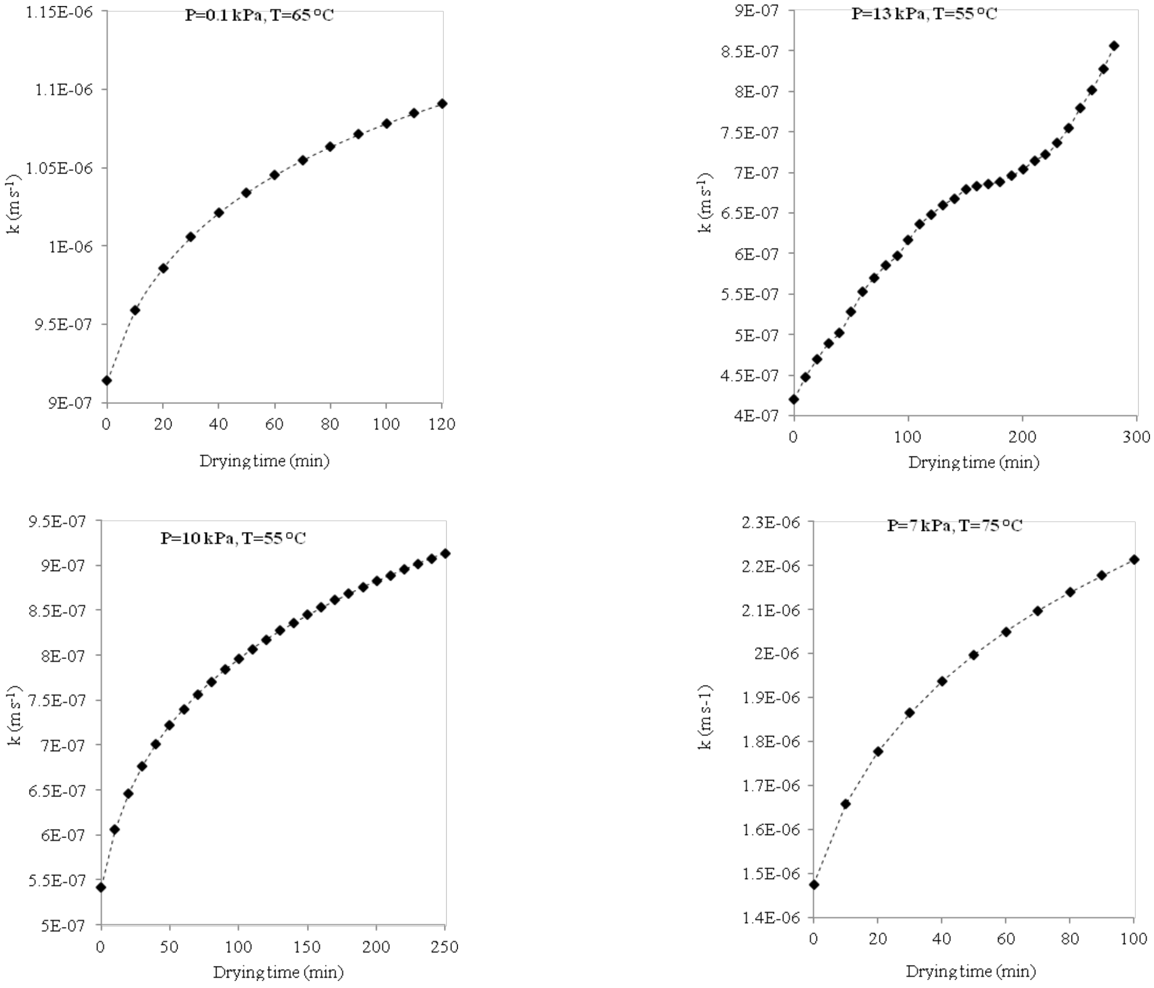

Fig. 2 Time evolution of convective mass transfer coefficient on the celeriac slices surface during vacuum drying.

As the results show, for all pressures, an increment in the temperature leads to an increment in the CMTC. The mass transfer rate from a wet surface strongly depends on the air velocity over the surface, and thicknesses of the thermal and concentration boundary layer along the surface. The thermal thickness and the concentration boundary layer originate from differences between the surface and free stream temperatures and concentrations, respectively. Higher drying temperatures increase evaporation capability of the surrounding medium of the drying object and lead to higher mass transfer rates. Some researchers have reported similar results in the literature [31, 32, 34-36].

As show, for all temperatures, CMTC decreased with any increment in the vacuum pressure. In fact, mass transfer in interface of the object and surrounding occurs due to vapour pressure difference. The increased pressure would lead to an increment in the surrounding air amount which resulting in increased vapour pressure and finally decreases convective mass transfer rates.

Furthermore, the relationship between average convective mass transfer coefficient, drying temperature and vacuum pressure, and respective R^2 and *RMSE* were obtained to be as follow:

$$k = 10^{-6} \times \left(0.002469P^2 + 0.001204T^2 + 0.1659P - 0.07256T - 0.004185PT + 1.461\right)$$

$$R^2 = 0.9745 \qquad RMSE = 1.161 \times 10^{-7}$$

4 Conclusions

In this study, mathematical modelling of drying curves and determination mass transfer parameters of celeriac slices during vacuum drying at different temperatures and pressures was carried out. The Midilli-Kucuk model was determined as the best model describing drying curves. The effective diffusivity values varied from 2.1908×10^{-10} (m^2/s) to 8.9304×10^{-10} (m^2/s), and increased with increasing temperature and decreasing vacuum pressure. The activation energy varied from 2.22 (kJ/mol) to 4.70 (kJ/mol). The values of convective mass transfer coefficient were in the range from 4.1268×10^{-7} (m/s) to 2.9931×10^{-6} (m/s). The obtained results showed that the CMTC had ascendant trend during the drying process. For all pressures, an increment in the temperature led to an increment in the CMTC. At each drying temperature, CMTC decreased with any increment in the vacuum pressure.

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