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Temperature controlled infrared drying kinetics of mussels

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Mussel has impressive nutritional values, which contains many vitamins, minerals and proteins by comparison with other shellfish. Infrared drying (IR) has gained popularity in the food industry due to its rapid drying rate/response time and superior thermal efficiency compared to traditional drying methods for the recent years. In this study, various temperatures (60, 70 and 80°C) were applied to mussels via infrared dryer to investigate the temperature effect on drying characteristics, effective moisture diffusivity and activation energy. The drying times are obtained as 405, 255 and 165 min for 60, 70 and 80°C, respectively. Drying temperature at 80°C was found as the optimum temperature in the experiments for quality of mussel and energy consumption. To identify the drying kinetic of mussel, seven mathematical models were applied to the experimental results and Alibas model provided to best estimation for each temperature according to drying data. The results are found as 0.999886, 0.999916 and 0.999964 for coefficient of determination (R^2); 0.000011, 0.000009 and 0.000006 for reduced chi-square (χ^2) and 0.002946, 0.002614 and 0.001854 for root mean square error (RMSE) at 60, 70 and 80°C, respectively. Effective moisture diffusivity values are found as 4.23×10^{-9}, 7×10^{-9} and 1.17×10^{-8} m^2/s at 60, 70 and 80°C, respectively. It is clearly seen that the effective moisture diffusivity values increased with temperature increment. The effect of temperature on the moisture diffusivity depends on Arrhenius equation. According to the relationship 49.67 kJ/mol is calculated as an activation energy of mussel.

Keywords: Mussel, infrared radiation, drying kinetic, mathematical modelling, activation energy.

Introduction

Drying, is a traditional process to purpose of removing moisture, which has been largely used in food and chemical industry. The process is inherently much complicated, and contains heat agents used for ensuring the desiccation of substances, and the mass transport[1]. Biological materials are dehydrated in order to conserve the products from spoilage. Microorganisms that leads to food degradation and decay cannot grow and live without water. In addition, many enzymes, which cause chemical transformation in products, cannot live in the absence of water[2]. Apart from preservation of mineral, vitamins and nutrients, the method helps reduce the ultimate volume and mass of products of costs of transportation and storage[3].

Drying is fundamentally carried out by forcing the heated air through the system in which the air acts as a carrier of moisture and heat[4]. However, IR drying does not need any absorbent media between the product and energy source. Since the IR energy penetrates directly to the internal surface of the substance, the drying becomes uniform and rapid[5]. Other advantages of using IR dryer contain easy control of material temperature and other process parameters, uniform temperature distribution, saving of energy according to other methods, short time of drying, high quality of final dried products, high degree heat transfer coefficients and clean operational environment along with space saving[3–5].

Due to given the high mineral and vitamin content, mussels are one of the most commonly consumed seafood for nutritional values. It is especially a logical choice for protein sources, which is about 55% on a dry basis; some can be transformed to bioactive peptides by enzymatic hydrolysis. In addition, mussels include highly desirable long-chain fatty acids such as EPA (eicosapentaenoic acid) and DHA (docosahexaenoic acid). These oils have many beneficial effects, for instance they reduce inflammatory conditions like arthritis and improve brain function. They also give important minerals such as zinc that support build immunity[6].

Today, the extensive variety of dried foods offered to consumers and the concern of fulfilling the quality requirements and energy savings emphasize the need to fully understand drying in order to optimize processes[7]. Mathematical modeling and optimization are very useful for the designing of the processes, improving the system, and increasing the efficiency without increasing the cost[8]. For drying process, it includes the determining of drying characteristics that define the basic reaction mechanisms and effects of certain process variables on moisture transfer. In industrial applications, kinetic models are usually experimental equations containing parameters that are main operation variables[9].

The determination of drying method depends on the chemical structure of the material and IR drying is a suitable and profitable method. Also taking into account all benefits of mussel, it needs more analyzing for food industry. To conclude, the aim of this study is to investigate the drying kinetics of mussels dried by IR method. Moreover, the effect of various temperatures of 60, 70 and 80°C on the drying rate, effective moisture diffusivities and activation energy were calculated.

Materials and methods:

Sample: Mussels were bought in October 2018 from a local supermarket in Istanbul, Turkey. Similar sized mussels were chosen for experiments, with an average diameter of approximately 3.7 cm. The beard in the mussels was cleaned. 100 g of mussel consists of 12.44 g of protein, 3.83 g of carbohydrate and 2.48 g of fat and has a calorific value of 87 kCal energy. The initial moisture content of mussel was obtained using the IR dryer at 105°C. The initial moisture content of the mussels was calculated to be 66.19% on wet basis correspondingly it was found to be 1.958 kg water/kg dry matter.

Drying procedure: Five mussels, which were the average weights 3.5–4.0 g were selected for each drying process. Mussels were weighted by using Radwag AS 220.R2 digital balance (Radwag, Radom, Poland), which has an accuracy of 0.001 g. Then, mussels was put in Radwag MA50.R IR dryer (Radwag, Radom, Poland), which is working to maximum temperature of 160°C was used for drying experiments. IR dryer temperature control was arranged to 60, 70 and 80°C for the experiments and total weight of sample was recorded at intervals of 15 min. Drying was continued below the 5% moisture was kept in product. When the drying was finished, the mussels were cooled at room temperature and they were packed by using polyethylene bags. Lastly, they were placed in a desiccator to keep in safe from moisture.

Modelling of drying kinetics: During drying, moisture content of product decreases in the process of time. The moisture removal is triggered by moisture diffusion from inner to surface layer of material during falling period. This eventually results in moisture mass transfer through evaporation to product's surrounding environment. The movement of diffusion is defined as Fick's second law of diffusion[10]. The moisture content (*M*), moisture ratio (*MR*) and drying rate (*DR*) formulas is given by eq. (1), eq. (2) and eq. (3), respectively.

$$M = \frac{m_w}{m_d} \quad (1)$$

$$MR = \frac{M_t - M_e}{M_0 - M_e} \quad (2)$$

$$DR = \frac{M_{t+dt} - M_t}{dt} \quad (2)$$

where M is the moisture content (kg water/kg dry matter), m_w is the water content (kg), m_d is the dry material content (kg). MR is the moisture ratio (dimensionless), M_t, M_0, and M_e relate to the moisture content at any drying time, initial moisture content and equilibrium moisture content (kg water/kg dry matter), respectively. DR is the drying rate (kg water/kg dry matter x min), M_{t+dt} is the moisture content at t + dt (kg water/kg dry matter) and t is the drying time (min)[11].

Data statistical analysis for drying: To choose the best drying model, moisture ratio values and drying times were fitted to several mathematical models as shown in Table 1 by using a computer programme: Statistica 8.0 (StatSoft, Tulsa, USA). Parameters of models were predicted using a non-linear regression procedure based on the Lavenberg-Marquardt algorithm.

Results were evaluated by using the coefficient of determination R^2, root mean square error (RMSE) and reduced chi-square (χ^2)[11]. In the literature, highest R^2 values and lowest χ^2 and RMSE values are determined as best results for estimation. R^2, χ^2 and RMSE equations are given in eqs. (4), (5) and (6), respectively:

$$R^2 \equiv 1 - \frac{\chi_{i=1}^{N}(MR_{\exp,i} - MR_{\mathrm{pre},i})^2}{\chi_{i=1}^{N}\left(MR_{\exp,i} - \left(\frac{1}{n}\right)MR_{\exp,i}\right)^2} \tag{4}$$

$$\chi^2 = \frac{\chi_{i=1}^{N}(MR_{\exp,i} - MR_{\mathrm{pre},i})^2}{N - z} \tag{5}$$

$$RMSE = \left(\frac{1}{N}\sum_{i=1}^{N}(MR_{\mathrm{pre},i} - MR_{\exp,i})^2\right)^{\frac{1}{2}} \tag{6}$$

where MR_{pre} and MR_{exp} show predicted and experimental values of moisture ratios, respectively. N is the total number of drying experiments, and z indicates the constant numbers in the mathematical models[11].

Calculation of the effective moisture diffusivity: Food products drying indicates a function of interior diffusion and in general, it takes place during the falling rate period. Various of drying processes in the falling rate period. The Fick's second law of diffusion is formulated in eq. (7):

$$M = \frac{\partial M}{\partial t} \nabla[D_{\mathrm{eff}}(\nabla M) \tag{7}$$

where, D_{eff} is effective moisture diffusivity (m^2/s) and is drying time (s). The analytical solution of Fick's second law, unsteady state diffusion in spherical coordinates with the same assumptions. These are:

Mass transfer (moisture migration) is by diffusion only.

Shrinkage is negligible

Coefficient of diffusion is constant

Temperature is constant during the drying process

By solving eq. (7), considering the assumptions the Fick's second law is given in eq. (8):

$$MR = \frac{6}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{n^2}\exp\left(-n^2\pi^2\frac{D_{\mathrm{eff}}.t}{r^2}\right) \tag{8}$$

where r (m) is the sample radius, mussel for this experiment and n was accepted as 1 to simplify the calculation. Logarithm (ln) is taken on both side in order to regulate exponential expresion. Latest form of equation is illustrated in eq. (9):

$$\ln(MR) = \ln\left(\frac{6}{\pi^2}\right) - \left(\pi^2\frac{D_{\mathrm{eff}}.t}{r^2}\right) \tag{9}$$

From the slope of the plot of ln MR against time at various temperatures effective moisture diffusivity (D_{eff}) is calculated.

Calculation of activation energy: The activation energy was obtained by using an Arrhenius type equation as shown in eq. (10).

$$D_{\mathrm{eff}} = D_0 \exp\left(-\frac{E_A}{R.T}\right) \tag{10}$$

where D_0 indicates the pre-exponential factor of the Arrhenius equation (m^2/s), E_A is activation energy value (kJ/mol), R is universal gas constant (8.314 J/mol.K) and T is absolute temperature of air (K)[17].

Results and discussion

Drying curves for mussels dried via infrared radiation: Initial average moisture content was determined 1.958 kg water/kg dry matter and the value reduced to 0.100, 0.085 and, 0.077 kg water/kg dry matter for 60, 70 and 80°C, respectively. The mussels were reached to these moisture content 405, 255 and 165 min, respectively. It can be evaluated as increment of temperature provides to reduction in drying time. Also, on the basis of these data Fig. 1 illustrated the drying curves as a function of radiation intensity. It means that when the temperature is arranged to 60, 70, and 80°C stepwise, radiation intensity also increases with temperature. A higher moisture removal rate is seen at higher radiation intensity.

Drying rate curve for mussels dried via infrared radiation: Fig. 2 indicates the drying rate curves of the mussel samples at the temperatures of 60, 70 and 80°C.

Drying rates increased with the increase in temperature. This means that water loss is rather excessive subject to heat and mass transfer at high temperature. Initial of the drying, drying rates were higher as it is seen Fig. 2 for all temperatures, and then they started to decrease with a decrease of moisture content in the mussels. The decrease in drying rate may be resulted from a reduction in the porosity of the mussel because of shrinkage, that increases resistance to movement of water and leads to further decreasing of drying rates[12]. Rising-rate drying period was detected at the beginning of the process for three temperature levels. Initial drying rates were zero before the drying and they increased to 0.011, 0.017 and 0.023 end of the rising-rate period for 60, 70 and 80°C, respectively. Constant-rate drying period was observed in 60 and 70°C. It only occured at 0.11 after rising-

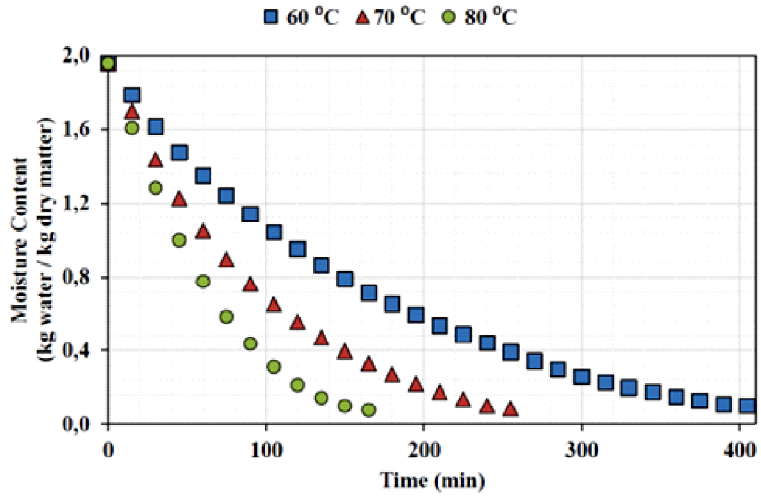

Fig. 1. Graph of moisture content against time for three different drying temperatures.

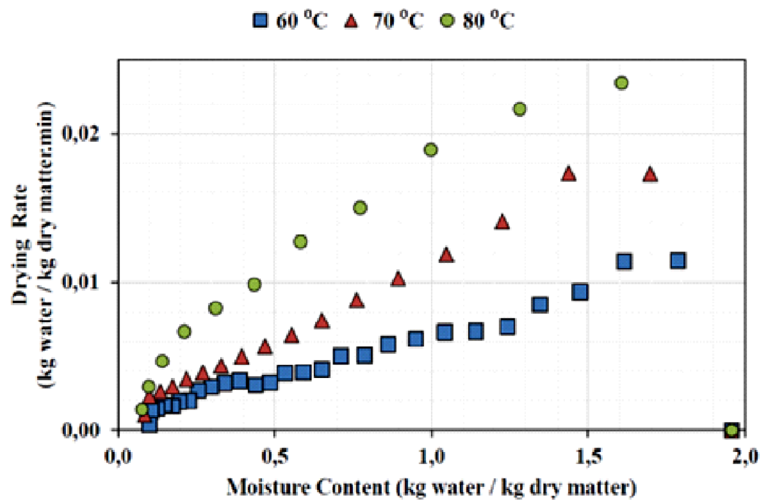

Fig. 2. A plot of drying rate against moisture content of mussels at different drying temperatures.

rate period for 70°C. Besides, constant-rate period was determined at a few points, which are 0.011, 0.07, 0.05, 0.04, 0.03 and 0.02 for 60°C. Generally drying process of mussels took place in the falling rate period for IR dryer. Initial of falling rate periods were 0.011, 0.017 and 0.023 and the period lasted until the points reach to 0.0004, 0.0011, 0.0014 at 60, 70 and 80°C, respectively.

Effective moisture diffusivity: From the slope of ln (*MR*) versus drying time (s) for mussels dried at 60, 70 and 80°C, effective moisture diffusivity values were calculated and found as 4.23×10^{-9}, 7.0×10^{-9} and 1.17×10^{-8} m^2/s at 60, 70 and

Table 1. Models and equations

Model name	Model equation	Ref.
Aghbaslo *et al.*	$MR = \exp(-k_1t/(1+k_2t))$	12
Alibas	$MR = a.\exp((-kt^n)+bt)+g$	13
Henderson and Pabis	$MR = a.\exp(-kt)$	14
Lewis	$MR = \exp(-kt)$	13
Midilli and Kucuk	$MR = a.\exp(-kt^n)+bt$	15
Parabolic	$MR = a+bt+cr^2$	16
Wang and Singh	$MR = \exp(-(t/b)^a)$	11

a, *b*, *c*, *g*, coefficients and *n*, drying exponent specific to each equation; k, k_1, k_2, drying coefficient specific to each equation; *t*, time.

80°, respectively. It is obviously clear that D_{eff} results increased with the temperature increase. The increase of IR level and temperature can be led to increase of the vapour pressure. It means vapour pressure is another effect to accelerate the drying process[15].

Activation energy: Arrhenius equation explained the

Table 2. Mathematical model constants and statistical parameters at different drying different temperatures for IR

Model	Parameter	IR temperature		
		60°C	70°C	80°C
Aghbashlo *et al.*	k_1	0.007163	0.009865	0.013330
	k_2	0.000111	–0.000631	–0.002259
	R^2	0.989533	0.999660	0.999832
	χ^2	0.000857	0.000031	0.000019
	RMSE	0.028202	0.005285	0.003999
Alibas	*a*	2.135180	0.871558	1.826902
	k	0.004760	0.010125	0.007855
	n	0.909040	1.030618	1.044414
	b	0.001180	–0.000520	0.003057
	g	–1.132570	0.130261	–0.826414
	R^2	0.999886	0.999916	0.999964
	χ^2	0.000011	0.000009	0.000006
	RMSE	0.002946	0.002614	0.001854
Hendersen and Pabis	*a*	0.944700	1.015915	1.037468
	k	0.006602	0.010884	0.016941
	R^2	0.995051	0.998482	0.993559
	χ^2	0.000405	0.000139	0.000734
	RMSE	0.019393	0.011115	0.024737
Lewis	*k*	0.007013	0.010709	0.016341
	R^2	0.989439	0.998125	0.991599
	χ^2	0.000832	0.000162	0.000871
	RMSE	0.028329	0.012352	0.028251
Midilli and Kucuk	*a*	0.950307	1.003115	0.997905
	k	0.010848	0.010256	0.008489
	n	0.874213	0.996863	1.143235
	b	–0.000237	–0.000143	–0.000144
	R^2	0.997620	0.999895	0.999809
	χ^2	0.000211	0.000011	0.000027
	RMSE	0.013448	0.002925	0.004260
Parabolic	*a*	0.903335	0.959763	0.989088
	b	–0.004427	–0.007571	–0.012066
	c	0.000006	0.000016	0.000039
	R^2	0.992585	0.994930	0.999162
	χ^2	0.000631	0.000495	0.000106
	RMSE	0.023737	0.020311	0.008924
Wang and Singh	*a*	–0.004898	–0.008183	–0.012318
	b	0.000006	0.000018	0.000040
	R^2	0.993713	0.992191	0.998971
	χ^2	0.000514	0.000715	0.000117
	RMSE	0.021857	0.025208	0.009889

temperature effect on the effective moisture diffusivity. The logarithms of the effective diffusivities which were obtained via slope of the curves drawn against the reciprocal of the absolute temperature in order to estimate the activation energy. Activation energy can be described as the minimum energy amount which must be supplied to trigger moisture diffusion from inside of material for drying process. In this study, activation energy of mussel was calculated as the slope of the linearized plot of logarithmic "D_{eff}" against reciprocal of absolute temperature. According to eq. (10), activation energy calculated as 49.67 kJ/mol.

Mathematical models for drying: Suitability of the obtained values to various drying models have been tested by using Statistica program. Aghbashlo *et al.*, Alibas, Henderson and Pabis, Lewis, Midilli and Kucuk, Parabolic, and Wang and Singh which were fitted to drying times against the experimental *MR*. By comparing the results obtained from the models, the lowest R^2 values detected as 0.989439 for IR drying. It can be explained that the experimental values were in good harmonization with the predicted values. It demonstrated that all chosen mathematical models described the relationship between the drying time and moisture ratio successfully[11].

Mathematical modelling for infrared radiation dryer: According to the drying values obtained from infrared radiation dryer, Alibas is determined as the most favorable model to estimate of the IR drying for each temperature of 60, 70 and 80°C with the values of: 0.999886, 0.999916, 0.999964 for R^2; 0.000011, 0.000009, 0.000006 for χ^2; 0.002946, 0.002614, 0.001854 for RMSE, respectively. All of the parameters of mathematical modelling are presented at Table 2.

Conclusions

This study focused to detection the feasibility of Fick's second law to describe the behavior of mussel which were dried via infrared radiation dryer. Also the effect of various drying temperature was investigated. Effective moisture diffusivity values are found as 4.23×10^{-9}, 7.0×10^{-9} and 1.17×10^{-8} m^2/s at 60, 70 and 80°C, respectively and activation energy of mussel is obtained as 49.67 kJ/mol. To describe the drying kinetics of mussels, various mathematical models were applied. R^2 values are found between 0.989439–0.999964, χ^2 values are found between 0.000006–0.000871, and RMSE values are found between 0.001854–0.028329. Among the models, Alibas model is detected as the best model for drying process.

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