Mathematical Modeling of Energy Consumption and Mass Transfer for Drying of Phimai Mee by Hot Air

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Received: 15 June 2023; Revised: 22 February 2024; Accepted: 1 March 2024; Available online: 8 March 2024

Abstract

The purpose of this research was to study a drying process that can help conserve Phimai Mee (Korat's stir-fried noodles) over a long preservation period. In the drying process tests of Phimai Mee, Air flow rates of 1.5, 2.0 and 2.5 m/s at temperature of 40°C, 50°C, and 60°C were applied. In the assessment of the drying process of Phimai Mee. Five distinct mathematical models in a computational setting. the drying characteristics of Phimai Mee, parameters from an mathematical models were used a computational setting. The drying characteristics of Phimai Mee were comprehensively analysed. Empirical formulae parameters were included in the nonlinear regression analysis of collected moisture ratio data. In evaluating the models for their predictive accuracy in the drying kinetics of Phimai Mee, the Demir et al. model was identified as the most precise. Additionally, The moisture diffusion in the Phimai Mee when tested according to Fick's law, varied between 0.03499 and 0.11816 m2/s. The results also showed that the drying process's moisture diffusion is temperature-dependent, which the Arrhenius equation, showing an activation energy range from 7.46 to 8.82 kJ/mol in all the conditions examined.

Keywords: Mathematical model, Drying kinetics, Moisture distribution, Thin layer, Phimai Mee

Introduction

Phimai Mee (Korat's stir-fried noodles) has been made for more than 100 years as a part of family cooking. As Phimai Mee became more popular, it was prepared for sale by drying the noodles in the sun to ensure long-lasting storage and easy transportation. This necessitated the study of drying parameters to develop an effective drying method that focuses on the thermal efficiency of the drying procedure. (Jindarat et al., 2011).

The drying process reduces the moisture content inside the product by the application of heat and mass transfer in a given mass of internal moisture which is transferred to the external surface of the product to evaporate into the air. Both of these are required for power control design and optimization in the drying process and occur simultaneously (Prommas et al., 2010). Drying by thermal processes using hot air flows through the product is, and has been, widely popular. However, the disadvantage of drying by this method is high heat energy consumption. (Mujumdar, 2007).

In the current research, a mathematical model was constructed to predict the drying effect to help design a drying mechanism suitable for the drying conditions. Researchers have proposed several mathematical models of drying process simulations to study drying behavior, such as the, Midilli model and, Newton model, among others. (Mbegbu et al., 2021).

The research focus in this study was to examine how various air temperatures (40°C, 50°C, and 60°C), and several air velocities (1.5, 2.0, and 2.5 m/s), impact the drying traits of Phimai Mee. The goal was to identify the most suitable mathematical model that aligns with the observed experimental drying data. Additionally, the study also determined effective moisture diffusivity (Deff), measured energy consumption, and calculated the activation energy (Ea) values.

Methods and Materials

Convection dryer

The Fig. 1 illustrates drying of Phimai Mee by convection used the experimental apparatus. The convection dryer comprised an electric heater, blower, PID temperature controller, and drying chamber. The blower draws ambient air into the dryer and the heater heats the incoming air. The hot air was blown into the drying chamber to dry the Phimai Mee with the temperature controlled by the PID temperature controller.

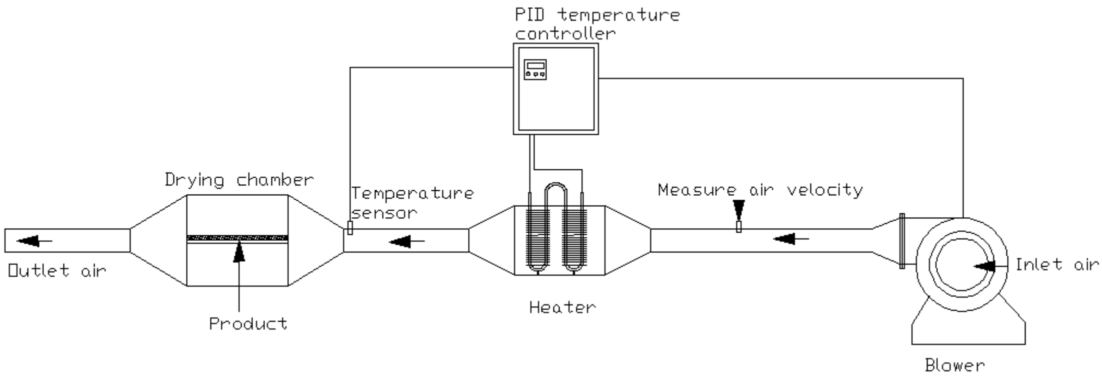


Figure 1 Schematic diagram of developed convection dryer

Phimai Mee

Phimai Mee is traditionally from Nai Mueang Subdistrict, Phimai District, Nakhon Ratchasima Province. The initial moisture content of Phimai Mee is determined by drying at 105°C for 24 hr (Hassan-Beygi, Aghbashlo, Kianmehr, & Massah, 2009). The noodles are weighed on a digital balance and the moisture content on a wet basis (M_w) is calculated from Equation 1. (Dinani et al., 2014)

$$M_w = \frac{w-d}{w} \tag{1}$$

where w is the initial weight of the sample (kg) and d is the weight of the dried sample (kg). In our experiment, the initial moisture content of the Phimai Mee was 41%(w.b.). The samples used in the drying experiments were stored at 5°C.

Drying experiment

The experimental drying process applied 3 levels of air temperature (40°C, 50°C, and 60°C) and 3 levels of air velocity (1.5, 2.0, and 2.5 m/s). Before the drying experiment, the dryer was opened to maintain a constant temperature in the drying chamber. Phimai Mee (500 g) was placed in a thin layer (~1 cm thickness) uniformly on a tray and these samples were baked in a chamber for 15 minutes, then the samples were weighed and the results recorded. The experiment was repeated 4 times, then the drying time was 40 minutes. The final moisture content 8.0% (w.b).

Mathematical modeling

The Table 1 presents the mathematical equations for predicting Phimai Mee drying kinetics to find the best model describing the kinetics of the air temperature drying process. Computer algorithms for Equation 2 and 3 were used to find the determination coefficient which has the largest value equal to R^2 and the smallest value of X^2 . These equations were derived from (Aregbesola et al., 2015). (Kipcak & Doymaz, 2020).

$$R^2 = 1 - \frac{\sum_{i=1}^{N}\left(MR_{iexp,i} - MR_{pre,i}\right)^2}{\sum_{i=1}^{N}(MR_{iexp,i} - (\ln)\sum_{i=1}^{N} MR_{pre,i}} \tag{2}$$

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

where $MR_{exp,i}$ is the experimentally observed moisture ratio, $MR_{pre,i}$ is the predicted moisture ratio, N is the number of observations and z is the number of constants in the model.

Mathematical models of 5 equations for analyzing the results of the Phimai Mee drying process were used to compare the moisture ratio (MR) data obtained from the experiment. Regression analysis using computer processing was used to determine the constant variables a, b, k and n

Table 1 Mathematical equations for predicting Phimai Mee drying kinetics

S. No	Model	Equation	Reference
1	Newton	MR= exp (-kt)	Reppich et al., 2021
2	Modified page	MR= exp $(-kt)^n$	Carvalho et al., 2022
3	Page	MR= exp $(-kt^n)$	Diamante et al., 2010
4	Henderson and pabis	MR = a exp (kt)	Verma et al., 2022
5	Demir et al.	MR= a exp $(-kt)^n$+b	Demir et al., 2007

The MR values were calculated using equations 4 (Karthikeyan & Murugavelh, 2018).

$$MR = \frac{M - M_e}{M_o - M_e} \tag{4}$$

Where: M is the moisture content at any time; M_e is the equilibrium moisture content and M_o is the initial moisture content (kg moisture/kg dry matter).

The water vapor equilibrium of products at various temperatures is called equilibrium humidity. Different temperatures will result in different relative humidities and consequently equilibrium humidity values of different. However, for the product whose initial moisture content is much greater than the equilibrium moisture content, the moisture ratio can be obtained from Equation 5.

$$MR = \frac{M}{M_o} \tag{5}$$

DR can be obtained from Equation 6. (Qiu et al., 2022)

$$DR = \frac{(M_{it} - M_{it-1})}{\Delta t} \tag{6}$$

where *DR* represents the drying rate (g moisture/g dry matter x h); M_{ti+1} represents the moisture content on a dry basis at time ti + 1 (g moisture/g dry matter); M_{ti} represents the moisture content at time ti, (g moisture/g dry matter); and Δt represents the time difference between ti + 1 and ti (h).

Effective diffusivity

Fick's law is used to describe the moisture diffusion coefficient. which is a physical property that shows the ability to move water in a product and can be calculated by Equation 7. (Nag & Dash, 2016).

$$\frac{\partial X}{\partial t} = \nabla\left(D_{eff}\nabla X\right) \tag{7}$$

According to Fick's Second Law for the diffusion of moisture, Phimai Mee is like a stone slab with endless dimensions. After solving the physical equation for the infinite slab, we built a model based on the assumption that the Phimai Mee is similar to an infinitely thin sheet. Equation 8 can be derived and can explain the change in effective moisture diffusion in the Phimai Mee.

$$MR = \frac{M_t - M_e}{M_i - M_e} = \frac{8}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{(2n-1)^2}exp\left(\frac{-D_{eff}(2n-1)^2\pi^2 t}{4L^2}\right) \tag{8}$$

where MR is moisture ratio (decimal), n is the number of terms taken into consideration, t is the time of drying (s), D_{eff} is effective moisture diffusivity (m^2/s), L is the thickness of the Phimai Mee (m)

The final answer for drying over a long time can be calculated using Equation 9. (Dincer & Dost, 1995).

$$lnMR = ln\frac{(M-M_e)}{M_o - M_e} = ln\frac{8}{\pi^2} - \left(\frac{D_{eff}\pi^2 t}{4L^2}\right) \tag{9}$$

The MR can be obtained using Equation 10. (Dincer, & Dost, 1995).

$$MR = \frac{8}{\pi^2} - \left(\frac{D_{eff}\pi^2 t}{4L^2}\right) \tag{10}$$

To plot ln (MR) versus time to determine the slope. Equation 11 is used.

$$slop = \frac{\pi^2 D_{eff}}{4L_2} \tag{11}$$

The change in water diffusion with temperature can be described by the classical Arrhenius type in Equation 12.

$$D_{eff} = D_o exp\left(-\frac{E_a}{RT}\right) \tag{12}$$

For calculating Ea, Equation (12) can be linearized as Equation 13.

$$\ln(D_{eff}) = \ln(D_o) - \left(\frac{E_a}{R}\right)\left(\frac{1}{T}\right) \tag{13}$$

The activation energy can be obtained from the slope of the line of the ln MR versus the time curve (Thuy et al., 2023).

Energy and Specific Energy Consumption

The SEC can be obtained by Equation 14.

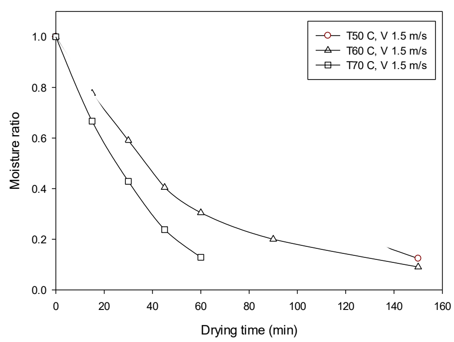
$$SEC = \frac{E_t}{\Delta w} \tag{14}$$

where Et is the Electrical energy used for drying and Δw is the change in the weight of each dried sample.

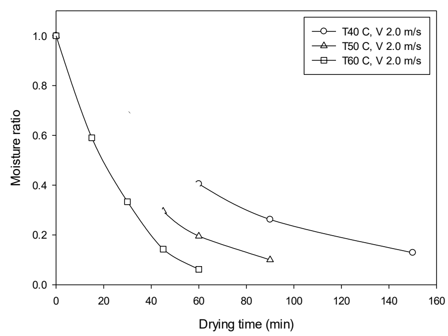
Results

Drying rate curve analysis

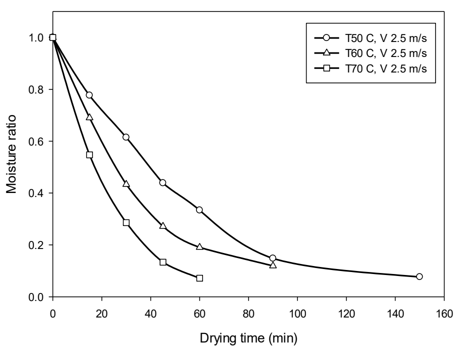
The Fig. 2 displays a graph showing the relationship between the moisture ratio and drying time for Phimai Mee, under varying conditions of air temperature (40°C, 50°C, and 60°C) and air velocity (1.5, 2.0, and 2.5 m/s). Initially, there was a noticeable link between the increase in air temperature and a constant air velocity. The data indicated an acceleration in the drying rate of Phimai Mee with rising temperatures, attributed to its initially high moisture content. This rate is observed to gradually decline as the drying process progresses, corresponding with the decreasing moisture content. The experiment conducted at air temperatures of 40°C, 50°C, and 60°C, also demonstrated variations in drying times at a consistent air velocity. At the same time, the air velocity also affects drying and the drying rate increases with air velocity. As a result, the time for drying Phimai Mee was reduced. This is consistent with what has been reported in several drying studies of biomaterials (Markowski et al., 2010).



(a)



(b)



(c)

Figure 2 Moisture ratio versus time at different temperatures for Phimai Mee (a) V 1.5 m/s (b) V 2.0 m/s (c) V 2.5 m/s

Specific energy consumption (SEC)

The findings revealed that a rise in air temperature influences the energy required for drying. In the early stages of drying, the heat efficiently evaporates water from the product's surface, which is initially high in moisture. As drying progresses and the surface moisture diminishes, the rate of water evaporation also reduces. This leads to a surplus of energy that is not utilized effectively, resulting in a higher specific energy consumption (SEC) value. The minimum value of SEC (9.85 kJ/g) was obtained for convective conditions with a drying air temperature of 40°C at an air velocity of 2.0 m/s. The maximum value of SEC (34.13 kJ/g) was obtained for convective conditions with an air velocity of 1.5 m/s and a drying air temperature of 50°C. Results indicated that an increase in drying temperature affects electric power consumption inversely. With increasing drying temperatures, Phimai Mee's drying time decreased, and electric power requirements decreased. With increasing air velocity, electric power is no different.

Table 2 Energy consumption for drying Phimai Mee by hot air

Hot air temperature	Air velocity (m/s)	Drying time (min)	Water evaporation (g)	Heater (kJ)	Blower (kJ)	SEC (kJ/g)
40		210	210	3036.20	73.74	14.81
50	1.5	210	210	7014.58	152.74	34.13
50		150	210	6673.59	131.67	32.41
40		180	193	2001.43	66.38	9.85
50	2.0	180	205	6558.72	137.49	31.89
60		150	212	6491.21	138.29	31.57
40		180	208	3092.80	69.70	15.06
50	2.5	180	207	3153.43	69.70	15.35
60		150	208	6554.21	145.22	31.91

Mathematical Modeling

Mathematical equations were used for computer analysis to predict the drying kinetics of Phimai Mee under different conditions. The constants of the mathematical equation are shown in Table 3, and the optimum equation was obtained by using the five mathematical equations as shown in Table 4.

A mathematical model for predicting the best drying kinetics was determined from the largest R^2 and X^2 least values. The optimal equation for predicting the drying effect was taken from Demir et al. As shown in the prediction results in Table 4, The selection model is suitable for predicting the drying process of Phimai Mee.

Table 3 Constant variables of the Demir model from Phimai Mee drying prediction processing

Model	Temperature ˚C	a	k	b
	40	1.125709	0.005052	-0126196
1.5	50	0.976407	0.010346	0.040060
	60	1.208175	0.010787	-0.206718
	40	1.075026	0.006258	-0.059575
2.0	50	1.017506	0.012842	-0.009930
	60	1.133874	0.015158	-0.133250
	40	1.222833	0.006647	-.221298
2.5	50	0.973196	0.015006	0.038772
	60	1.045936	0.019095	-0.044342

Table 4 Coefficients of the mathematical drying model at different temperatures and moisture

Model	Temperature C	R^2			X^2		
		1.5 m/s	2.0 m/s	2.5 m/s	1.5 m/s	2.0 m/s	2.5 m/s
Newton	40	0.99812878	0.96380365	0.99656624	0.00203056	0.44800327	0.00328720
	50	0.99713485	0.99934213	0.99779646	0.00367243	0.00075235	0.00250662
	60	0.99670415	0.99666598	0.99922138	0.00321223	0.00386980	0.00089673
Page	40	0.93718648	0.96764908	0.99940170	0.06608348	0.40217392	0.00057357
	50	0.99715170	0.99969540	0.99781094	0.00365087	0.00034840	0.00249017
	60	0.96241237	0.99944011	0.99985886	0.36004916	0.00065076	0.00016259
Modified page	40	0.99812878	0.96389936	0.99656624	0.00203056	0.04480032	0.00328720
	50	0.99713485	0.99934213	0.99779646	0.00367243	0.00075235	0.00250662
	60	0.99670415	0.99665980	0.99922138	0.00321223	0.00386980	0.00089673
Henderson and Pabis	40	0.99939043	0.96455757	0.99704575	0.00174685	0.43991386	0.00282707
	50	0.99356440	0.99942727	0.99783312	0.00356440	0.00065501	0.00246497
	60	0.99701227	0.99685386	0.99926146	0.00291237	0.00365206	0.00085059
Demir et al.	40	0.99990152	0.96511905	0.99974987	0.00010695	0.04330685	0.00023982
	50	0.99789701	0.99945132	0.99833736	0.00269655	0.00062750	0.00189183
	60	0.99981863	0.99964138	0.99952388	0.00017703	0.00041686	0.00027427

Effective moisture diffusivity

The slope of the relationship of ln (MR) versus drying time, was linear as shown in Fig. 3, there was a linear relationship. The moisture diffusion coefficient of Phimai Mee drying can be obtained from this Slope.

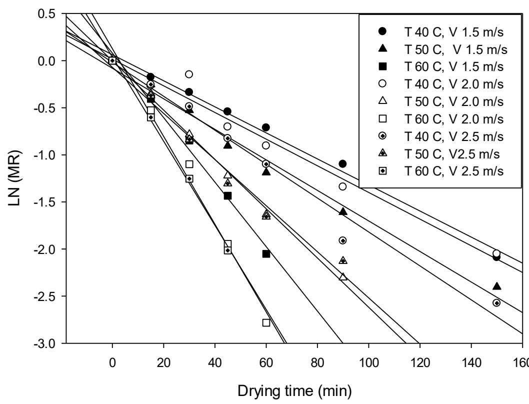


Figure 3 ln (MR) against time (s) for thin-layer drying of all temperature hot air and air velocity

Drying air temperature greatly affects the values of D_{eff} for high moisture Phimai Mee, as seen in Table 4. It was found that when the drying temperature and air velocity were increased, the effective moisture diffusion coefficient increased according. which is similar to previous findings, such as peaches (Promvonge et al., 2011). (Coradi, et al., 2014) It has been mentioned that removing water from grains with a lower moisture content generally demands more energy compared to wetter products. This supports the observation that in products with a higher water content, the binding strength between water molecules and dry matter substantially weakens. Variations in the heat values observed in different products can be accounted for by considering the intrinsic properties unique to each product.

Table 4 Moisture diffusion coefficients at various drying temperatures and air velocities

T(C)	V 1.5 m/s		V 2.0 m/s		V 2.5 m/s	
	D_{eff}	R^2	D_{eff}	R^2	D_{eff}	R^2
40	0.03499	0.9929	0.03601	0.9707	0.04564	0.9081
50	0.04108	0.9863	0.06643	0.9971	0.06212	0.9803
60	0.08672	0.9911	0.11816	0.9876	0.11309	0.9971

Effective moisture diffusivity

The Fig. 4 illustrates the relationship between ln (Deff) and 1/T in the drying process of Phimai Mee. The Ea was determined to be in the range of 7.46 to 8.82 kJ/mol under all tested conditions, as deduced from Equation 12. This indicates that a considerable amount of energy is initially required for water evaporation, especially given the high moisture content in Phimai Mee. This process also tends to induce unfavorable alterations in the chemical properties of the product during this phase, as noted by Kingsly, Goyal, Manikantan, and Ilyas in 2007. Furthermore, it is observed that an increase in air velocity and the temperature of the hot air leads to a decrease in the activation energy.

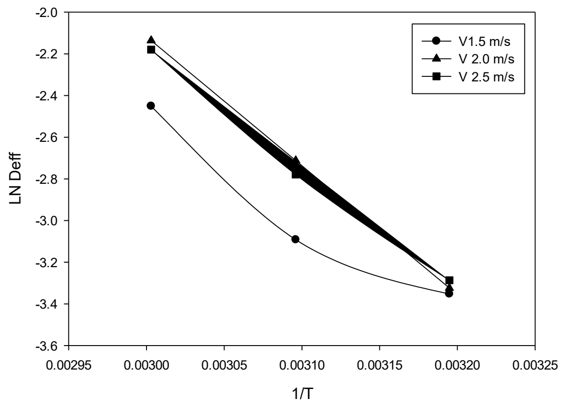


Figure 4 ln (D_{eff}) versus 1/T at different levels of air velocities for thin-layer drying of high moisture Phimai Mee

Conclusion and Suggestions

The drying behavior of Phimai Mee was analyzed at air temperatures of 40°C, 50°C, and 60°C. The drying duration for the sample noodles reduced as the air temperature increased. The specific energy consumption for drying the noodles ranged from 9.85 to 34.13 kJ/g. The Demir et al. thin layer drying model was most effective in predicting the drying kinetics of Phimai Mee with high moisture content. The determination of effective moisture diffusivity values was conducted using Fick's Second Law. The activation energy (Ea) for drying Phimai Mee was found to be between 7.46 and 8.82 kJ/mol, aligning with findings from various other product drying studies. The research also noted that higher hot air temperatures significantly enhanced moisture diffusion during the drying of Phimai Mee.

Acknowledgement

The research team would like to thank the Faculty of Engineering and Technology, Rajamangala University of Technology Isan for the research experimental sites and experimental research tools.

The author also thank Mr Roy I. Morien of the Naresuan University Graduate School for his editing of the grammar, syntax and general English expression in this manuscript.

Author Contributions

Author 1 (Mongkolchai Kampagdee): Conceptualization of the research, Development or design of methodology, Data analysis and interpretation, Investigation, Manuscript writing, Manuscript review and editing.

Author 2 (Virat Wangkuanklang): Collection of data, Manuscript review and editing.

Author 3 (Nopparat Amattirat): Development or design of methodology, Data analysis and interpretation, Manuscript writing, Manuscript review and editing.

Conflict of Interests

The authors declare no conflicts of interest.

Funding

No funding was received for this study.

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