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Mathematical Modeling on Hot Air Drying of Thin Layer Fresh Tilapia Fillets

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Key words: tilapia fillet, hot air drying, drying characteristics, model

The hot convective drying of fresh tilapia fillets was evaluated in a heat pump dryer. The influence of the drying temperature (35, 45 and 55°C), hot air velocity (1.50, 2.50 and 3.50 m/s) and thickness (3, 5 and 7 mm) of the tilapia fillets on the moisture ratio and drying rate has been studied. It shows that drying process took place in falling rate periods. The experimental drying data of fresh tilapia fillets under different conditions was fitted to nine different commonly used thin-layer drying models by nonlinear fitting methods and all the models were compared according to three statistical parameters, *i.e.* coefficient of determination, the reduced chi-square and the root mean square error. It was found that the coefficient of determination values of Page were higher than 0.99254, and the corresponding reduced chi-square and the root mean square error values were lower than 0.000632219 and 0.023854, respectively, indicating that the Page model is the best to describe drying curves of fresh tilapia fillets among them. Effective moisture diffusivity ranged from 6.55×10^{-10} to 1.23×10^{-9} m^2/s calculated using the Fick's second law. With the increase of the drying temperature and the hot air velocity, the effective moisture diffusivities D_{eff} increased. The value of drying activation energy of tilapia fillets with thickness of 3 mm at hot air velocity 2.50 m/s was 17.66 kJ/mol, as determined from the slope of the Arrhenius plot, $\ln(D_{eff})$ *versus* $1/T_a$.

Notations

MR – moisture ratio(-),
M_0, M_e, M_t, M_i – initial moisture content, equilibrium moisture content, moisture content of the product at time t, moisture content of the product at time i, (%),
U_i – drying rate of the product at time i (g/(g·h)),
D_{eff} – effective diffusivity (m^2/s),
L_0 – half thickness of slab (m),
D_0 – pre-exponential factor of the Arrhenius equation (m^2/s),
R – universal gas constant (kJ/mol·K),
T_a – absolute temperature (K),
E_a – activation energy (kJ/mol),
R^2 – correlation coefficient (-),
χ^2 – reduced chi-square (-),
$RMSE$ – root mean square error (-).
T – temperature of hot air (°C),
h – thickness of tilapia fillets (mm),
V – velocity of hot air (m/s).

INTRODUCTION

Tilapia has been an important species in freshwater aquaculture, in view of the rapid expansion of tilapia culture in the world, especially in China, where the production of tilapia reached more than 100 million tons in 2007, accounting for more than 45% in the total world production [Li *et al.,* 2009]. Due to the characteristics of white meat, small thorn, nutrient-rich, tilapia is widely favoured by domestic and foreign markets.

Preservation is quite an important issue for fish due to the easily perishable character. Among the preservation methods, smoking, salting and deep frying give rise to health and environmental concerns, however, drying has been proven to be an efficient and main processing method for fish preservation, which allows obtaining the final products of high nutritive and sensory quality. The substantial objective of drying products is to extend the safe storage period of the fish by reducing microbiological activity [Shitanda & Wanjala, 2006].

Drying of moist materials, including simultaneous heat and mass transfer, is a complicated process. Thin-layer drying models for describing the drying phenomenon of agricultural products are usually based on liquid diffusion theory, and the process can be explained by the Fick's second law [Doungporn *et al*., 2012]. The thin-layer drying models can be categorised as theoretical, semi-theoretical and empirical models. The semi-theoretical model based on the theory

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TABLE 1. Mathematical models given by various authors for drying curves.

Model	Expression	Reference
Lewis	$MR = \exp(-k \cdot t)$	Bruce [1985]
Page	$MR = \exp(-k \cdot t^n)$	Page [1949]
Henderson and Pabis	$MR = a \cdot \exp(-k \cdot t)$	Henderson & Pabis [1961]
Logarithmic	$MR = a \cdot \exp(-k \cdot t) + c$	Togrul & Pehlivan [2002]
Two-term model	$MR = a \cdot \exp(-k_0 \cdot t) + b \cdot \exp(-k_1 \cdot t)$	Henderson [1974]
Approximation of diffusion	$MR = a \cdot \exp(-k \cdot t) + (1-a) \exp(-k \cdot a \cdot t)$	Yaldiz *et al.* [2001]
Wang and Singh	$MR = 1 + a \cdot t + b \cdot t^2$	Wang & Singh [1978]
Simplified Fick's diffusion	$MR = a \cdot \exp(-c(t/L^2))$	Diamante & Munro [1991]
Modified Page equation-II	$MR = \exp(-c(t/L^2)^n)$	Diamante & Munro [1991]

and the drying kinetics experimental, is derived from the simplification of Fick's second law of diffusion or modification of the simplified model, which has been widely used to describe the drying characteristics. Mathematical models are listed in Table 1. Drying characteristics and dynamics models of several agricultural products have been reported [Vega-Galvez *et al*., 2009; Figiel, 2007; Doymaz, 2012; Doymaz *et al*., 2011; Tajner-Czopek *et al*., 2007; Orikasa *et al*., 2008; Tunde-Akintunde & Ogunlakin, 2011; Zaremba *et al*., 2007]. But the drying characteristics of fresh tilapia fillets have not been thoroughly studied [Kituu *et al.,* 2010], especially in a heat pump dryer which can satisfy the need of large-scale fish drying in the food processing industry. Thus, it is of importance and necessity to research the drying characteristics of the fresh tilapia fillets in a heat pump dryer. The purpose of this study is to investigate the drying characteristics of the fresh tilapia fillets in a heat pump dryer, build its drying dynamic model, and determine effective diffusivity D_{eff} and drying activation energy E_a under different drying conditions.

MATERIALS AND METHODS

Sample preparation

Fresh tilapias (Oreochromisniloticus) with the average weight of 500–600 g were purchased from a local fish market in Zhanjiang, China. They were quickly transported to the laboratory in sealed polystyrene boxes containing ice. Tilapias were headed, gutted, skinned and cleaned, then cut into fillets with the size of 60× 40× 3 mm (5 or 7 mm). The fish fillets were immersed in the flow of ozone water at the concentration of 11 mg/L for 10 min to sterilize.

Experimental apparatus

An analytical balance (JA2003, Shanghai Balance Instrument Plant, China) with measurement precision of ±0.01 g was used for mass measuring. Drying temperature and air velocity data were collected by multi-channel digital instrument XSD(XSD/A-H3IIIS2, Automation Equipment Co., Ltd. Guangzhou Kunlun). The temperature was measured by Duwei ATH402 plastic pipe temperature and humidity transmitter (Hefei Dewey Instrument Co., Ltd. production). The hot air velocity was measured by Deweida EE65 air velocity transmitter (Shenzhen Deweida Instrument Co., Ltd. Production).

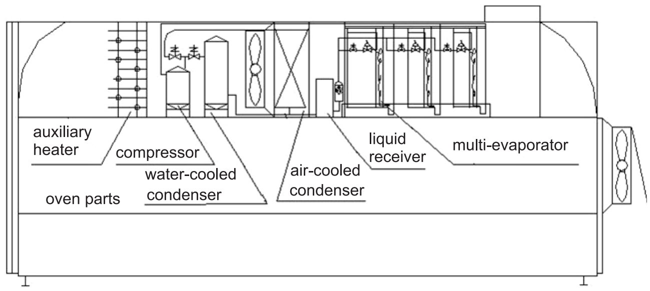

FIGURE 1. The schematic of the heat pump dryer.

Experimental procedure

Drying experiments were performed at different temperatures (35, 45 and 55°C), at different air velocities (1.50, 2.50 and 3.50 m/s) and at different thickness (3, 5 and 7 mm) in the heat pump dryer (Figure 1). The weight of the sample was measured at one hour intervals. For every batch of dried sample, the moisture content was determined, the drying procedure was not stopped until the moisture content did not change any more. Each run in the experiment was done in triplicate.

Theoretical considerations

Moisture content

The moisture content of the test sample was determined according to the vacuum oven method [AOAC, 2005]. At regular time intervals during the drying period, samples were taken out and dried in a dryer at 105°C for drying to constant weight and weighed (DZF-6050, Shanghai Experiment Instrument Co. Ltd., China).

Mathematical modeling of the thin–layer drying curves

For the investigation of drying characteristics of fresh tilapia fillets, it is of vital importance to model drying behaviours effectively. The experimental drying data were fitted to 9 commonly used thin-layer drying models (Table 1).

Calculation of moisture rate (*MR*)

MR represents the moisture ratio and can be expressed as follows:

$$MR = (M_t - M_e)/(M_0 - M_e) \quad (1)$$

where M_t is the moisture content of the product at each moment, M_0 is the initial moisture content and M_e is the equilibrium moisture content.

Calculation of drying rate

U_i represents the drying rate and can be described by Falade method:

$$U_i = (M_i - M_t)/(t - i) \quad (2)$$

where U_i is the drying rate of the product at each moment, M_i is the moisture content of the product at *i*, *t* is the end of time period *t-i*, and *i* is the beginning of time period *t-i*.

Calculation of effective moisture diffusivities

Fick's diffusion equation can be used to describe the drying characteristics of biological products in a falling rate period. For long drying period, it can be simplified [Tutuncu & Labuza, 1996] as follows:

$$\ln MR = \frac{8}{\pi^2} - \frac{\pi^2 D_{eff} t}{4L_0^2} \tag{3}$$

where D_{eff} is the effective moisture diffusivity (m²/s), and L_0 is the half thickness of slab(m). The effective moisture diffusivity was calculated using the method of slopes. It is typically determined by plotting experimental drying data in terms of ln(*MR*) *versus* time [Lomauro *et al.,* 1985]. From Eq. (3), a plot of ln(*MR*) *versus* time gives a straight line with a slope of:

$$\text{Slope} = -\frac{\pi^2 D_{eff}}{4L_0^2} \tag{4}$$

Calculation of activation energy

The relation between temperature and the effective moisture diffusivity can be described by an Arrhenius-type relationship [Akgun & Doymaz, 2005; Sanjuan *et al.,* 2003] as follows:

$$D_{eff} = D_0 \exp\left(\frac{E_a}{RT_a}\right) \tag{5}$$

where D_0 is the pre-exponential factor of the Arrhenius equation (m²/s), *R* is the universal gas constant (kJ/mol·K), and T_a is the absolute temperature (K), E_a is the activation energy (kJ/mol). From the slope of the straight line of, the plot of $\ln D_{eff}$ *versus* $1/T_a$ is a straight line with a slope of:

$$\text{Slope} = -\frac{E_a}{R} \tag{6}$$

Then, the activation energy, E_a, could be calculated.

Correlation coefficients and error analyses

The correlation coefficient (R^2), the reduced chi-square (χ^2) and the root mean square error (*RMSE*) were used to evaluate the goodness of fit of the tested mathematical models to the experimental data [Doungporn *et al.,* 2012]. It has been accepted that the higher the R^2 values and the lower the χ^2 and RMSE values, the better is the goodness of fit [Doungporn *et al.,* 2012].

RESULTS AND DISCUSSION

Changing of water content and drying rate
The influence of the temperature of hot air on *MR* and drying rate

The influence of the temperature (35, 45 and 55°C) of hot air on *MR* and drying velocity is shown in Figures 2–3. In the experimental temperature range, the higher hot air temperature led to the faster drying rate and the shorter drying time, indicated by the fact that drying times to reach the equilibrium moisture content were 19.2, 17.0 and 13.0 h at 35, 45 and 55°C, respectively. As the drying air temperature rises, the transfer rate of moisture from the internal of the drying tilapia fillets to its surface and the evaporization potential of moisture at the surface increased, resulting in the higher drying rate. In addition, the drying process took place in the falling rate period except a very short accelerating period at the beginning. Therefore, internal mass transfer resistance controls the drying time. In the initial period of the drying, the times to remove 50% moisture are 4, 2.1 and 1.4 h at 35, 45 and 55°C, respectively, which are merely 21, 13 and 11% of the total drying time. The moisture ratio reduced faster in the beginning than that at the end. This observation is consistent with previous results, as observed by Kituu *et al.* [2010]. That can be attributed to the fact that the tilapia fillets contain a large quantity of bulk water in the beginning, relatively easier to be transferred to the sur-

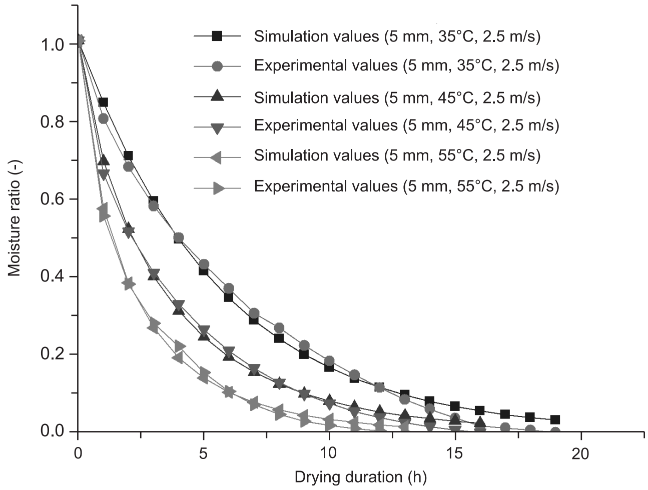

FIGURE 2. The influence of the temperature of hot air on *MR*. Comparison between the values of the Page model and the experimental data at different drying temperatures (hot air wind speed at 2.5 m/s, fillet thickness at 5 mm).

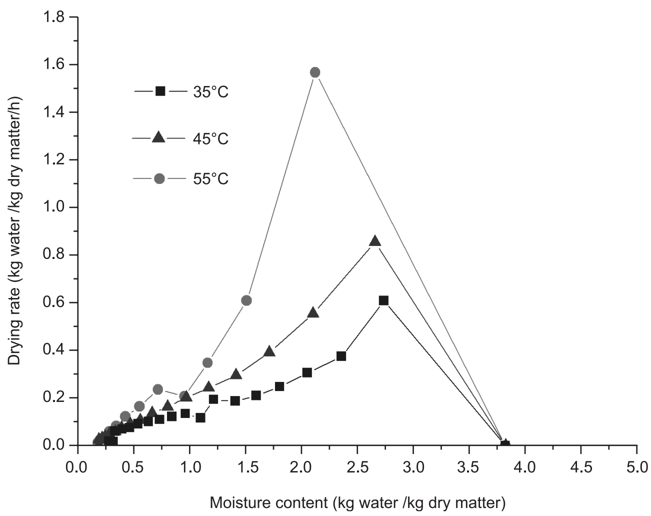

FIGURE 3. The influence of the temperatures of hot air on drying rate (hot air wind speed at 2.5 m/s, fillet thickness at 5 mm).

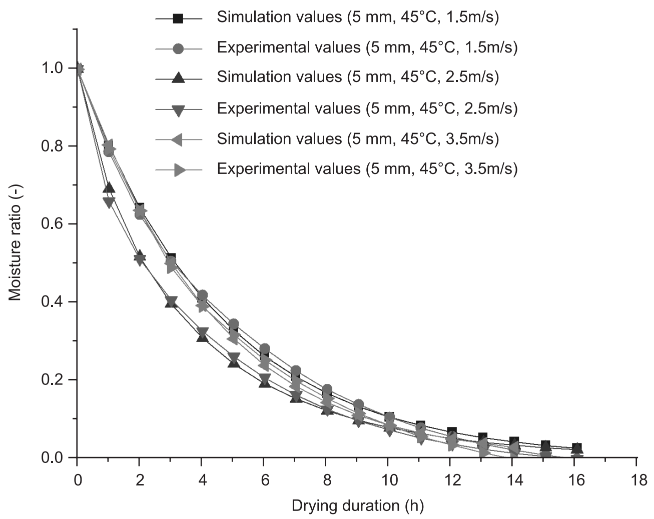

FIGURE 4. The influence of hot air velocity on *MR.* Comparison between the values of the Page model and the experimental data at different hot air velocity (hot air temperature at 45°C, fillet thickness at 5 mm).

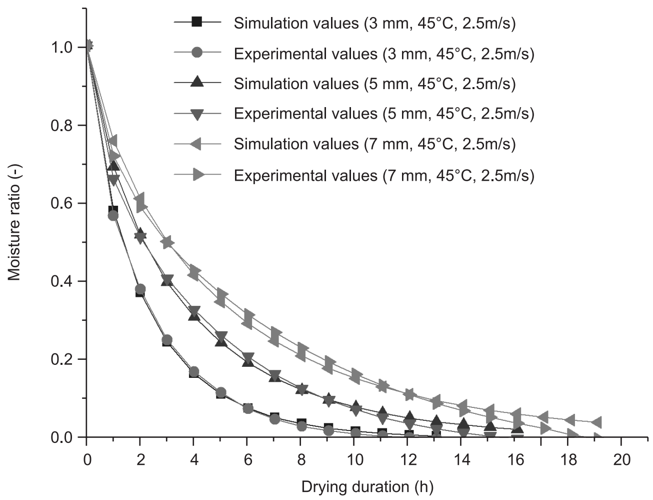

FIGURE 6. The influence of fillet thickness on *MR.* Comparison between the values of the Page model and the experimental data at different thickness of tilapia fillets (hot air temperature at 45°C, hot air velocity at 2.5 m/s).

face and evaporated. As drying time increased, the bulk water between cells significantly reduced, the bound water is more difficult to be transferred, so the drying process becomes slow. In the latter period, the fibers of tilapia fillets contract, even lead to the 'hard shell' effect, which causes the significant decrease of the diffusive rate and the drying rate, especially at higher drying temperature. Obviously, the drying process is controlled by internal diffusion.

The influence of the velocity of hot air on *MR* and drying rate

With the velocity of the hot air increasing, the drying rate of tilapia fillet increased, as shown in Figures 4–5. Comparing Figure 4 with Figure 2 and Figure 6, it can be found that the spaces between experimental drying curves in Figure 4 are nearer than those in Figure 2 and Figure 6, which means that increasing the velocity of the hot air cannot shorten the drying time notably, on the contrary, it may only result in wasting energy. The results proved that the drying process of tilapia fillets was controlled by internal moisture diffusion. As the evaporation rate of moisture in the surface of tilapia fillet was faster than moisture diffusion within the fillet, internal moisture did not have enough time to transfer onto the surface for evaporating, that's the main reason why the velocity of the hot air had less obvious effect on moisture ratio and drying speed.

The influence of fillet thickness on *MR* and drying rate

The curves of moisture ratio *versus* drying time and drying rate *versus* moisture content at different thickness of tilapia fillets (3 5 and7 mm) are depicted in Figures 6–7. The times to reduce 50% moisture content are 1.3, 2 and 3 h at the thickness of 3, 5 and 7 mm, respectively, which occupied only 10, 13 and 16% of the total drying time. Thinner thickness and larger specific surface area of the tilapia fillet meant larger fillet surface area, bigger convection heat transferring area and higher

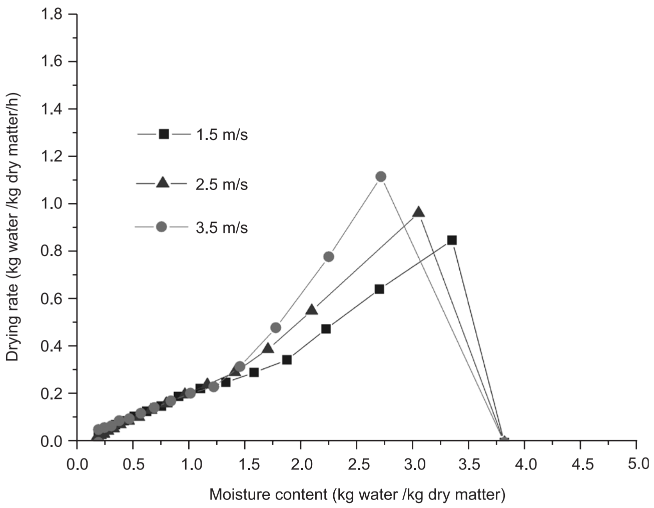

FIGURE 5. The influence of hot air velocity on drying rate (hot air temperature at 45°C, fillet thickness at 5 mm).

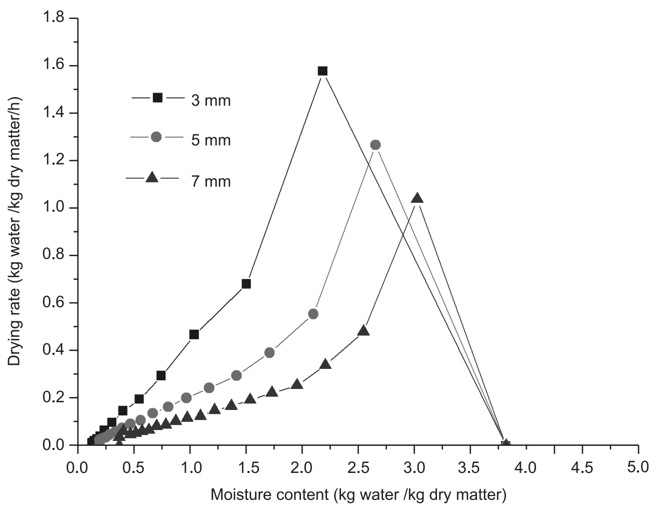

FIGURE 7. The influence of fillet thickness on drying rate (hot air temperature at 45 °C, hot air velocity at 2.5 m/s).

heat-flow density, which resulted in faster drying speed. Since internal moisture diffusion was the critical control step, reducing the thickness of the fillet could shorten the diffusion distance of the moisture and thus decrease the resistance of the internal diffusion.

Fitting of the drying curves

The moisture content data observed in the drying experiment under different conditions were fitted to the 9 commonly used thin-layer drying models listed in Table 1. The statistical results of different models such as coefficient of determination (R^2), the reduced chi-square (χ^2) and the root mean square error (*RMSE*) values are summarised in Table 2. In all cases, except R^2 value of Wang and Singh model was only 0.83488, all other R^2 are higher than 0.98442, and corresponding χ^2 and *RMSE* values were lower than 0.00119 and 0.033414, respectively, of which the R^2 values of Page are all higher than 0.99254, and corresponding χ^2 and RMSE values are lower than 0.000705442 and 0.023759, indicating the data are fitted to the Page model quite well.

TABLE 2. Statistical results obtained from different thin-layer drying models.

T(°C)	*h*(mm)	*V*(m/s)	Constant				R^2	χ^2	*RMSE*
Lewis			*k*						
35	3	1.5	0.00662				0.99551	3.48385×10^{-4}	0.018193
35	5	2.5	0.17844				0.99284	6.07266×10^{-4}	0.024021
35	7	3.5	0.14386				0.99485	4.12897×10^{-4}	0.019896
45	3	2.5	0.47259				0.99543	3.748×10^{-4}	0.018651
45	5	3.5	0.23619				0.99715	2.65841×10^{-4}	0.015748
45	7	1.5	0.1589				0.99472	4.42022×10^{-4}	0.020538
55	3	3.5	0.55882				0.99946	5.2872×10^{-5}	0.006933
55	5	1.5	0.29906				0.99664	2.78972×10^{-4}	0.016163
55	7	2.5	0.27641				0.98442	0.00119	0.033414
Page			*k*	*n*					
35	3	1.5	0.27844	0.92965			0.99677	2.50182×10^{-4}	0.015
35	5	2.5	0.17242	1.01743			0.99254	6.32219×10^{-4}	0.023854
35	7	3.5	0.14483	0.99686			0.99461	4.31579×10^{-4}	0.019885
45	3	2.5	0.54517	0.86131			0.99939	4.97781×10^{-5}	0.006532
45	5	3.5	0.21661	1.05235			0.99775	2.09349×10^{-4}	0.013466
45	7	1.5	0.14929	1.03024			0.99476	4.38325×10^{-4}	0.019966
55	3	3.5	0.57983	0.95676			0.99972	2.69449×10^{-5}	0.004695
55	5	1.5	0.33656	0.91953			0.99833	1.38425×10^{-4}	0.011011
55	7	2.5	0.35812	0.83528			0.99336	5.05866×10^{-4}	0.02113
Henderson and Pabis			*k*	*a*					
35	3	1.5	0.23977	0.96828			0.99641	2.78138×10^{-4}	0.015827
35	5	2.5	0.17646	0.98871			0.9926	6.27059×10^{-4}	0.023759
35	7	3.5	0.14189	0.98633			0.99486	4.12218×10^{-4}	0.01944
45	3	2.5	0.46064	0.97461			0.9958	3.44085×10^{-4}	0.017176
45	5	3.5	0.23846	1.00984			0.99706	2.73979×10^{-4}	0.015406
45	7	1.5	0.15814	0.99515			0.99448	4.61651×10^{-4}	0.020483
55	3	3.5	0.55574	0.99399			0.99945	5.42484×10^{-5}	0.006662
55	5	1.5	0.29133	0.97408			0.99722	2.30356×10^{-4}	0.014186
55	7	2.5	0.25899	0.93893			0.98824	8.95603×10^{-4}	0.028107
Logarithmic			*k*	*a*	*c*				
35	3	1.5	0.23095	0.97344	-0.01093		0.9966	2.63501×10^{-4}	0.014967
35	5	2.5	0.14706	1.02983	-0.06635		0.9973	2.28909×10^{-4}	0.013946
35	7	3.5	0.12253	1.01719	-0.05233		0.99769	1.8476×10^{-4}	0.012715
45	3	2.5	0.47754	0.96917	0.00987		0.99599	3.2896×10^{-4}	0.01608
45	5	3.5	0.21146	1.0383	-0.04412		0.99932	6.33171×10^{-5}	0.007117

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T(°C)	h(mm)	V(m/s)	Constant				R^2	χ^2	$RMSE$
45	7	1.5	0.13373	1.03242	-0.06117		0.99851	1.2485×10^{-4}	0.010379
55	3	3.5	0.55741	0.99335	9.2388E-4		0.99938	6.06205×10^{-5}	0.00664
55	5	1.5	0.28952	0.97505	-0.00185		0.99702	2.47157×10^{-4}	0.014164
55	7	2.5	0.26096	0.93795	0.00211		0.98742	9.58666×10^{-4}	0.028096
Two-term model			K_0	K_1	a	b			
35	3	1.5	0.23979	0.23975	0.48409	0.48419	0.99597	3.12905×10^{-4}	0.015827
35	5	2.5	0.17643	0.17647	0.37188	0.61684	0.99168	7.05442×10^{-4}	0.023759
35	7	3.5	0.14188	0.14188	0.42081	0.56551	0.99434	4.5344×10^{-4}	0.01944
45	3	2.5	0.4033	0.4033	0.8496	0.1504	0.9999	7.93149×10^{-6}	0.00238
45	5	3.5	0.23845	0.23847	0.40075	0.60909	0.99653	3.23793×10^{-4}	0.015406
45	7	1.5	0.15812	0.15815	0.38882	0.60633	0.99387	5.12946×10^{-4}	0.020483
55	3	3.5	0.53127	0.31592	0.94637	0.05363	0.99977	2.24768×10^{-5}	0.003782
55	5	1.5	0.27442	0.27442	0.91583	0.08417	0.99891	9.04244×10^{-5}	0.008254
55	7	2.5	0.23073	0.23073	0.83582	0.16418	0.99684	2.40487×10^{-4}	0.013569
Approximation of diffusion			k	a					
35	3	1.5	0.29686	0.6323			0.99548	3.50499×10^{-4}	0.017762
35	5	2.5	0.19926	1.38731			0.993	5.93506×10^{-4}	0.023108
35	7	3.5	0.15461	1.3013			0.99477	4.19251×10^{-4}	0.0196
45	3	2.5	2.3721	0.16825			0.99985	1.25531×10^{-5}	0.00328
45	5	3.5	0.27375	1.46018			0.99792	1.94066×10^{-4}	0.012961
45	7	1.5	0.18024	1.41876			0.99523	3.99127×10^{-4}	0.019045
55	3	3.5	0.65758	0.64897			0.99956	4.34387×10^{-5}	0.005962
55	5	1.5	0.42101	0.52046			0.99727	2.26166×10^{-4}	0.014076
55	7	2.5	1.52699	0.15483			0.99544	3.4708×10^{-4}	0.017506
Wang and Singh			a	b					
35	3	1.5	-0.14989	0.0054			0.91941	0.00625	0.075003
35	5	2.5	-0.12448	0.00393			0.97329	0.00226	0.045139
35	7	3.5	-0.1017	0.00265			0.97008	0.0024	0.046882
45	3	2.5	-0.23964	0.0133			0.83488	0.01354	0.10774
45	5	3.5	-0.16716	0.00714			0.97989	0.00187	0.040307
45	7	1.5	-0.11206	0.0032			0.97732	0.0019	0.041539
55	3	3.5	-0.30317	0.02142			0.89652	0.01014	0.091074
55	5	1.5	-0.18496	0.00832			0.92429	0.00628	0.074116
55	7	2.5	-0.17105	0.00717			0.89547	0.00796	0.083824
Simplified Fick's diffusion			a	c	L				
35	3	1.5	0.96805	0.04488	0.43341		0.99619	2.95136×10^{-4}	0.015843
35	5	2.5	0.98878	8.58442	6.97429		0.99217	6.63944×10^{-4}	0.023759
35	7	3.5	0.98637	16.17871	10.67795		0.99461	4.31847×10^{-4}	0.01944
45	3	2.5	0.97463	2.86365	2.49344		0.99542	3.75366×10^{-4}	0.017176
45	5	3.5	1.00989	5.81458	4.9377		0.99682	2.9681×10^{-4}	0.015406
45	7	1.5	0.99521	14.40629	9.54386		0.99419	4.85948×10^{-4}	0.020483
55	3	3.5	0.99402	2.72443	2.21462		0.99938	6.10401×10^{-5}	0.006663
55	5	1.5	0.97416	6.28429	4.64576		0.99701	2.481×10^{-4}	0.014208
55	7	2.5	0.93891	5.55731	4.63247		0.9874	9.59574×10^{-4}	0.028107
Modified Page equation-II			n	c	L				
35	3	1.5	0.92932	0.43236	1.26681		0.99658	2.64909×10^{-4}	0.015
35	5	2.5	1.01688	0.33768	1.39075		0.9921	6.69431×10^{-4}	0.023854

Continued on the next page

T(°C)	h(mm)	V(m/s)	Constant			R^2	χ^2	*RMSE*
35	7	3.5	0.99704	0.33521	1.52347	0.99436	4.5212×10^{-4}	0.019885
45	3	2.5	0.86118	0.69831	1.15444	0.99934	5.43047×10^{-5}	0.006532
45	5	3.5	1.05253	0.43418	1.39158	0.99757	2.26789×10^{-4}	0.013466
45	7	1.5	1.03	0.33314	1.47609	0.99449	4.61406×10^{-4}	0.019966
55	3	3.5	0.95674	0.44007	0.86574	0.99969	3.03133×10^{-5}	0.004695
55	5	1.5	0.91963	0.54986	1.30599	0.9982	1.4907×10^{-4}	0.011011
55	7	2.5	0.83494	0.54272	1.28216	0.99289	5.42011×10^{-4}	0.02113

The quadratic polynomial equation in one variable was used to fit the parameters k and n in Page model so as to improve the accuracy, and the fitted expression of k and n in different conditions are listed in Table 3. The comparison between experimental moisture ratio at different conditions and that predicted by the Page model are shown in Figure 2, Figure 4 and Figure 6. The predicated values are in good agreement with the experimental ones, indicating that the drying behaviour of tilapia fillets can be well predicted and described by the Page model.

Determination of effective moisture diffusivities

The results have shown that internal mass transfer resistance controls the drying time due to the presence of a falling rate drying period. Therefore, the values of the effective moisture diffusivities at the drying experiment under different conditions are calculated by using Eqs. (3) from Fick's second law and shown in Table 4. The effective moisture diffusivities of tilapia fillets with thickness of 5 mm at drying temperature 35, 45 and 55°C and hot air velocity 1.50, 2.50 and 3.50 m/s are in the range of 6.55351×10^{-10} to 1.23229×10^{-9} m^2/s, which were consistent with the previous studies that the values of the effective moisture diffusivities ranged from 10^{-9} to 10^{-11} m^2/s [Madamba, 1996], from 10^{-8} to 10^{-12} m^2/s [Zogzas *et al.,* 1996] for food materials. The values of D_{eff} are comparable with the reported values of 3.32 – 90.0 × 10^{-10} m^2/s for berberis fruits at 50–70°C [Aghbashlo *et al.,* 2008], and 6.27 – 35.0 × 10^{-10} m^2/s for orange slices at 40–80°C [Rafiee *et al.,* 2010]. In the same thickness of tilapia fillets, the values of the effective moisture diffusivities increase with the increase of the drying temperature and the hot air velocity. It could be explained as follows: the increased heat of raising drying temperature will improve the activity of the movement of water molecules, thus increase the diffusion rate of water; tilapia fillets dried at higher air velocity, which benefit the heat and mass exchange of fish fillets and hot air, so that the moisture content and water vapour partial pressure on fillet surface reduced, and accelerated the fillets internal moisture diffusion.

Determination of activation energy

The values of activation energy are calculated by Arrhenius-type equation, that is, calculated according to the slope of Arrhenius plot, ln(D_{eff}) *versus* $1/T_a$ Eqs. (6). The relation-

TABLE 3. The simulated expression of parameters of k and n.

Experimental conditions		The expression of k	The expression of n
35°C	3.5 m/s	k=0.72717–0.15891h+0.01082h^2	n=0.62441+0.12914h-0.01085h^2
45°C	2.5 m/s	k=0.97399–0.17548h+0.01085h^2	n=0.93592–0.03217h+0.00243h^2
55°C	1.5 m/s	k=0.12759+0.10229h-0.0121h^2	n=1.14096–0.07144h+0.00543h^2
3 mm	55 °C	k=-0.24801+0.49178V-0.07293V^2	n=1.68947–0.67593V+0.13331V^2
5 mm	45 °C	k=-0.56506+0.7476V-0.14979V^2	n=1.98916–0.9454V+0.19364V^2
7 mm	35 °C	k=0.00556+0.14724V-0.0307V^2	n=1.2985–0.35885V+0.07791V^2
1.5 m/s	7 mm	k=1.04803–0.04461T+0.0005476T^2	n=-1.11272+0.09667T-0.00109T^2
2.5 m/s	5 mm	k=-0.54124+0.02106T-0.00001905T^2	n=2.66485–0.06956T+0.0006426T^2
3.5 m/s	3 mm	k=-3.85156+0.18895T0.00197T^2	n=4.08854–0.14977T+0.00169T^2

TABLE 4. The effective moisture diffusivities of tilapia fillets at different conditions.

Temperature T/°C	Hot air velocity V/ m/s	Linear simulated equation	R^2	*The slope: B*	D_{eff} / m^2/s
35	1.5	lnMR=0.36066–6.46806×$10^{-5}t$	0.94685	-6.46806×10^{-5}	6.55351×10^{-10}
45	1.5	lnMR=0.22935–7.56278×$10^{-5}t$	0.95764	-7.56278×10^{-5}	7.66270×10^{-10}
55	1.5	lnMR=0.14485–9.12538×$10^{-5}t$	0.9754	-9.12538×10^{-5}	9.24594×10^{-10}
55	2.5	lnMR=0.04829–1.15489×$10^{-4}t$	0.97833	-1.15489×10^{-4}	1.17015×10^{-9}
55	3.5	lnMR=0.11826–1.21622×$10^{-4}t$	0.97694	-1.21622×10^{-4}	1.23229×10^{-9}

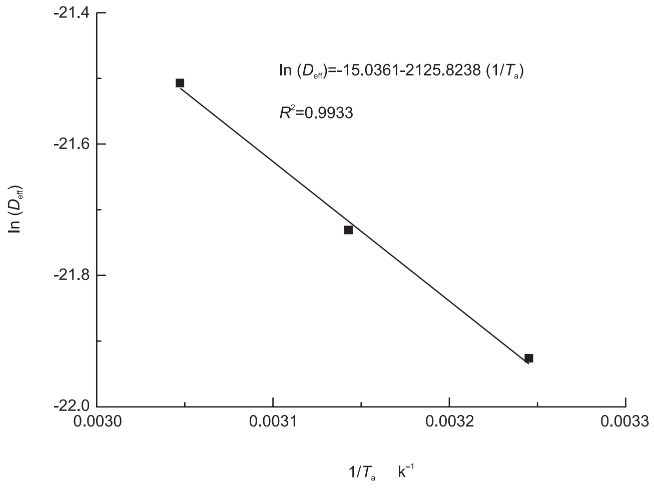

FIGURE 8. Arrhenius-type relationship between effective moisture diffusivity and reciprocal absolute temperature.

ship between ln(D_{eff}) and reciprocal of absolute temperature was shows in Figure 8, in which the slope of the fitted line in the Figure 8 is -E_a/R.

The effective moisture diffusivities of tilapia fillets with thickness of 3 mm at hot air velocity of 2.50 m/s are expressed as follows:

$$D_{\mathrm{eff}} = 2.95\times10^{-7}\exp\left(-\frac{2125.8238}{T_{\mathrm{a}}}\right) \quad (R^2 = 0.9933)$$

From the line slope -E_a/R, the values of activation energy can be obtained and the value of activation energy for the whole falling rate period was 17.66 kJ/mol. This value is similar to those proposed in the literature by several authors for different fruits and vegetables such as 11.4–22.3 kJ/mol in mango [Corzo *et al*., 2008], and 22.66–30.92 kJ/mol in apples [Meisami-asl *et al.*, 2010], respectively. The values of activation energy were within the general range of 12.7 to 110 kJ/mol for various food materials [Zogzas *et al.,* 1996].

CONCLUSION

Constant drying rate period was not observed, the drying process took place in the falling-rate period. With the increase of the drying temperature, drying velocity and reduction of the thickness, the moisture ratio decreased and the drying rate increased. Among the nine tested models, the Page model predicts and describes the drying process more accurately than others. The values of effective moisture diffusivity are in the range of 6.55×10^{-10} to 1.23×10^{-9} m^2/s. With the increase of the drying temperature and the hot air velocity, the effective moisture diffusivity D_{eff} increased. The value of drying activation energy of tilapia fillets with thickness of 3 mm at hot air velocity of 2.50 m/s is 17.66 kJ/mol.

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