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

| Model                  | Expression                                                                 | Reference               |
|------------------------|---------------------------------------------------------------------------|-------------------------|
| Lewis                   | \( MR = \exp(-kt) \)                                                      | Bruce [1985]            |
| Page                   | \( MR = \exp(-kt^a) \)                                                   | Page [1949]             |
| Henderson and Pabis     | \( MR = a\exp(-kt) \)                                                   | Henderson & Pabis [1961]|
| Logarithmic             | \( MR = a\exp(-kt) + c \)                                                | Togrul & Pehlivan [2002]|
| Two-term model          | \( MR = a\exp(-kt) + b\exp(-k't) \)                                     | Henderson [1974]        |
| Approximation of diffusion | \( MR = a\exp(-kt) + \frac{(1-a)\exp(-k'at)}{1} \)                       | Yaldiz et al. [2001]    |
| Wang and Singh          | \( MR = 1 + ar^2 + b/r^2 \)                                              | Wang & Singh [1978]     |
| Simplified Fick’s diffusion | \( MR = a\exp(-c(t/L)^n) \)                                             | Diamante & Munro [1991]|
| Modified Page equation-II | \( MR = \exp(-c(t/L)^n) \)                                               | 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-Akinntunde & Ogulnik, 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. The experimental drying data were fitted to 9 common used thin-layer drying models (Table 1).

**MATERIALS AND METHODS**

**Sample preparation**
Fresh tilapias (Oreochromis niloticus) 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 were collected by multi-channel digital instrument 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-Akinntunde & Ogulnik, 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. The experimental drying data were fitted to 9 common used thin-layer drying models (Table 1).

**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:

\[
MR = \frac{(M_i - M_f)}{(M_0 - M_f)}
\]

where \( M_i \) is the moisture content of the product at each moment, \( M_0 \) is the initial moisture content and \( M_f \) is the equilibrium moisture content.

**Calculation of drying rate**
\( U_i \) represents the drying rate and can be described by Falade method:

\[
U_i = \frac{(M_i - M_f)}{(t - i)}
\]
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:

$$
\ln MR = \frac{8}{\pi^2} \frac{D_{ef} t}{4 L_0^2}
$$

where $D_{ef}$ is the effective moisture diffusivity (m$^2$/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:

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

### 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:

$$D_{ef} = D_0 \exp \left(-\frac{E_a}{RT_a}\right)$$

where $D_0$ is the pre-exponential factor of the Arrhenius equation (m$^2$/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 $\ln(D_{ef})$ versus $1/T_a$ is a straight line with a slope of:

$$\text{Slope} = \frac{E_a}{R}$$

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

### Correlation coefficients and error analyses

The correlation coefficient ($R^2$), the reduced chi-square ($\chi^2$) 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 $\chi^2$ 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 vaporization 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-
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 and 7 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
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 ($\chi^2$) 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 $\chi^2$ 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 $\chi^2$ 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 | $R^2$  | $\chi^2$ | RMSE  |
|-------|-------|--------|----------|--------|---------|-------|
| Lewis |       |        |          |        |         |       |
| 35    | 3     | 1.5    | 0.00662  | 0.99551| 3.48385×10^{-4} | 0.018193 |
|       | 5     | 2.5    | 0.17844  | 0.99238| 6.07266×10^{-4} | 0.024021 |
|       | 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 |
|       | 5     | 3.5    | 0.23619  | 0.99715| 2.65841×10^{-4} | 0.015748 |
|       | 7     | 1.5    | 0.1589   | 0.99472| 4.42022×10^{-4} | 0.020538 |
| 55    | 3     | 3.5    | 0.55882  | 0.99946| 5.2872×10^{-4}  | 0.006933 |
|       | 5     | 1.5    | 0.29906  | 0.99664| 2.78972×10^{-4} | 0.016163 |
|       | 7     | 2.5    | 0.27641  | 0.98442| 0.000119       | 0.033414 |
| Page  |       |        |          |        |         |       |
|       | 3     | 1.5    | 0.27844  | 0.92965| 0.99677  | 2.50182×10^{-4} | 0.015 |
|       | 5     | 2.5    | 0.17242  | 0.99254| 6.32219×10^{-4} | 0.023854 |
|       | 7     | 3.5    | 0.14483  | 0.99461| 4.31579×10^{-4} | 0.019885 |
| 45    | 3     | 2.5    | 0.54517  | 0.97461| 4.97781×10^{-4} | 0.006532 |
|       | 5     | 3.5    | 0.21661  | 0.99775| 4.38325×10^{-4} | 0.019966 |
|       | 7     | 1.5    | 0.14929  | 0.99476| 2.69449×10^{-4} | 0.004695 |
| 55    | 3     | 3.5    | 0.57983  | 0.99936| 0.99945  | 5.42484×10^{-5} | 0.001101 |
|       | 5     | 1.5    | 0.33656  | 0.99833| 0.99461  | 1.38425×10^{-4} | 0.02113 |
|       | 7     | 2.5    | 0.35812  | 0.99336| 0.99551  | 8.95603×10^{-4} | 0.028107 |
| Henderson and Pabis |       |        |          |        |         |       |
|       | 3     | 1.5    | 0.23977  | 0.97344| 0.96828  | 0.9641  | 2.78138×10^{-4} | 0.015827 |
|       | 5     | 2.5    | 0.17646  | 0.98871| 0.9926  | 6.27059×10^{-4} | 0.023759 |
|       | 7     | 3.5    | 0.14189  | 0.99486| 4.12218×10^{-4} | 0.01944 |
| 45    | 3     | 2.5    | 0.46064  | 0.97461| 0.9958  | 3.44085×10^{-4} | 0.017176 |
|       | 5     | 3.5    | 0.23846  | 1.00984| 0.99706  | 2.73979×10^{-4} | 0.015406 |
|       | 7     | 1.5    | 0.15814  | 0.99448| 4.61651×10^{-4} | 0.020483 |
| 55    | 3     | 3.5    | 0.55574  | 0.99399| 0.99945  | 5.42848×10^{-5} | 0.006662 |
|       | 5     | 1.5    | 0.29133  | 0.97408| 0.99722  | 2.30356×10^{-4} | 0.014186 |
|       | 7     | 2.5    | 0.25899  | 0.93893| 0.98824  | 8.95603×10^{-4} | 0.028107 |
| Logarithmic |       |        |          |        |         |       |
|       | 3     | 1.5    | 0.23095  | 0.97344| -0.01093| 0.9966  | 2.63501×10^{-4} | 0.014967 |
|       | 5     | 2.5    | 0.14706  | 1.02983| -0.06635| 0.9973  | 2.28909×10^{-4} | 0.013946 |
|       | 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 |
|       | 5     | 3.5    | 0.21146  | 1.0383 | -0.04412| 0.99932 | 6.33171×10^{-5} | 0.007117 |

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### Approximation of diffusion

| $T(°C)$ | $k(\text{mm})$ | $V(\text{m/s})$ | $a$ | $b$ | $R^2$ | $\chi^2$ | RMSE |
|---------|----------------|-----------------|-----|-----|-------|----------|-------|
| 35      | 3              | 1.5             | 0.39686 | 0.6323 | 0.95458 | 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             | 0.37212 | 0.16825 | 0.99895 | 1.25531×10⁻⁴ | 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 | 0.99972 | 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

| $T(°C)$ | $k(\text{mm})$ | $V(\text{m/s})$ | $a$ | $b$ | $R^2$ | $\chi^2$ | RMSE |
|---------|----------------|-----------------|-----|-----|-------|----------|-------|
| 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

| $T(°C)$ | $k(\text{mm})$ | $V(\text{m/s})$ | $a$ | $c$ | $L$ | $R^2$ | $\chi^2$ | RMSE |
|---------|----------------|-----------------|-----|-----|-----|-------|----------|-------|
| 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 | 0.01994 |
| 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 | 6.10401×10⁻⁴ | 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 | 9.59754×10⁻⁴ | 0.028107 |

### Modified Page equation-II

| $T(°C)$ | $k(\text{mm})$ | $V(\text{m/s})$ | $n$ | $c$ | $R^2$ | $\chi^2$ | RMSE |
|---------|----------------|-----------------|-----|-----|-------|----------|-------|
| 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 |

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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 predicted 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, were consistent with the previous studies that the values of the effective moisture diffusivities ranged from \( 10^{-9} \) to \( 10^{-11} \) m²/s [Madamba, 1996], from \( 10^{-4} \) to \( 10^{-12} \) m²/s [Zogzas et al., 1996] for food materials. The values of \( D_{eff} \) are comparable with the reported values of 3.32 – 90.0 \( \times \) 10⁻¹⁰ m²/s for berberis fruits at 50–70°C [Aghbashlo et al., 2008], and 6.27 – 35.0 \( \times \) 10⁻¹⁰ m²/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-

| Experimental conditions | \( k \) | \( n \) |
|------------------------|------|------|
| 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           | \( k=0.97399-0.17548h+0.00185h^2 \) | \( n=0.93592-0.03217h+0.00243h^2 \) |
| 55°C 1.5 m/s           | \( k=0.12759+0.10229h-0.0211h^2 \) | \( n=1.14096-0.07144h+0.00543h^2 \) |
| 3 mm 55°C              | \( k=0.24801+0.49178V-0.02793V^2 \) | \( n=1.68947-0.67593V+0.13331V^2 \) |
| 5 mm 45°C              | \( k=0.56506+0.7476V-0.14979V^2 \) | \( n=1.98946-0.9454V+0.19364V^2 \) |
| 7 mm 35°C              | \( k=0.00556+0.14724V-0.0307V^2 \) | \( n=1.2985-0.3885V+0.07791V^2 \) |
| 1.5 m/s 7 mm           | \( k=1.04803-0.04461T+0.0005476T^2 \) | \( n=1.11727+0.09667T-0.001097T^2 \) |
| 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           | \( k=3.85156+0.18895T+0.00197T^2 \) | \( n=4.08854-0.14977T+0.00169T^2 \) |

**TABLE 3.** The simulated expression of parameters \( k \) and \( n \).

| Temperature T/°C | Hot air velocity V/m/s | Linear simulated equation | \( R^2 \) | The slope: B | \( D_{eff} \) m²/s |
|-------------------|------------------------|--------------------------|-------|----------|-------------|
| 35                | 1.5                    | lnMR=0.36066–6.46806×10⁻⁹t | 0.9465 | -6.46806×10⁻⁹ | 6.55531×10⁻¹⁰ |
| 45                | 1.5                    | lnMR=0.22935–7.56278×10⁻⁹t | 0.9576 | -7.56278×10⁻⁹ | 7.66270×10⁻¹⁰ |
| 55                | 1.5                    | lnMR=0.14485–9.12538×10⁻⁹t | 0.9754 | -9.12538×10⁻⁹ | 9.24594×10⁻¹⁰ |
| 55                | 2.5                    | lnMR=0.04829–1.15489×10⁻⁹t | 0.9783 | -1.15489×10⁻⁹ | 1.17015×10⁻⁹  |
| 55                | 3.5                    | lnMR=0.11826–1.21622×10⁻⁹t | 0.9769 | -1.21622×10⁻⁹ | 1.23229×10⁻⁹  |

**TABLE 4.** The effective moisture diffusivities of tilapia fillets at different conditions.
ship between ln(Def) 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:

\[
D_{eff} = 2.95 \times 10^{-7} \exp \left( \frac{2125.8238}{T_a} \right) \quad (R^2 = 0.9933)
\]

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 \times 10^{-10} to 1.23 \times 10^{-8} 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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