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Desorption isotherms and drying characteristics of Nile tilapia fish sheet

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Abstract

This study aimed to investigate desorption isotherm properties and drying behavior of fish sheets prepared from minced Nile tilapia at various conditions. Desorption isotherms of fish sheet samples were determined at 25ºC, 35ºC and 50ºC over a water activity (a_w) range of 0.33-0.96. Five sorption isotherm equations including the Modified Halsey, Modified Oswin, Modified Henderson, Modified Chung-Pfost and Mujica model were fitted to the experimental desorption data. In convection drying experiments, fish sheet samples were dried in a single layer at 50ºC, 60ºC and 70ºC with a constant air velocity of 0.5 m/s. The experimental drying data were then fitted to the Newton, Page, Henderson and Pabis and Two-term exponential models. Desorption isotherms of Nile tilapia fish sheet behaved like a type II in the BET classification and had a sigmoid form. At any given moisture content, an a_w of the sample increased with increasing temperature. The Modified Oswin gave the best fit to the experimental desorption data. The total heat of desorption of water decreased continuously with increasing equilibrium moisture content. Drying chiefly occurred in the falling rate period and the drying rate increased with temperature. The Page's equation gave the best fit to the experimental drying data over the respective range of temperatures studied, with corresponding R^2, SEE and RMSE varying from 0.995 to 0.997, 0.012 to 0.015, and 0.011 to 0.014 respectively. The moisture diffusivity increased from 1.108×10^{-11} m^2/s at 50ºC to 1.752×10^{-11} m^2/s at 70ºC. The temperature dependence of moisture diffusivity was successfully described by the Arrhenius-type equation.

Introduction

Nile tilapia is a common freshwater fish, belonging to the family Cichlidae (Agnese *et al.*, 1997). It grows rapidly, reproduces easily, and adapts to a wide range of environmental conditions (Duan et al., 2011). Due to its mild flavor, and good texture, Nile tilapia is widely accepted and used in many cuisines; not being proscribed by any religious observance (Duan *et al.*, 2011). It is exported as a whole fish or as fillets. Nile tilapia is a valuable source of nutrients as it contains ~15% protein, 0.7% fat, and many minerals. It comprises, however, of up to 80% water and is thus highly perishable (Alemu *et al.*, 2013), so processing and preservation are necessary for extending the shelf life. Air-drying is a common method of preserving fish and fish products by removing the moisture necessary for bacterial and mold to thrive and by inactivating the enzymes present in fish muscle (Bellagha *et al.*, 2002; Djendoubi *et al.*, 2009). Fish sheets are a fish-based snack prepared by mixing minced fish with sugar, soy sauce, pepper and salt until a cohesive mass is obtained. The mixture is pressed to form a thin sheet of 1.5 mm thickness and dried at 60ºC for 2-3 h before deep-frying (Jantaranukul, 2010). Drying is, therefore, an essential step of fish sheets production.

The relationship between equilibrium moisture content (EMC) and the water activity (a_w) of food, over a range of values and at a constant temperature yields a moisture sorption isotherm when expressed graphically (Al-Muhtaseb *et al.*, 2002). Isotherms can be divided into two categories, adsorption and desorption. The former is important in storage and the later for drying (Rojanakorn, 2004). The desorption isotherm determines the lowest attainable or final moisture content to which a food material can be dried at a particular drying temperature and relative humidity (Rojanakorn, 2004). Net isosteric heat of sorption (q_{st}) is an important thermodynamic parameter estimated from the experimental desorption isotherms through the Clausius-Clapeyron equation (Hadrich *et al.*, 2008; Djendoubi *et al.*, 2009; Toujani *et al.*, 2011). It represents the difference between total heat of desorption and the latent heat of water vaporization (at the same temperature) and plays an important role in determining energy requirements for drying (Toujani *et al.*, 2011). Due to the complexity of the physicochemical structure of food, theoretical prediction of the sorption heat of water is

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not feasible. Thus, it is necessary to determine this value experimentally from moisture sorption data (Tsami *et al.*, 1991; Delgado and Sun, 2002a).

Knowledge of desorption isotherms is of primary importance when describing the drying process and its kinetics (Sun and Woods, 1997). It is, therefore, necessary to study the desorption isotherms of various foods and to describe them mathematically. Drying is a thermal process in which heat and moisture transfer occur simultaneously. Development of mathematical models of the process helps understand and, to some extent, control it. The most appropriate drying model should incorporate desorption equations so that it provides the time to final moisture content, corresponding to the water activity for safe storage (Rojanakorn, 2004).

Many researchers have reported the desorption isotherms and drying characteristic for many types of fish. Toujani *et al.* (2011) reported that the desorption isotherms of silverside fish *(Atherina)* determined at 40ºC–70ºC and 0.058-0.89 a_w were well fitted and described by the Peleg model albeit this model did not take temperature into account. Djendoubi *et al.* (2009) found that among the 3 models tested, the Page model was the best for simulating the drying kinetics of sardine muscle between 40ºC and 80ºC. Bellagha *et al.* (2007) observed that drying salted sardine at 40ºC, 15% RH and 1.5 m/s air velocity had two falling rate periods, the first being affected by the salting method.

Although the production of fish sheet from various kinds of fish (including Nile tilapia) is established in many parts of Thailand, information on desorption isotherms and drying characteristics is limited. Therefore, this research aimed to determine the desorption isotherms and drying characteristics of Nile tilapia fish sheet.

Materials and Methods

Preparation of fish sheet

Fish sheet, a fish-based snack was prepared by mixing 1000 g of minced Nile tilapia with 50 g soy sauce, 100 g water, 100 g sugar, 4 g salt and 2 g finely ground white pepper in a mixer (Crypto peerless E10, The Netherlands) at high speed for 3 minutes until cohesive. The mixture (200±2 g) was put in plastic bags (24 x 32 cm), pressed to form a thin sheet (1.5+0.1 mm) by using a wooden rolling pin then cut into pieces measuring 3 x 3 x 3 cm.

Desorption isotherm experiment

In preparation for the desorption isotherm, 35 pieces of fresh fish sheet (3 x 3 x 3 cm) samples were dried in a tray dryer (Armfield Limited, Hampshire, England) at 50^{o}C with a constant air velocity of 0.5 m/s. Five randomly chosen pieces of fish sheet were removed from the dryer at a pre-set time. This process was repeated six more times resulting in 7 groups of sample with different moisture contents. Desorption isotherms of all groups of fish sheet at 25ºC, 35ºC and 50ºC were determined (Trirattanapikul and Phoungchandang, 2014) with a water activity meter (Aqual Lab Series 3TE, Device, America), which can perform temperature-controlled a_w measurements with an accuracy of 0.01%. This range of temperature was selected because 50^{o}C and 25^{o}C are the maximum and minimum temperatures to be accurately controlled by the instrument (Aqual Lab Series 3TE, Device, America) as recommended by the manufacturer guideline. As the effect of temperature on desorption isotherms was investigated, the three different temperatures (25ºC, 35ºC and 50ºC) were used. The temperature of the measurement chamber was regulated to a set point by a controller with 0.3ºC accuracy. The moisture content of all fish sheet samples was measured according to the AOAC method (AOAC, 2000).

Five isotherm equations including the Modified Halsey (Eq. 1) (Chen and Morey, 1989), the Modified Oswin (Eq. 2) (Chen and Morey, 1989), the Modified Henderson (Eq. 3) (Chen and Morey, 1989), the Modified Chung-Pfost (Eq. 4) (Chen and Morey, 1989), and the Mujica (Eq. 5) (Comaposada *et al.*, 2000) were used to fit the experimental desorption data. These models were selected because they take into account the effect of temperature on the desorption isotherm.

$$M_e = \left[\frac{-\exp(C_1 + C_2 T)}{\ln(RH_e)}\right]^{1/C_3} \quad (1)$$

$$M_e = (C_1 + C_2 T)\left(\frac{RH_e}{1 - RH_e}\right)^{C_3} \quad (2)$$

$$M_e = \left[\frac{\ln(1 - RH_e)}{-C_1(T + C_2)}\right]^{\frac{1}{C_3}} \quad (3)$$

$$M_e = \frac{1}{-C_3}\ln\left[\frac{(T + C_2)\ln RH_e}{-C_1}\right] \quad (4)$$

$$M_e = \frac{1}{((C_1 T + C_2) - (C_3 T + C_4) RH_e)} \quad (5)$$

M_e is the equilibrium moisture content (% db.), RH_e the equilibrium relative humidity (decimal), T the temperature (ºC) and C_1, C_2, C_3, C_4 the model parameters.

A non-linear regression analysis was used to calculate the best-fit values of the model parameters in Eqs. 1-5 using SPSS, Version 19. The suitability of the equations for fitting the experimental data was evaluated and compared using the determination coefficient (R^2), the Standard Error of Estimate (SEE) and the Root Mean Square Error, as follows:

$$SEE = \sqrt{\frac{\sum_{i=1}^{n}(m_i - d_i)^2}{n-N}} \quad (6)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(m_i - d_i)^2}{n}} \quad (7)$$

m_i is moisture content (% db.) calculated by the model, d_i the experimental moisture content (% db.), n the number of experimental data and N the number of model's parameters (Vega-Galvez *et al.*, 2011).

Net isosteric heat of desorption (q_{st}) can be estimated at any moisture content by using the Clasius-Clapeyron equation: plot the sorption isostere as $\ln(a_w)$ against the reciprocal temperature (1/T) and determine the slop of the straight line ($-q_{st}/R$) , where R is the universal gas constant (Iglesias and Chrife, 1976; Delgado and Sun, 2002a). The total heat of desorption (Q_{st}) is, then obtained by adding the net isosteric heat of desorption (q_{st}) to the latent heat of vaporization of pure water (43.436 kJ/mole) (L_r) (Eq. 8).

$$Q_{st} = q_{st} + L_r \quad (8)$$

This experiment was performed in triplicate and the mean values were reported.

Drying experiment

The 3 x 3 x 3 cm pieces of fish sheet (~500 g) were dried in a single layer at 50ºC, 60ºC and 70ºC in a tray dryer (Armfield Limited, Hampshire, England) with a constant air velocity of 0.5±0.1 m/s, measured by an anemometer (Sato Keiryoki, model 3K-27V No. 7680-00, Tokyo, Japan). A relative humidity meter (VAISALA MODEL HMP-5D, DELTA OHM-VIAG, Galilei, Italy) with an accuracy of 0.01% was used to measure the relative humidity (RH) of the drying air. An average RH of hot air throughout the drying process was used (viz., 0.495, 0.401 and 0.314 at 50ºC, 60ºC and 70ºC, respectively). The mass loss of the sample was recorded every 5 min using a data logger (DT 800 Data Taker, Scoresby, Victoria, Australia). The drying was terminated when the final moisture content reached 10±1% (db.), which was within permission limit (10±2% db.), as specified by the Thai Industrial Standard (TIS) No.701-2530 for fish chip or cracker (Jantaranukul, 2010)

The experimental drying data were fitted to 4 thin-layer drying models using non-linear regression (SPSS, Version19) viz., the Newton model (Eq. 9) (Lewis, 1921), the Page equation (Eq. 10) (Page, 1949), the Henderson and Pabis model (Eq. 11) (Henderson and Pabis, 1961) and the two-term exponential model (Eq. 12) (Berhimpon *et al.*, 1996).The goodness of fit of the models to the experimental data was evaluated and compared using the determination coefficient (R^2), the Standard Error of Estimate (SEE), and the Root Mean Square Error.

$$\frac{M - M_e}{M_o - M_e} = \exp(-kt) \quad (9)$$

$$\frac{M - M_e}{M_o - M_e} = \exp(-kt^n) \quad (10)$$

$$\frac{M - M_e}{M_o - M_e} = A\exp(-kt) \quad (11)$$

$$\frac{M - M_e}{M_o - M_e} = A\exp(-kt) + (1 - A)\exp(-Bkt) \quad (12)$$

M is moisture content at any time (% db.), M_e the equilibrium moisture content (% db.), M_o the initial moisture content (% db.), t the drying time (min), k the drying rate constant (min^{-1}), and n A and B the model parameters.

The effective moisture diffusivity (D_{eff}) during drying was determined by fitting the drying data to the solution of Fick's second law of diffusion for an infinite slab (Eq. 13) (Vega-Galvez *et al.*, 2011).

$$\frac{M - M_e}{M_o - M_e} = \frac{8}{\pi^2}\exp\left(-\frac{\pi^2 D_{eff} t}{4L^2}\right) \quad (13)$$

D_{eff} is the effective moisture diffusivity (m^2/s), t the drying time (min) and L the half-thickness of the slab (m).

The temperature dependence of effective moisture diffusivity can be represented by an Arrhenius equation (Eq. 14) (Vega-Galvez *et al.*, 2011).

$$D_{eff} = D_o \exp(-\frac{E_a}{RT}) \quad (14)$$

R is the universal gas constant (8.314 J/mol K), E_a the activation energy (kJ/mol), D_o the Arrhenius factor (m^2/s) and T the absolute temperature (K).

This experiment was performed in triplicate and the mean values were reported.

Results and Discussion

Desorption isotherms of Nile tilapia fish sheet

Desorption isotherms of Nile tilapia fish sheet at 25ºC, 35ºC, and 50ºC are presented in Figure 1. All isotherms had the typical type II sigmoid shape common to most food materials. The equilibrium moisture content (EMC) increased gradually at a_w

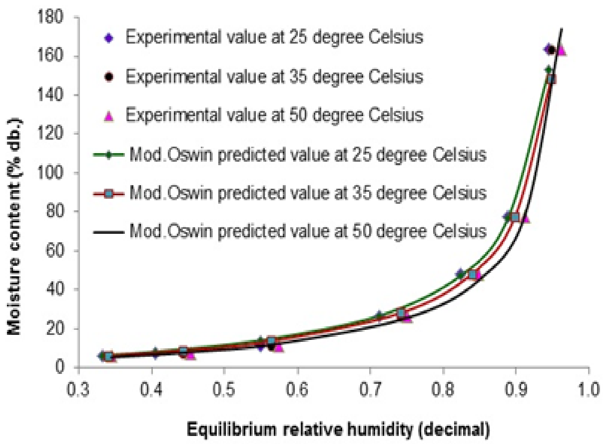

Figure 1. Experimental and Modified Oswin predicted desorption isotherms of Nile tilapia fish sheet at 25°C, 35°C and 50°C

below 0.5 followed by a sharp increase above ~ 0.8 a_w. The steepness of the curve at a high a_w indicates the presence of free water in the porous structure of food materials (Sing *et al*., 2001). Similar trends were observed by Ariahu *et al*. (2006) for fresh water crayfish and Singh *et al.* (2006) for raw goat meat. In the current study, the effect of temperature on desorption isotherms was observed (Figure 1). At any given moisture content, higher temperatures resulted in progressively higher a_w values as generally observed for high protein foods (Ariahu *et al*., 2006; Singh *et al*., 2006; Djendoubi *et al*., 2009). This signifies that at any a_w, Nile tilapia fish sheet becomes less hygroscopic with each increment of temperature. The term "hygroscopicity" refers to the property of moisture absorption which occurs under normal atmospheric condition (Palish and Ruszkowska, 2007). The hygroscopic properties of food materials were affected by many factors including the composition of material, sample treatment such as drying temperature and drying method as well as rewetting method, relative humidity and temperature of surrounding air, the difference between the partial pressure of water in atmosphere and the vapour pressure of the food products (Chen and Tao, 1994; Igathinathane *et al*., 2009).

The results of goodness of fit of the models to experimental desorption data in terms of estimated parameters and values of statistical parameters are presented in Table 1. The Modified Oswin is the best model for describing the experimental desorption isotherms of fish sheet, as it presents the lowest SEE (2.752% db.) and RMSE (2.547% db.) and the highest R^2 (0.998). A comparison between experimental and the predicted desorption isotherms using the Modified Oswin is presented in Figure 1, confirming that the Modified Oswin is the best model for desorption isotherms of Nile tilapia fish sheet in

Table 1. Estimated parameters of models used to describe desorption isotherms of Nile tilapia fish sheet and corresponding statistical parameters

Parameters	Model				
	Mod. Halsey	Mujica	Mod. Henderson	Mod. Oswin	Mod. Chung-Pfost
C1	2.641	0.001	-652.610	14.095	137.492
C2	-0.014	0.114	546928.000	-0.092	132.259
C3	1.011	0.001	-21.454	0.902	0.022
C4	-	0.116	-	-	-
R2	0.994	0.992	0.796	0.998	0.863
SEE (% db.)	4.302	5.175	25.834	2.752	21.071
RSME (% db.)	3.983	4.656	23.923	2.547	19.508

the range of a_w and temperatures investigated.

Delgado and Sun (2002a) reported that experimental desorption isotherms of cooked and cured beef and pork were described well by the Iglesias and Chirife equation for a_w between 0.10 and 0.94 and over the temperature range of 10ºC-50ºC. The same researchers (2002b), however, concluded that among the models tested, the Ferro Fontan model was the best for describing experimental desorption isotherms of chicken over the a_w and temperature range 0.07-0.94 and 4ºC-30ºC. Ahmat *et al*. (2014) demonstrated that the GAB model was the most accurate for explaining desorption behavior of fresh beef for all temperatures (30ºC-50ºC) and all levels of water activity (0.08-0.8). Toujani *et al*. (2011) found that the Peleg model suitably represented desorption isotherms of silverside fish *(Atherina)* for a_w between 0.058 and 0.89 and over the temperature range of 40ºC-70ºC. Hadrich *et al.* (2008) reported that the Oswin model showed the best fit for experimental desorption isotherms of Tunisian sardine *(Sardinella aurita)* over the respective a_w and temperature range 0.10-0.75 and 25ºC-50ºC. By contrast, the Peleg model suitably represented desorption isotherms of sardine muscle for a_w between 0.10 and 0.80 and over the temperature range of 40ºC-80ºC (Djendoubi *et al*., 2009). Based on the results of the current study and other published results, it will be difficult to find a specific mathematical model that accurately describes desorption isotherms in the whole range of a_w and temperature for different muscle foods. This may be because the depression of water activity in foods or biological materials is due to a combination of factors, each of which may be predominant in a given range of water activity (Karel, 1973). In addition, moisture sorption isotherms of foods represent the integrated hygroscopic properties of many constituents whose sorption properties may change as a result of physical and/or chemical reactions induced by heating, cross-linking and denaturation of protein and shrinkage (Iglesias and Chirife, 1976; Dincer and Esin, 1996). Moreover, as a food sorbs water, it usually undergoes changes to its constituents, dimensions and other properties. Water sorption, for example, causes phase transitions of sugars present in foods (Karel, 1973; Iglesius *et al.*, 1975)

In the current study, desorption isotherms of fish sheet from Nile tilapia was successfully described by the Modified Oswin:

$$M_e = (14.095 - 0.092T)\left(\frac{RH_e}{1 - RH_e}\right)^{0.902} \quad (15)$$

M_e is the equilibrium moisture content (% db.) and RH_e the equilibrium relative humidity (decimal).

Eq. 15 was then used to predict the equilibrium moisture content of the samples being dried at different drying conditions of known drying temperatures and relative humidity.

The respective Me of fish sheet dried at 50ºC: RH 0.495, 60ºC: RH 0.401 and 70ºC: RH 0.314 predicted by the Modified Oswin (Eq. 15) was 9.34%, 5.98% and 3.79% (db.). These values were then used to determine the drying kinetics of Nile tilapia fish sheet in the drying experiment.

Isosteric heat of desorption

The moisture dependence of the total heat of desorption (Q_{st}) of Nile tilapia fish sheet estimated using experimental desorption data and the Clasius-Clapeyron equation (Figure 2) illustrated a continuous decrease in the Q_{st} with an increasing moisture content. At low moisture contents, the Q_{st} was higher than at high moisture contents, indicating that water molecules are strongly bound with the solid matrix. Thus, a large amount of energy is needed to remove this water. A decrease in Q_{st} at high moisture content implies that the water-solid interactions are weakened and not so much energy is needed to remove this water. Tasmi (1991) suggested that a sharp rise in the total heat of desorption at low moisture contents was due to the existence of highly active polar sites on the surface of biological materials, which are covered with water molecules forming a mono-molecular layer that is difficult to eliminate. Similar results were reported by Sing *et al.* (2006) for raw goat meat, Haddrich *et al.* (2008) for Tunisian Sardine *(Sardinella aurita)*, Clemente *et al.* (2009) for frozen raw pork meat, Toujani *et al*. (2011) for silverside fish *(Atherina)* and Ahmat *et al*. (2014) for fresh beef.

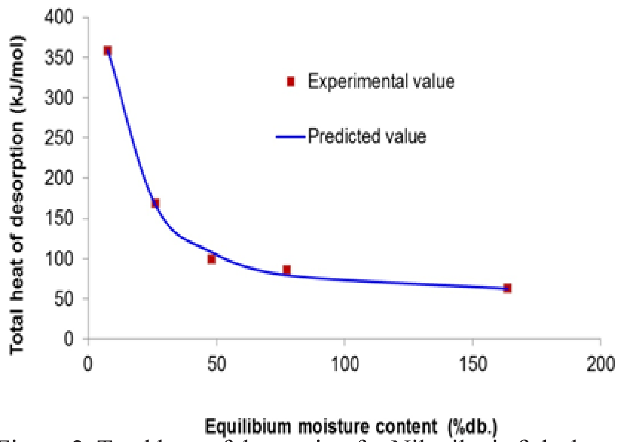

Figure 2. Total heat of desorption for Nile tilapia fish sheet at various moisture contents

The total heat of desorption (Q_{st}) of Nile tilapia fish sheet can be expressed as a function of the equilibrium moisture content (M_e):

$$Q_{st} = \frac{1}{1x10^{-2} + 1x10^{-3}M_e - 6.5x10^{-7}M_e^2} \quad (R^2=0.998) \quad (16)$$

Drying kinetics

The respective variation of moisture ratio and corresponding drying rates of fish sheet samples with drying time are presented in Figure 3(a) and Figure 3(b). The constant drying rate period was not detected and drying of fish sheet samples chiefly occurred in the falling rate period, indicating that the diffusion process is the likely physical mechanism of moisture removal from the fish sheet. Toujani *et al*. (2011) reported that during the falling rate of the drying process, the predominant mechanism of mass transfer is internal mass diffusion. Furthermore, the effect of drying temperature on drying rate was also observed (Figure 3(b)). The drying rate of fish sheet samples increased with increasing temperature. The rate of water diffusion in the product being dried in the falling rate period increases with increasing temperature, resulting in a higher rate of water removal during drying. This is because as drying temperature increases, the pressure of moisture inside the sample is substantially raised. By comparison, as the equilibrium moisture content of sample diminishes, the driving force or the moisture gradient between the center and the surface of sample is elevated (Jittanit, 2011). An increment of drying temperature speeds up the drying process, shortening drying time. Many authors have reported the positive temperature dependence of drying rate in muscle food products, including shark fillets (Mujaffar and Sankat, 2005), sardine muscle (Djendoubi *et al.*, 2009) and silverside fish (Toujani *et al*., 2011). The correlation among moisture content, water activity and drying rate was reported by some researchers (Prachayawarakorn *et*

Table 2. Results of fitting statistics of various models at different drying temperatures

Temperature (ºC)	Models	Estimated parameters				Statistical parameters		
		K (min^{-1})	n	A	B	R^2	SEE	RMSE
50	Newton	0.004	-	-	-	0.969	0.037	0.038
	Page	0.012	0.796	-	-	0.995	0.015	0.014
	Henderson and Pabis	0.003	-	0.900	-	0.985	0.027	0.027
	Two term	0.004	-	201.116	1.000	0.969	0.038	0.039
60	Newton	0.005	-	-	-	0.982	0.031	0.030
	Page	0.013	0.830	-	-	0.997	0.013	0.012
	Henderson and Pabis	0.005	-	0.917	-	0.99	0.023	0.023
	Two term	0.005	-	123.501	1.000	0.982	0.031	0.031
70	Newton	0.008	-	-	-	0.981	0.032	0.031
	Page	0.021	0.818	-	-	0.997	0.012	0.011
	Henderson and Pabis	0.008	-	0.921	-	0.988	0.058	0.057
	Two term	0.008	-	1.25	1.000	0.981	0.084	0.082

al., 2002; Sa-adchom *et al*., 2011). At higher moisture content and water activity, the drying rate was greater that at lower moisture content and water activity. Prachayawarakorn *et al.* (2002) reported that the degree of shrinkage of shrimp muscle which reflects the degree of protein cross-linking was found to be higher with an increment of moisture content, drying temperature and drying rate. Sa-adchom *et al.* (2011) also reported that as the drying rate was increased the cross-linking among muscle fibers of superheated steam dried pork (investigated by scanning electron microscopy micrograph) was increased, indicating more severe protein denaturation.

Experimental drying data at different drying conditions were fitted with 4 models (viz., the Newton, Page, Henderson and Pabis, and two-term exponential models). The Me at different drying conditions was predicted by Eq. 15 then used to determine the drying constant (k), constants A and B, and the drying exponent "n" in the drying models tested.

Among the 4 models tested, the Page equation gave the best fit to the experimental drying data over the range of temperatures studied (Table 2) (R^2 range, 0.995 to 0.997). It also provided the lowest SEE and RMSE (viz., 0.012 to 0.015 and 0.011 to 0.014 respectively). The consistency between the experimental drying data and the Page predicted values is presented in Figure 3. The results of the current study agree with Djendoubi *et al.* (2009) who reported that the Page model adequately described the drying kinetics of sardine muscle dried at 40ºC, 50ºC, and 70ºC. Guan *et al*. (2013) demonstrated that the Page model was the best model to describe drying curves of fresh tilapia fillets, dried under different drying regimes. Ikonic *et al.* (2012) similarly reported that the Page model satisfactorily represented the drying characteristics of Petrovskáklobása (an artisan fermented sausage), under both traditional and industrial conditions.

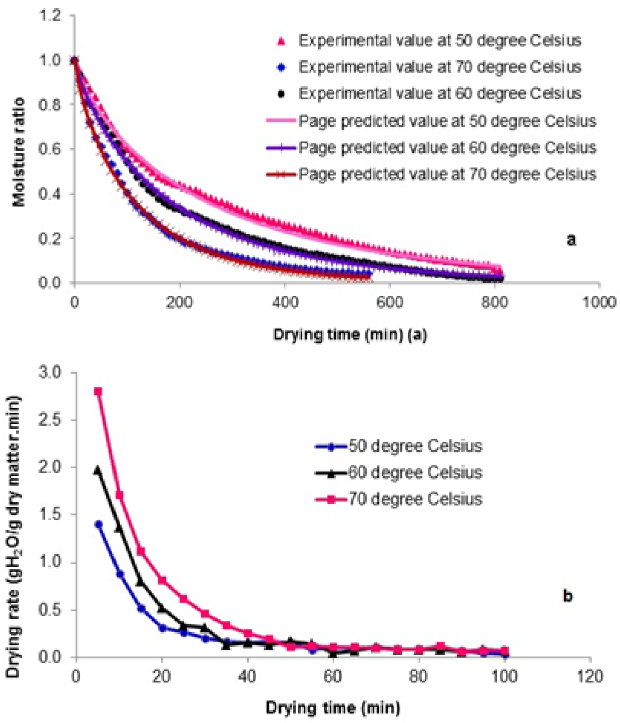

Figure 3. Variation of moisture ratio (a) and drying rate (b) of Nile tilapia fish sheet with drying temperature

Effective moisture diffusivity (D_{eff}) is the imperative physical property, indicating how promptly the moisture is able to transfer from the inside to the surface of the product (Jittanit, 2011). The D_{eff} of fish sheet samples during drying increased from 1.11x10^{-11} m^2/s at 50ºC to 1.75x10^{-11} m^2/s at 70ºC. This is because the increased vapor pressure within the fish sheet as a result of an increment of drying temperature accelerates the moisture diffusion process (Karathanos *et al*., 1990). Panagiotou *et al.* (2004) reported these values range between 10^{-11} m²/s and 10^{-9} m²/s for drying fish. Djendoubi *et al*. (2009) also reported that effective moisture diffusivity of sardine muscle during drying increased from 1.38x10^{-11} m^2/s at 40ºC to 2.21x10^{-11} m^2/s at 70ºC. Thuwapanichayanan *et al*. (2011) concluded that moisture movement inside the product was in liquid form when the D_{eff} values ranged between 10^{-11} m^2/s and 10^{-9} m/s^2.

The relationship between effective moisture diffusivity and drying temperature of Nile tilapia sheets was expressed by:

$$D_{eff} = 3.128\, exp\left(\frac{-21.231}{R}.\frac{1}{T_K}\right) \quad (R^2=0.924) \qquad (17)$$

Generally, activation energy (E_a) is defined as the minimum energy required for initiating moisture diffusion within a product (Shahi *et al*., 2014). The E_a of drying process of Nile tilapia sheets calculated from the Arrhenius relationship was 21.231 kJ/mol, indicating that at least 21.231 kJ of energy is necessary to initiate the diffusion process of 1 mole of moisture within the fish sheet sample. Zogzas (1996) reported that the activation energy of most food products lies between 12.7 and 110 kJ/mol.

Conclusion

Desorption isotherms of Nile tilapia fish sheet over the range of a_w (0.33–0.96) and temperature (25ºC–50ºC) studied exhibited a S-shape, corresponding to a type II BET classification. The equilibrium moisture content decreased with each increment of temperature. The Modified Oswin was the most suitable for describing the relationship between equilibrium moisture content, water activity and temperature; as it provided the highest R^2 and the lowest SEE and RMSE. The total heat of desorption decreased continuously with a rise in moisture content. Drying the fish sheet at 50ºC, 60 ºC and 70ºC primarily occurred in the falling rate period. The Page equation adequately described the drying behavior of the fish sheet. The effective moisture diffusivity of the fish sheet during drying ranged between 1.11x10^{-11} m^2/s and 1.75x10^{-11} m^2/s, increasing with increased temperature. The temperature dependence of this value was successfully expressed by Arrhenius type equation. The temperature of 70ºC was recommended for Nile tilapia fish sheet drying as it provided the highest moisture diffusivity and drying rate.

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