Desorption Isotherms and Drying Characteristics of Carrot Using Tray and Heat Pump−Assisted Dehumidified Drying

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Abstract

Desorption isotherms of sliced carrots have been measured. A non-linear regression program was applied to the experimental data to fit with any of the four moisture sorption isotherm models. The Modified Chung-Pfost and Modified Henderson showed the best fit to both the function $RH_e = f(X_e, T)$ and $X_e = f(RH_e, T)$, respectively. Sliced carrots were pretreated by blanching prior to drying at three temperatures of 40, 50 and 60 °C in tray and heat pump-dehumidified dryers. The drying data were fitted to the Modified Page model. The drying constant was related to air temperature using Arrhenius model. Effective moisture diffusivities were determined using the drying data. Heat pump-dehumidified drying and blanching reduced drying times. Quality evaluation by color values, rehydration ratio and β - carotene content showed the best quality for sliced carrots pretreated by blanching and dried at 40°C in the heat pump-dehumidified dryer.

Keywords: Carrot, β - carotene, Heat pump-dehumidified drying, Tray drying

Introduction

The relationship between total moisture content and the water activity of food, over a range of values, and at a constant temperature, yields a moisture sorption isotherm when expressed graphically. A desorption isotherm is found by placing an initially wet material under the same relative humidities and measuring the weight loss (Labuza, 1968).

There are various methods for the preservation of fruit and vegetable but canning and drying are commonly practiced in industrial processing. Drying is an ancient method for food preservation. Nowadays, this process is important to the industry due to its reduction of the cost of packaging, storing and transportation by reducing both weight and volume of the final product.

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Carrots are a good source of α- and β-carotene, and lutein. Up to now, β-carotene has been the most studied carotenoid. Besides its provitamin A activity, other physiological roles such as cell-to-cell communication, immuno modulatory effect and UV skin protection have been documented. Knowledge of the other carotenoids is rapidly expanding. The xanthophylls, lutein and zeaxanthan are the only carotenoids presented in the macula region of the retina, probably functioning as blue light filters and singlet oxygen quenchers (Van den Berg et al., 2000).

Many researchers have performed various numerical and experimental investigations on the heat pump dehumidified dryer for drying of different biomaterial products. Simulation models of the heat pump dehumidified dryer were developed by Alves-Fillho et al. (1997) for fruit and root drying, Achariyaviriya, et al. (2000) for fruit drying and Phoungchandang (2008) for some herbs. Designs of the heat pump dehumidified dryer were performed by Ogura, et al. (2005) for a control strategy for chemical heat pump dryer, Saensabai and Prasertsan (2007) for condenser coil optimization and component matching and Pal and Khan (2008) for calculation steps for the design of different components. However, various types of products have been dried in experimental heat pump-dehumidified dryer. Dried products include biomaterials (Alves-Filho and Strommen, 1996), sawn rubber, wood and banana (Prasertsan and Saenabai, 1998), bananas (Chua et al., 2001), holy basil leaves (Phoungchandang et al., 2003), garlic (Boonnattakorn et al., 2004), mangoes (Chottanom and Phoungchandang, 2005), ginger (Hawlader et al., 2006; Phoungchandang et al., 2009), composite food products (Rahman et al., 2007), red pepper (Alves-Filho et al., 2007), protein (Alves-Fiho et al., 2008), kaffir lime leaves (Phoungchandang et al., 2008a) and white mulberry leaves (Phoungchandang et al., 2008b).

Drying models

In this work, the general approaches of Sun and Woods (1994) for wheat, Kaur et al. (2006) for tomato peel, Janjai et al. (2006) for longan, Basu et al. (2007) for xantan gum, Krupinska et al. (2007) for various kinds of wood, Phoungchandang et al. (2008a) for kaffir lime leaves and Phoungchandang et al. (2008b) for white mulberry leaves were adopted and developed from the review of isotherm determination in Sun and Woods (1993) for wheat and Basu et al. (2006a; 2006b) for foods. This involved fitting 4 well-established forms for the sorption model to desorption data for sliced carrots in order to establish the best fit. The following isotherm models were selected.

1. Modified Henderson model, MH

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

$$RH_e = 1-\exp\left[-C_1(T+C_2)X_e^{C3}\right] \qquad (2)$$

2. Modified Oswin model, MO

$$X_e = \frac{C_1 + C_2 T}{\left[\dfrac{1}{RH_e} - 1\right]^{1/C_3}} \qquad (3)$$

$$\frac{1}{RH_e} = \left[\frac{C_1 + C_2 T}{X_e}\right]^{C_3} + 1 \qquad (4)$$

3. Modified-Chung-Pfost model, MCP

$$X_e = \frac{1}{-C_3} \ln\left[\frac{(T + C_2)\ln(RH_e)}{-C_1}\right] \qquad (5)$$

$$RH_e = \exp\left[\frac{-C_1}{T + C_2} \exp(-C_3 X_e)\right] \qquad (6)$$

4. Modified Halsey model, MHAL

$$X_e = \left[\frac{-\ln(RH_e)}{\exp(C_1 + C_2 T)}\right]^{-1/C_3} \qquad (7)$$

$$RH_e = \exp\left[-\exp(C_1 + C_2 T) X_e^{C_3}\right] \qquad (8)$$

Equations (2), (4), (6) and (8) for RH_e are fitted by minimizing the standard error of estimate:

$$SEE = \sqrt{\frac{\sum_{i=1}^{n} (RH_e - RH_p)^2}{n - 1}} \qquad (9)$$

where n-1 gives the number of degrees of freedom of the fitting equation. Equations (1), (3), (5) and (7) are all fitted by minimizing the SEE based on measured and predicted values of X.

Drying constant

The relationship analogous to Newton law of cooling is often used in drying analysis in order to describe the falling rate period. The rate of moisture loss is assumed to be proportional to the moisture remaining to be lost shown as follows:

$$\frac{dX}{dt} = -K(X - X_e) \tag{10}$$

By integration, this yields the Newton or exponential drying model

$$\frac{X - X_e}{X_0 - X_e} = \exp(-Kt) \tag{11}$$

A modified form of Page's drying model is employed to describe the experimental data.

$$\frac{X - X_e}{X_0 - X_e} = \exp\left(-(Kt)^N\right) \tag{12}$$

Phoungchandang and Woods (2000) proposed the Zero model because the equilibrium moisture content of banana was close to 0.

$$X = X_0 \exp(-Kt) \tag{13}$$

The movement of moisture occurs by diffusion and is analogous to that of heat conduction in solids. The following equation was used to describe the falling rate drying period.

$$\frac{X - X_e}{X_0 - X_e} = A.\exp(-Kt) \tag{14}$$

The drying constant, K, can be related to temperature using Arrhenius model.

$$K = a.\exp\left(-\frac{b}{T + 273.15}\right) \tag{15}$$

The drying exponent, N, can be related to relative humidity and temperature.

$$N = A.RH^B.\exp(C/T) \tag{16}$$

The drying data can be used to determine effective moisture diffusivity, D_{eff} from the diffusion model.

$$\frac{X - X_e}{X_o - X_e} = \frac{8}{\pi^2}\exp\left[-\frac{\pi^2 D_{eff} t}{4L^2}\right] \tag{17}$$

The objectives of this work were to establish the desorption isotherms for sliced carrots. This work was also focused on the measurement of drying constant, drying exponent as well as effective moisture diffusivity in the drying model over a range of temperature and humidity for sliced carrots by tray and heat pump dehumidified drying. β-carotene content, color values and rehydration were also determined to evaluate the drying process.

Materials and Methods

Carrots, New Kuroda (*Daucus carota* Linn.) were harvested from Petchaboon province, Thailand. Mature carrots were 90-110 days old. The diameter and length of carrots were approximately 6.0 cm and 18 cm, respectively. Carrots were cleaned in 5 ppm chlorinated water, peeled and sliced into 0.2 cm thickness using a manual slicer. Moisture content, protein, fiber, ash, fat and carbohydrate were determined.

Desorption isotherms

Two hundred grams of sliced carrots were placed on a pre-weight drying tray in order to proceed to the drying process using a tray dryer (Armfild Limited, Hampshire, England) at 60°C to obtain seven different levels of moisture content (Phoungchandang and Woods, 2000). The dried carrots of 0.5 g were measured for equilibrium relative humidity at 19.8, 34.9 and 49.8°C by using Aqual Lab (Series 3TE, Devices America) that is specially designed for dewpoint temperature measurement of water activity or relative humidity at equilibrium state with an accuracy of 0.01%. The temperature of the measurement chamber is regulated to a set point by a controller with accuracy to 0.3°C and its range is 15-50°C.

Air drying procedure

The tray dryer (Armfild Limited, Hampshire, England) used in the experiments was described by Phoungchandang et al. (2009). The heat pump-dehumidified dryer used in the experimental was described by Phoungchandang et al. (2003) as shown in Figure 1. The basic components of the heat pump system comprise an expansion valve, two heat exchangers (evaporator and condenser) and a compressor. The drying chamber dimension is 0.95 x 1.8 x 1.7 m. The compressor is of the refrigerated-cooled reciprocating type with a capacity of 250 W. The air passes over an electrically heated element with a capacity of 1300 W. The velocity of air is regulated by a fan at 0.5 m/s. The air passes into the central section of the drying chamber where four trays of material to be dried are suspended in the air stream.

The effect of air drying temperature on the drying process of sliced carrots was investigated at a load of 200 g and were dried in a thin layer at 40, 50 and 60°C in a tray dryer (TD) (Armfild Limited, Hampshire, England) and a heat pump-dehumidified dryer (HPD) (Phoungchandang et al., 2003). An anemometer (MODEL 3K-27V No. 7680-00, SATO KEIRYOKI, Tokyo, Japan) with an accuracy of 0.01 m/s was used to measure air velocity. The air velocity of both dryers was maintained constant at 0.5 m/s (Sun and Woods, 1994). A relative humidity meter (VAISALA MODEL HMP-5D, DELTA OHM-VIAG, Galilei, Italy) with an accuracy of 0.01% RH was used to measure the relative humidity (RH) of drying air every 30 minutes. An average relative humidity of air throughout the drying was used. The weight loss of the sample was recorded every 10 minutes by using a data logger (DT 800, Data Taker, SCORESBY, Victoria, Australia). The drying was terminated when the moisture content of the sample was recorded to be 6.0 % d.b.

Color measurement

The color of sliced carrots was determined before and after drying using Hunter Lab (Ultra Scan, XE U3115, Color Global Co, America). The color was measured in terms of Hunter L^* a^* and b^* valve. Hunter L^* represents the lightness or darkness of the object and it is measured on a scale from 0 to 100. L^* values of 100 represents white and L^* of 0 represents black. Hunter a^* represents redness (+) or greenness (-). Hunter b^* represented yellowness (+) or blueness (-).

The samples were ground using a grinder and a sample size of 5 g was used for color measurement. For each sample, three replications of the color test were performed. Total color difference was also determined.

$$\Delta E^* = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{1/2} \tag{18}$$

where $\Delta L^* = L^* - L_f^*$, $\Delta a^* = a^* - a_f^*$, $\Delta b^* = b^* - b_f^*$ and L^*, a^* and b^* are the color coordinates of the sample and L_f^*, a_f^* and b_f^* are the color coordinated of the fresh sample.

Rehydration ratio

Dried sliced carrots of 5 g were soaked in water at 50°C. Weight gains were monitored by taking out samples from the soaking water and weighing them regularly until the weight was constant. Rehydration ratio was calculated by dividing weight of rehydration sliced carrots with dried sliced carrots (Phoungchandang et al., 2009).

β-carotene determination

β-carotene in carrots was determined using A.O.A.C. (2000).

Data analysis procedure

Desorption isotherm data were fitted to four sorption isotherm models in equations (1)-(8). Drying experiments were performed in duplicate and the average values were fitted to the drying models (NT=Newton, MP=Modified Page, HP= Henderson and Pabis and ZR= Zero model). The model parameters were processed by non-linear regression technique using SPSS 16.0 for Windows. The quality of fit of the tested models was evaluated using the coefficient of determination (R^2) and standard error of estimate (SEE). A completely randomized 2x2x3 factorial experiment was used to study the main factors of drying process; pretreatments, tray, heat pump-dehumidified dryer and drying temperature and interactions between main factors. Two replications were used to determine each parameter. SPSS 16.0 for Windows was used to calculate analysis of variance (ANOVA). Duncan's multiple range test was used to determine the significant treatments at a 95% confidence interval.

Results and Discussion

Chemical composition

The mean moisture content of sliced carrots was 86.86 % w.b. (SD = ± 0.49). Protein, 10.80 % d.b. (SD = ± 1.78); fiber, 10.01 % d.b. (SD = ± 1.21); ash, 3.57 % d.b. (SD = ± 0.37); fat, 3.11 % d.b. (SD = ±1.14) and carbohydrate, 72.52 % d.b (SD = ± 2.94) were detected.

Desorption isotherms

Results within the range of 19.8 to 49.8°C in temperature and 0.30 to 0.80 in RH for sliced carrot are presented in Figure 2. Equations (1) to (8) were fitted to the data using SPSS 16.0 for Windows. Both $X_e = f(RH_e, T)$ and $RH_e = f(X_e, T)$ equation forms were fitted, as minimizing the error or in the prediction of X_e or RH_e generated different constants in the fitted equation (Sun and Woods, 1994). The Modified Chung-Pfost and Modfied Henderson showed the best fit to both the function $RH_e = f(X_e, T)$ and $X_e = f(RH_e, T)$, respectively (Table 1). Modified Chung-Pfost and Modified Henderson models were good models for starchy grains and fibrous materials (Chen and Morey, 1989). Sliced carrots contained rather high fiber content of 10.01±1.21% d.b. Phoungchundang et al. (2003) also found that Modified Henderson model was a good model for holy basil leaves which contained high fiber content.

Modeling of drying kinetics

The experimental conditions for the tray and heat pump-dehumidified dryer of sliced carrots are summarized in Table 3. The drying data obtained were fitted by four drying models. The X_e of carrots predicted from the Modified Henderson model was used to determine drying constant, K and also drying exponent, N. However, the "Zero model" used the simplified moisture ratio as X/X_0 instead of $(X-X_e)/(X_0 - X_e)$. The R^2 values for the model were greater than 0.9333 with low SEE indicating a good fit. The high R^2 values and low SEE values were obtained from the Modified Page model both in TD and HPD (Figure 3 and 4, Table 2).

All drying was in the falling rate period (Figure 3 and 4). The exponent N was added to drying constant and drying time of the Newton model to increase the dependence of temperature and relative humidity of drying air. The K and N values increasing with temperature obtained form HPD were higher than that TD because of lower RH of drying air at the same drying temperature (Table 3). The N values of HPD were higher than that of TD. This can be noted that the RH and temperature of drying air influenced K and N values (Phoungchandang, 2008; Phoungchandang et al., 2009; Phoungchandang et al., 2008a; Phoungchandang et al., 2008b). The drying constants increased with blanching treatment (Table 3). Statistical calculation indicated that blanching had a significant positive effect on the drying constant. The results agreed with Phoungchandang (1986). Fitting the Arrhenius relationship resulting K and drying air temperature, calculated over the full drying period (Table 4), gave the equation for TD and HPD and also for fresh (F) and blanched (B) sliced carrots (Table 4). The relationship of the drying exponent N, RH and temperature of drying air for TD and HPD and also for fresh and blanched sliced carrots are shown in Table 4.

The effective moisture diffusivities (D_{eff}) were calculated by using the method of slopes (equation (17) and Table 3). They were determined by plotting experimental data in terms of ln(MR) versus t (Chottanom and Phoungchandang, 2005; Phoungchandang et al., 2009; Phoungchandang et al., 2008a; Phoungchandang et al., 2008b). The effective moisture diffusivities from this work were in the range of 6.39 E-11 to 1.94 E-10 m^2/s and 8.34 E-11 to 2.77 E-10 m^2/s for TD and HPD, respectively. The results were in good agreement with kaffir lime laves (Phoungchandang et al., 2008a) and white mulberry leaves (Phoungchandang et al., 2008b). Zogzas et al. (1996) reported that moisture diffusivities in foodstuff were in the range of 10E-11 to 10E-9 m^2/s and were increased with the increasing temperature of the drying air from 40 to 60°C.

Color value

The effect of drying and blanching treatment on color value of dried sliced carrots were also investigated. The results are presented in Table 3. At higher temperatures, the browning was greater. At 40°C, there was less browning and lower total color difference (ΔE^*) (Table 3). However, dried sliced carrots obtained from blanching treatment and dried at 40 °C in HPD showed the lowest color difference due to low drying temperature and short drying time of HPD (Phoungchandang et al., 2009) (Table 3). Phoungchandang (1986) reported that blanching could inhibit enzymatic browning. However, non enzymatic browning reaction was the main factor affecting color value of dried sliced carrots (Phoungchandang et al., 2009; Phoungchandang, 1986).

Rehydration ratio

The rehydration is important to determine the time required to attain the original fresh carrot condition prior to cooking. The rehydration ratio of blanching treatment and drying at temperature of 40°C in HPD was 13.88 which provided the highest rehydration ratio ($p \leq 0.05$). The low rehydration ratio could be due to the damage of cells due to high drying temperature (Phoungchandang et al., 2009) as shown in Table 3.

β-carotene content

The results revealed that HPD retained higher carotenoid content than TD because of short drying time. Moreover, low temperature of drying air also retained higher carotenoid content (Table 3).

The highest carotenoid remaining was 58.05% at drying temperature of at 40°C in HPD (Table 3). Many researchers also found that HPD and low drying temperature could retain higher active ingredients (Phoungchandang et al., 2009; Phoungchandang et al., 2008a; Phoungchandang et al., 2008b).

Conclusions

The desorption isotherms for sliced carrots were fitted to the Modified Chung-Pfost and Modified Henderson models for both $RH_e = f(X_e, T)$ and $X_e = f(RH_e, T)$, respectively. The drying data were fitted to the Modified Page model which gave two empirical drying parameters namely the drying constant, K and drying exponent, N. The drying constant increased with blanching treatment. HPD could reduce drying time. The drying constant in the Modified Page model was related to air temperature using Arrheniues model. Moisture diffusivities of blanching sliced carrots were higher than fresh sliced carrots. The effective moisture diffusivities were in the range of 6.39E-11 to 1.94E-10 and 8.34 E-11 to 2.77 E-10 m^2/s for TD and HPD, respectively. Quality evaluation by color value, rehydration ratio and β-carotene content showed the best quality for sliced carrots pretreated by blanching and dried at 40°C in HPD.

Nomenclature

a, b	empirical constant in drying models
A, B	empirical constant
C, C_1, C_2, C_3	empirical constant
D_{eff}	effective moisture diffusivity, m^2/s
K	drying constant, 1/min
L	half thickness of sliced carrot, m
n	number of data points
N	drying exponent
RH	relative humidity, decimal
R^2	coefficient of determination
t	time, min
T	temperature, °C
X	moisture content, % d.b.

Subscripts

e	equilibrium
o	initial
m	measured
p	predicted

References

Achariyaviriya, S., Soponronnarit, S. and Terdyothin, A. 2000. Mathematical model development and simulation of heat pump fruit dryer. **Drying Technol.** 18:479-491.

Alves-Filho, O. and Strommen, I. 1996. Application of heat pump in drying of biomaterials. **Drying Technol.** 14: 2061-2090.

Alves-Filho, O. Eikevik, T.M. and Goncharova-Alves, S.V. 2008. Single and multistage heat pump drying of protein. **Drying Technol.** 26(4): 470-475.

Alves-Filho, O., Eikevik, T.M. and Mulet, A. 2007. Kinetics and mass transfer during atomospheric freeze drying of red pepper. **Drying Technol.** 25 (7-8): 1156-1161.

Alves-Filho, O., Strommen, I. and Thorbergsen, E. 1997. Simulation model for heat pump dryer plants for fruit and roots. **Drying Technol.** 15: 1369-1398.

A.O.A.C. 2000. **Official method of analysis.** Association of Official Chemists, Arlington, V.A. 1298p.

Basu, S., Shivhare, U.S. and Mujumdar, A.S. 2006a. Models for sorption isotherms for foods: A review. **Drying Technol.** 24(8): 917-930.

Basu, S., Shivhare, U.S. and Mujumdar, A.S. 2006b. Models for sorption isotherms for foods: A review. **Drying Technol.** 24(12): 1705.

Basu, S., Shivhare, U.S. and Mujumdar, A.S. 2007. Moisture adsorption isotherms and glass transition temperature of xanthan gum. **Drying Technol.** 25(9): 1581-1586.

Boonnattakorn, R., Phoungchandang, S., Leenanon, B., Khajarern, S. and Khajarern, J. 2004. The comparative study of garlic powder processing by heated air and dehumidifier heat pump dryer. **Food J.** 34 (3): 248-260.

Chen, C.C. and Morey, R.V. 1989. Comparison of four EMC/ERH equations. Am. Soc. **Agric. Eng.** 32(3): 983-990.

Chua, K.J., Mujumdar, A.S., Hawlader, M.N.A., Chou, S.K. and Ho, J.C. 2001. Convective drying of agricultural products: Effect of continuous and stepwise change in drying air temperature. **Drying Technol.** 19: 1949-1960.

Chottanom, P. and Phoungchandang, S. 2005. The development of osmotically dehydrated mangoes using conventional drying and dehumidified drying. **Chem. Eng. Transac.** 6: 897-902.

Hawlader, M.N.A., Perena, C. and Tian, M. 2006. Comparison of the retention of 6 - gingerol in drying of ginger under modified atmosphere heat pump drying and other drying methods. **Drying Technol.** 24(1): 51-56.

Janjai, S., Bala, B.K. and Tohsing, K. 2006. Equilibrium moisture content and heat of sorption of longan (*Dimocarpus longan* Lour.). **Drying Technol.** 24(12): 1691-1696.

Kaur, D., Wani, A.A. and Sogi, D.S. 2006. Sorption isotherms and drying characteristics of tomato peel isolated from tomato pomace. **Drying Technol.** 24(11): 1515-1520.

Krupinska, B., Strommen, I. and Pakowski, Z. 2007. Modeling of sorption isotherms of various kinds of wood at different temperature conditions. **Drying Technol.** 25(9): 1463-1470.

Labuza, T.P. 1968. Sorption phenomena in foods. **Food Technol.** 22:15-24.

Ogura, H., Yamamoto, T. and Otsubo, Y. 2005. A control strategy for a chemical heat pump dryer. **Drying Technol.** 23 (6): 1189-1203.

Pal, U.S. and Khan, M.K. 2008. Calculation steps for design of different components of heat pump dryer under constant drying conditions. **Drying Technol.** 26(7): 864-872.

Phoungchandang, S. 1986. Development of a small scale processing system for green peas. Master degree thesis, Asian Institute of Technology, Bangkok. 76p.

Phoungchandang, S. 2008. Simulation model for heat pump-assisted dehumified air drying for some herbs. **World J. Agric. Sci.** 5(2): 138-142.

Phoungchandang, S., Nongsang, S. and Sanchai, P. 2009. The development of ginger drying using dry drying, heat pump dehumidified drying and mixed mode solar drying. **Drying Techol.** 27(10): 1123-1131.

Phoungchandang, S., Sanchai, P. and Chanchotikul, K. 2003. The Development of dehumidifying dryer for Thai herb drying (Kaprao leaves). **Food J.** 33(2): 146-155.

Phoungchandang, S., Srinukroh, W. and Leenanon, B. 2008a. Kaffir lime leaf (*Citrus hystric* DC.) drying using tray and heat pump dehumidified drying. **Drying Technol.** 26(12): 1602-1609.

Phoungchandang, S., Tochip, L. and Srijesdaruk, V. 2008b. White mulberry leaf drying by tray and heat pump dehumidified dryers. **World J. Agric. Sci.** 4(5): 844-851.

Phoungchandang, S. and Woods, J.L. 2000. Moisture diffusion and desorption isothems for banana. **J. Food Sci.** 64(4): 651-657.

Prasertsan, S. and Saensabai, P. 1998. Heat pump drying of agricultural materials. **Drying Technol.** 16: 235-250.

Rahman, S.M.A., Islam, M.R. and Mujumdar, A.S. 2007. A study of couple heat and mass transfer in composite food products during convective drying. **Drying Technol.** 25(7-8): 1359-1368.

Saensabai, P. and Prasertsan, S. 2007. Condenser coil optimization and component matching of heat pump dryer. **Drying Technol.** 25(9): 1571-1580.

Sun, D.W. and Woods, J.L. 1993. The moisture content/relative humidity relationship for wheat-a review. **Drying Technol.** 11(7): 1523-1551.

Sun, D.W. and Woods, J.L. 1994. The selection of sorption isotherm equations for wheat based on the fitting of available data I. **Stored Product Res.** 30(1): 27-43.

Van den Berg, H., Faulks, R., Fernando, G.H., Hirschberg, J., Olmedilla, B. and Sandmann, G. 2000. The potential for the improvement of carotenoid levels in food and the likely systemic effects. **J. Sci. Food Agric.** 80: 880-912.

Zogzas, N.P., Marculiz, Z.B. and Marinos-Kouris, D. 1996. Moisture diffusivity data complilation in foodstuft. **Drying Technol.** 14(10): 2225-2253.

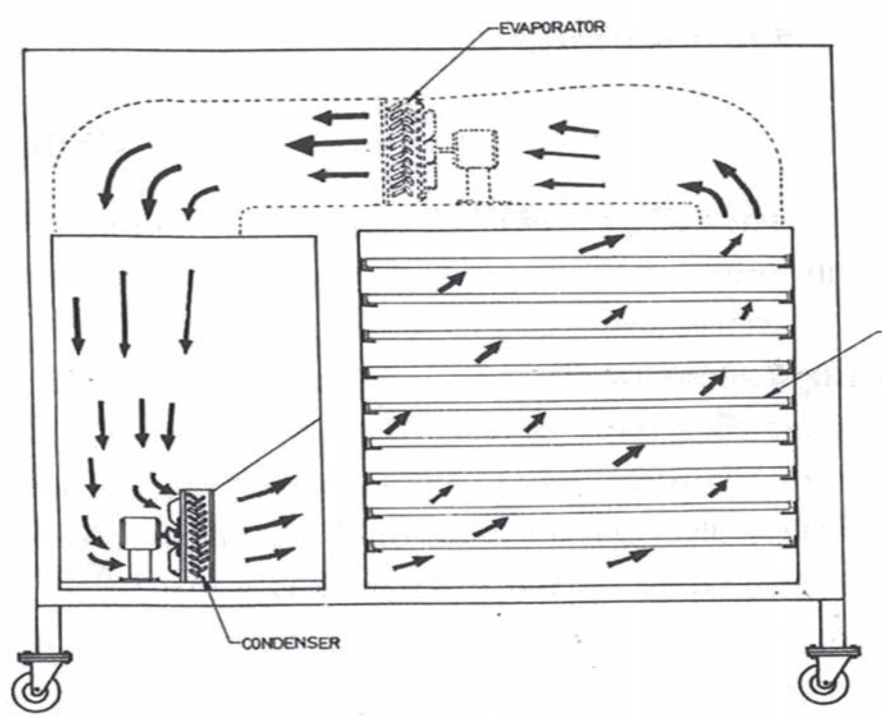

Figure 1. Heat pump-dehumidified dryer (Phoungchandang et al., 2003)

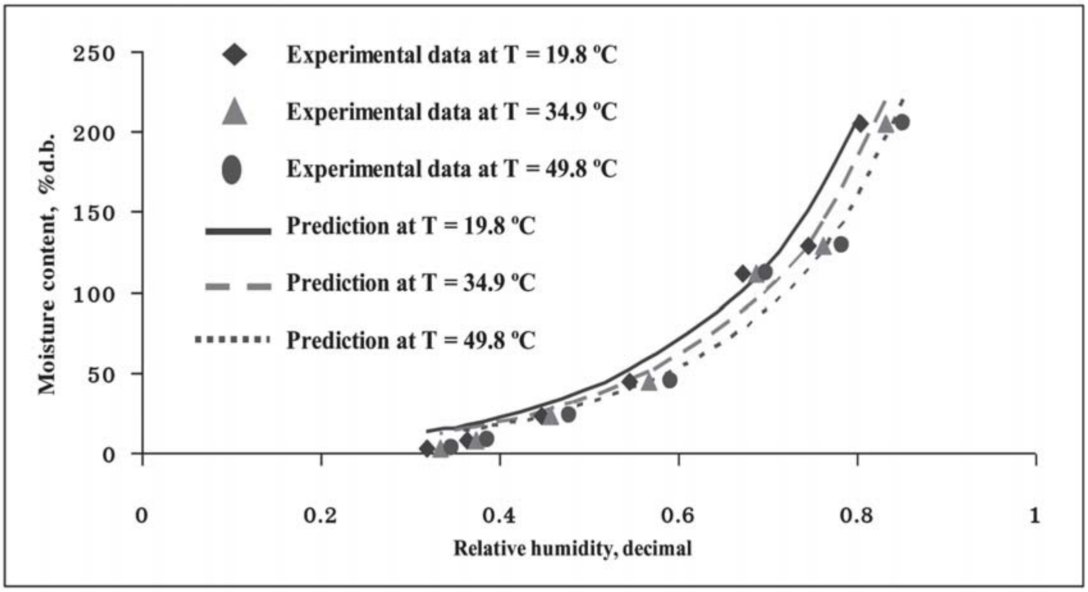

Figure 2. Desorption isotherms at 19.8, 34.9 and 49.8°C as predicted using the fitted Modified Henderson model for sliced carrots compared with the observed experimental data.

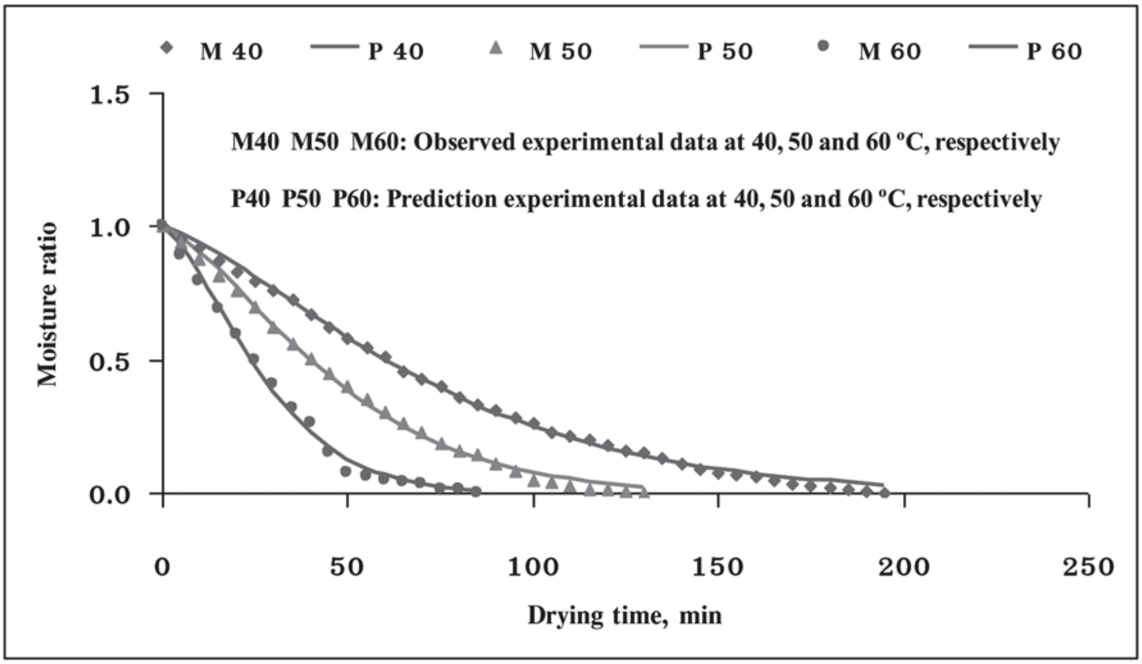

Figure 3. Moisture ratio of blanched sliced carrots predicted from the Modified Page model compared with the observed experimental data from TD.

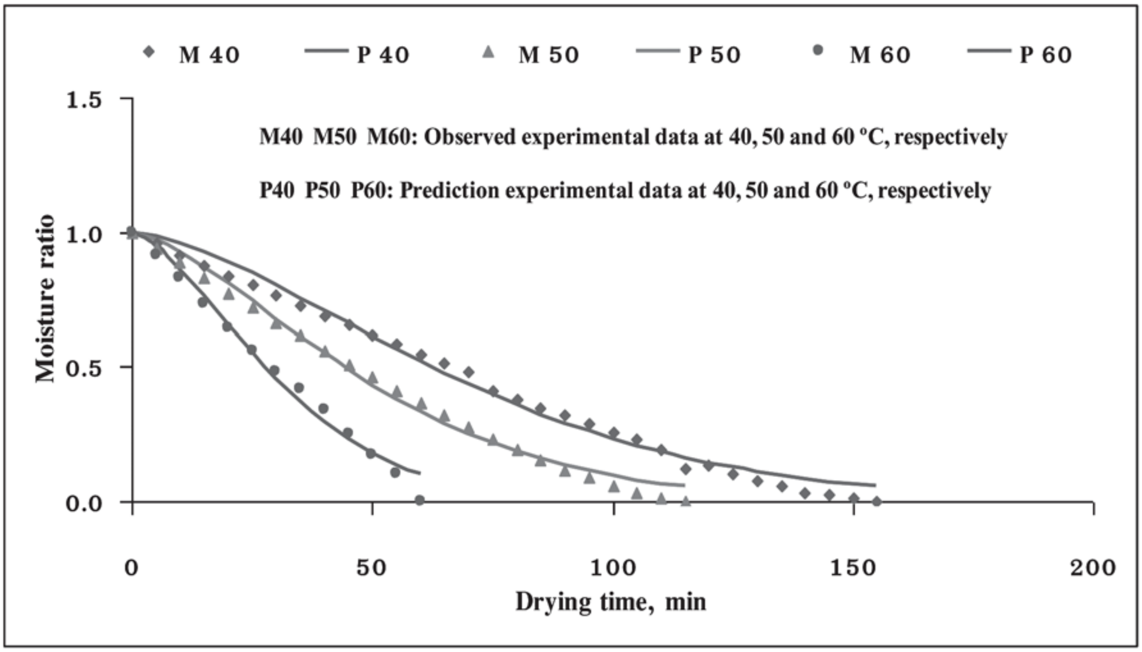

Figure 4. Moisture ratio of blanched sliced carrots predicted from the Modified Page model compared with the observed experimental data from HPD.

Table 1. Constants of desorption isotherms for sliced carrots

Model	C_1	C_2	C_3	SEE (%d.b.)	R^2
$RH_e=f(X_e,T)$					
Modified Oswin	27.3095	-0.2031	0.5232	0.0020	0.9741
Modified Hasey	0.8263	-0.0037	0.3699	0.0029	0.9961
Modified Henderson	0.0008	248.6316	0.3693	0.0012	0.9402
Modified Chung-Pfost	291.8905	252.6195	0.0095	0.0011	0.9934
$X_e=f(RH_e,T)$					
Modified Owin	49.2942	-0.3740	0.9011	10.3394	0.9787
Modified Halsey	2.6365	-0.0085	0.7515	13.7193	0.9959
Modified Henderson	0.0005	183.5886	0.5182	6.3854	0.9665
Modified Chung-Pfost	216.2021	180.4076	0.0091	10.8940	0.9960

Table 2. Results of statistical analysis on the modeling of sliced carrots

Dryer	Pre-drying treatment	Temp (°C)	R^2				SEE (%d.b.)			
			NT	HP	MP	ZR	NT	HP	MP	ZR
TD	Fresh	40	0.9762	0.9827	0.9977	0.9734	0.0022	0.0015	0.0002	0.0024
		50	0.9712	0.9802	0.9966	0.9730	0.0028	0.0020	0.0003	0.0026
		60	0.9495	0.9725	0.9897	0.9501	0.0036	0.0027	0.0010	0.0050
	Blanching	40	0.9713	0.9823	0.9972	0.9793	0.0027	0.0017	0.0003	0.0019
		50	0.9458	0.9589	0.9910	0.9467	0.0055	0.0042	0.0009	0.0054
		60	0.9330	0.9452	0.9825	0.9333	0.0068	0.0056	0.0018	0.0068
HPD	Fresh	40	0.9721	0.9825	0.9963	0.9755	0.0027	0.0017	0.0003	0.0023
		50	0.9672	0.9814	0.9975	0.9736	0.0033	0.0017	0.0002	0.0025
		60	0.9650	0.9724	0.9939	0.9650	0.0035	0.0028	0.0006	0.0035
	Blanching	40	0.9692	0.9796	0.9975	0.9717	0.0030	0.0020	0.0002	0.0027
		50	0.9634	0.9745	0.9974	0.9644	0.0038	0.0027	0.0003	0.0037
		60	0.9420	0.9523	0.9860	0.9421	0.0062	0.0051	0.0015	0.0061

Table 3. Drying time, RH, X_e, K and N values obtained from the Modified Page model, D_{eff}, ΔE^*, rehydration ratio and carotenoid content

Dryer	Predrying treatment	Temp (°C)	Drying time	RH (decimal)	X_e (%.d.b.)	K (min^{-1})	N	D_{eff} (m^2/s)	R^2	ΔE^*	Rehydration	β-carotene content (mg/100g) (d.b.)
TD	Fresh	40	230	0.2723	9.0457	0.0111	1.3326	6.39E-11	0.8874	7.86^{i}	11.58^{cd}	3260.05 ± 0.23^{d}
		50	165	0.2056	3.7030	0.0167	1.3481	9.86E-11	0.8817	15.11^{e}	8.30^{h}	2364.31 ± 0.70^{h}
		60	120	0.1571	1.9228	0.0197	1.3851	1.12E-10	0.8769	23.53^{a}	5.79^{l}	1679.51 ± 0.53^{k}
	Blanching	40	195	0.2590	6.7082	0.0121	1.3593	7.26E-11	0.8822	6.59^{k}	12.78^{bc}	3905.69 ± 5.02^{b}
		50	130	0.1797	2.7717	0.0177	1.4206	1.12E-10	0.8767	13.88^{g}	9.94^{f}	3095.36 ± 0.05^{f}
		60	80	0.1225	1.1455	0.0284	1.4846	1.94E-10	0.8797	20.31^{c}	7.44^{j}	2069.01 ± 1.16^{i}
HPD	Fresh	40	220	0.2741	7.6256	0.0125	1.3409	8.34E-11	0.8992	7.14^{j}	11.94^{c}	3336.58 ± 3.27^{c}
		50	140	0.1809	2.8114	0.0169	1.3790	1.12E-10	0.8789	13.95^{f}	8.91^{g}	2470.28 ± 1.59^{g}
		60	105	0.1385	1.4771	0.0199	1.3861	2.10E-10	0.8851	23.11^{b}	6.19^{k}	1778.09 ± 1.24^{j}
	Blanching	40	155	0.2344	5.3694	0.0127	1.3651	8.77E-11	0.8470	5.10^{l}	13.88^{a}	3919.29 ± 6.32^{a}
		50	115	0.1638	2.2767	0.0194	1.4225	1.85E-10	0.8460	12.72^{h}	10.46^{e}	3138.82 ± 5.50^{e}
		60	60	0.1159	1.0222	0.0329	1.5050	2.77E-10	0.8634	19.71^{d}	7.65^{i}	2068.23 ± 5.20^{i}
	Fresh											6751.42

Different superscripts in the same column mean that the values are significantly different ($p \leq 0.05$)

Table 4. Constants of Arrhenius model and equation (16)

Drying method		Constant			R^2	SEE (min^{-1})
		A	B	C		
Arrhenius model						
TD	Fresh	85.0635	2781.0840	-	0.9702	1.04E-06
	Blanching	30267.4679	4626.3806	-	0.9949	6.95E-07
HPD	Fresh	22.1173	2331.9829	-	0.9760	3.33E-07
	Blanching	189279.0001	5188.0521	-	0.9951	1.04E-06
Equation (16)						
TD	Fresh	0.9050	-0.1755	6.0431	1.0000	4.93E-32
	Blanching	1.2134	-0.1051	-1.1383	1.0000	7.40E-32
HPD	Fresh	4.9905	-1.0148	79.1184	0.9954	2.71E-06
	Blanching	0.6982	-0.2703	11.1346	0.9667	0.00E+00