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Determination of Sliced Pineapple Drying Characteristics in A Closed Loop Heat Pump Assisted Drying System

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ABSTRACT. Pineapple (*Ananascomosus*) slices were dried with the aid of a heat pump assisted dryer (HPD). During this process, air velocity was kept constant at 1m/s, while air temperatures were changed as 37°C, 40°C and 43°C. The drying air was also circulated by using an axial fan in a closed cycle and fresh air was not allowed into the system. The drying rate and drying time were significantly influenced by drying temperature. It was observed that drying temperatures had significant effects on the drying rate and drying time. During the conduct of the study, pineapple slices were dried at 37, 40 and 43°C for 465, 360 and 290 min, respectively. The specific moisture extraction ratio (SMER) values were observed to change as drying temperatures were changed. The drying rate curves indicated that the whole drying process occurred in the falling rate period. Seven well-known thin-layer models (Lewis, Henderson &Pabis, Logarithmic, Page, Midilli & Kucuk, Weibull and Aghbashlo et al.) were employed to make a prediction about drying kinetics through nonlinear regression analysis. The Midilli & Kucuk and Aghbashlo et al. models were consistent with the experimental data. Fick's second law of diffusion was used to determine the moisture diffusivity coefficient ranging from 3.78×10^{-9} to 6.57×10^{-9} m^2/s the each of the above mentioned temperatures. The dependence of effective diffusivity coefficient on temperature was defined by means a fan Arrhenius type equation. The activation energy of moisture diffusion was found to be 75.24kJ/mol.

Keywords: Heat pump, dryer, pineapple, drying, drying kinetics

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1. Introduction

The pineapple (*Ananascomosus*) is a tropical plant with an edible multiple fruit consisting of coalesced berries, also called pineapples (Morton 1987; Omolola et al. 2017). Pineapples can be consumed fresh, cooked, juiced, or preserved. Drying is one of the oldest methods of preserving agricultural products by using heat and mass transfer. It has become necessary because most fruits are highly perishable owing to their high moisture content and the need to make them available all year round and at locations where they are not produced. In addition to preservation, the reduced weight and bulk of dehydrated products decreases packaging, handling and transportation costs (Omolola et al. 2017). There are many investigations on hot air drying, vacuum drying, freezing drying and heat pump drying (HPD) systems to improve drying quality and energy efficiency. The HPD system is the most advanced system because of lowest energy consumption (Colak and Hepbasli, 2009; Filho et al. 1996). According to numerous studies, color and flavor quality of agricultural products dried by using HPD system were better than products dried by using conventional dryer with hot air (Strommen et al. 1994; Prasertsan et al. 1998; Soponronnarit et al. 1998; Teeboonma et al. 2003). There are many studies about dried agricultural products such as kiwi, avocado, mango, papaya, apple, bananas, pepper, mushroom, tomato, herbs ginseng, echinace, carrot etc. by using HPD system(Coşkun et al. 2017, Aktas and Kara, 2013; Juan et al. 2013; Aktas et al. 2012; Ceylan 2009;Aktas et al. 2009; Aghbashlo et al. 2009 ; Pal et al. 2008; Teeboonma et al. 2003; Chua et al. 2001; Phani and Greg, 2005; Queiroz et al. 2004; Achariyaviriya et al. 2000; Soponronnarit et al. 1998; etc.) can be given as examples.

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There are various studies about drying pineapple by using different drying methods including microwave-vacuum drying (Corrêa et al. 2011), hot-air drying (Agarry et al. 2013; Olanipekun 2015; Kingsly et al. 2009; Gujral et al. 2013; Ramallo and Mascheroni, 2012), and solar drying (Bala et al. 2003). But, there is no information in literature for drying of pineapple slices in the closed loop heat pump dryer. The purpose of this study was to investigate effect of drying air temperature on the drying behavior of pineapple slices, to fit the experimental data to seven thin-layer models, and to calculate the effective moisture diffusivity and activation energy of pineapple in the closed loop HPD system.

2. Materials and Methods

In this study, 600 g. pineapple slices with a thickness of 6 mm were dried employing a closed loop heat pump assisted dryer (HPD) system. A 5 gram sample of the pineapple slices were heated at 70°C for 18 min until the equilibrium moisture content was reached. The initial dry basis moisture content of the pineapple slices was measured to be 10.765 g water/g dry matter. The pineapple slices were dried until the moisture content reached 0.333 g water/g dry matter. The experiments were performed at 1 m/s constant air velocity and three different drying chamber temperatures (37, 40 and 43°C). HPD system is made up of a drying chamber, a heat pump, a circulating duct and a fan. Drying chamber has dimension of 0.60 m width, 0.60 m height and0.60 m length. The heat pump (HP) is composed of a compressor, a condenser, a metering device and two condensers. Refrigerant 134a is used in this system. During the process, the drying air was circulated in closed-loop by an axial fan and not allowed to let the fresh air in. In this system, firstly the drying air leaving from evaporator enters the internal condenser (E) where it absorbs heat from refrigerant and then enters the drying chamber (A) to dry the product. Second the humid and warm air leaving drying chamber (B) enters to evaporator to remove moisture (C). Third, dry and cold air leaving from evaporator (D) enters the internal condenser again to warm up. Thus the cycle continues. During the experiments, the drying chamber temperature was maintained at 37, 40 and 43°C using a thermostat which controlled two solenoid valves. One of them was placed at the by-pass line, while the other was placed at the liquid line, as seen in Fig. 1. When the air temperature in drying chamber reached the set value**,** the solenoid valve at the liquid line closed, the other at the by-pass line opened, so, the external condenser was also activated with the internal condenser. Measurement devices and their specifications are given in Table 2.

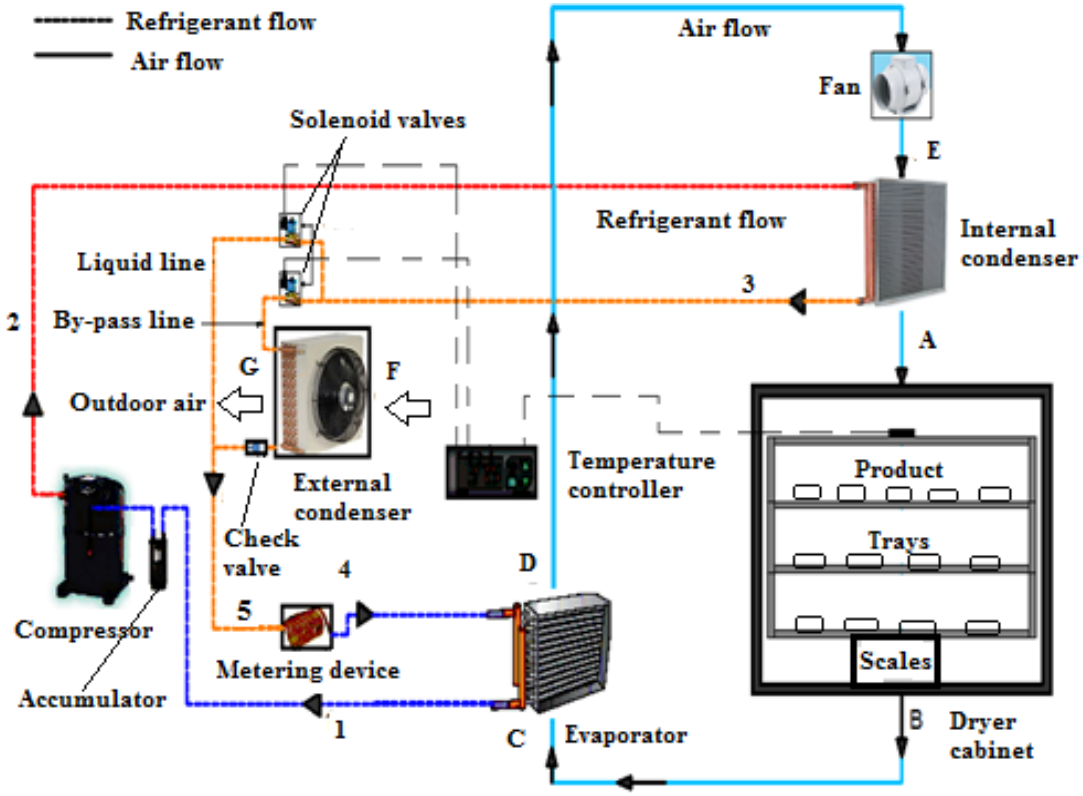

Fig. 1 Experimental set-up

Table 1.
Technical specifications of heat pump components

Components	*Specifications*
Evaporator	Aluminum finned tube, 2.78 m^2
Metering device (capillary tube)	1 meter length, 0.0015 meter diameter
Internal condenser	Aluminum finned tube, 3.60 m^2
External condenser	Aluminum finned tube, 1.56 m^2
Compressor	Rotary type, cylinder volume, 8.6 cm^3, nominal power 750 W.

Table 2.
Measurement devices

Measured quantities	*Measurement devices*	*Measurement ranges*	*Accuracies*
Product mass	Electronic scale	0-70 kg	±2 g
Air velocity	Rotating anemometer	0.1-10 m/s	±0.1 m/s
Air temperature in drying chamber	Electronic thermostat	(-50) – (+130)°C	±0.1°C
Temperature and relative humidity of air in air duct	Hygro-thermometer	0-100% (-40)- (+80)°C	±2% RH ±0.4°C
Refrigerant pressures	Electronic manifold	0-50 bar	±0.1 bar
Refrigerant temperatures	Data logging thermometer	(-40) – (+250)°C	±0.5°C
Power consumptions	Electrical power meter	150 -300 V	0.5 s/day

3. Analysis

3.1. Mathematical Modeling of HPD System

Performance of a dryer is commonly defined by specific moisture extraction ratio (SMER). It was calculated as follow,

$$SMER = \dot{m}_w / \dot{W}_{total} \quad (1)$$

Here, $\dot{m}_w$ is amount of evaporated water from product, $\dot{W}_{total}$ is total energy input, which includes energy consumptions of compressor, inlet and outlet fans. Heat pump performance is also defined by coefficient of performance (COP). It was calculated as follow,

$$COP = \dot{Q}_a / \dot{W}_{total} \quad (2)$$

Here, $\dot{Q}_a$ is amount of heat transferred to drying air.

3.2. Mathematical Modeling of the Drying Curves

In this study, seven common thin-layer drying models which is given in Table 3 were used to consistent with experimental data obtained at three different air temperatures of 37, 40 and 43°C to describe drying characteristics of pineapple.
The moisture content of pineapple slices was calculated by eq. (3)

$$M = (W_i - W_d)/(W_d) \quad (3)$$

Moisture ratio of pineapple slices was calculated by eq. (4)

$$MR = (M_t - M_e)/(M_0 - M_e) \quad (4)$$

MR was simplified to M_t/M_0 instead of $(M_t - M_e)/(M_0 - M_e)$. Because the values of M_e are too small to compared to M_t or M_0 for a long period of time (Olimat 2017).

Table 3.
Drying models

Model names	Moisture Ratio (MR)
Henderson &Pabis	$MR = a\exp(-kt)$
Lewis	$MR = \exp(-kt)$
Page	$MR = \exp(-kt^n)$
Logarithmic	$MR = a\exp(-kt) + c$
Aghbashlo et al.	$MR = \exp[-(at)/(1+bt)]$
Midilli&Kucuk	$MR = a\exp(-kt^n) + bt$
Weibull	$MR = \exp\left(-\left(\frac{t}{b}\right)^a\right)$

a, b, c, n, k,: empirical constants and coefficients in drying models

3.3. Data Analysis

The statistical analysis of the experimental data was performed by Statistica 8.0.550 sotfware (StatSoft Inc., Tulsa, OK, USA). Non-linear regression procedure based on the Levenberg-Marquardt algorithm was used to predict the parameters of the models. To select most suitable drying model, some useful parameters, such as coefficient of determination (R^2), reduced chi-square (χ^2) and root mean square error (*RMSE*) were used. These parameters were defined by using following equations:

$$R^2 = 1 - \left[\sum \left(MR_{pre,i} - MR_{\exp,i} \right)^2 \right] / \left[\sum_{i=1}^{N} \left(\overline{MR}_{pre} - MR_{\exp,i} \right)^2 \right] \quad (5)$$

$$\chi^2 = \sum_{i=1}^{N} \left(MR_{\exp,i} - MR_{pre,i} \right)^2 / (N - z) \quad (6)$$

$$RMSE = \left[\frac{1}{N} \sum_{i=1}^{N} (MR_{pre,i} - MR_{exp,i})^2 \right]^{1/2} \quad (7)$$

Higher R^2 and lower χ^2 and *RMSE* values indicate good fitness of the established model (Akpinar and Toraman, 2016).

3.4. Determination of Effective Moisture Diffusivity and Activation Energy

Fick's second law of diffusion equation, represented as a mass-diffusion equation for drying agricultural products in a falling rate period as shown in Eq. (8)

$$\frac{\partial M}{\partial t} = \nabla \left[D_{eff} (\nabla M) \right] \quad (8)$$

Diffusion equation (Eq. 9) for slab geometry was solved by (Crank 1975), assuming uniform initial moisture distribution, constant diffusivity with negligible shrinkage and resistance:

$$MR = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} exp\left(- \frac{(2n+1)^2 \pi^2 D_{eff} t}{4L^2} \right) \quad (9)$$

When the time increased, only the first term can be used to estimate the drying rate (n=0), and then Eq. (10) converges into:

$$MR = \frac{8}{\pi^2} \exp \left[(-\pi^2 D_{eff} t) / (4L^2) \right] \quad (10)$$

The values of effective moisture diffusivity (D_{eff}) are determined by the slope of a straight line when ln (*MR*) versus time is plotted from eq. (11):

$$Slope = (\pi^2 D_{eff}) / (4L^2) \quad (11)$$

An Arrhenius type equation is generally used to model the effect of temperature on the effective moisture diffusivity:

$$D_{eff} = D_0 \exp \left[(-E_a) / (R(T + 273.15)) \right] \quad (12)$$

4. Results and Discussion

4.1. System Performance

Experiments were performed at 23.1°C outdoor temperature and 50% relative humidity conditions. At the end of the experiments mean COP and SMER values obtained represented in Table 4. The higher SMER values were obtained during about the first two hours, than SMER values decreased due to drying rate. The highest SMER value was obtained as 0.264 kg/kWh at drying air temperature of 43°C, while the lowest value was obtained as 0.218 kg/kWh at 37°C.

It is clear that increase in drying air temperature caused a decrease in drying time. The drying time of samples decreased from 465 min. to 290 min.as the air temperature was increased from 37°C to 43°C. These results are consistent with the results of Marcel et al. (2013) and Olanipekun (2015) for pineapple slices.

Table 4.
Mean COP and SMER values

Drying Temperature (°C)	COP_{mean}	$SMER_{mean}$ (kg/kWh)
37	2.988	0.218
40	3.114	0.230
43	3.259	0.264

4.2. Drying Curves

Changing of moisture content with drying time for pineapple slices at 37, 40 and 43°C is shown in Fig. 2.

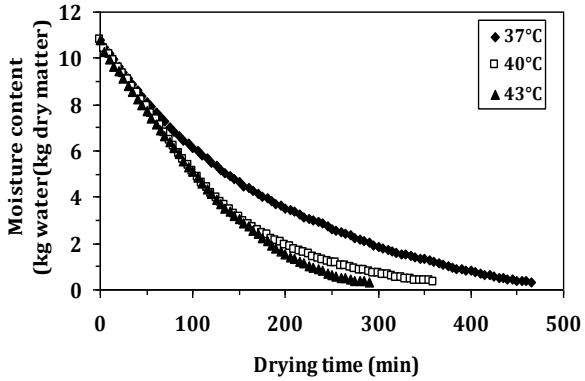

Fig. 2 Drying curves of pineapple slices

4.3. Evaluation of Drying Models

Non-linear regression analysis was applied in accordance with seven drying models listed in Table 5. The best mathematical model was chosen to fit the experimental data based on maximized R^2 and minimized χ^2 and *RMSE*. The results of statistical analysis for several models were presented in Table 5.

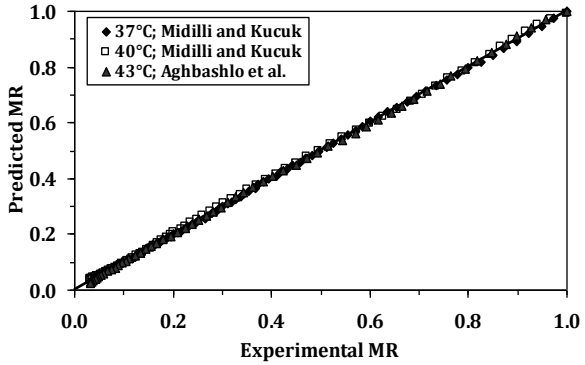

Fig. 3 The experimental MR versus the predicted MR for selected models

At the end of analysis, it was shown that the predicted variables are consistent with the experimental results for some models. Especially, the model of Midilli & Kucuk shows good agreement at drying air temperature of 37 and 40°C, while the model of Aghbashlo et al. (2009) indicates good agreement at 43°C, so these models could be used satisfactorily to estimate the drying kinetics of pineapple. The R^2, $\chi^2$and RMSE values for the selected models change between 0.9976 and 0.9998, 0.000009 and 0.000203 and 0.024175 and 0.101808, respectively. Fig.3 shows the experimental data with the predicted ones using different models for pineapple slices at 37, 40 and 43°C.

Table 5.
Statistical values of thin-layer drying of pineapple slices

T	Model name	R^2	χ^2	RMSE
37°C	Lewis	0.9963	0.000264	0.126891
	Henderson & Pabis	0.9967	0.000237	0.117119
	Logarithmic	0.9995	0.000032	0.047444
	Page	0.9977	0.000162	0.098458
	Weibull	0.9978	0.000162	0.098457
	Midilli & Kucuk	0.9998	0.000009	0.024175
	Aghbashlo et al.	0.9987	0.000091	0.076644
40°C	Lewis	0.9875	0.001053	0.237945
	Henderson & Pabis	0.9936	0.000549	0.163617
	Logarithmic	0.9969	0.000268	0.109637
	Page	0.9995	0.000036	0.041289
	Weibull	0.9995	0.000035	0.041289
	Midilli & Kucuk	0.9997	0.000026	0.037088
	Aghbashlo et al.	0.9976	0.000203	0.101808
43°C	Lewis	0.9768	0.001718	0.277698
	Henderson & Pabis	0.9834	0.001251	0.236054
	Logarithmic	0.9980	0.000146	0.077452
	Page	0.9970	0.000224	0.098827
	Weibull	0.9970	0.000224	0.098828
	Midilli & Kucuk	0.9994	0.000040	0.035910
	Aghbashlo et al.	0.9997	0.000019	0.025291

4.4. Effective Moisture Diffusivity and Activation Energy

The effective moisture diffusivity (D_{eff}) of pineapple slices was calculated by using Eq. (12) and it was obtained at drying air temperature of 37, 40 and 43°C as 3.78×10^{-9}, 5.37×10^{-9} and 6.57×10^{-9} m²/s, respectively. As expected that the D_{eff} values were observed rising depending on increase of drying air temperature. Increase in drying air temperature may be cause in greater absorption of moisture, that increases the moisture gradient between the product and ambient and that brings about an increase in the effective moisture diffusivity. Results obtained from this study for pineapple slices are similar to results of Olenipekun et al. (2015). The D_{eff} values must be within the normal range 10^{-12} - 10^{-8} m²/s for drying of food materials (Zogzas et al. 1996). D_{eff} values for pineapple slices obtained from this study are close to the values of 6.64×10^{-7} to 12.93×10^{-7} m²/s reported by Gujral et al. (2013) at different air temperatures. The differences between the results may be because of the structure of composition, shape and initial moisture content, besides the drying temperature, pre-treatments, and drying equipment. To calculate activation energy, a graph was plotted $\ln(D_{eff})$ versus (1/(T+273.15)) as seen in Fig.4. The effect of temperature on D_{eff} of the samples with following coefficients was determined by Eq. (13):

$$D_{eff} = 1.823\times10^{4}\exp\left[-(9050.6)/((T+273.15)\right] \quad (R^2: 0.9783) \qquad (13)$$

The activation energy of pineapple was calculated as75.24kJ/mol by using Eq. (14).This value is in the range of 12.7-110 kJ/mol for various foods reported by Zogzas et al. (1996). The similar value is proposed in the literature for drying of pineapple by Olanipekun et al (2015).

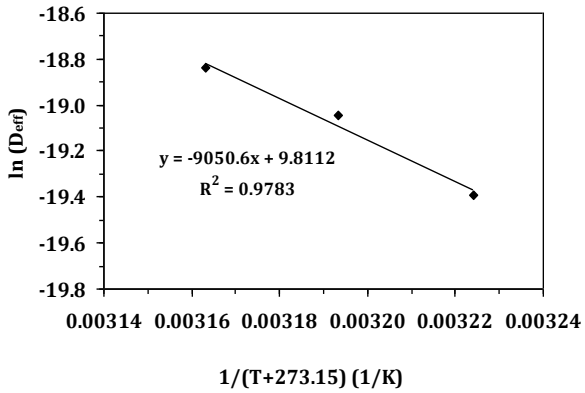

Fig. 4 Arrhenius-type relationship between effective moisture diffusivity and drying air temperature

5. Conclusions

Drying characteristics of pineapple slices dried by a closed loop HPD system at drying air temperature of 37, 40 and 43°C were examined. Seven thin-layer drying models were applied and fitted to the experimental data to determine the drying kinetics of pineapple slices. Drying by a heat pump assisted dryer should be at as high a drying temperature as possible. Because, higher COP and SMER values were obtained at higher drying air temperatures. According to the results of regression analysis, the experimental data were well predicted by the Midilli & Kucuk and Aghbashlo et al. models. D_{eff} values of pineapple slices were obtained as the range of 3.78×10^{-9} to 6.57×10^{-9} m²/s. Activation energy of pineapple was found as 75.24 kJ/mol. It is clearly seen that these results agree with data reported in literature.

Nomenclature

HPD	heat pump drying,
SMER	specific moisture extraction ratio,

$\dot{m}_w$	amount of evaporated water from product,
M	moisture content (g water/g dry matter),
COP	coefficient of performance,
$\dot{Q}_a$	amount of heat transferred to drying air,
W_i	weight of sample (g),
$\dot{W}_{total}$	total energy input,
W_i	initial matter content of sample (g),
W_d	dry matter content of sample (g),
M_0	initial moisture content (g water/g dry matter),
M_e	equilibrium moisture content (g water/g dry matter),
M_t	the moisture content at t time (g water/g dry matter),
t	drying time (min),
T	temperature (°C)
R^2	correlation index,
X^2	reduced chi-square,
RMSE	root mean square error,
a, b, c, k, n	constants in the drying models,
$MR_{exp,i}$	experimental dimensionless moisture ratios,
$MR_{pre,i}$	predicted dimensionless moisture ratios,
N	number of observations,
Z	number of constants,
D_{eff}	effective moisture diffusivity (m^2/s),
L	the half-thickness of the slab in samples (m),
n	positive integer,
D_0	pre-exponential factor (m^2/s),
E_a	activation energy (kJ/mol),
R	universal gas constant (kJ/(mol×K)),
T	temperature (°C),

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