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Intermittent Hot Air, Dehumidified Air, Heat Pump and Convective Cum Vacuum Microwave Drying Characteristics and Models

***Chung Lim Law*[1]**
***Chien Hwa Chong*[1]**
***Adam Figiel*[2]**
[1]*Faculty of Chemical and Environmental Engineering, The University of Nottingham, Malaysia Campus, Broga Road, 43500 Semenyih, Selangor Darul Ehsan, Malaysia.*
[2]*Institute of Agricultural Engineering, Wroclaw University of Environmental and Life Sciences, Chelmonskiego 37/41 Street,Wroclaw 51-630, Poland.*
**E-mail:* Chung-Lim.Law@nottingham.edu.my

An intermittent hot air dehumidified air dryer, a heat pump dryer and a convective vacuum microwave dryer was designed and manufactured to dried fruits product. Fresh apple, pear, ciku, papaya and mango were chosen as raw materials. The decreased of moisture ratio with drying time were modeled using semi-empirical Page equation. This model gave excellent fit for all experimental data with coefficient of determination higher than 0.9882. In addition, drying characteristics of fruits dried using convective vacuum microwave (C/VM), cyclic temperature profile (CTP), step-up temperature profile (STP) and heat pump (HP) dryers can be obtained from the analysis of model parameters. Drying characteristics versus moisture content curve were used to verify the parameter asymptotic value. Drying characteristics exhibited by various fruit samples in this study were first falling rate periods, second falling rate periods, increasing rate periods, constant rate periods and initial transient periods depending on the application of processing and tempering. The application of convective cum vacuum microwave (C/VM) in drying of fruits gave the shortest drying time compared to other drying methods. The effective diffusivity value obtained by C/VM was between 7.08 x 10^{-8} to 4.30 x 10^{-6} m/min, which is relatively high compared to fruits dried using other drying methods (2.07x 10^{-8} to 5.93 x 10^{-8} m2/min). The results revealed that the drying time for fruits undergone C/VM drying were 50% shorter compared to samples undergone CTP, STP and HP drying. Total drying time needed was between 310 to 490 minutes for drying of selected fruits using C/VM dryer.

Keywords: heat pump, intermittent hot air dehumidified air, convective cum vacuum microwave, drying characteristics, effective diffusivity

INTRODUCTION

In this study, hybrid or advance drying techniques, viz. intermittent hot air dehumidified air, heat pump and combined convective vacuum microwave drying method were used for drying of fruits. Drying characteristics of each drying methods in drying of different fruits were discussed. It is hypothesized that the application of intermittent drying techniques may increase the moisture removal from interior to the surface and evaporation by applying inactive drying condition, which is commonly known as tempering period. It is useful for rapid internal moisture diffusion coupled with active drying where drying mediums such as hot air dehumidified air or superheated steam is used. This drying methods can produce dried fruits with better quality product also is part of the significance of intermittent drying. It has been reported that intermittent drying could produce better product quality in drying of guava, banana and potato (Chua et al. 2000). Further, the used of C/VM drying methods also can reduce the processing time because of large vapor pressure differential between the middle and the surface of the material which allows rapid removal of internal moisture, whereas microwaves stimulate vibration of water (resulting in internal heat generation) by penetrating through the entire samples.

In this study, two stage drying, advance and intermittent drying methods have been used to dry five selected fruits. In addition, the combined two stage drying techniques in reducing the processing time was presented and discussed in this study. Furthermore, drying model parameters with physical meaning were discussed. These parameters are going to be used for estimate the effective diffusivity values.

MATERIALS AND METHODS

Materials

Fresh samples e.g., apple (*Malus domestica*), pear (*Pyrus pyrifolia*), ciku (*Manilkara zapota*), papaya (*Carica papaya*) and mango (*Mangifera indica*) were purchased from a local fruit supplier (Semenyih, Selangor, Malaysia, Latitude 20 57′ °N and Longitude 1010 50′6°E. The apple, pear, papaya and mango were cut into dimension of 15 mm cubic using a stainless steel knife. The ciku was cut into rectangular prism with Length, width and height of 0.05, 0.01 and 0.015 (m), respectively.

Methods

Intermittent hot air dehumidified air dryer (CTP and STP), a heat pump dryer (HP) and a convective vacuum microwave drying (C/VM).

Drying models

The moisture ratio was determined from the equation (1):

$$M_R = \frac{M_{(t)} - M_e}{M_0 - M_e} \quad (1)$$

where $M(t)$ denotes moisture content after drying time t, Me stands for equilibrium moisture content, and $M0$ is initial moisture. The equilibrium moisture content Me was determined at the final stage of drying as an asymptotic value of the function fit to the experimental points using Table Curve 2D Windows v2.03. Drying kinetics consisted of one, two or three periods despite of the method applied for fruit samples dehydration. Convective pre-drying was divided into two periods. The first one was described using linear equation (2) and the second one by an exponential equation (3):

$$M_R = a - b.t \quad (2)$$

$$M_R = ae^{-\frac{t}{b}} \quad (3)$$

VM finish drying had also exponential character. VM finish drying took place in the third period of combined C/VM drying.

Cyclic temperature profile (CTP) drying was divided into three periods: exponential – linear – exponential, while step-up temperature (STP) drying consisted of two periods: linear – exponential. VHP drying kinetics was described in one period of drying using a two – term exponential model (4):

$$M_R = ae^{-\frac{t}{b}} + ce^{-\frac{t}{d}} \quad (4)$$

All equations 2, 3 and 4 were fit to the experimental points at the highest value of determination coefficient, r^2.

The values of effective diffusion, D_{ef} for drying of apple, pear, papaya and mango were determined at the falling rate periods of drying from the equation (5):

$$D_{ef} = \frac{L^2}{b \cdot 3\pi^2} \quad (5)$$

Where:

D_{ef} = Effective diffusion coefficient (m^2.min^{-1})
L = Size of cube sample (m)
b = Parameter of drying kinetics equation (min)

$$D_{ef} = \frac{4}{b \cdot \pi^2 \left[\frac{1}{\left(\frac{L}{2}\right)^2} + \frac{1}{\left(\frac{W}{2}\right)^2} + \frac{1}{\left(\frac{H}{2}\right)^2} \right]} \quad (6)$$

Where:

D_{ef} = Effective diffusion coefficient (m^2.min^{-1})
L = Length of the sample (m)
W = Width of the sample (m)
H = Height of the sample
b = Parameter of drying kinetics equation (min)

RESULTS AND DISCUSSION

Drying characteristics and drying kinetics

Fig. 1 shows the drying characteristics of fruits dried by using different drying methods viz., C/VM, STP, CTP and HP. It is noticeable that the drying rate curves have a few critical moisture content points. These results in the existence of various drying periods namely initial transient period, increasing rate period and multiple distinctive falling rate periods throughout the drying process. An obvious inflection point can be clearly seen from the curve that dried by the C/VM methods because of two stages drying. An extremely high increasing rate period can be seen from the graph at the final stage of VM drying. A great increment of drying rates during VM drying was because of rapid removal of water from the internal structure of fruits by the microwave energy. In convective method hot air transfers energy to the surface of fruit cube and in the same time absorbs water from the surface. The gradients of temperature and water diffusion are opposite. This creates non-uniform distribution of moisture inside the cube. An external layer composed of well dried cells coats internal part with higher moisture content. In VM method the difference in moisture content between the external and internal parts of fruit cube is lower since water diffusion and temperature gradients are corresponded. This is because of internal heating provided by microwaves. In combined method C/VM convective pre-drying is necessary to remove large amount of water at satisfied drying rate typical for the first drying period. The non-uniform distribution of moisture inside the cube created by convective pre-drying enhances the process of VM finish drying. During VM drying the energy of microwaves is absorbed by water located in the internal part of pre-dried cube. This creates a relatively large vapor pressure in the middle of the material, allowing rapid transfer of moisture to the surrounding vacuum and preventing structural collapse. This process, well-known as the puffing phenomenon, creates a porous texture of the food and in this way it reduces its density (Sham et al., 2001). Additionally the capacity of vacuum pump can be lower because the excess of water was removed during convective pre-drying.

For heat pump drying, the drying kinetics of fruits undergone HP drying gave highest drying rates value at the initial stage of drying compared to other drying methods. During HP drying, the samples temperature and chamber relative humidity were as low as 36°C and 18%, respectively. Initial drying rate is relatively high compared to other drying methods. It is because of the low relative humidity. During drying of green sweet pepper, Pal et al. (2008) found that relative humidity is the prominent factor during initial stage of drying. This is because of high moisture gradient between the surface and environment. Referring to the later stage of HP drying curve, the drying rates were lower compared to others. At the later stage of HP drying, temperature acts as the main driving force for moisture diffusion.

At the initial stage of drying, drying rates of fruits undergone STP drying is very low because of the cold air supplied to the samples. The cold air temperature and relative humidity were about 10°C and 68%, respectively. When hot air was channeled to the samples, a significant increased of drying rate can be seen from Fig. 1. Bulk moisture removal effect occurred because of the application of hot air. During

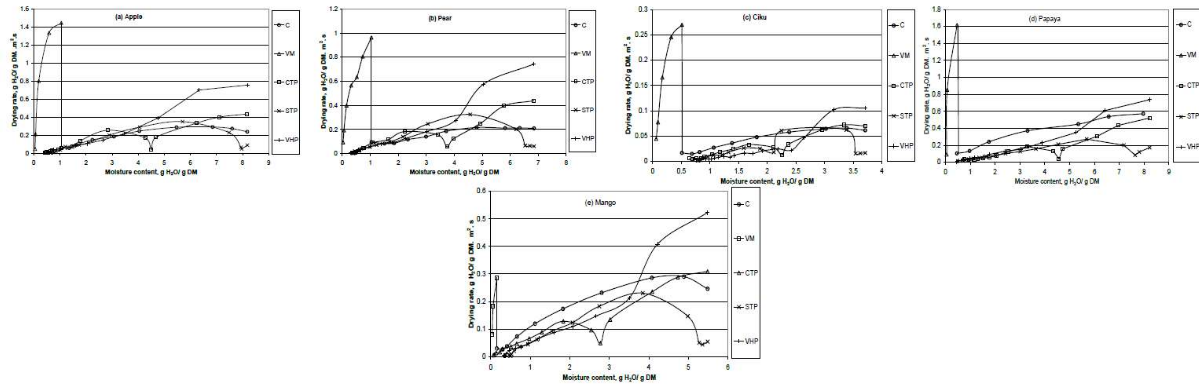

Figure 1. Drying rate versus moisture content for apple, pear, ciku, papaya and mango undergone convective vacuum microwave (C/VM), cyclic temperature profile (CTP), step-up temperature profile (STP) and heat pump (HP) drying.

Table 1. Parameters (*a*, *b*, *c*, *d*) of drying models and effective diffusion coefficients Def (m2 min-1) for fruits dried by different methods.

Drying method	Fruit	I				II				III			
C/VM		$M_R = a - b \cdot t$				$M_R = a \cdot e^{-\frac{t}{b}}$				$M_R = a \cdot e^{-\frac{t}{b}}$			
		a	B $x10^3$	r^2		a	b	r^2	D_{ef} $x10^8$	a	b	r^2	D_{ef} $x10^6$
	Apple	1.007	2.83	0.9994		0.6596	215.0	0.9979	3.522	0.1310	5.315	0.9846	1.431
	Pear	1.002	2.54	0.9998		0.6988	250.5	0.9983	3.037	0.1571	9.336	0.9822	0.8148
	Ciku	1.000	2.99	0.9994		0.6378	230.3	0.9988	2.967	0.1369	7.440	0.9953	0.9183
	Papaya	0.9652	5.30	0.9987		0.6604	107.4	0.9968	7.083	0.0564	1.768	0.984	4.302
	Mango	1.003	4.12	0.9977		0.5175	128.9	0.9989	5.901	0.0280	4.8905	0.9909	1.555
CTP		$M_R = a \cdot e^{-\frac{t}{b}}$				$M_R = a - b \cdot t$				$M_R = a \cdot e^{-\frac{t}{b}}$			
		a	b	r^2	D_{ef} $x10^8$	a	B $x10^4$	r^2		a	B	r^2	D_{ef} $x10^8$
	Apple	1.002	201.2	0.9997	3.781	0.5488	4.44	0.9994		0.4910	131.6	0.9954	5.780
	Pear	0.9848	198.2	0.9882	3.838	0.5576	7.11	0.9885		0.4720	128.2	0.9983	5.934
	Ciku	1.0059	211.2	0.9987	3.235	0.5670	7.10	0.9890		0.4817	186.1	0.9988	3.671
	Papaya	0.9902	186.7	0.9920	4.074	0.5285	4.20	0.9885		0.4730	178.9	0.9987	4.252
	Mango	1.001	201.5	0.9999	3.755	0.5502	7.30	0.9998		0.4658	178.0	0.9988	4.273
STP		$M_R = a - b \cdot t$				$M_R = a \cdot e^{-\frac{t}{b}}$							
		a	B x 10^4	r^2		a	b	r^2	D_{ef} $x10^8$				
	Apple	1.9998	7.42	0.9901		0.9259	169.9	0.9980	4.477				
	Pear	1.001	8.11	0.9996		0.9110	162.9	0.9987	4.670				
	Ciku	0.9993	9.05	0.9998		0.8845	211.1	0.9760	3.237				
	Papaya	0.9899	10.4	0.9697		0.8656	250.3	0.9998	3.039				
	Mango	1.000	7.99	0.9919		0.9175	180.0	0.9986	4.226				
HP		$M_R = a \cdot e^{-\frac{t}{b}} + a \cdot c^{-\frac{t}{d}}$											
		a	b	c	d	r^2	D_{ef} $x10^8$						
	Apple	0.7051	1.961	0.2992	39.58	0.9990	3.879						
	Pear	0.7628	203.8	0.2377	23.83	0.9996	3.732						
	Ciku	0.7956	328.9	0.2079	24.05	0.9970	2.077						
	Papaya	0.806	220.4	0.2201	33.83	0.9997	3.451						
	Mango	0.8417	201.9	0.1586	18.33	0.9996	3.768						

I, II,III – periods of drying

r^2 – coefficient of determination

cooling period, fruits cell's structure will shrink. When hot air charged to the fruits, the cell structure w illexpand. Thus, bulk moisture move from the internal part to the fruits surface. This increment of drying rate is because of the drying temperature difference between the active hot air drying and cold air tempering w as as high as 40°C, w hich created agreater driving force for diffusion of internal moisture.

For fruits undergone CTP drying, a minimum point can be seen from the drying rate versus moisture content curve. The decreasing of drying rate at this point is because of the implementation of cold air drying between two hot air drying periods. Resuming of hot air drying after the cold air tempering period also create a puffing condition, w here bulk moisture diffuse to the surface of the samples.

Comparison of overall drying duration

Drying of apple, pear, mango, ciku and papaya by the C/VM method required shorter drying duration compared to other drying methods. The total drying time used for drying of apple, pear, ciku and mango using the C/VM methods was about 490 minutes. For papaya that dried under the C/VM method, about 310 minute was needed, which is the faster compared to other drying methods. The drying time is extremely short because of uniform penetrating energy with the application of microwave power between 120 –360 W during second stage of drying. In addition, puffing effects occurred during C/VM drying could be one of the reasons because of large vapor pressure gradient between the samples interior and surface creates an internal moisture vibration. According to Kaensup et al., (2002), during vacuum microwave drying, moisture at the inner part of the samples would remove rapidly with increasing vapor pressure.

Convective vacuum microwave (C/VM) drying curves

For parameters obtained from linear eq. (2), the *a* is the initial value of moisture ratio during drying. The *b* value is a drying rate at the first drying period calculated by differentiation of eq. (2). It is obvious that the higher *b* value the higher decrease in moisture ratio per minute. For parameters obtained from exponential eq. (3), parameter *a* can be treated as critical point, MR*cr* that divides the drying process into constant rate period and falling rate period. In this case the *b* parameter corresponds to time constant. In the falling rate period described by eq. (3) the higher *b* value the lower decrease in moisture ratio per minute is observed. The *b* value during drying period I and II were between 2.54×10^{-3} to 5.30×10^{-3} and 107 to 250, respectively (Table 1). First falling rate period and second falling rate period were exhibited during drying period II and III.

Cyclic temperature profile (CTP) drying curves

The features of this drying profile are cold air can be supplied to the samples in the middle of drying process. Parameter *b* obtained from the linear model as shown in Table 1 ranges from 4.2×10^{-4} to 7.11×10^{-4}. This value indicates that the drying rate was extremely slow. The purpose of applied cold air in the drying process is to reduce the surface temperature to avoid case hardening effect. The pore and cell structure of the samples could be retained throughout the cold air tempering period. More moisture could diffuse to the sample surface for evaporation. As mention in C/VM drying models, *a* value is the moisture ratio of the samples. In this case *a* value indicates initial moisture ratio for the cold air period. During cold air tempering period, moisture reduction rate is very low, which is about 13% throughout the tempering period.

Step-up temperature profile (STP) drying curve

STP drying consisted of two drying period: linear (I) and exponential (II). Parameters used in this models are *a* and *b*. At the initial stage of drying, cold air was channeled to the fruits. Moisture evaporated from the samples at this stage was about 10% of the initial moisture content based on the *a* values shown in Table 1. Cold air tempering allows internal moisture diffuse to the samples surface while maintaining the surface temperature at low level. When hot air applied to the samples, bulk moisture at the sample surface was removed through evaporation.

Heat pump (HP) drying curve

The drying equation used to model the drying kinetics of fruits under HP was two term exponential model. This model consists of four parameters. Combination of parameter *a* and *c* represent the moisture content of fruits and b is selected as drying constant for effective diffusivity determination. The samples undergone HP drying exhibited an initial transient period and one falling rate period. Referring to Fig. 1, the initial transient period only happened at the first 30 minutes of drying when the moisture content decreased from 8 – 6 g H_2O/ g DM, 7 – 4 g H_2O/ g DM, 3.8 – 2.5 g H_2O/ g DM, 8.3 – 5.5 g H_2O/ g DM, 5.5 – 3.5 g H_2O/ g DM for apple, pear, ciku, papaya and mango, respectively.

CONCLUSIONS

Overall drying time for production of dried apple, pear, papaya, mango and ciku by using C/VM was between 306 to 504 min, which is about 50% shorter than other drying methods tested in this study. The effective diffusivity value was between 7.08×10^{-8} to 1.56×10^{-6} m^2/min, which were higher than fruits undergone CTP, STP and HP drying methods (2.08×10^{-8} to 5.78×10^{-8} m^2/min). The models asymptotic values represent the moisture content and critical moisture content of the drying profile.

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