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The Effect of Infrared on Diffusion Coefficients and Activation Energies in Convective Drying: A Case Study for Banana, Cassava and Pumpkin

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Abstract: Experiments of convective drying on thin slices (0.5 cm) of banana, cassava and pumpkin were carried out under three air temperatures of 85, 90 and 95°C at constant 2 m sec^{-1} of air velocity with and without application of infrared in the drying process. The drying characteristics included diffusion coefficient and activation energy were evaluated under the influence of the infrared radiation. Tutuncu model was used in order to evaluate the effective diffusion coefficient and activation energies of samples under different values of parameters of temperature and infrared conditions during drying. The results indicate that the effective diffusion coefficients increased with increasing of the air temperature and increase in the infrared radiation. The diffusion coefficient values were found to be between 1.85×10^{-9} to 7.02×10^{-9} m^2 sec^{-1} for banana, 1.18×10^{-9} to 6.16×10^{-9} m^2 sec^{-1} for cassava and 1.12×10^{-9} to 3.64×10^{-9} m^2 sec^{-1} for pumpkin respectively for lowest temperature of 85°C and no infrared radiation to highest temperature of 95°C and highest infrared of 200 W. The activation energies were found to be between 15.89-19.75 kJ mol^{-1} for banana, 26.44-32.85 kJ mol^{-1} for cassava and 27.83-29.26 kJ mol^{-1} for pumpkin respectively for the same condition.

Key words: Agricultural products, convective drying, diffusivity, mathematical model, Arrhenius relation

INTRODUCTION

Drying is an essential and significant process for the food industry in order to preserve food quality and food stability by lowering the water activity through the decrease of moisture content. At higher moisture level, microorganisms caused the food spoilage and food decay is unable to grow and multiply in the absence of sufficient water (Ayanoglu *et al*., 2005). In addition, the deterioration reactions which will promote undesired changes in the chemical composition of the food are greatly minimized since the microorganism's enzymes cannot function without water (Earle, 1983).

The dried fruits and vegetables are in high and noticeable increasing demand in the market. Dried fruits and vegetables have high commercial value demanded by the gastronomic business including dessert, ice cream, cocktails, salads and sweet cuisine (Lemus-Mondaca *et al*., 2009). Apart of them, drying can provide an extension of shelf-life, lighter weight for transportation, better return for the farmer and less space for storage (Noomhorm, 2007; Sthishkumar *et al*., 2009). Thus, drying is important process for the food industry to preserve the aroma, color and flavor characteristics of the food and prevent spoilage of the food (Abano, 2010; Bulent Koc *et al*., 2007).

Infrared drying has been considered as an artificial method analogous to sun drying method. The advantages of applying infrared to drying process including versatility, simplicity of equipment, fast response of drying, easy installation to any drying chamber and low capital cost (Sun *et al*., 2007). Infrared drying also gives the advantages of shorter drying time, high energy efficient, high quality products, uniform temperature in the product and reduced air flow across the product for convective drying (Sharma *et al*., 2005).

The fundamental principle of the infrared drying is the transformation of infrared radiation energy into movement of the water molecules in the drying process (Hui and Welti-Chanes, 2008). In infrared drying, the heat is directly transferred in the emitted electromagnetic waves and absorbed into solid material and moisture, thus regenerating heat. The radiation of infrared is transferred from heating element and reaches on the exposed food surfaces, penetrates into the internal of the food (Pan *et al*., 2008). The infrared creates molecular vibration of the material and the energy of radiation is converted into heat leading to evaporation. The radiation tends to selectively in the region having highest moisture content (Pan *et al*., 2008). This will enhance molecular diffusion within the food and promotes more rapid moisture evaporation from product surface.

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Mathematical models are used to describe the kinetics characteristic of the drying process in order to improve, design or control the drying system. The thin layer model is the model widely used for description of the drying process. These models have been categorized as theoretical, semi-theoretical and empirical models. Theoretical models take into account only internal resistance while the semi-theoretical and empirical models take into account only external resistance to moisture transfer between product and air (Hii *et al*., 2009; Akpinar, 2006). Crank model and Tutuncu model are theoretical models and they are simplification of Fick's second law of diffusion (Crank, 1975; Tutuncu and Labuza, 1996). Semi-theoretical models have been the simplification or modification models from the Fick's second law of diffusion with the assumptions of diffusion-based moisture migration, negligible shrinkage, constant diffusion coefficients and temperature (Lewis, 1921; Page, 1949; Henderson and Pabis, 1961; Yagcioglu *et al*., 1999; Henderson, 1974; Rahman *et al*., 1998; Sharaf-Elden *et al*., 1980; Verma *et al*., 1985; Midilli *et al*., 2002). However, the models are only valid within certain temperature, relative humidity, air velocity and moisture content range. These models are one of the semi-theoretical thin layer drying models. Empirical models derive a direct relationship between average moisture content and drying time but neglect fundamentals and parameters of the drying process (Wang and Singh, 1978). Therefore, these models cannot give clear and accurate of the fundamental of the drying processes which is do not provide physical description such as mass transfer coefficient and moisture diffusivity although they may describe the drying curve for the conditions of the experiments. Wang and Singh model is one example of these models. Table 1 represents the thin layer drying models.

Table 1: Thin layer drying models.

Models	References
$M_R = \exp(-kt)$	Lewis (1921)
$M_R = \exp(-kt^n)$	Page (1949)
$M_R = a\exp(-kt)$	Henderson and Pabis (1961)
$M_R = a\exp(-kt)+c$	Yagcioglu *et al.* (1999)
$M_R = a\exp(-k_o t)+b\exp(-k_1 t)$	Henderson (1974) and Rahman *et al.* (1998)
$M_R = a\exp(-kt)+(1-a)\exp(-kat)$	Sharaf-Elden *et al.* (1980)
$M_R = 1 + at + bt^2$	Wang and Singh (1978)
$M_R = a\exp(-kt)+(1-a)\exp(-gt)$	Verma *et al.* (1985)
$M_R = a\exp(-kt^n)+bt$	Midilli *et al.* (2002)
$M_R(t)=\frac{8}{\pi^2}\sum_{n=0}^{1}\frac{1}{(2n+1)^2}$ $\exp\left(\frac{(2n+1)^2\pi^2 D_{eff}{}^{t}}{4l^2}\right)$	Crank (1975)
$L_n M_R(t)=Ln\frac{8}{\pi^2}-\frac{\pi^2 D_{eff}{}^{t}}{4L^2}$	Tutuncu and Labuza (1996)

MATERIAL AND METHODS

Experiment rig: A pilot plant test dryer used in this study is shown in Fig. 1. The dryer is a conventional convective drying tray dryer (170.2 cm×20.7 cm×20.7 cm) by modified with an infrared lamp (11). The tray dryer is enclosed insulated drying chamber (2) in which trays (4) are located at the middle of the dryer with opening door (5) which is used for insertion or removal of the test samples. This equipment mainly consist of heating element (6) (0-3000 W) and fan (8) (0-235 $ft^3\ m^{-1}$). The heating element and fan which are located on the right side of the dryer provides hot air for the convective drying. Air inside the tray dryer is heated by eight coils of electrical heaters in which each of 375 W and blower fans are installed inside to ensure proper circulation and heat transfer. The hot air collects the moisture from the drying sample and passed to the opposite side (left) of dryer. The air velocity can be changed by regulating the fan speed. The air velocity is measured by using an anemometer (Turbometer Electronic Wind Speed Indicator) with the measurement unit of m/s. Air velocity was measured at the (10) downstream from the drying chamber. The weight of the samples are measured by an electronic balance (1) (Shimadzu UX6200H) with measurement range 0.5-6200 g and accuracy ±0.01 g located on the top of dryer. A control panel (9) to control the temperature (heater power), infrared power and fan speed is fixed outside the dryer. Infrared lamp which is located on the top of the dryer is

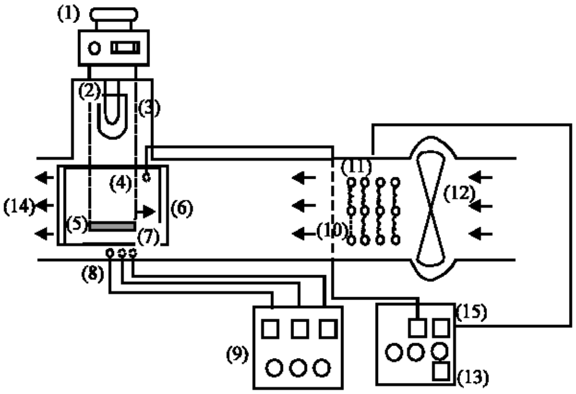

Fig. 1: Schematic diagram of pilot plant test dryer. (1): Electric balance, (2): IR lamp, (3): Drying chamber, (4): Tray thermocouple, (5): Trays, (6): Opening door, (7): Rectangular vibrating plate, (8): Piezoelectric vibrating transducers, (9): Sonicator, (10): Heating element, (11): Heater thermocouple, (12): Fan blower, (13): Control panel, (14): Downstream of dryer, (15): Digital temperature controller

used to provide infrared radiation. The dryer is equipped with white glass infrared lamps of power 230 W by emitting radiation with infrared wavelength 700-1400 nm and reach the surface of the sample placed at distance 100-150 mm below the source.

Sample preparation: Fresh and ripe bananas were obtained from the local supermarket in Nibong Tebal, Malaysia. The banana slices was prepared by peeling the skin and then cut into slices of 0.5 cm thickness. The thickness is measured by caliper and only samples within ±2% of thickness are selected.

Drying procedure: Approximate 5-10 samples are placed into a petri dish. The temperature (between 85°C and 95°C) and infrared (between 0 to 200 W) are set to desired values. Air velocity is set to 2 m sec^{-1} at the exit of the fan. The system was run for about half an hour to reach steady conditions of temperature. Petri dish with samples is placed into the tray dryer and the weight is recorded by mean of the balance. The door of the dryer was properly closed to ensure no leakage of hot air. Weight of sample and tray is weighed by balance every fifteen minutes for first one hour, every thirty minutes for next two hours and every one hour subsequently for determination of drying curves. The final dry weight of samples in each tray is evaluated. Experiment is terminated when the weight of samples reach 10% above the dry weight. The experiment is repeated for different designed condition for different selected materials.

Mathematical modelling: As discussed earlier, thin layer model is widely used models for drying process. Eq. 1 which represents the Tutuncu model (Tutuncu and Labuza, 1996) was used in this study in order to estimate the diffusivity of moisture within the samples:

$$\mathrm{Ln}\, M_R\, (t) = \mathrm{Ln}\frac{8}{\pi^2} - \frac{\pi^2 D^t_{eff}}{4L^2} \qquad (1)$$

where, M_R is the moisture ratio of sample at time, t; D_{eff} is the moisture diffusion coefficient; L is the thickness of the sample; π is equal to 3.1416.

The data collected from experiment was applied in this model in order to determine the diffusion coefficient. The evaluation of the activation energy is accomplished by using the Arrhenius equation as shown below:

$$D_{eff} = D_O \exp\left(\frac{-E_a}{RT}\right) \qquad (2)$$

where, D_o is the Arrhenius constant (m^2/s); E_a is the activation energy (kJ moL^{-1}); T is the temperature of drying air (K) and R is the gas constant (kJ $moL^{-1}\cdot K$).

RESULTS AND DISCUSSION

Effective diffusion coefficient: Table 2 represents the variation of effective diffusion coefficients (D_{eff}) of banana, cassava and pumpkin for different temperatures and infrared radiations. It can be seen that the value of effective diffusion coefficients increased with increasing of values of temperature (Kouchakzadeh, 2011) and infrared power. The values of effective diffusion coefficients for banana have been found to be lower than for cassava and pumpkin.

As indicated by Noomhorm (2007), drying rate consist of three periods, including warming up, constant rate and falling rate. The moisture is removed by evaporation from the saturated surface and the area of saturated surface gradually decreases, followed by water evaporation in the interior parts of the sample. During the falling rate period, the drying rate is controlled by diffusion of moisture from the interior of the material slabs to the surface (Chong *et al*., 2008). Thus, diffusion coefficient is essential parameters in drying process.

From Table 2, it can be seen that the value of effective diffusion coefficients increases with increase of values of temperature and infrared power. This is because more energy adsorbed on the sample surface from infrared radiation for moisture evaporation and thus increased the diffusion coefficient. Same of the result observed in Togrul (2006) study as well. The values of infrared for banana have been found to be lower than for cassava and

Table 2: Effective diffusion coefficients (D_{eff}) of banana, cassava and pumpkin

		Effective diffusion coefficient (D_{eff}) (× $10^9 m^2 sec^{-1}$)		
		Infrared power (W)		
Materials	Temperature (°C)	0	100	200
Banana	85	1.13	1.52	2.95
	87	1.18	1.75	3.38
	89	1.23	1.99	3.80
	91	1.27	2.23	4.23
	93	1.32	2.46	4.66
	95	1.37	2.70	5.08
Cassava	85	1.18	1.72	4.29
	87	1.26	1.95	4.66
	89	1.34	2.17	5.04
	91	1.42	2.40	5.41
	93	1.50	2.63	5.79
	95	1.59	2.86	6.16
Pumpkin	85	1.02	2.66	4.56
	87	1.09	2.88	4.93
	89	1.16	3.10	5.30
	91	1.23	3.32	5.66
	93	1.30	3.53	6.03
	95	1.37	3.75	6.39

Table 3: Arrhenius constant and activation energies of banana, cassava and pumpkin

Materials	Infrared power	Activation energy, (kJ moL^{-1})	Arrhenius constant, (D_o) ($m^2\ sec^{-1}$)
Banana	0	19.75	4.34×10^{-7}
	100	19.38	2.82×10^{-6}
	200	15.89	6.18×10^{-6}
Cassava	0	32.85	2.42×10^{-5}
	100	31.94	1.88×10^{-4}
	200	26.44	4.27×10^{-4}
Pumpkin	0	29.26	1.74×10^{-5}
	100	28.87	4.03×10^{-5}
	200	27.83	6.42×10^{-5}

pumpkin. This could be as a result of the sticky nature of the flesh of the banana which restricts the moisture movement.

Arrhenius constant and activation energy: The variation of Arrhenius constant (D_o) of different infrared radiation power for banana, cassava and pumpkin as shown in Table 3. It can be observed that the value of Arrhenius constant increased with increase of infrared power. The values of Arrhenius constant increased in banana, pumpkin and cassava. From Table 3, it can be seen that Arrhenius constant and activation energy of banana is also lower than cassava and pumpkin due to the same reason.

Table 3 represents the variation of activation energy (E_a) of different infrared radiation power for banana, cassava and pumpkin. It can be seen that the value of activation energy decreased with increase of infrared power. The values of activation energy for banana also found to be lower than for cassava and pumpkin.

The activation energy is the energy barrier in order to activate moisture diffusion (Hii *et al.*, 2009). As the infrared radiation increased, the temperature increased as well, result in increased of energies for the drying process and thus decreased the activation energies.

CONCLUSION

This study was carried out to investigate the influence of the infrared on the effective diffusion coefficient and activation energy for banana, cassava and pumpkin. The effective diffusion coefficient increased with increasing of the infrared power. The effective diffusion coefficient and activation energy were found to be between 1.85×10^{-9} to 7.02×10^{-9} $m^2\ sec^{-1}$ and 15.89-19.75 kJ mol^{-1} for banana, 1.18×10^{-9} to 6.16×10^{-9} $m^2\ sec^{-1}$ and 26.44-32.85 kJ mol^{-1} for cassava and 1.12×10^{-9} to 3.64×10^{-9} $m^2\ sec^{-1}$ and 27.83-29.26 kJ mol^{-1} for pumpkin respectively.

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