

Kinetic Study of Drying and Oil Intake During Deep-Fat Vacuum Frying of Blanched Snake Fruit Slices

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Abstract
In this work, an experimental study of deep-fat vacuum frying of pre-treated original fruit from South-East Asian, i.e., snake fruit, is conducted. Then the kinetics of drying and oil intake under vacuum frying conditions are investigated by using constant effective diffusivity of water and logistic oil content models. Its comparison to those on atmospheric condition based on the thermal-driven concept is also discussed. It is demonstrated that the constant effective water diffusion and logistic oil content models are fitted very well with the experimental data. The effective diffusivity increases with the increase of oil temperature under vacuum condition and its values are smaller than those under atmospheric frying. On the other hand, the specific rate of oil content (k) has no specific trend. Moreover, the specific rates of oil content for atmospheric conditions are larger than those corresponding values for vacuum conditions.
Keywords: Deep-fat, vacuum frying, oil temperature, drying rate, oil absorption, snake fruit chips

1. Introduction

Deep-fat frying is a traditional cooking method which is defined as a method to cook the food by immersing it within a high temperature of the oil, usually greater than water boiling point (Hubbard & Farkas, 2000; Sahin et al., 1999). During the frying process, heat and mass transfer occur simultaneously and quickly. However, deep-fat frying is subject to yield the products with high content of fat, a mean cause of coronary heart disease, cancer of breast and prostate (Andrés-Bello et al., 2011). In recent years, consumer's demand for low-fat products has been a stimulus for food industries to produce low oil content products but still preserve its flavor. Several alternative technologies have been developed to overcome this issue, such as extrusion, drying, but none of them are successful since its qualities, in terms of flavor, texture, and colour are not as high as one produced by traditional deep-fat frying (Dueik et al., 2010).

On the other hand, vacuum frying is a promising food processing technology to produce snacks, vegetables, and other products with low oil content and desired flavor, color, and texture. Vacuum frying is defined as a frying method at pressures below atmospheric level. Due to low pressure, the boiling points of both oil and water are also low. Hence, vacuum frying does not need temperature as high as the traditional cooking method. Besides its advantages on preserving the flavor and characteristics of its preference, vacuum frying technology can also preserve the nutritional compounds (Da Silva & Moreira, 2008) and has less adverse effects on oil quality (Karacabey et al., 2016; Mariscal & Bouchon, 2008; Shyu et al., 1998).

Many previous experimental studies have been conducted to investigate the structure changes and the effects of important parameters during conventional frying under atmospheric conditions, see for example: Bouchon and Aguilera (2001); Li et al. (2016). It is commonly accepted that moisture and oil contents, temperature, porosity, pre and post-treatment, and frying time are important factors that influencing the fried-product quality in conventional frying (Bouchon & Aguilera, 2001). Despite data and information generated by these experimental studies are very useful in practice, the mechanisms of frying process of food are still not fully understood due to its complex heat and mass transfer. On the other hand, attempts have been made in developing mathematical models in order to obtain a better understanding of transport phenomena or kinetics during conventional frying, see for example Alvis et al. (2009), Ahromrit and Nema (2010), Pedreschi et al. (2005), Sahin et al. (1999). However, only a few studies are concerned on deep-fat vacuum frying in the open literature, see for example: Andrés-Bello et al. (2011); Da Silva and Moreira (2008); Pan et al. (2015). As pointed out by Troncoso and Pedreschi (2009), the transport phenomena during vacuum frying is more complicated than that during conventional frying.

In this work, an experimental study of the pre-treated original fruit from Indonesia, Malaysia, and Brunei, i.e., snake fruit during deep-fat vacuum frying is conducted. The pre-treated snake fruit slices are performed by immersing them in boiling water for specific time duration. Its comparisons to those on atmospheric frying based on the thermal-driven concept are also demonstrated. Moreover, the kinetic of moisture loss and oil absorption based on the existing model and empirical correlation respectively are developed in order to obtain a better understanding of vacuum frying process of snake fruit slices.

2. Research Methodology

2.1. Experimental Setup

Slices were cut from snake-fruit with the thickness of 3 mm and the surface area of 6.25 cm^2 (with the same edge sizes) and then rinsed in distilled water. Slices were then blanched in boiling water for 5 min and were dried by using the paper towel and placed on the wire tray for 5 min to ensure that excess moisture is removed from slice surface.

The experiment was performed using a vacuum frying machine with a capacity of 3 kg/h. A half-cylindrical shape of the inner basket as a vacuum-frying chamber is connected to a vacuum pump. A heating system consisting of a two-stage stove with a solenoid valve automatically controlled by programming logic controller supplies the heat into the chamber until the desired temperature is achieved. Four oil temperature levels of 60, 70, 80, 90 ^oC are performed while the chamber pressure keeps constant at 0.012 MPa. Moreover, two atmospheric conditions with oil temperatures of 108.5 and 118.5 ^oC, which correspond to vacuum temperatures 60 and 70 ^oC respectively based on the thermal-driven concept, are also performed. Maximum frying time is set to 10 minutes. Samples were collected every two minutes. Fresh soy oil was used in all experiments at each temperature. Before frying process started, 25 slices of snake fruit were put in the inner basket and the vacuum pump was turned on to allow the heat chamber achieve the desired pressure. When the pressure gage achieved this pressure, the basket was immersed in the hot oil. Once the samples were fried, the vacuum frying machine was automatically turned off. The vessel was then pressurized to atmospheric pressure and the chamber lid was opened. The products were removed from the basket and they were allowed to cool to room temperature. The excess oil in the product surface was then removed using paper towels.

2.1. Mathematical Modeling

To desrcibe the moisture loss at instantaneous frying time, a model based on Fick's law of diffusion which originally developed by Crank (1975) as expressed in the following equation is applied:

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

M_t is defined as m_t/m_o. Where m_t is instantaneous moisture content, m_o is initial moisture content. L, t, b are the half thickness of the slice, frying time, and dimensionless parameter respectively. D_{eff} is the effective diffusivity which is assumed to be a constant. Whilst the oil absorption is described by the logistic model developed by Chen and Ramaswamy (2002) as follows:

$$\frac{Y - Y_e}{Y_o - Y_e} = Ae^{-kt} \quad (2)$$

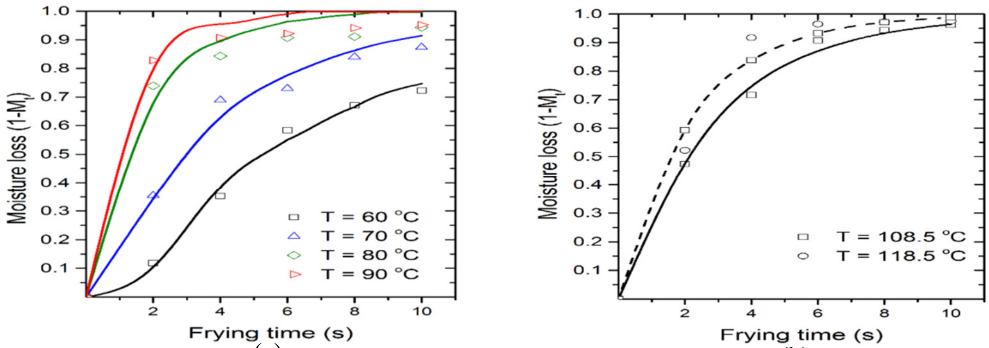
Where Y, Y_e, Y_o, k are respectively oil content at time t, oil content at equilibrium, initial oil content, and specific rate of oil absorption. To obtain D_{eff} in Eq. 1 and k in Eq. 2, a nonlinear regression procedure is performed by minimizing the RMS (root mean square) of the difference between experimental and fitting data.

3. Results and Discussion

3.1. Moisture Loss

In this section, the effects of oil temperature on moisture loss during deep-fat vacuum and atmospheric frying and the kinetics of water loss are discussed.

Figure 1 illustrates the experimental data and its correlations from Eq.1 of moisture loss of snake fruit slice during (a) vacuum frying, and (b) atmospheric frying under different oil temperatures. As shown in Figure 1, in general, the moisture loss increases as the oil temperature increases. The moisture loss also increases with the increase of frying time. For vacuum frying. at high oil temperature, the initial curve gradient is initially very high for about 3 minutes and it then decreases sharply as the frying time increases. Different profiles are attributed at lower temperatures. At low oil temperatures, the moisture loss increases with lower slopes in the range of frying time of 0-3 minutes and then increases with higher slopes if compare to those at high oil temperatures at higher frying time. On the other side, the trends of frying time vs moisture loss in atmospheric conditions (Figure 1b) are similar to those in vacuum conditions for the same thermal-driven temperatures (60 and 70 ^oC). However, the rates of moisture loss for atmospheric frying are greater than those for vacuum frying. The similar results for vacuum frying of blanched potato slices have been reported by Troncoso and Pedreschi (2009).



(a) (b)

Figure 1. Moisture Loss of Snake Fruit Slice during Vacuum Frying under Different Oil Temperatures (Symbols) and its Correlations from Eq. 1 (Lines) (a) Vacuum, (b) Atmospheric Frying

The fitted data of moisture loss using constant diffusion model of Eq. 1 has a good accuracy as indicated by its low RMS values (Table 1). It can be seen that the model is fitted very well at which the RMS values are less than 10% for all cases. Table 1 also depicts that the effective diffusivity increases with the increase of oil temperature under vacuum condition. Furthermore, the effective diffusivities for vacuum frying of snake fruit slices are between 2E-10 to 1E-09 which are generally smaller than those for potato tissue (Saravacos & Maroulis, 2001) with similar oil temperatures, in the order of 10^{-2}. It also can be seen from Table 1 that

Table 1. Effective Diffusivity for Vacuum and Atmospheric Frying under Different Oil Temperatures

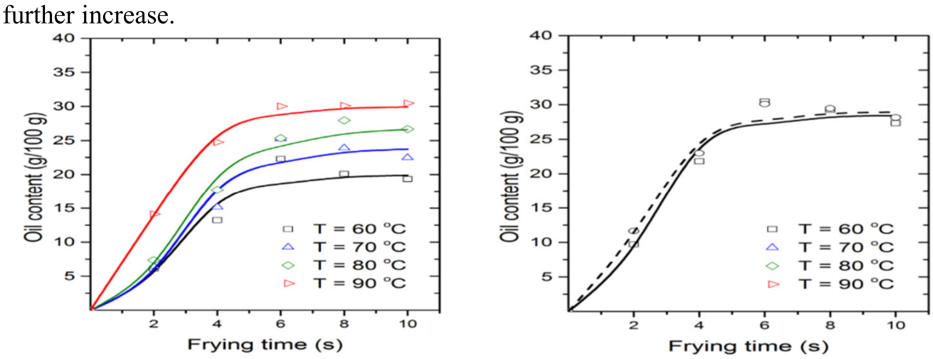
	Temperature (°C)					
	Vacuum				**Atmospheric**	
	60	70	80	90	108.5	118.5
D_{eff} (m^2/s)	2.18E-10	3.96E-10	9.01E-10	1.26E-09	5.44E-10	7.25E-10
RMS (%)	6.85	5.62	7.04	5.65	2.67	7.33

effective diffusivities for atmospheric frying are larger but in the same order than those for vacuum frying with the same thermal driving force.

It should be noted that the effective water diffusivity in Eq. 1 is assumed to be a constant during the frying. In reality, the water diffusion is influenced by other parameters such as porosity, pressure drop, capillary pressure, etc. Under the current condition in which foods have high moisture content due to blanched pre-treatment (the initial moisture content is 90.1% of total slice weight), the molecular diffusion of liquid and capillary pressure might be the most important mechanisms of water transport. Hence, the values of D_{eff} in Table 1, despite its small values of RMS, are rough approximation. To obtain its accurate values, a numerical method which considers all mechanisms of water transport is required.

3.2. Oil Intake

Oil absorption during deep-fat vacuum frying is difficult to measure accurately since it occurs mainly at post-treatment stage and often simultaneously with depressurization process. Figure 2 depicts the experimental data and its correlations from Eq.2 of oil content of snake fruit slice during (a) vacuum frying, and (b) atmospheric frying under different oil temperatures. As described in this figure, the curve trends are similar for all cases. The oil content increases steeply with the increase of frying time (until t = 4 min) and then increases gradually as the frying time further increase.



(a) (b)

Figure 2. Oil Content in of Snake Fruit Slice during Vacuum Frying under Different Oil Temperatures (Symbols) and its Correlations from Eq. 2 (Lines) (a) Vacuum, (b) Atmospheric Frying

In addition, Figure 2a shows that the higher oil temperature, the higher oil content. However, for atmospheric frying, increasing the temperature of 10 ^oC has the negligible effect on the oil content in snake fruit slice (Figure 2b). Moreover, similar to the moisture loss, the rates of oil intake for atmospheric frying at oil temperatures of 108.5 and 118.5 ^oC are greater than those for vacuum frying under the equivalent thermal-driven force of 60 and 70 ^oC respectively (Figure 2). For example, the oil content in fried snake fruit slice under vacuum condition at 60 ^oC and t = 4 min can decrease at about 40% of that under atmospheric condition. When comparing Figs. 1 and 2, it can be implied that the oil content has a strong relation to the moisture loss. The increase of oil content with the increase of oil temperature during vacuum frying (Fig. 2a) corresponds to the increase of moisture loss (Fig. 1a). Furthermore, the smaller oil content in snake fruit slice under vacuum frying condition than that under atmospheric frying condition is due to the decrease of moisture loss at the same frying time.

Table 2. Oil Intake Constant for Vacuum and Atmospheric Frying under Different Oil Temperatures

	Temperature (^oC)					
	Vacuum				**Atmospheric**	
	60	70	80	90	108.5	118.5
k (s^{-1})	9.79E-03	8.68E-03	8.16E-03	1.07E-02	1.13E-02	1.10E-02
A	2.31	2.13	1.97	1.94	2.58	2.28
RMS (%)	11.25	10.47	6.27	2.63	6.56	4.73

The curve of frying time vs oil content using Eq. 2 fits very well with experimental data as indicated by its low RMS values (Table 2), which in general, they are less than 15%. Table 2 also depicts that the specific rate of oil content (k) decreases when the oil temperature increases from 60 to 80 ^oC and then increases as the oil temperature further increases to 90 ^oC. For atmospheric frying condition, according to Eq. 2, the negligible effect of temperature is related to the insignificant changes of both specific rate of oil content and A constant. However, the specific rates of oil content for atmospheric condition are larger than those corresponding values for vacuum condition.

4. Conclusion

An experimental study of deep-fat frying, both under vacuum and atmospheric pressure, for snake fruit slices have been conducted and the kinetic model of moisture loss and oil content is measured by using the existing models in the open literature. It is demonstrated that the constant effective water diffusion and logistic oil content models are fitted very well with the experimental data. The effective diffusivity increases with the increase of oil temperature under vacuum condition. Whilst effective diffusivities for atmospheric frying is larger but in the same order than those for vacuum frying with equivalent thermal driving force.

On the other hand, the specific rate of oil content (k) has no specific trend. It decreases when the oil temperature increases from 60 to 80 ^oC and then increases as the oil temperature further increases to 90 ^oC. For atmospheric frying condition, under current experimental condition, the negligible effect of temperature is related to the insignificant changes of both specific rate of oil content and A constant. The specific rates of oil content for atmospheric condition are larger than those corresponding values for vacuum condition.

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