UNIVERSITI PUTRA MALAYSIA

KINETIC MODEL OF DRYING PROCESS OF PUMPKIN (CUCURBITA MOSCHATA DUCHESNE EX POIR.) IN A CONVECTIVE HOT AIR DRYER

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By

ONWUDE DANIEL IROEMEHA C.

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Master of Science

March 2016

DEDICATION

With all my love, I dedicate this thesis to my wonderful and precious mum.

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the Degree of Master of Science

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Pumpkins are highly perishable and must be preserved properly in order to increase shelf life and enhance carotenoid yield extraction. Convective hot air drying is the most suitable method of pumpkin preservation. The aim of this study was therefore to develop a computer simulation program for the prediction of the drying kinetics of pumpkin (*Cucurbita moschata*) in a convective hot air dryer.

The study investigated the effect of temperature (50, 60, 70 and 80 ^oC), material thickness (3, 5 and 7 mm) and drying air velocity (0.6 and 1.2 m/s) on the drying kinetics of pumpkin in a convective hot air dryer. Thin-layer drying method was used to obtain experimental data. The experimental data were modelled using empirical and semi-theoretical thin layer drying models. The best fitting model was evaluated based on the coefficient of determination (R^2) and sum of square error (*SSE*). The Hii *et al.* model, page and two term model showed excellent fit with the experimental data, thus can best describe the drying behaviour of pumpkin. The experimental data was further used to estimate the effective moisture diffusivities and activation energy of pumpkin by linear regression analysis based on the solutions of Fick's second law of diffusion or its simplified form. The calculated value of moisture diffusivity varied from a minimum of 1.94182×10^{-8} m^2/s to a maximum of 9.19583×10^{-8} m^2/s, while activation energy varied from 5.02158 kJ/mol to 32.14542 kJ/mol. The results indicated that with increasing temperature, the drying time was reduced. Furthermore, the drying time to reach safe moisture content of <2% increased as the slice thickness increased from 3 mm to 7 mm. Also, the effective moisture diffusivity increased as drying temperature increased and an increase in the slice thickness resulted in a corresponding increase in the activation energy for pumpkin slices. Subsequently, a computer program using MATLAB software was developed (LABUSIMSOFT) to predict the appropriate drying models at different drying conditions. Graphical User Interface (GUI) was created to show the simulation results graphically and also in generating the optimum drying conditions.

The results of colour change during the drying process showed that there was a decrease in the three colour parameters (L*, a*, b*) as the drying temperature and time increased. The Chroma value decreased with a corresponding decrease in temperature

and drying time during the convective hot air drying of pumpkin. Similarly, the hue angle increased with an increase in drying time. The browning index (BI) increased slightly with an increase in drying time and temperature However, this changes were not significantly different between samples dried at 50 °C and 80 °C at 5% significant level using Tukey HSD.

The results of the effect of drying temperature on hardness, cohesiveness, fracturability, springiness, resilience and total carotenoid content (TCC) showed that the drying temperature affected the hardness properties considerably when compared to the control (fresh) sample. Likewise, the cohesiveness and springiness of pumpkin was approximately constant throughout all drying conditions. The total carotenoid content (TCC) of the dried sample was also measured. The results showed that the drying temperature affects the total carotenoid content (TCC) of pumpkin significantly. The TCC reduced as the temperature increased but at a higher temperature of 80 ^{o}C, there was a sudden increase in the value of TCC due to a shorter drying time. Overall the study established that, the drying kinetics of pumpkin; depends on drying temperature and material thickness. However, to get the most optimum combination, the developed simulation software (LABUSIMSOFT) rapidly generated the optimum drying conditions of 78 ^{o}C drying temperature, 5 mm sample thickness and a drying time of 350 minutes resulting in $3.3\,x\,10^{-8}$ m^2/s and 24.8347 kJ/mole activation energy. Consequently, the overall colour and textural properties, and total carotenoid content could be retained by using the optimum drying conditions.

This study found that the developed computer simulation software has great potential as a simple and yet effective tool for predicting the drying time, optimizing and monitoring the drying process of pumpkin. The results of this study can be applied in the effective design and optimization of industrial convective hot air dryers.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk Ijazah Master Sains

MODEL KINETIK PENGERINGAN LABU (*CUCURBITA MOSCHATA* DUCHESNE EX POIR.) DI DALAM PENGERING UDARA PANAS OLAKAN

Oleh

ONWUDE DANIEL IROEMEHA C.

Mac 2016

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Labu adalah sangat mudah rosak dan perlu dipelihara dengan baik untuk meningkatkan jangka hayat dan meningkatkan pengeluaran hasil karotenoid. Pengeringan adalah salah satu kaedah yang sesuai digunakan untuk pemeliharaan labu. Tujuan kajian ini adalah untuk mengenal pasti kesan pengeringan pada parameter kinetik untuk pengeringan labu manis dalam pengering udara panas olakan dan menghasilkan model ramalan.

Kajian ini menyelidik kesan suhu (50 ^oC, 60 ^oC, 70 ^oC dan 80 ^oC), ketebalan bahan (3 mm, 4 mm, 5 mm dan 7 mm) dan halaju udara pengeringan (0.6 m/s dan 1.2 m/s) pada kinetik pengeringan labu (*Cucurbita moschata*) dalam pengering udara panas olakan. Kaedah pengeringan lapisan nipis telah digunakan untuk mendapatkan data kajian. Model yang terbaik telah dihasilkan berdasarkan pekali penentuan (R^2) dan Jumlah kesilapan persegi (*SSE*). Model Hii *et al.*, Page dan Two Term menunjukkan penyesuaian terbaik dengan data eksperimen, sekaligus menggambarkan ciri-ciri pengeringan labu. Data eksperimen tersebut kemudiannya digunakan untuk menganggarkan kelembapan kemerasapan dan tenaga pengaktifan labu dengan analisis regresi linear berdasarkan penyelesaian melalui hukum kedua Fick atau bentuknya yang mudah. Nilai kelembapan kemeresapan berubah dari nilai minimum 1.94182×10^{-8} m^2/s ke nilai maksimum 9.19583×10^{-8} m^2/s, manakala tenaga pengaktifan berubah daripada 5.02158 kJ/mol hingga 32.14542 kJ/mol. Hasil kajian menunjukkan bahawa dengan peningkatan suhu, masa pengeringan telah dikurangkan. Tambahan pula, masa pengeringan untuk mencapai kandungan lembapan sebanyak <2%, juga turut meningkatkan ketebalan kepingan daripada 3 mm hingga 7 mm. Selain itu, kemeresapan kelembapan juga turut meningkat dengan peningkatan dalam suhu pengeringan, ketebalan kepingan dan tenaga pengaktifan untuk kepingan labu. Di samping itu, program komputer menggunakan perisian MATLAB telah dihasilkan iaitu (LABUSIMSOFT) untuk meramal model pengeringan yang sesuai pada keadaan pengeringan yang berbeza. Graphical User Interface (GUI) telah dicipta untuk menunjukkan hasil simulasi grafik dan juga menjana keadaan pengeringan yang optimum.

Hasil kajian menunjukkan bahawa terdapat peningkatan dalam tiga parameter warna (L*, a*, b*) sejajar dengan peningkatan masa dan suhu pengeringan. Nilai kroma

menurun dengan penurunan suhu dan masa pengeringan semasa pengeringan udara panas olakan labu. Perkara tersebut turut direkodkan oleh nilai sudut warna dengan peningkatan dalam masa pengeringan. Browning Index (BI) meningkat sedikit dengan peningkatan masa pengeringan dan suhu. Walau bagaimanapun, perubahan tersebut tidak berbeza secara ketara antara sampel dikeringkan pada suhu 50 ° C dan 80 ° C pada dengan aras keertian 5% menggunakan Tukey HSD.

Oleh yang demikian, sampel labu yang telah dikeringkan dianalisis untuk mengenalpasti perubahan warna, kekerasan, kesepaduan, keretakan, kelentingan, daya tahan dan jumlah kandungan karotenoid (TCC), dengan sampel segar sebagai bahan kawalan. Begitu juga, kesepaduan dan kekenyalan labu adalah sama dalam semua keadaan pengeringan. Jumlah kandungan karotenoid (TCC) bagi sampel kering juga diukur. Hasil kajian menunjukkan bahawa suhu pengeringan memberi kesan yang ketara kepada jumlah kandungan karotenoid (TCC). TCC telah berkurang apabila suhu bertambah tetapi pada suhu yang lebih tinggi daripada 80 ^{o}C, terdapat peningkatan mendadak dalam nilai TCC kerana masa pengeringan yang lebih singkat. Secara keseluruhan, kinetik pengeringan labu bergantung kepada suhu pengeringan dan ketebalan bahan. Walau bagaimanapun, untuk mendapatkan kombinasi yang paling optimum, perisian simulasi (LABUSIMSOFT) telah dihasilkan dalam keadaan optimum pengeringan seperti berikut: 78 ^{o}C bagi suhu pengeringan, 5 mm bagi sampel ketebalan dan 350 minit bagi masa pengeringan yang merekodkan tenaga pengaktifan sebanyak 3.3 x 10^{-8} m^2/s dan 24.8347 kJ/mol. Akhir sekali, jumlah kandungan karotenoid boleh dikekalkan dengan menggunakan keadaan pengeringan optimum yang telah disyorkan.

Kajian ini mendapati bahawa perisian simulasi komputer yang dibangunkan berpotensi sebagai alat yang mudah dan efektif untuk meramal masa pengeringan, mengoptimumkan dan memantau proses pengeringan labu. Hasil kajian boleh digunakan dalam reka bentuk yang efektif untuk pengering perolakan industri.

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I certify that a Thesis Examination Committee has met on 10 March 2016 to conduct the final examination of Onwude Daniel Iroemeha C. on his thesis entitled "Kinetic Model of Drying Process of Pumpkin (*Cucurbita moschata* Duchesne ex Poir.) in a Convective Hot Air Dryer" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Master of Science.

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M_0	Initial moisture content (g water/ g dry solid)
M_e	Equilibrium moisture content (g water/ g dry solid)
M	Moisture content at any time t (g water/ g dry solid)
MR	Moisture ratio
MC_w	Moisture content (wet basis)
MC_d	Moisture content (dry basis)
D	Effective moisture diffusivity (m^2s^{-1})
E_a	Activation energy
x	Direction of material dimension (m)
t	Time (s)
k, g, h, k_1, k_2, k_0	Drying constant (s^{-1})
$d, n, a, b, c, \propto$	Model constant
r	Radius of cylinder
z	Direction of thickness
h^*	Half thickness sample (m)
D_{efy}	Effective diffusivity with shrinkage (m^2s^{-1})
V	Sample volume (m^3)
V_0	Initial volume of sample (m^3)
V_e	Volume at equilibrium (m^3)
R^2 or r^2	Coefficient of determination
r or R	Correlation coefficient
SSE	Sum square error
$RMSE$	Root mean square error
x^2	Reduced chi-square
EF	Modelling efficiency
MBE	Mean bias error
MPE	Mean percent error
$RRMS$	Mean relative error root square (%)
w	Width (mm)
h	Thickness (mm)
L	Length (mm)
A^2	Area (mm^2)
T	Temperature (°C)
T_a	Ambient temperature (°C)
V	Air velocity (m/s)
R. H	Relative humidity (%)
EA	Exposed area (m^2)
P_d	Power density (W)
S_R	Solar radiation (W/m^2)
P	Power intensity (W/m^2)
I	Solar intensity (kW/m^2)
C_s	Sucrose concentration
$Nacl$	Sodium chloride
T_I	Inlet temperature
RSM	Response surface method
GA	Genetic algorithm

SDA	Single layer drying apparatus
TTD, TD	Tunnel and tray dryer
CTD	Cabinet tray dryer
OD	Oven dryer
FIR	Far infrared radiation
TCD	Tunnel convection dryer
$LHCD$	Laboratory hot air convective dryer
HCD	Hot air convective dryer
$LTCD$	Laboratory thermal convective dryer
DMO	Domestic microwave oven
ID	Infrared dryer
STD	Solar tunnel dryer
OSD	Open sun drying
MD	Microwave dryer
ISD	Indirect solar dryer
ATB	Aerothermic blower
$PPCD, PSD$	Pilot plant convective dryer
FBD	Fludized bed dryer
$IFSD$	Indirect forced solar dryer
IR	Infrared radiation drying
OMD	Osmotic dehydration
TCD	Total colour difference
$w.b$	Wet basis
$d.b$	Dry basis
$ANOVA$	Analysis of variance
TCC	Total carotenoid content

CHAPTER 1

INTRODUCTION

1.1 Background

Pumpkin is one of the most widely known fruits grown for commercial purposes; both for fresh fruit market and food processing industries. It is also a good source of carotenoids, mainly α-carotene and β-carotene which are useful in medical, pharmacological and cosmetics industries (Arima and Rodriguez Amaya, 1990; Murkovic *et al.*, 2002; Dutta *et al.*, 2006; Garcia *et al.*, 2007). Carotenoids are phytochemical components that reduce the risk of degenerative diseases such as cancer and diabetes. They are also responsible for the attractive colour of many fruits and vegetables. Carotenoids are said to be prone to isomerization and oxidation during processing due to inappropiate drying conditions, heat-treatment and exposure to light, resulting in some loss of colour and biological activity alteration (Rodriguez-Amaya, 2002). Thus, proper information of the processing condition must be provided to ensure that the extraction of the carotenoids from pumpkins will produce optimum output without appreciable loss of nutrients.

Drying is a part of the many processes involved in the extraction of carotenoids from fruits. It is a simultenoeous heat and mass transfer process that results in the reduction of moisture level from high to very low. This process is also useful in order to extend shelf life, reduce the bulk of the produce and ultimately ease transportation. Usually, the drying process results in coagulation of the protein fraction and permits convenient separation of the lipid fraction besides generating a typical aroma of the end product (Fruhwirth and Hermetter, 2007). There are many available drying methods currently been used in postharvest technology such as vacuum, microwave, heat pump, supercritical, freeze and hot air drying. According to Kudra and Mujumdar (2009), despite recent developments in novel drying technologies, conventional technologies are still widely preferred in the industries as compared to novel technologies due to the simplicity of dryer construction, ease of operation, as well as the status of familiarity (Araya-Farias and Ratti, 2008). Furthermore, drying is estimated to consume 10–15% of the total energy consumption of all the food industries in developed countries (Keey, 1972; Klemes *et al.*, 2008). Thus, it is energy-intensive. In a nutshell, drying is arguably the most long-standing, diverse, and conventional operation.

Convective hot air drying is the most widely used method, which is naturally harmless and non-toxic, provides a more uniform, hygienic, rapid and attractively coloured dried product (Doymaz, 2007; Rodríguez *et al.*, 2014; Tzempelikos *et al.*, 2015). In addition, it is a low cost method which uses hot air as a drying medium to remove moisture from the fresh produce (Prachayawarakorn *et al.*, 2008; Nawirska *et al.*, 2009). Jayaraman and Das Gupta, (2014) also reported that for drying fruits and vegetables, convective hot air drying is the most preferred method due to both its simplicity and economical advantage. Convective hot air drying, account for more than 85% of industrial dryers and more than 99% of the applications involve removal of moisture (Mujumdar, 2000; 2007; Aghilinategh *et al.*, 2015).

Basically, drying is a complex thermal process in which unsteady heat and moisture transfer occur simultaneously (Akoy, 2014). Since the process is energy intensive, the efficiency of drying with respect to energy and time is an important economic consideration. Therefore, it is also important to develop a better understanding of the controlling parameters of this complex process to ensure the optimum output during processing. Although considerable studies have been performed on the drying method of agricultural products, reliable simulation models of drying kinetics for pumpkins are still limited.

1.2 Problem Statement

Convective hot air drying of pumpkin, which is often one of the most used methods of preservation, is also widely used in the industry due to its simplicity and affordability. Industrial drying usually takes place at very high temperatures with less information on the appropriate drying conditions that would retain or minimize the loss of quality parameters (colour, texture and carotenoids) while reducing the total drying time.

In Malaysia, carotenoids are major sources of industrial pigments for health and cosmetics products. These carotenoids are extracted industrially from Pumpkin (*Cucurbita moschata*), which is extensively grown in Malaysia. Drying is the most time and energy consuming unit operation during the industrial extraction of pumpkin. However, carotenoids undergo degradation during this process due to factors such as a long processing time and inappropriate processing temperature (Akanbi and Oludemi, 2004; Nor, 2013). Thus, the engineering processes that will minimize carotenoid degradation, maintain the colour and textural properties during the industrial hot air drying of pumpkin becomes very essential. Modelling the drying processes can help in selecting the appropriate or optimum drying conditions, so that the drying process of pumpkin can be optimized as a means of maintaining the product's optical properties, reducing carotenoid losses and improving product quality. Its application is therefore essential for a wide range of technologies, including online monitoring of the drying process of fruits and vegetables. This can be achieved by integrating computer simulation software with the dryer.

Few studies on the colour kinetics of food materials have been reported in the scientific literature. Gamli (2011) studied the colour changes of tomato puree and the kinetic modelling of the colour changes of some fruits, such as kiwifruits (Mohammadi *et al.,* 2008) and apple, banana and carrots (Krokida *et al.,* 2007) have also been investigated. More so, studies on the effect of process storage conditions and packaging on the colour properties of other fruits have been reported (Bechoff *et al.* 2011; Guiné *et al.,* 2011; Divya *et al.,* 2012; Bechoff *et al.,* 2015). However, no study has been reported on the colour change kinetics of pumpkin during convective hot air drying process, with particular emphasis on the selection of a suitable kinetic model in predicting the colour stability.

The current industrial drying of pumpkin (*Cucurbita moschata*) is carried out at different temperatures, which may adversely affect the total carotenoid content. This current practice of using hot air dryers is also time consuming and greatly affected by parameters such as air velocity, air temperature and material thickness. The effect of these parameters on the drying process of pumpkin can be investigated by determining the drying kinetics. The use of drying kinetics to describe the combined macroscopic and microscopic medium of heat and mass transfer during drying is also essential in engineering designs. The drying kinetics of several food product have been determined using thin-layer models (Erbay and Icier, 2010), which are significant in deciding the ideal drying conditions, for process optimisation and product quality improvement (Giri and Prasad, 2007). Many mathematical thin layer models are available from literatures, however their application is determined by the type of material to be dried (Akpinar, 2006a; Doymaz, 2007; Guine *et al.*, 2011). Therefore, another challenge for engineers is to evaluate the most suitable thin layer model in order to develop a simulation that can predict the best drying time. With this, postharvest losses associated to hot air industrial drying of pumpkin will be greatly minimized thereby improving product quality and increasing food availability at an affordable cost to the populace and also generate great earnings to the farmers.

Furthermore, studies on drying of pumpkin do not consider the shrinkage effect. However, this phenomenon have been found to be a major factor in describing and optimizing the drying process of most fruits and vegetables. Therefore, the increasing demand for high quality and shelf-life dried pumpkin products requires optimization of the drying process conditions with the purpose of identifying optimal drying time, reduction in the total cost of production and improvement in the overall drying process efficiency. The knowledge of the drying kinetics and subsequently, the selection of an appropriate thin-layer drying model can be used to develop a simulation program in order to predict the best drying time, select appropriate drying conditions thereby optimizing the drying process. Particularly, the simulation program can adequately generate optimum drying parameters and time, the generated values can then be used on the dryers by the engineer or operator in the industry in order to reduce drudgery, reduce processing time, maintain product quality, maximize the energy required, thereby increasing the efficiency of the overall production process.

Several studies have proposed different models in determining the drying kinetics of various fruits and vegetables in hot air dryers (Erbay and Icier, 2010). The drying kinetics of Pumpkins (*C. maxima and C. pepo*) have also been investigated (Akpinar 2006a; Perez and Schmalko 2009; Guine *et al.,* 2011). However, there is no study on the best drying parameters (temperature, thickness and air velocity) and time for the convective hot air drying of pumpkin (*C. moschata*). In addition, no existing computer simulation program for modelling the drying kinetics of fruits and vegetables in general, and pumpkin (*Cucurbita moschata*) in particular. This gap in knowledge could affect process optimization and modelling the moisture changes during the post-harvest processing of pumpkin (*Cucurbita moschata*). Hence, a study of kinetic modelling for the drying process of pumpkins in a convective hot air dryer in order to develop a computer simulation program for identifying best drying time becomes indispensable. Thus, the following existing problems associated with the industrial drying of pumpkin (*Cucurbita moschata*) in Malaysia can be addressed:

- Inappropriate drying parameters
- Longer drying time leading to high cost of production
- Reduction in total carotenoid content during hot air drying.

As a consequence, the drying kinetics of pumpkins in a convective hot air dryer was investigated with a view to develop a computer simulation program for predicting the best drying conditions and time, and also describing the drying process. The model and simulation program could be used as a baseline for the drying processes of other tropical fruits and vegetables.

1.3 Objectives

The main objective of this study is to develop a computer simulation program for predicting the most suitable drying conditions and time of pumpkin (*Cucurbita moschata*) in a convective hot air dryer.

The specific objectives are:

i. To determine the drying kinetics of pumpkin using a convective hot air dryer and to identify the best thin layer drying model(s) for the development of simulation program.

ii. To estimate the moisture diffusivity and activation energy requirement of pumpkin during drying process.

iii. To determine the effect of drying on the texture, colour and total carotenoid yield.

1.4 Scope and Limitations

The study exclusively involved only thin layer convective hot air drying of pumpkin (*Cucurbita moschata*) at temperature range of 50 °C to 80 °C, thickness of 3 mm to 7 mm and constant air velocity of 1.2 m/s and limited to textural properties, colour and total carotenoid content determination.

1.5 Thesis Layout

The thesis consists of five chapters, and each chapter is divided into several sub-sections. Chapter one gives information about the background of the research, the knowledge gap, drawback, and statement of problem, specific objectives and the scope of study. Chapter two is the literature review. A review on pumpkin and physiochemical properties of pumpkin was carried out. Most importantly, modelling thin-layer drying of fruits and vegetables, and pumpkin in particular, was extensively and comprehensively reviewed so that readers will have a better understanding into thin layer kinetic modelling of the drying process of fruits and vegetables in general, and pumpkin in particular. Chapter three focused on methodology used in the drying experiments. This chapter also give insight on the procedures used in the colour, texture and carotenoid measurements. The different thin layer models, computer simulation and optimization process were well documented in this chapter. Chapter four presents the findings of the research. Particular emphasis on the drying rate curve, moisture ratio curve, effect of drying on colour, texture and carotenoid contents, and results of the developed computer simulation program were appraised in this chapter. Finally, the conclusions and recommendations based on the current research are presented in Chapter five.

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