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DEVELOPMENT OF CLOSED-LOOP CONTROL SYSTEM FOR MICROWAVE FREEZE-DRYING OF CARROT SLICES

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DEVELOPMENT OF CLOSED-LOOP CONTROL SYSTEM FOR MICROWAVE FREEZE-DRYING OF CARROT SLICES

By

NARATHIP SUJINDA

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

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Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirements for the Degree of Doctor of Philosophy

DEVELOPMENT OF CLOSED-LOOP CONTROL SYSTEM FOR MICROWAVE FREEZE-DRYING OF CARROT SLICES

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Chairman : Prof. Rosnah Shamsudin, PhD
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Microwave freeze-drying (MFD) is the process that applies the microwave as the energy source to freeze-dry the food product. It is a complex process due to the combination of microwave power, vacuum pressure, drying time, material temperature and moisture content that affects the drying rate, product quality, and energy consumption. The proper control of MFD process conditions to achieve the optimum drying performance and quality of products is a challenge for researcher. Therefore, the objective of this research was to design the MFD process strategy called dynamic microwave logic control (DMLC) and integrated into the closed-loop control (CLC) system for improving the MFD performance. In the first part of this research, the uncertainty of the measurement system and moisture content calculation was evaluated following the Guide to the expression of uncertainty in measurement or GUM (ISO, 2008) to verify the accuracy of the measurement systems and the calculation of the moisture content. The results show that the uncertainty of temperature measurement is ±1.5°C or 3.9% from full scale range of 30 – 50°C, the uncertainty of weight measurement is ±0.347 grams or 0.8% from full scale range of 0 – 150 grams, and the uncertainty of real-time moisture content calculation is ±1% (wet basis). As the results, the measurement systems were acceptable for using in the CLC system with no affected in terms of process control and product quality which confirm by the same later results in repetition of each treatment in this research. In the second part, the temperature variations during MFD of carrot slices was study by applying the closed-loop temperature control (CLT) system to control the carrot slices temperature in the final stage of MFD process. The MFD with CLT can improved the temperature control efficiency up to 60% compared to the MFD without CLT while provided the product quality similar to freeze drying (FD). Therefore, the CLT was applied to use with the MFD process for develop CLC system in the final part of this research. In the final part, the CLC system was developed to improve the MFD process and to examine the effects of a DMLC on the drying characteristics of MFD. The development consists of two sections. In the first section, the MFD process was examined to obtain the strategy for drying the carrot slices using microwave powers of 100 W, 200 W, and 300 W, with a temperature profile of the sample from -15°C to 40°C, and the final moisture content of 6% (wet basis). In the second section, the DMLC was strategically developed based on a drying-phase configuration and dynamic control between the microwave power and real-time moisture content sensing to provide feedback to the CLC system. After developed the DMLC, it was integrated into the CLC system. The results showed that applying the DMLC into the control logics, the CLC can work properly in MFD process by shortened the drying time by 62.4% and 23.4% compared with those of FD and MFD with no DMLC, respectively. The MFD-DMLC provided the final product with a quality equivalent to that of the FD process but achieved the 44.3% better SMER, which indicated the more efficient drying process with lower energy consumption. The findings from this research suggested that the DMLC based on the moisture content and temperature of the samples could be combined with the MFD process to enhance its efficiency while maintaining the superior quality of the FD process.

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PEMBANGUNAN SISTEM KAWALAN GELUNG TERTUTUP UNTUK PENGERINGAN SEJUK BEKU GELOMBANG MIKRO HIRISAN LOBAK MERAH

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Pengeringan sejuk beku mikrogelombang (PSBM) adalah proses yang menggunakan mikrogelombang sebagai sumber tenaga untuk mengering sejuk bekukan sesuatu produk makanan. Ini adalah proses yang rumit kerana kombinasi antara kuasa mikrogelombang, tekanan vakum, waktu pengeringan, suhu bahan, dan kandungan lembapan, akan mempengaruhi kadar pengeringan, kualiti produk, dan penggunaan tenaga. Pengawalan keadaan proses PSBM yang betul bagi mencapai prestasi pengeringan yang optimum dan kualiti produk adalah satu cabaran bagi penyelidik. Oleh itu, objektif kajian ini adalah untuk mereka strategi bagi proses PSBM yang disebut sebagai kawalan logik mikrogelombang dinamik (KLMD) dan diintegrasikan ke dalam sistem kawalan gelung tertutup (KGT) untuk meningkatkan prestasi PSBM. Pada bahagian pertama penyelidikan ini, ketidakpastian berkenaan sistem pengukuran dan pengiraan kandungan lembapan telah dinilai mengikut Panduan penyataan ketidakpastian dalam pengukuran atau GUM (ISO, 2008) untuk mentahkikkan ketepatan sistem pengukuran dan pengiraan kandungan lembapan. Hasil kajian menunjukkan bahawa ketidakpastian pengukuran suhu adalah ± 1.5ºC atau 3.9% dari julat berskala penuh 30 - 50ºC, ketidakpastian pengukuran berat adalah ± 0.347 gram atau 0.8% dari julat berskala penuh 0 - 150 gram, dan ketidakpastian pengiraan kandungan lembapan pada masa nyata adalah ± 1% (asas basah). Hasil kajian menunjukkan sistem pengukuran dapat diterima untuk digunakan di dalam sistem KGT tanpa menjejaskan kawalan proses dan kualiti produk yang kemudiannya disahkan oleh hasil keputusan yang sama dimana setiap rawatan diulangi dalam penyelidikan ini. Pada bahagian kedua, variasi suhu semasa PSBM irisan lobak merah dikaji dengan menerapkan sistem kawalan suhu gelung tertutup (KSGT) untuk mengawal suhu irisan lobak merah pada tahap akhir proses PSBM. PSBM dengan KSGT dapat meningkatkan kecekapan kawalan suhu sehingga 60% berbanding dengan PSBM tanpa KSGT, disamping dapat memberikan kualiti produk yang serupa dengan produk yang menggunakan proses pengeringan sejuk beku (PSB). Oleh itu, KSGT digunakan bersama dengan proses PSBM untuk membangunkan sistem KGT di bahagian akhir penyelidikan ini. Pada bahagian yang terakhir, sistem KGT dibangunkan untuk meningkatkan proses PSBM, dan untuk memeriksa kesan KLMD kepada ciri-ciri pengeringan PSBM. Pembangunan ini terdiri daripada dua komponen. Pada komponen yang pertama, proses PSBM diperiksa bagi memperoleh strategi untuk mengeringkan irisan lobak merah dengan menggunakan kuasa mikrogelombang pada 100 W, 200 W, dan 300 W, dengan profil suhu sampel dari -15ºC hingga 40ºC, dan kandungan lembapan yang terakhir adalah 6% (asas basah). Pada komponen yang kedua, KLMD dibangunkan secara strategi berdasarkan konfigurasi fasa pengeringan dan kontrol dinamik antara kuasa mikrogelombang dan pengesan kandungan lembapan pada masa nyata untuk memberikan maklum balas kepada sistem KGT. Setelah pembangunan KLMD, ia diintegrasikan ke dalam sistem KGT. Hasil kajian menunjukkan bahawa penerapan KLMD ke dalam logik kawalan, KGT dapat berfungsi dengan baik dalam proses PSBM dengan memendekkan waktu pengeringan masing-masing dengan 62.4% dan 23.4% berdasarkan perbandingan diantara PSB dengan PSBM tanpa KLMD. PSBM-KLMD memberikan kualiti akhir produk dengan kualiti yang setara dengan proses PSB tetapi mencapai 44.3% lebih tinggi berbanding SMER. Hasil kajian ini mencadangkan bahawa KLMD berdasarkan kandungan lembapan dan suhu sampel dapat digabungkan dengan proses PSBM untuk meningkatkan kecekapannya sambil mengekalkan kualiti proses PSB yang unggul.

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LIST OF ABBREVIATIONS

ANOVA	the analysis of variance
CLC	closed loop control system
CLT	closed loop temperature control system
DMLC	dynamic microwave logic control
EC	energy consumption
FD	freeze drying
MFD	microwave freeze-drying
OFT	optic fiber temperature sensor
OPC	open loop control system
RMSE	root mean square error
SMER	specific moisture extraction rate
SSE	sum of squared error
TDT	total drying time
USB	universal serial bus

LIST OF NOMENCLATURES

A_1	the coefficient of regression equation
a	the equation constants
B_1	the coefficient of regression equation
b	the equation constants
C_1	the coefficient of regression equation
c	the equation constants
D	the moisture diffusivity (m^2/s)
D_1	the coefficient of regression equation
D_{APP}	the apparent moisture diffusivity (m^2/s)
D_{AVG}	the average moisture diffusivity (m^2/s)
d	the equation constants
d_i	the diameter of the fresh carrot slices (m)
d_f	the diameter of the dried carrot slices (m)
F_0	the Fourier number
f	the functional relationship
h^*	the half thickness of slab (m)
k	the drying rate constant (min^{-1})
k_c	the coverage factor
L	the thickness of the carrot slices (m)
M	the moisture content (% wet basis)
M_e	the equilibrium moisture content (% wet basis)
M_f	the final moisture content (% wet basis)
M_i	the initial moisture content (% wet basis)
M_t	the initial moisture content at time t (% wet basis)
M_r	the real-time moisture content (% wet basis)
MR	the moisture ratio
$MR_{exp,i}$	the initial experimental moisture ratio

$MR_{pre,i}$	the initial prediction moisture ratio
N	the number of input quantity
n	the equation constants
n_t	the number of terms (a positive integer)
q	the expected value of a quantity
$\bar{q}$	the arithmetic mean
R	the equivalent radius
r	the cylinder radius
r^2	the corresponding values of coefficients of determination
$s(q_s)$	The experimental standard deviation
T_{air}	the air temperature (°C)
T_f	the final state temperature (°C)
T_h	the holding value of temperature (°C)
T_m	the pre-set values for the material temperature (°C)
T_r	the real-time material temperature (°C)
T_{rd}	the temperature reading of the OFT (°C)
T_x	the temperature measurement of the OFT
t	time (s)
t_p	the t-factor from the t-distribution table
U_{MC}	The uncertainty of real-time moisture content calculation (% wet basis)
U_T	the uncertainty of the temperature measurement (°C)
$U_{W,in}$	the uncertainty of the initial weight measurement (grams)
$U_{W,r}$	the uncertainty of the real-time weight measurement (grams)
U_y	the uncertainty of the measurement result
$u_{T,x}$	the combined standard uncertainty of the temperature measurement (°C)
$u_{T,rd}$	the standard uncertainty of the temperature reading (°C)
$u_{cb,t}$	the uncertainty of OFT base on its calibration data (°C)
$u_{cb,w}$	the uncertainty of load-cell base on its calibration data (grams)

$u_{rot,es}$	the estimated uncertainty of the load-cell due to the effect of the rotation tray (grams)
$u_{vc,es}$	the estimated uncertainty of OFT due to the effect of the vacuum pressure (°C)
$u_{W,rd}$	the standard uncertainty of the weight reading (grams)
$u_{W,x}$	the combined standard uncertainty of the weight measurement (grams)
$u_{x,i}$	the Type A standard uncertainty
u_y	the combined standard uncertainty
$u_{\Delta T,cert}$	the standard uncertainty of the OFT base on its calibration data correction (°C)
$u_{\Delta T,res}$	the standard uncertainty of the OFT resolution correction (°C)
$u_{\Delta T,vc}$	the standard uncertainty of OFT due to the effect of the vacuum pressure (°C)
$u_{\Delta W,cb}$	the standard uncertainty of the load-cell base on its calibration data (grams)
$u_{\Delta W,res}$	the standard uncertainty of the load-cell resolution (grams)
$u_{\Delta W,rot}$	the standard uncertainty of load-cell due to the effect of the rotation tray (grams)
$u_{\Delta W,vc}$	the standard uncertainty of load-cell due to the effect of the vacuum pressure (grams)
v_{eff}	the effective degrees of freedom
v_i	the degrees of freedom
$v_{T,eff}$	the effective degrees of freedom of the combined standard uncertainty of the temperature measurement
$v_{T,cb}$	the degrees of freedom of the standard uncertainty of the OFT base on its calibration data
$v_{T,rd}$	the degrees of freedom of the standard uncertainty of the temperature reading
$v_{T,res}$	the degrees of freedom of the standard uncertainty of the OFT resolution correction
$v_{T,vc}$	the degrees of freedom of the standard uncertainty of OFT due to the effect of the vacuum pressure
$v_{w,eff}$	the effective degrees of freedom of the combined standard uncertainty of the weight measurement

$v_{W,cb}$	the degrees of freedom of the standard uncertainty of the load-cell base on its calibration data
$v_{W,rd}$	the degrees of freedom of the standard uncertainty of the weight reading
$v_{W,res}$	the degrees of freedom of the standard uncertainty of the load-cell resolution
$v_{W,rot}$	the degrees of freedom of the standard uncertainty of load-cell due to the effect of the rotation tray
$v_{W,vc}$	the degrees of freedom of the standard uncertainty of load-cell due to the effect of the vacuum pressure
W_{in}	the initial materials weight (grams)
W_r	the real-time materials weight (grams)
W_{rd}	the weight reading of the load-cell (grams)
W_x	the weight measurement
X^2	the chi-square
X_N	the input quantity
x_N	the estimated input quantity
Y	the output of measured quantity
y	the measurement result
ΔT_{cb}	the temperature correction of the OFT reading based on its calibration data (^oC)
ΔT_{res}	the temperature correction due to the resolution of the OFT (^oC)
ΔT_{vc}	the temperature correction of the OFT due to the vacuum pressure (^oC)
ΔW_{cb}	the weight correction of the load-cell based on its calibration data (grams)
ΔW_{res}	the weight correction due to the resolution of the load-cell (grams)
ΔW_{rot}	the weight correction of the load-cell due to the effect of rotation tray (grams)
ΔW_{vc}	the weight correction of the load-cell due to the effect of the vacuum pressure (grams)

CHAPTER 1

INTRODUCTION

1.1 Significance of research

Freeze-drying (FD) has been suggested as a way for the storage of fruits and vegetables in the food industries. This method is considered the most appropriate for retaining the organoleptic and nutritional properties compared to other typical drying methods. Nonetheless, the disadvantage of FD is the time-consuming drying period that utilizes much energy. It has a high operation cost and high energy consumption, resulting from the inadequate heat supply operated through a heated plate from the exterior to the interior of the material being dried (Cao et al., 2018b; Wu et al., 2020). Hence, decreases in the drying period and energy usage, and retaining the product's quality are significant concerns that need to be resolved.

Microwave freeze-drying (MFD) is a drying process that applies microwave energy as a heating source to the FD process (Duan et al., 2010a). Thus, microwave energy offers an alternative heat source to reduce the drying period and energy usage (Cao et al., 2018a; Huang et al., 2009) while considerably increases the drying rate (Ozcelik et al., 2019) due to rapid heating in materials through the use of microwave energy. The heat generation by microwave energy in the materials involves two mechanisms: ionic polarization and dipole rotation. These mechanisms occur simultaneously, as the electrical oscillation induces the ions to align the ions within the electromagnetic field. The electromagnetic energy in this process is converted to kinetic energy and absorbed in all parts of the material (Song et al., 2018; Varith et al., 2007) which is influenced by the dielectric properties of food materials. For this reason, the MFD process can reduce the drying time by half (Duan et al., 2010b; Wang et al., 2010a) and up to 30% of the energy consumption while obtaining a product quality similar to FD (Jiang et al., 2013). Thus, MFD is an effective drying method that could solve the weakness of traditional FD. Moreover, microwave heating can eliminate microorganisms as well (Duan et al., 2007a)

In the MFD process, the complex parameters among the microwave power levels, moisture content, material temperature, and vacuum pressure affect the drying rate, product quality, and energy consumption. The higher microwave power could reduce the drying time and increase the drying rate by more than the lower power, but the higher microwave power could also result in low product quality (Ambros et al., 2018; Duan et al., 2007a; Wang et al., 2009). Additionally, the relationship between the microwave power levels, moisture content, and vacuum pressure level would need to be considered for the designing of the MFD process. This was because the possibility of corona discharging during the process could consume excessive microwave energy, burn the drying material, and damage the magnetrons (Duan et al., 2010b). Thus, it would be necessary to set the vacuum pressure to a range of 50 - 100 Pa to ensure that plasma discharge would not occur during the MFD process (Duan et al., 2008b; Li et al., 2019; Ren et al., 2015; Wang et al., 2009). The relationship among the material temperature, microwave power level, and moisture content of the material is also essential. This would affect the efficiency of the MFD process and the product quality of the result (Duan et al., 2010b). Ren et al. (2015) reported using a step-down microwave power loading scheme with mushrooms to be microwave freeze-dried to enhance their quality. Besides, Liu et al., 2017 found that the MFD process with a dynamic microwave loading scheme increased the mushrooms' porosity and shortened the drying time. According to dielectric properties, a multistage microwave loading scheme was also reported by Duan et al., 2012 and Li et al., 2019. These were able to reduce the drying time and obtain a better quality of dried products.

Even though the multistage microwave loading schemes proposed by Liu et al. (2017) and Duan et al. (2012) were not reported as real-time process control, they have shown a potential to the MFD process achieve better product quality and drying efficiency. Furthermore, Sujinda et al. (2020) examined MFD using a closed-loop temperature control system that incorporated a multistage microwave loading scheme. The results showed some improvement in the MFD process, which was denoted in this work as a dynamic microwave logic control (DMLC). There were two main types of loop control in the MFD process: the open-loop and closed-loop controls. The open-loop control system is a single communication format with no feedback to control the MFD process and relies upon the output of the process; for example, the on-off control of a magnetron with a fixed timing cycle in a household microwave oven. On the other hand, the closed-loop control (CLC) system is a process control with the feedback of the output, e.g., moisture content or temperature of the product, to modify the input; such as the power level of the microwave, so to achieve better efficiency in the drying process (Drof and Bishop, 2017; Mayr and Bryant, 1971)

To develop the condition of the MFD process and improve the efficiency of the CLC system, a study of the drying kinetics would be useful for understanding the MFD profiles and their characteristics and to optimize the MFD to maximize the quality of the products. The studies on MFD of cabbage by Duan et al. (2007) and MFD of onion slices by Abbasi and Azari, 2009 have proven that the findings from drying kinetics could be used as the basis for the optimization of the MFD process; such as increasing the microwave power in the first stage of MFD was able to increase the drying rate, and decreasing the microwave power in last stages of MFD was able to maintain the product quality. Moreover, moisture diffusivity was another index to indicate the efficiency of the MFD process. Past studies have also shown effective diffusivity in the MFD process due to the altered appearance of the drying material, e.g., porosity and shrinkage of the sample. Because of the excessive heat levels, while conducting MFD, the samples experienced a high internal vapor gradient that increased the pore formation and moisture diffusivity (Feng et al., 2001; Narjes et al., 2018; Sharma and Prasad, 2001; Wang et al., 2007a). Thus, using drying kinetics and moisture diffusion were proposed to develop the CLC system, which was able to explain the phenomena of the MFD process in each stage. If the focus on the drying kinetics and moisture diffusion were intended to select appropriate drying conditions and control MFD processes, a better understanding of the drying rate would help develop a CLC system to enhance the MFD process.

Therefore, this research aimed to develop the logical design of the DMLC for the CLC-MFD. The study involved developing a MFD drying strategy that led to the design of the CLC system with the DMLC in the later part. As a food model, Carrot slices were used in this work to evaluate the energy consumption and product quality to match that of the CLC-MFD. The researcher's goal was to enhance the efficiency of MFD and to improve the product quality when compared to that of the FD process.

1.2 Objective of research

1. To investigate the temperature variation during MFD of carrot slices using a closed-loop temperature control system (CLT) to improve temperature variations and study their effects on the product quality.
2. To develop a closed-loop control (CLC) system to improve the microwave freeze-drying (MFD) process.
3. To examine the effects of a dynamic microwave logic control (DMLC) on the drying characteristics of MFD.

1.3 Scope of research

This research involves designing a DMLC and developing a suitable CLC of microwave power levels in the range of 100 – 300 W at frequency 2.45 GHz for the MFD process. The MFD process was examined to obtain the drying strategy on the carrot slices using microwave power of 100, 200, and 300 W with a temperature profile of the sample range from -15^{o}C to 40^{o}C. The material thickness was 10 mm, the diameter of about 35 mm, the material weight of 100 g, the constant vacuum pressure of 100 Pa, and a cold trap temperature of -40^{o}C. The final moisture content of carrot slices for all MFD drying conditions and FD was 6% (wet basis). The DMLC was strategically developed based on the drying kinetics and drying characteristics of the MFD process. The drying time, color, texture, rehydration ratio, shrinkage, and energy consumption were compared with the FD to assess the performance of CLC-MFD.

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BIOADATA OF STUDENT

Narathip Sujinda was born in Thailand on 23rd May 1986. He attended primary and secondary school at Dara Academy, Chiang Mai, Thailand. In 2005, He was offered to continue his study at Maejo University (MJU), Chiang Mai, Thailand as a bachelor student of Food Engineering in the Faculty of Engineering and Agro-industry. In 2008, He had joined an Embedded Systems and RFID Innovation Camp and Contest, and he had been awarded the 1st prize (Electronics in Agriculture (Agritronics) Categories) from Thailand's National Electronics and Computer Technology Center (NECTEC). After graduated in 2009, He had experience worked at Crispy Veg and Fruit Co., Ltd. as Head of production and Engineer and was promoted to plant supervisor in the latter. In October 2011, He completed the master's program with a master's degree in Agricultural Process Engineering from the Faculty of Engineering and Agro-industry, Maejo University, and continue his study in Dual Degree Ph.D. Program between Maejo University, Thailand (MJU) and Universiti Putra Malaysia, Malaysia (UPM) under International Collaborative Program. In 2021, he had been awarded the Doctor of Engineering in Food Engineering from Maejo University and the Doctor of Philosophy in Agricultural Process Engineering from Universiti Putra Malaysia. In addition, he also has experience in the business of food engineering, agriculture technology and smart farming technology. He had been the founder and CEO of Quality Sense Engineering Co., Ltd from 2009 until 2021 while studying for a master's and Ph.D.

LIST OF PUBLICATIONS

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