Maejo Int. J. Sci. Technol. **2020**, *14*(01), 81-92

Maejo International Journal of Science and Technology

ISSN 1905-7873
Available online at www.mijst.mju.ac.th

Full Paper

Closed-loop temperature control during microwave freeze-drying of carrot slices

Narathip Sujinda [1, 2], Jaturapatr Varith [1, *], Somkiat Jaturonglumlert [1] and Rosnah Shamsudin [2]

[1] Graduate Program of Food Engineering, Faculty of Engineering and Agro-industry, Maejo University, Chiang Mai 50290, Thailand

[2] Department of Process and Food Engineering, Faculty of Engineering, Universiti Putra Malaysia, Selangor 43400, Malaysia

* Corresponding author, e-mail: varithj@gmaejo.mju.ac.th

Received: 11 November 2018 / Accepted: 16 March 2020 / Published: 23 March 2020

Abstract: Temperature variations during microwave freeze-drying (MFD) of carrot slices and how closed-loop temperature control (CLT) improved such variations were investigated. The carrot slices were dried to a final moisture content of 6% with a terminal temperature of 40ºC using 100-watt microwave power under 100-Pa vacuum pressure. The results showed that the MFD process consisted of two phases, viz. sublimation and desorption drying. In the sublimation drying phase, ice, due to its low dielectric permittivity, absorbed little microwave energy. This caused a slow rising of temperature of carrot slices at the early stage of drying. After the moisture decreased below 45%, the sample temperature increased sharply until it reached the temperature of the chamber, indicating the onset of desorption drying phase. In this phase, the sample temperature rose faster than that in the sublimation phase. Without CLT, the temperature of carrot slices varied by 25ºC in the desorption drying phase of MFD. After applying CLT to the MFD process, the variation in temperature of the carrot slices was reduced to 11ºC, equivalent to a temperature control improvement of 56%. The MFD with CLT system also significantly reduced the drying time and energy consumption by 35-40%.

Keywords: carrot slices, microwave freeze-drying, sublimation, desorption, closed-loop temperature control

Maejo Int. J. Sci. Technol. **2020**, *14*(01), 81-92

INTRODUCTION

Freeze-drying (FD) is considered a premium drying method normally used to achieve high-quality frozen food products. However, this technique requires low temperature and high vacuum pressure. It also requires a long drying cycle and becomes costly due to high energy consumption, particularly in industrial applications [1]. Reductions in processing time and cost of energy consumption for freeze drying while maintaining the quality of the final product are essential developments that need to be addressed. Previous research suggested that microwave radiation could be a superior alternative heat source in the FD process since it helps reduce energy consumption and drying time [2-4]. The rapid volumetric heat due to microwave energy in biological materials is known to involve two mechanisms: a dipole rotation and ionic conduction. These occur simultaneously when the ions are induced by the electrical oscillation to align with the electromagnetic field. The electromagnetic energy in this process is converted to kinetic energy and absorbed in all parts of the material [5, 6]. This generation of microwave heating as a heat source can be beneficial to the FD process as it may resolve the problems of long processing time and high energy consumption.

Microwave freeze-drying (MFD) utilises microwave energy as an energy source for FD, which shortens the drying time [7]. Many studies have examined MFD technology with a specific focus on the development of heat and mass transfer models to achieve the best heat and mass transfer rates [8-12]. The studies have mainly highlighted the effect of MFD on food materials such as cabbage [13] and sea cucumber [14, 15]. MFD and vacuum pressure were found to affect the internal structure and quality of potato slices compared to FD [16]. Similarly, at a constant vacuum pressure of 100-Pa, MFD treatment affected the characteristics of banana crisps as well as those of dried onion slices [17-19]. Ren et al. [20] reported that a step-down microwave power loading scheme in MFD of mushrooms is recommended for achieving a higher level of quality. Liu et al. [21] used a dynamic microwave loading scheme based on porosity during the MFD process to reduce the drying time and maintain excellent product quality. It was later concluded that MFD had a positive impact on the quality and time of processing of food products. However, no study has examined temperature variations during the MFD process for food products.

In general a fixed level of microwave power is used throughout the entire microwave drying process. Further, the temperature of the drying sample is usually not controlled. As a result, an increase in the temperature of the sample to an unpleasantly high level can cause product charring at the last stage. When microwave drying is combined with freeze-drying, the problem becomes more complex due to temperature variations [22]. To improve this, temperature control during MFD can be applied. Temperature control can be done either by open-loop control or closed-loop (feedback) control. The open-loop control system is dependent on the process input while the closed-loop control system is dependent on the output [23]. The difference between the open- and closed-loop control systems is the presence of feedback in the closed-loop system. In a closed-loop system the accuracy of control is increased when the feedback is passed back from the output to the control system to adjust the input [24-26]. The relationship of one system variable to another is maintained by considering the different functions of the variables in which the difference is used as a controlling method. In this study a closed-loop temperature control (CLT) system was employed in MFD to monitor

Maejo Int. J. Sci. Technol. **2020**, *14*(01), 81-92

the material temperature and feedback signal so that a constant material temperature could be maintained. The objective of this research is to investigate the temperature variation during MFD of carrot slices using CLT to improve temperature variations and study its effects on the product quality.

MATERIALS AND METHODS

Sample Preparation

Fresh carrots stored at 4 ± 0.5ºC were used in this study. The carrots were trimmed, peeled, washed and sliced to a thickness of 10-mm. The sliced sample was frozen at -35ºC for at least 8 hr before MFD and FD treatments.

Microwave Freeze-dryer

Figure 1 exhibits the schematic diagram of a laboratory-scale microwave freeze-dryer used in this work. The dryer consisted of a rotating tray inside the MFD chamber. A load cell connected under the tray was situated in the middle of the drying chamber to determine the weight loss of the sample during the drying process. The transmitter output of the load-cell was connected to a signal converter, a data-logger and a personal computer to estimate real-time weight loss. Vapour condensation during the drying process was accomplished by using a cold trap at -40°C. Constant vacuum pressure at 100 Pa was applied inside the MFD chamber where the samples were placed. A magnetron to generate microwave at 2.45 GHz was used with power adjustable from 0 to 1,100 watt with a 100-watt increment. The position of magnetron installation was the same as in a household microwave oven to ensure that the wave radiated evenly. The temperatures of the sample and drying chamber were detected with type-K thermocouple probes shielded with stainless steel (SS316) in a cylindrical shape that can operate in a microwave field [27, 28]. One probe with a diameter of 1.5 mm was attached to the sample while another with a diameter of 4.0 mm was used to monitor the temperature of the MFD drying chamber. To continuously record the temperature, the thermocouples were connected to a transmitter and a data-logger, which enabled data to be transmitted to a personal computer.

Experimental Procedure

Experimentation was conducted using three drying methods, namely FD, MFD without CLT, and MFD with CLT.

FD: The experiment was conducted using a freeze-dryer (Model Scanvac Coolsafe 110-4, Labogene ApS, Denmark). The cooling system was set at -40ºC. One hundred grams of the sample with 10-mm material thickness were dried at 100-Pa constant vacuum pressure until the sample moisture content was reduced to 6% (wet basis). Material temperature was monitored, but not controlled.

MFD without CLT: The experiment was conducted at a fixed microwave power of 100 watts. The cooling system was set at -40 ºC. One hundred grams of the sample with 10-mm material thickness were dried at 100-Pa constant vacuum pressure until the moisture content was reduced to 6%. Material temperature was monitored, but not controlled. The microwave was controlled with the on/off duty cycle operation of the magnetron.

Maejo Int. J. Sci. Technol. **2020**, *14*(01), 81-92

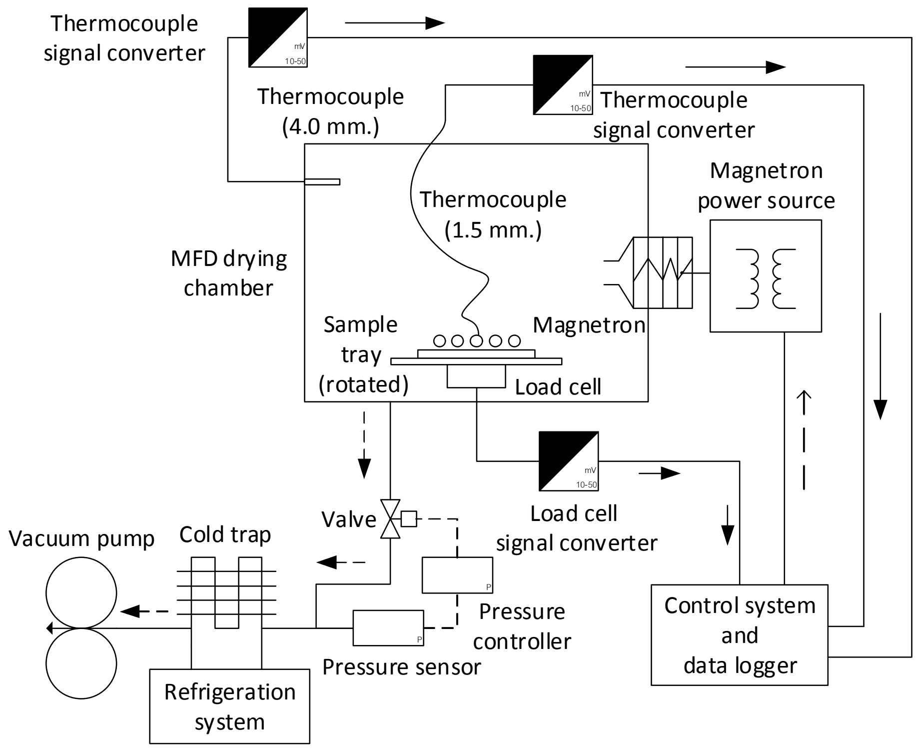

Figure 1. Schematic diagram of laboratory-scale microwave freeze-dryer

MFD with CLT: The experiment was conducted by applying a microwave power of 100 watts with CLT at a constant temperature of 40°C. The temperature of the cooling systems was set at -40°C. One hundred grams of the sample with 10-mm material thickness were dried at a constant vacuum pressure of 100 Pa until the sample moisture content was reduced to 6%.

All experiments were carried out in triplicate to obtain the average material temperature and moisture content. In all the treatment conditions, the dried samples were stored in aluminium foil bags and sealed for further qualitative analysis. The temperature curve and drying curve of the material were analysed using the average of its temperature and moisture content.

Qualitative Analyses of Samples

Colour analysis

A spectrophotometer (MiniScan XE Plus model, Hunter Associates Laboratory Inc., USA) was used to measure the colour of the dried samples. A certified standard white and black plate was used to calibrate the spectrophotometer. Three spots on the sample were randomly selected for measurement. CIE-lab scale, namely L*, a*, and b*, was used to indicate colour quality, where the luminance or lightness was expressed by L*. For the two chromatic components, green to red colour quality was expressed by a* while blue to yellow colour quality was expressed by b*.

Texture analysis

A texture analyser (TA-XT2, Stable Micro System Ltd., UK) with a 2-mm-diameter cylinder probe was used to measure the texture of the dried samples. The samples were tested using a probe with pre-test, penetrating and post-test speeds of 2, 2 and 3 mm/s respectively. The deformation ratio was set at 50% and the trigger force was 20 g. Texture Exponent 32 software (Stable Micro System Ltd., UK) was used to record and analyse a force-time curve. The maximum force required to break a 10-mm-thick sample was defined as the hardness. Fracturability, a property used to identify the crispiness of a sample, was analysed using the first peak of force at which the first significant break occurred in the curve between the starting point and the highest peak.

Rehydration ratio

Three grams of dried carrot samples were immersed in 300 ml of distilled water at 25ºC, periodically sampled out and weighed after draining excessive water to evaluate the rehydration ability. The rehydration ratio was calculated (= weight of rehydrated sample/weight of dried sample). Analysis was done in triplicate.

Energy consumption

Total energy consumption during MFD was calculated from the input microwave power (100 watts), the cold trap system, and the vacuum pump power (100 Pa). During the FD process, the energy consumption only involved the input cold trap system and the vacuum pump power. Measurement was done using a power meter (PZEM-061, Ningbo Peacefair Electronic Co., China). The reading obtained in kWh was converted to MJ (1 kWh = 3.6 MJ).

Statistical Analysis

Analysis of variance (ANOVA) was conducted using SPSS 24.0 (SAS Institute Inc., USA). Significant difference ($p < 0.05$) was determined using Duncan's test.

RESULTS AND DISCUSSION

Variation of Temperature during MFD Process

Figure 2 presents variations of temperature of the carrot slices and the drying chamber versus moisture content during FD, MFD without CLT, and MFD with CLT of carrot slices at the microwave power of 100 watts and the terminal temperature of 40°C. The results show that the traditional FD process requires a longer drying time (15 hr) due to the low heat transfer rate inside the samples at low vacuum pressure [29], while MFD and MFD with CLT requires a shorter drying time (9 hr) due to the volumetric-heat generation inside the samples [5, 6].

In Figure 2, both MFD with and without CLT process clearly show two phases. The first, the sublimation phase, exhibits a gradual increase in temperature. The second, the desorption phase, comprises an initial sharp increase followed by a slower increase in sample temperature until the terminal moisture content is achieved. During the sublimation phase, the ice sublimes until the moisture content drops to approximately 45%. After that, the sample temperature increases sharply until it reaches the chamber temperature, which indicates the onset of the desorption phase. Thus, the moisture content of 45% can be regarded as the

Maejo Int. J. Sci. Technol. **2020**, *14*(01), 81-92

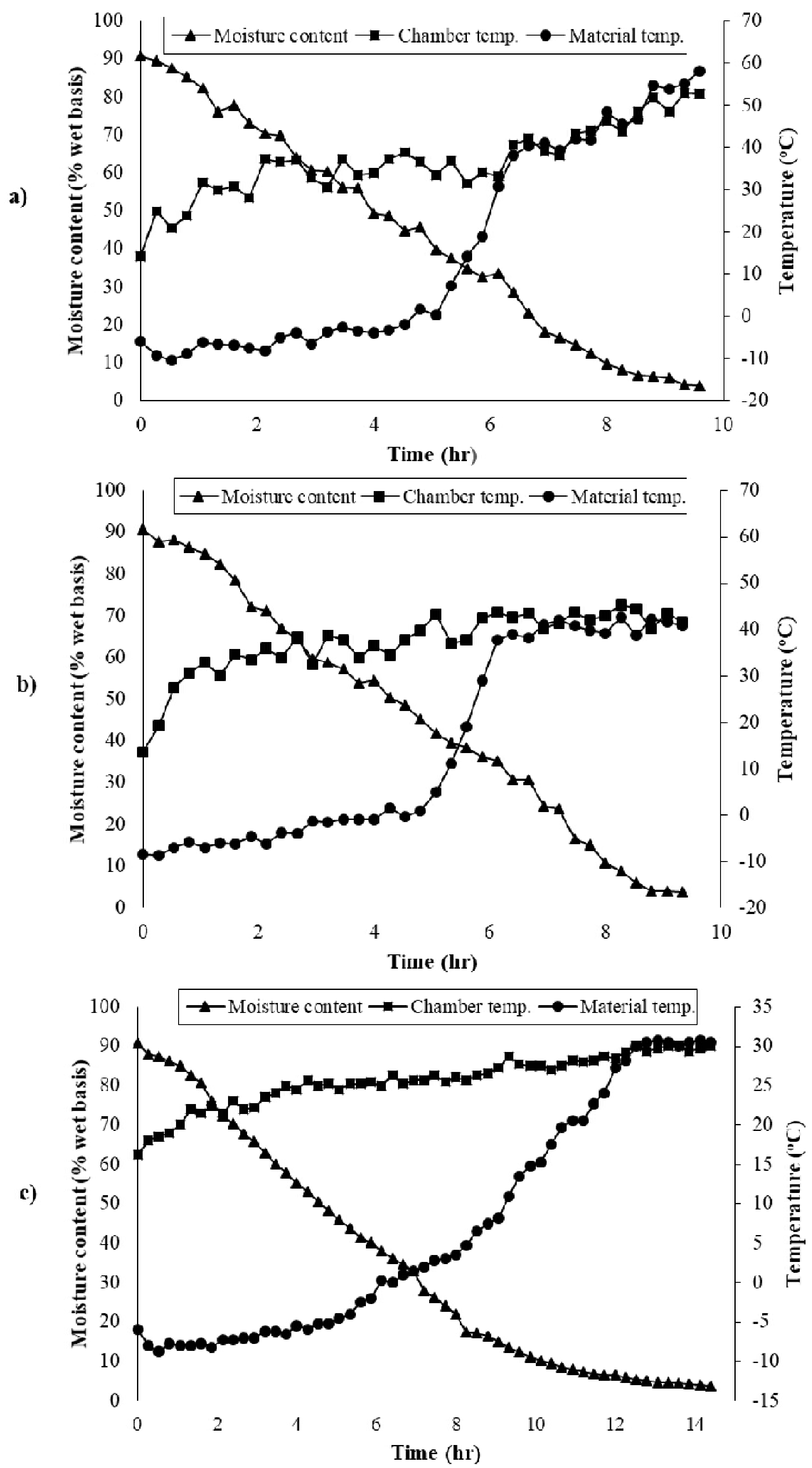

Figure 2. Moisture content and temperature of carrot slices and drying chamber from different drying methods: (a) MFD; (b) MFD with CLT; (c) FD

transition moisture content and denotes the end-point of sublimation and the onset of the desorption phase.

In the sublimation phase the ice absorbs a small amount microwave energy at the beginning since the water molecules in the ice are locked by hydrogen bonds in a crystal structure [30]. These bonds inhibit the water molecules from rotating, which results in a low dielectric permittivity of ice. This phenomenon causes an initial slow increase in material temperature. At the onset of the desorption phase when the moisture content is reduced below the transition moisture content of 45%, the product temperature exhibits an initial sharp increase that later flattens out until it reaches the temperature of the chamber. It is possible that the majority of ice may have already sublimed in this phase and only non-frozen water remains inside the carrot. The non-frozen water can then absorb the energy generated from the microwave in the desorption phase better than in the sublimation phase due to the increased effectiveness of the dipole rotation and oscillation of ions.

In the desorption phase the temperature of the carrot slices dried with MFD without CLT increases continuously until the end of the process. Due to a high temperature variation in this process, the products became charred. In the MFD with CLT process, however, the variation in the temperature of the carrot slices in the desorption drying phase is less than that occurring in the non-CLT system. This results in a more-desired quality of the final products.

Control of Temperature Variation in MFD with CLT Process

When the CLT was implemented in the MFD process by using feedback temperature control to maintain a constant final product temperature of 40ºC, the temperature variation in the sample was reduced. Figure 3 compares the temperature profile of MFD with CLT to that of MFD without CLT at a microwave power of 100 watts using an on/off cycle during the sublimation and desorption phases. For both methods, the on/off cycle continued until the desired moisture content of the carrot slices was achieved. In MFD without CLT process the temperature of the material increased continuously from the 7.5^{th} hr of drying time to the end. The sample temperature reached over 60ºC between the 8^{th} - 9^{th} hr of drying time. At this stage, the temperature fluctuation was in a range of 45-70ºC, i.e. 25º fluctuation. With this high and wide-range temperature variation, the charring of the carrot slices was observed, which negatively affected the quality of the final product. In contrast, the MFD with CLT system provided better control of the temperature variation, which was in a range of 34-45ºC or 11º fluctuation. This accounted for 56% improvement in temperature control efficiency. With better temperature variation control using CLT, the product quality was better than that obtained from the non-CLT system.

It should be noted that the results were still less effective in the desorption phase, even though the on/off cycle of the magnetron was well controlled to maintain the product temperature in the sublimation phase. With the CLT system, as the magnetron was turned on, the carrot temperature increased and overshot the desired final temperature of 40ºC. At the 6^{th} hr of drying time with the CLT system, the temperature reached 46ºC in most cases. In some treatments, the feedback signal in the CLT requested the magnetron to be “off”. However, the physical duty cycle was still in the “on” status and could not be turned off until the cycle finished. As the magnetron was still in the “on” cycle, the sample temperature increased

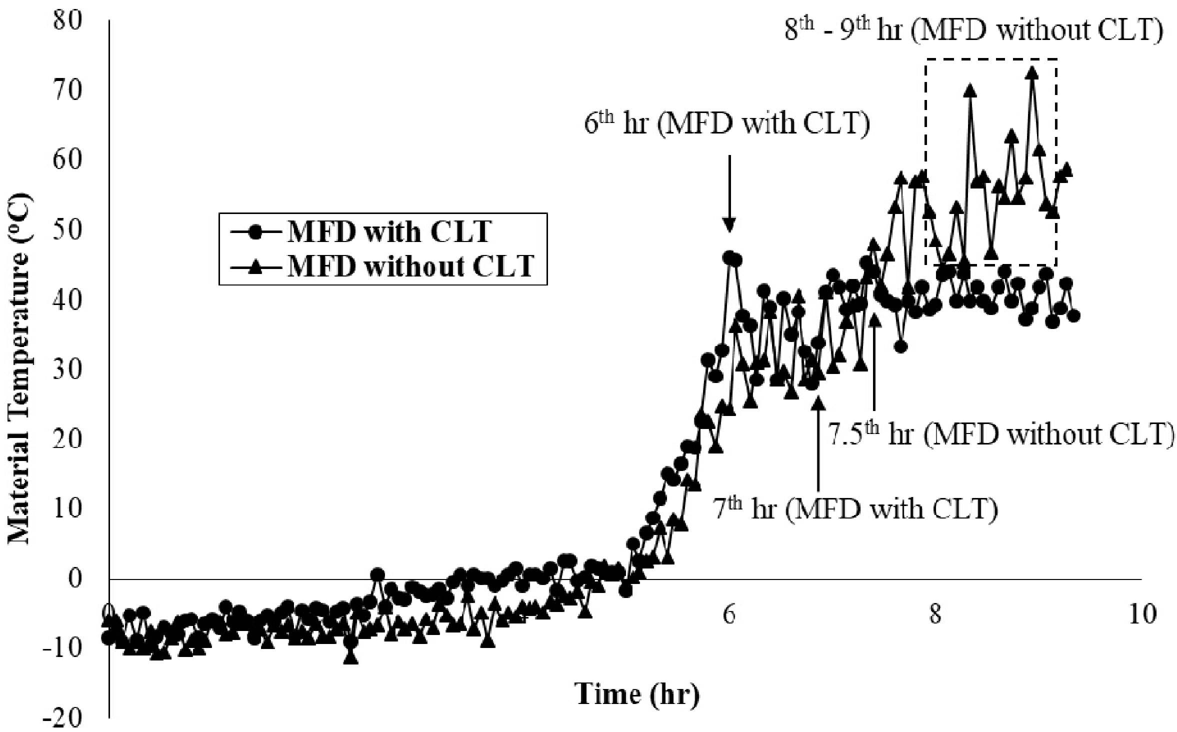

Figure 3. Temperature curve of carrot slices in MFD with CLT compared to MFD without CLT at 100-watt microwave power

continuously and overshot. On the other hand, when the duty cycle was "off" but the feedback signal in the CTL requested "on", the magnetron remained off until the cycle finished. This caused the sample temperature to decrease continuously and undershoot (Figure 3 at the 7th hr). Thus, even though the CLT can control the temperature fluctuation better within a temperature of 11°C compared to 25°C the without CLT, a more efficient feedback control to minimise temperature fluctuation is of interest in the future. From this work, it seems that the on/off duty cycle provides good control of the magnetron at the sublimation stage with a temperature fluctuation range of 5°C. Thus, it is suggested that further development of the process control for MFD should involve the control system being divided into two stages. For the sublimation stage, the microwave power on/off cycle should be designated. For the second stage of desorption, the coupled feedback CLT system with logic control is proposed to achieve a better temperature control.

Quality of Products and Energy Consumption

The overall colour of the carrot dried using MFD with CLT was not significantly different ($p \geqslant 0.05$) from that using FD, nor was there any significant difference in the rehydration ratio, crispiness or hardness, as shown in Table 1. In comparing the energy consumption both the MFD with and without CLT consumed about 40% less energy than did the FD due to a significant reduction in drying time. However, MFD without CLT yielded a less desired product quality due to temperature overshooting during the end of the desorption phase, which resulted in a significant decrease in L* and an increase in a* and b* values, as

Maejo Int. J. Sci. Technol. **2020**, *14*(01), 81-92

indicated by the darker colour of the carrot slices. It also resulted in the charring of the carrot sample, which negatively affected the quality of the final product.

Table 1. Product quality and energy consumption obtained from different drying methods

	FD	MFD without CLT	MFD with CLT
Product quality			
L*	64.69 ± 2.79^{a}	47.68 ± 4.53^{b}	61.02 ± 4.37^{a}
a*	25.16 ± 3.06^{a}	32.07 ± 3.31^{b}	27.99 ± 2.61^{a}
b*	29.79 ± 1.46^{a}	37.07 ± 2.32^{b}	33.34 ± 6.06^{ab}
Crispness (kg.s)	3.58 ± 0.22^{a}	3.95 ± 0.61^{b}	3.77 ± 0.27^{ab}
Hardness (kg)	0.80 ± 0.11^{a}	1.08 ± 0.29^{b}	0.97 ± 0.19^{ab}
Rehydration ratio	5.66 ± 0.12^{a}	5.31 ± 0.17^{a}	5.44 ± 0.42^{a}
Energy consumption (MJ)	5.33 ± 0.03^{a}	3.34 ± 0.02^{b}	3.27 ± 0.03^{b}

Note: Values followed by the same superscript letters within the same row are not significantly different from each other ($p \geqslant 0.05$).

The effects of temperature variation from the different drying processes can be physically observed, as shown in Figure 4. The removal of water during the drying process affects the appearance of the final product as rapid water loss causes the hardness of the sample to increase. The samples were observed to retain their initial shapes with minor shrinkage in all drying methods, which is due to the fact that the removal of moisture from the sample occurred under low vacuum pressure, low temperature and low microwave power. These observations are in good agreement with the findings in other studies [15, 31-33].

(a) (b) (c)

Figure 4. Dried carrot slices from different drying methods: (a) FD; (b) MFD with CLT; (c) MFD without CLT

Maejo Int. J. Sci. Technol. **2020**, *14*(01), 81-92

CONCLUSIONS

Our findings indicate that MFD with CLT positively reduces the variation in temperature of carrot slices during the desorption drying phase by 56% compared to MFD without CLT. The drying time and energy consumption of the MFD with CLT are also reduced by 35-40% while product quality similar to that by FD process is obtained. In future work, improvement in the process involving a more accurate temperature feedback control to obtain a smoother temperature control in the desorption drying phase is suggested. Besides, a more sophisticated CLT system should be introduced to improve the efficiency of the MFD process.

REFERENCES

1. X. Duan, G. Y. Ren and W. X. Zhu, "Microwave freeze drying of apple slices based on the dielectric properties", *Drying Technol.*, **2012**, *30*, 535-541.
2. S. Ambros, M. Oezcelik, E. Dachmann and U. Kulozik, "Microwave freeze drying of fruit foams for the production of healthy snacks", *World Acad. Sci. Eng. Technol.*, **2017**, *11*, 1135-1135.
3. X. Cao, M. Zhang, A. S. Mujumdar, Q. Zhong and Z. Wang, "Effect of microwave freeze-drying on quality and energy supply in drying of barley grass: Freeze/microwave freeze drying on barley grass", *J. Sci. Food Agric.*, **2017**, *98*, 1599-1605.
4. L. Huang, M. Zhang, A. S. Mujumdar, D. Sun, G. Tan and S. Tang, "Studies on decreasing energy consumption for a freeze-drying process of apple slices", *Drying Technol.*, **2009**, *27*, 938-946.
5. C. Song, T. Wu, Z. Li, J. Li and H. Chen, "Analysis of the heat transfer characteristics of blackberries during microwave vacuum heating", *J. Food Eng.*, **2018**, *223*, 70-78.
6. J. Varith, P. Dijkanarukkul, A. Achariyaviriya and S. Achariyaviriya, "Combined microwave-hot air drying of peeled longan", *J. Food Eng.*, **2007**, *81*, 459-468.
7. X. Duan, M. Zhang, A. S. Mujumdar and R. Wang, "Trends in microwave-assisted freeze drying of foods", *Drying Technol.*, **2010**, *28*, 444-453.
8. J. I. Lombraña, I. Zuazo and J. Ikara, "Moisture diffusivity behavior during freeze drying under microwave heating power application", *Drying Technol.*, **2001**, *19*, 1613-1627.
9. Z. Tao, H. Wu, G. Chen and H. Deng, "Numerical simulation of conjugate heat and mass transfer process within cylindrical porous media with cylindrical dielectric cores in microwave freeze-drying", *Int. J. Heat Mass Transfer*, **2005**, *48*, 561-572.
10. W. Wang and G. Chen, "Numerical investigation on dielectric material assisted microwave freeze-drying of aqueous mannitol solution", *Drying Technol.*, **2003**, *21*, 995-1017.
11. W. Wang and G. Chen, "Heat and mass transfer model of dielectric-material-assisted microwave freeze-drying of skim milk with hygroscopic effect", *Chem. Eng. Sci.*, **2005**, *60*, 6542-6550.
12. Z. H. Wang and M. H. Shi, "Numerical study on sublimation-condensation phenomena during microwave freeze drying", *Chem. Eng. Sci.*, **1998**, *53*, 3189-3197.
13. X. Duan, M. Zhang, and A. S. Mujumdar, "Studies on the microwave freeze drying technique and sterilization characteristics of cabbage", *Drying Technol.*, **2007**, *25*, 1725-1731.

14. X. Duan, M. Zhang, X. Li and A. S. Mujumdar, "Microwave freeze drying of sea cucumber coated with nanoscale silver", *Drying Technol.*, **2008**, *26*, 413-419.
15. X. Duan, M. Zhang, A. S. Mujumdar and S. Wang, "Microwave freeze drying of sea cucumber (*Stichopus japonicus*)", *J. Food Eng.*, **2010**, *96*, 491-497.
16. R. Wang, M. Zhang, and A. S. Mujumdar, "Effects of vacuum and microwave freeze drying on microstructure and quality of potato slices", *J. Food Eng.*, **2010**. *101*, 131-139.
17. S. Abbasi and S. Azari, "Novel microwave–freeze drying of onion slices", *Int. J. Food Sci. Technol.*, **2009**, *44*, 974-979.
18. H. Jiang, M. Zhang, Y. Liu, A. S. Mujumdar and H. Liu, "The energy consumption and colour analysis of freeze/microwave freeze banana chips", *Food Bioprod. Process.*, **2013**, *91*, 464-472.
19. H. Jiang, M. Zhang and A. S. Mujumdar, "Microwave freeze-drying characteristics of banana crisps", *Drying Technol.*, **2010**, *28*, 1377-1384.
20. G. Y. Ren, F. L. Zeng, X. Duan, L. L. Liu, B. Duan, M. M. Wang, Y. H. Liu and W. X. Zhu, "The effect of glass transition temperature on the procedure of microwave-freeze drying of mushrooms (*Agaricus bisporus*)", *Drying Technol.*, **2015**, *33*, 169-175.
21. W. C. Liu, X. Duan, G. Y. Ren, L. L. Liu and Y. H. Liu, "Optimization of microwave freeze drying strategy of mushrooms (*Agaricus bisporus*) based on porosity change behavior", *Drying Technol.*, **2017**, *35*, 1327-1336.
22. Z. Li, G. S. V. Raghavan and V. Orsat, "Temperature and power control in microwave drying", *J. Food Eng.*, **2010**, *97*, 478-483.
23. J. J. Distefano, A. Stubberud and I. J. Williams, "Schaum's Outline of Feedback and Control Systems", 2nd Edn., McGraw-Hill, New york, **1995**, p.512.
24. O. Mayr, "The Origins of Feedback Control", 1st Edn., MIT Press, Cambridge (MA), **1970**, p.151.
25. R. C. Drof and R. H. Bishop, "Modern Control System", 11th Edn., Prentice Hall, Upper Saddle River, **2007**, p.1007.
26. S. Simrock, "Tutorial on control theory", Proceedings of International Conference on Accelerator and Large Experiment Physics Control Systems, **2011**, WTC Grenoble, France.
27. D. Luan, J. Tang, P. D. Pedrow, F. Liu and Z. Tang, "Performance of mobile metallic temperature sensors in high power microwave heating systems", *J. Food Eng.*, **2015**, *149*, 114-122.
28. D. Luan, J. Tang, P. D. Pedrow, F. Liu and Z. Tang, "Using mobile metallic temperature sensors in continuous microwave assisted sterilization (MATS) systems", *J. Food Eng.*, **2013**, *119*, 552-560.
29. A. M. Ceballos, G. I. Giraldo and C. E. Orrego, "Effect of freezing rate on quality parameters of freeze dried soursop fruit pulp", *J. Food Eng.*, **2012**, *111*, 360-365.
30. M. Tanaka and M. Sato, "Microwave heating of water, ice, and saline solution: molecular dynamics study", *J. Chem. Phys.*, **2007**, *126*, 034509.
31. R. Wang, M. Zhang and A. S. Mujumdar, "Effect of osmotic dehydration on microwave freeze-drying characteristics and quality of potato chips", *Drying Technol.*, **2010**, *28*, 798-806.

Maejo Int. J. Sci. Technol. **2020**, *14*(01), 81-92

32. R. Wang, M. Zhang, A. S. Mujumdar and J. C. Sun, "Microwave freeze-drying characteristics and sensory quality of instant vegetable soup", *Drying Technol.*, **2009**, *27*, 962-968.
33. Q. Zhang, G. Zhang, G. Mu and Y. Liu, "Freeze and microwave vacuum combination drying technique for sea cucumber", *Int. J. Agric. Biol. Eng.*, **2012**, *5*, 83-89.