Hybrid (Osmotic, Microwave-vacuum) Drying of Strawberries and Carrots

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ABSTRACT

The main purpose of this study was to improve the performance of microwave assisted drying. The osmotic treatment was used as pretreatment due to its inherent low energy requirement attributes. The vacuum was applied to microwave drying system to capture low temperature vaporization concepts. The whole process might be called "osmotically dehydrated microwave vacuum drying". Carrots and strawberries were selected to study as a representative of vegetables and fruits, respectively.

The laboratory scale microwave vacuum dryer was setup and the preliminary tests were done with carrots and strawberries. The occurrence of condensation of vapor in vacuum container was found during the drying trials. The location of the open-ended valve which controls the vacuum level was found to have an influence on the condensation. The re-location of valve which allowed air passage to the vacuum container was able to decrease the condensation. The input power for the microwave vacuum drying could not be greater than 1.5 W/g. The continuous use of input power caused the high temperature in the process. The pulse mode (on/off) was recommended for further studies.

Water removal and solid gain of osmotic treatment were considered as factors that affect the dielectric properties dielectric constant (ε') and the loss factor (ε"). The experiment was set up to investigate the influence of osmotic conditions to dielectric properties. Two osmotic agents, sucrose and salt, were used for carrots; but only sucrose was used for strawberries. The effects of variations in sucrose and salt concentrations, solution temperatures, and length of immersion time on the dielectric properties were studied. The empirical models were generated from response surface methodology (RSM) to predict ε' and ε" for the various ranges of osmotic conditions considered in this thesis.

As a consideration of the osmotic pre-drying treatment, it was considered appropriate to maximize water loss (WL) and minimize solid gain (SG). The parameter appropriate to study this situation was WL/SG. The optimum conditions of osmotic process to acquire the maximum ratio of WL/SG were investigated. The results of the optimum conditions for carrots were found to be sucrose concentration 50%(w/w), salt concentration 5%(w/w), temperature 20ºC and immersion time 3 hours 38 minutes. The optimum conditions for strawberries were found to be sucrose concentration 60 %(w/w), temperature 20ºC and immersion time 24 hours.

The microwave vacuum drying was then studied as a technique combined with the osmotic pretreatment. The studies were performed on carrots and strawberries. The input power levels 1 and 1.5 W/g with different power modes (continuous, 45s on/15s off and 30s on/30s off) were experimentally studied with a certain condition of osmotic treatment, which was acquired from the previous study. Osmotic treatment prior to microwave vacuum of carrots showed the advantage in most cases; fast drying time, less energy consumption and superior quality aspects except the taste which was affected from the salt. The study of strawberries did not show great advantage of osmotic pretreatment. The drying time and energy consumption of the process with and without osmotic pretreatment were the same but the process with osmotic pre-treatment resulted in better quality of dried strawberries.

The microwave vacuum drying of carrots and strawberries after osmotic pretreatment did not show constant rate period in drying rate curve while the processes without osmotic treatment of strawberries showed longer constant rate period than those observed for carrot drying. According to these phenomena, thin layer models of Lewis and Henderson & Pabis were fitted to the observed data which showed excellent fit for the process without constant rate period; but Page's model was a good fit for both constant rate and falling rate period of microwave vacuum drying.

RÉSUMÉ

Le but principal de cette étude était d'améliorer l'exécution du séchage micro-onde. Un traitement osmotique a été employé comme prétraitement pour ses qualités de concentration à faible besoin en énergie. Le vide a été appliqué au système de séchage micro-onde pour bénéficier des concepts de vaporisation à basse température. Le processus de séchage peut donc s'intituler « séchage micro-onde sous vide de produits osmotiquement déshydratés ». Des carottes et des fraises ont été choisies pour cette étude à titre de légumes et de fruits, respectivement.

L'équipement de laboratoire de micro-onde sous vide a été mis au point et des essais préliminaires ont été faits avec des carottes et des fraises. De la condensation de la vapeur s'est retrouvée dans le récipient sous vide pendant les essais de séchage. L'emplacement de la valve qui régule le niveau de vide s'est avéré influencer la présence de condensation. La relocalisation de cette valve a permis le passage d'air dans le récipient de vide diminuant ainsi la condensation. La puissance d'entrée pour le séchage micro-onde sous vide n'a pas pu être plus élevée que 1.5 W/g. L'utilisation en continu de la puissance d'entrée micro-onde a entraîné la hausse de la température lors du séchage. Le mode d'impulsion ("Marche/Arrêt") a été recommandé pour les études subséquentes.

L'extraction d'eau et l'apport de matières solides du traitement osmotique ont représentés des facteurs influençant les propriétés diélectriques (la constante diélectrique (ε') et le facteur de perte (ε")). L'étude à été formulée afin d'établir l'influence des conditions osmotiques et des propriétés diélectriques. Deux composés osmotiques, le saccharose et le sel, ont été utilisés pour les carottes alors que seul le saccharose a été utilisé pour les fraises. Les effets des variations des concentrations en saccharose et en sel, de la température des solutions, et de la variation du temps d'immersion sur les propriétés diélectriques ont été étudiés. Des modèles empiriques ont été formulés grâce à la méthodologie de surface de réponse (RSM) pour prévoir les valeurs de ε' et ε" pour les diverses gammes des conditions osmotiques considérées dans cette étude.

Ainsi les paramètres considérés pour le pré-traitement de concentration étaient de maximiser la perte d'eau (WL) et de minimiser le gain de matières solides (SG). L'indicateur approprié pour le contrôle de cette situation était le rapport WL/SG. Les conditions optimales du processus osmotique visant à acquérir le meilleur rapport de WL/SG ont été étudiées. Les conditions optimales pour les carottes se sont avérées être une concentration de 50% (m/m) en saccharose, une concentration de 5% (m/m) en sel, une température de 20ºC et un temps d'immersion de 3 heures et 38 minutes. Les conditions optimales pour les fraises se sont avérées être une concentration de 60 % (m/m) en saccharose, une température de 20ºC et un temps d'immersion de 24 heures.

Le séchage micro-onde sous vide a été alors étudié à la suite du traitement osmotique. Les études ont été réalisées sur des carottes et des fraises. Une puissance d'entrée de 1 et 1.5 W/g opérant avec différents modes de puissance (en continu, 45s marche/15s arrêt et 30s marche/30s arrêt) ont été étudiés. Le traitement osmotique précédant le séchage micro-onde sous vide des carottes s'est avéré dans la plupart des cas avantageux; un temps de séchage plus court, une réduction de la consommation d'énergie et une qualité supérieure sauf pour le goût qui fut été affecté par sel. L'étude des fraises n'a pas démontré l'avantage du prétraitement osmotique. Le temps et la consommation d'énergie avec ou sans prétraitement osmotique étaient identique, cependant le traitement osmotique a eu comme conséquence une meilleure qualité des fraises sèches.

Le séchage micro-onde sous vide des carottes et des fraises à la suite d'un prétraitement osmotique n'a pas montré de période constante du taux de séchage dans la courbe de séchage tandis que le séchage sans traitement osmotique des fraises montrait une plus longue période constante de taux que celles observées pour le séchage de carotte. Selon ces phénomènes, les modèles de Lewis, Henderson et Pabis ont été adaptés avec succès aux données observées pour le séchage sans période constante; toutefois, le modèle de la Page était un meilleur choix pour le séchage avec période constante et période décroissante du taux pour le séchage micro-onde sous vide.

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I would like to dedicate this work to my grandmother, Mrs.Chan Chaipuak, who passed away in Thailand while I spent my time in Canada. God bless you and give you peace.

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CONTRIBUTIONS OF AUTHORS

The work presented here was performed by the candidate and supervised by Dr. G.S.V. Raghavan of the Department of Bioresource Engineering, Macdonald Campus of McGill University, Montreal. The research project was conducted in the Department of Biorecource Engineering, Macdonald Campus, McGill University, Montreal. Yvan Gariepy helped in setup the microwave vacuum dryer. Dr. Valérie Orsat and Dr. Darwin Lyen assisted to carry out the publications.

The authors for all the articles are shown as the following:

Chapter IV: V.Changrue, G.S.V. Raghavan, Y. Gariepy and V. Orsat

Chapter V: V.Changrue, G.S.V. Raghavan, D.Lyew and V. Orsat

Chapter VI, VII and VIII: V.Changrue, G.S.V. Raghavan and V. Orsat.

NOMENCLATURE

a^*	Chromacity coordinate (redness or greenness)
Δa^*	Difference in chromacity coordinate a^* between fresh and dried samples
a_w	Water activity
a/b	Redness indicator
COR	Coefficient of rehydration
CCD	Central composite design
CCC	Circumscribed central composite design
ΔE	Total colour difference between fresh and dried samples
FCC	Face-centered central composite design
ICC	Inscribed central composite design
b^*	Chromacity coordinate of fresh cranberries
Δb^*	Difference in chromacity coordinate b^* between fresh and dried samples
D_{eff}	Moisture diffusivity (m^2/s)
h^o	Hue angle in chromacity
k	Drying constant (h^{-1})
L^*	Chromacity coefficient (lightness)
ΔL^*	Difference in chromacity coefficient between fresh and dried samples
m	Initial sample mass (kg)
m_1	Initial mass of the sample (kg)
m_2	Final mass of the sample (kg)
m_{dh}	Mass of dehydrated sample (g)
m_i	Moisture content of fresh sample (g)
m_{os}	Moisture content of osmotically dehydrated sample (g)
m_{rh}	Mass of rehydrated sample (g)
M	Moisture content (ratio, dry basis)
M_{dh}	Moisture content of the dry sample (%, wet basis)
M_e	Equilibrium moisture content (ratio, dry basis)
M_f	Final moisture content (ratio, dry basis)
M_{in}	Initial moisture content (%, wet basis)

M_o	Initial moisture content (ratio, dry basis)
MR	Moisture ratio, dimensionless
MR_{exp}	Experiment moisture ratio
MR_{pred}	Predicted moisture ratio
MW	Microwave
MVD	Microwave vacuum drying
n, a,	coefficients in empirical models
n_c	Number of center runs of central composite design
OS	Osmotic dehydration
P	Input power (W)
R	Radius, m
RMSE	Root mean square error
RSM	Response surface methodology
r^2	Coefficient of determination
s_i	Solid content of osmotically dehydrated product
S_b	Bulk shrinkage coefficient
s_{os}	Solid content of fresh sample, g
Sa	Salt
SEC	Specific energy consumption (J/kg water)
SG	Solid gain (%)
Su	Sucrose
t	Time (s, min, hour)
$\tan \delta$	Loss tangent
HSD	Honestly significant difference
$V_{b(x)}$	Bulk volume m^3 at moisture content X
$V_{b,o}$	Bulk volume m^3 at initial moisture
W_i	Initial weight of fresh sample (g)
w.b.	Wet basis
WL	Water loss (%)
X	Moisture content (ratio, dry basis)
X_0	Initial material moisture content (ratio, dry basis)

X_e	Equilibrium moisture content (ratio, dry basis)
X_t	Moisture content at any time t (ratio, dry basis)
ε	Electric permittivity complex
ε'	Dielectric constant
ε''	Loss factor
α	Distance from center to stars point of central composite design

CHAPTER I

GENERAL INTRODUCTION

1.1 Background

Among the many postharvest operations of agricultural products, *drying* is the most widespread through out the world. Besides preserving seasonal commodities, drying also saves storage space and reduces transportation costs. For example, upon drying and compressing, most products weigh one twentieth as much as the raw material, and occupy about one fortieth of the storage space (Greensmith, 1998).

The basic concept of drying is water removal. The surface water of the product is changed to vapor and removed in the first stage, the inside water will then migrate to the surface and be subsequently removed. Two important aspects of drying are: (1) How to evaporate the moisture, and (2) how to enhance the removal of vapor. A number of heat sources have been used to change liquid water to vapor. Among them, the dielectric heating has been shown to be able to greatly reduce the drying time and improve heat penetration. Convection and vacuum have been used to aid the removal of vapor.

Besides providing fiber, fruits and vegetables are also important sources of essential dietary nutrients, vitamins and minerals. Since fresh fruits and vegetables have moisture content higher than 80% (w.b.) and short shelf lives, they are classified as perishable commodities. Keeping the produce fresh is the best way to maintain its values, but most storage techniques require a low temperature which requires high cost. Therefore, drying is more suitable for postharvest management especially for countries with poorly established low temperature and thermal processing facilities.

The challenge of fruits and vegetables drying is to reduce the moisture content of product to a level where microbiological growth will not occur and to simultaneously keep the nutritive value high. A number of drying techniques have been developed over the years. Applying heat to drying process through conduction, convection and radiation are the basic techniques to change water to vapor. The selection of the drying method is dependent on the condition of the products, economy and/or social conditions. Energy use is a critical issue due to increasing of gas prices and has become an important factor in all industrial sectors. The drying process is no exception to these trends. To reduce the reliance on fossil fuels, electricity can be used as an alternate source of energy for the drying process. This is based on the assumption that electricity can be generated by a renewable energy source i.e. hydro power and wind power (Raghavan et al., 2005; Raghavan et al., 1998)

One electric drying technology is the microwave oven. Microwave has been shown to have low energy consumption (Tulasidas et al., 1995). Volumetric heating and reduced processing time are two factors that make microwaves an attractive source of thermal energy. Although the distinct advantage of microwave heating has been revealed for a long time, the application in drying at industrial level is still limited. Some of limiting factors are the high initial costs, loss of aroma and the sensory quality attributes and non-uniformity of dried product.

The microwave by itself can do only raising the product temperature in order to change moisture to vapor; it requires other techniques to remove the vapor. Convective drying is a conventional way for removing vapor. Another unique technique is the vacuum. Since the boiling temperature of water is reduced under subatmospheric pressure, another benefit of vacuum is to provide the phase change at low temperatures which is expected to produce better quality dried product. However, due to the high costs and longer process, the application of vacuum in drying process is still limited.

The idea to combine fast heating of microwave and low temperature processing of vacuum has been investigated by a number of researchers. The results show that the vacuum-microwave drying is an alternative way to improve the quality of dried products. It has been used successfully for several products such as orange powder, cranberries, potatoes, bananas, and carrots (Attiyate 1979; Yongsawatdigul et al., 1996; Kubota et al., 1992; Drouzas et al., 1996. Tein et al.,1998).

Osmotic dehydration is used to remove water for heat sensitive products with low energy consumption at low temperatures. Since osmotic process cannot remove moisture to a level that will avoid microbial growth, it is a suitable method for pretreatment only. It is a simultaneous process between lowering water content and increasing dry matter using osmotic agents. A number of studies have proven that gaining of osmotic agent can improve nutritional, sensorial and functional properties of the dried food. Venkathachalapathy and Raghavan (1998) used the osmotic process prior to microwave drying. The results lead to acceptable dried product with lower energy consumption.

This study aims to prove that combining microwave vacuum drying with osmotic dehydration can improve the performance of microwave drying of fruits and vegetables. Strawberries and carrots were selected to be representative of fruits and vegetables respectively. First, a laboratory set up of microwave vacuum dryer was designed, installed and tested. The optimum osmotic conditions were established. The dielectric properties after osmotic processing were also studied. An empirical model of microwave vacuum drying after osmotic pretreatment was established.

1.2 Hypothesis

The osmotic dehydration is the first step of the process to remove moisture with the purpose of low energy consumption. The 50% water of material is expected to be removed by this stage. Further drying of osmotically treated samples is carried out in a microwave vacuum dryer.

The hypothesis of this study is that it is possible to combine the advantages from fast drying time of microwave heating, low temperature process of vacuum and low energy consumption of osmotic process for drying of fruits and vegetables.

CHAPTER II

GENERAL OBJECTIVES

The main objective of this research was to determine the operating conditions of osmotic pre-treatment and microwave vacuum drying. In order to achieve this, the following specific objectives were pursued:

1. To design and construct a microwave vacuum dryer.
2. To examine the performance of microwave vacuum dryer
3. To optimize the osmotic conditions for processing carrots and strawberries.
4. To study and measure the changes in the dielectric properties of carrots and strawberries after osmotic process among the various osmotic conditions.
5. To evaluate the drying kinetics of osmotically dehydrated microwave vacuum drying of carrots and strawberries.
6. Generate empirical models to predict the drying kinetics of microwave vacuum of osmotically dehydrated carrots and strawberries.

CHAPTER III

LITERATURE REVIEW

3.1 Introduction to drying

The objective of drying is to remove water until the water activity is low enough to prevent growth of microorganisms. The drying process not only decreases the water content of the product, but also affects other physical and chemical properties, which will change the shape, crispness, hardness, aroma, flavor and nutritive value of the fresh produce. Heat is usually required to remove the water. Hot dry air is passed through a moist product until the water becomes vapor which is then removed. Convection, conduction and radiation are the phenomena occurring in the drying process. Theoretical concepts of drying deal with air-water mixture properties which consist of moisture content, wet bulb and dry bulb temperature, and adiabatic saturation. The concept of adiabatic saturation line is summarized in Figure 3.1. It shows no changes in the wet bulb temperature but the relative humidity increases due to the absorption of moisture from a drying product.

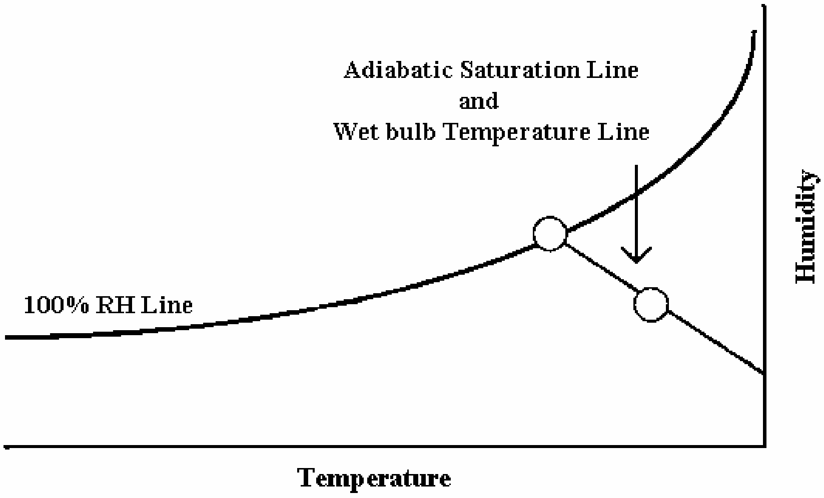

Figure 3.1 Representation of adiabatic saturation in the psychrometric chart

(Barbosa- Canovas and Vega-Mercado, 1996)

The mechanisms of drying involve vaporization of surface water and water movement under capillary forces, diffusion of liquid, and water vapor. Figure 3.2 shows a typical drying curve. The first stage of conventional drying is when only free moisture at the surface is removed so the drying rate is constant. This is called the "constant rate period". At the end of constant rate period, dry spots appear on the surface of the material and the drying rate decreases. This is the beginning of the "falling rate period". Once the surface is completely dried, moisture is transported from inside of the product to the surface by capillary action. The third drying period is called "the second falling rate" and the drying rate is lower than the previous step (Mujumdar and Menon, 1995).

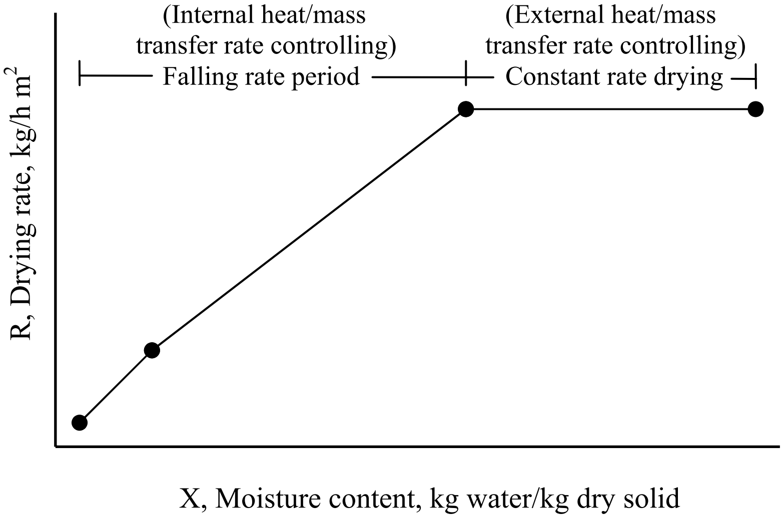

Figure 3.2 Typical drying rate curve under constant-drying conditions (Adapted from Mujumdar and Sirikalaya, 2000)

There are a number of techniques that could be applied to improve the performance of the drying process. To improve the uniformity of dried product, high speed forced air can be used in the processes known as spouted bed drying and fluidized bed drying. Rotating the drying container has been used to achieve the same effect as in spouted bed and fluidized bed drying.

Passing hot air through the product is known as a convective drying. Hot air not only heats the product but also removes the vapor. Some products are sensitive to heat, therefore processing under low temperature is required. A vacuum or subatmospheric pressure environment can be used for low temperature processes. A vacuum results in a low boiling temperature and high gradient for removal of vapor.

The removal of water during the drying process can occur not only as a result of heating, but also due to sublimation and osmosis. Applying sublimation to remove moisture is known as freeze drying. Vacuum drying at low temperature (freeze dehydration) was developed to overcome the loss of aroma and flavor. Some food products that are commercially freeze dried include: coffee, vegetables, fruits and meats.

Osmotic dehydration is water removal by soaking material in a hypertonic solution. Water will move from the material to the osmotic agent by the phenomenon of osmosis which will occur even at room temperature. Osmotic dehydration removes water without a phase change hence causes less temperature damage to the product and it retains many of its natural components. So it is ideal for heat sensitive process (Jayaraman and Das Gupta, 1992). Another advantage of osmotic dehydration is that it consumes less energy in comparison to traditional air-drying methods (Shi et al., 1997). Generally it does not remove moisture to a level that avoids microbial growth. Combining osmotic with other applications could be possible for industrial drying.

3.2 Drying of fruits and vegetables

The most drying of fruits and vegetables has been done with convective dryers. Some physical properties are changed by this drying technique e.g. loss of color, change in texture and shrinkage. Chemical changes causing loss of flavor and nutrients also occur during convective drying (Krokida and Marinos-Kouris, 2003). Some dried fruits and vegetables are not ready to eat since they require rehydrating before they can be used in cooking; but the properties of rehydrated products are poor. A number of studies have tried to overcome the problems attributed to conventional convective drying.

The temperature used in the process is an important factor in solving these problems. Studies have shown that drying under low temperature provides a distinctly better quality of dried product, but the operating times and operating costs are generally unacceptable (Beaudry et al., 2004). Thus, to maintain the original quality of the fresh product, a drying process with decreased time and cost would be ideal.

Jayaraman and Das Gupta (1992) classified drying process of fruits and vegetables into three basic types: Solar drying, atmospheric drying and subatmospheric dehydration (vacuum shelf/belt/drum and freeze dryer).

3.2.1 Solar drying

Solar-drying exists at varying levels of technology. The radiant energy from the sun is used both directly and indirectly on the product being dried. Some pretreatments are typically applied to solar drying. For example, fresh prunes pretreated with sulfur dioxide are immersed in a 0.25% - 1% hot lye solution for 5-30 s; and grapes may be treated (Heid and Joslyn, 1967). Pretreatment techniques can be varied by using different solutions, temperatures, and duration of dipping times. Some samples of solar drying are shown in Table 3.1.

Table 3.1 Solar cabinet drying throughput

Product	Amount of fresh matter dried per unit time[a]	Maximal allowable temperature (°C)
Apricots	4.0 kg/2 days	66
Garlic	2.6 kg/2 days	60
Grapes	5.7 kg/4 days	88
Okra	3.0 kg/2 days	66
Onions	3.0 kg/2 days	71

[a] Cabinet dimensions, 1.93 x 0.6 m.

Source: Grabowski et al., (2003)

3.2.2 Atmospheric drying

Atmospheric drying can be categorized as either Batch type (kiln, tower and cabinet dryer) or continuous (tunnel, belt, belt-trough, fluidized bed, explosion puff, foam-mat, spray, drum and microwave heated) (Jayaraman and Das Gupta, 1992). In the past, the quality of dried fruits and vegetables obtained by conventional air drying were not as good when compared to other preservation techniques. This was due to excessive thermal damage.

3.2.3 Subatmospheric

The boiling point of water can be lowered under vacuum or subatmospheric conditions. Drying under a vacuum can be used to improve the quality of heat sensitive products. Freeze drying is a commercially available vacuum drying method that can be applied to many agricultural products. Fruits and vegetables are often dried by this technique. The advantage of freeze drying over other methods of drying is the superior quality of the dried product and that no shrinkage occurs. The dried product structure is almost the same as the raw material. The only disadvantage of this technique is the high costs of installation and operation.

3.3 Pretreatments of fruits and vegetables prior to drying

The diffusion of moisture through thick and waxy skin products is difficult during the drying process. In order to improve the drying rate of high moisture materials with thick layers, skin pretreatments prior to drying can be considered. These consist of mechanical and chemical pretreatments and osmotic dehydration.

3.3.1 Skin pretreatments

The objective of skin pretreatment is to increase the permeability of the skin. Skin pretreatments of fruit and vegetable can be done by chemical and/or mechanical methods.

Chemical pretreatment is achieved by dipping materials in alkaline solutions. Mechanical pretreatments are techniques to change the structure of the skin by puncturing, cutting or abrading the skin before drying.

Venkatachalapathy and Raghavan (1998) studied pretreatments consisting of dipping starwberries in solutions of 1% ethyl oleate and 0.5% sodium hydroxide. Results strawberries showed that these pretreatment greatly enhanced the drying rates of whole berries in convection and microwave drying. Tulasidas et al. (1995) also used ethyl oleate pretreatment prior to microwave drying of grapes. Although they obtain an acceptable quality dried product without pretreatment, the use of ethyl oleate did reduce the drying time and led to better quality. Ponting and McBean (1970) found that although the ethyl esters of fatty acid in the C_{10}-C_{18} range were the most effective for drying pretreatment, ethyl oleate was not only more effective but convenient to handle.

In terms of mechanical pretreatment, Di Matteo et al. (2000) found that removal of the waxy layer from grape skin by an inert abrasive material was more effective than chemical pretreatment. However the abrasive pretreatment led to darker raisins, which is less attractive to consumers. Shi et al. (1997) perforated whole tomatoes with fine needles at densities of 40, 50, 80, and 120 holes/cm^2. They found that the amount of water removal was directly related to the number of pinholes.

3.3.2 Osmotic dehydration

Some crops may be harvested at low moisture contents, especially in the case of grains and cereals. However, fruits and vegetables are harvested at higher levels of moisture because of the nature of the commodity. For high moisture products, decreasing the moisture content can be done prior to proper drying. Osmotic dehydration is a pretreatment technique, which decreases the water activity (a_w) and requires little energy. Although it doesn't remove enough moisture to produce a fully dried product, it works well as a pretreatment for drying process (Barbosa-Canovas and Vega-Mercado, 1996).

In osmotic dehydration, the product is placed in hypertonic solutions or substances, such as granular sugar, granular salt, syrups or salt solutions. The movement of moisture from the product to the hypertonic solution or substance is governed by the difference in osmotic pressures. Not only is the moisture removed from the product but the hypertonic solution or substance diffuses into the product (Figure 3.3). Nsonzi and Ramaswamy (1998) modeled the mass transfer process with respect to moisture loss and solids gain. They stated that even though the moisture loss and solids gain occurred at the same time, the rate of moisture loss was much higher than the rate of solids gain. The unique advantage of osmotic dehydration is lower energy use and less thermal damage to products since lower temperatures are used, and nutrients are retained (Shi et al., 1997).

The application of osmotic dehydration to fruits, and to a lesser extent to vegetables, has received attention in recent years as a technique for production of intermediate moisture foods and shelf-stable foods, or as a pretreatment prior to drying in order to reduce energy consumption and heat damage (Jayaraman and Das Gupta, 1992).

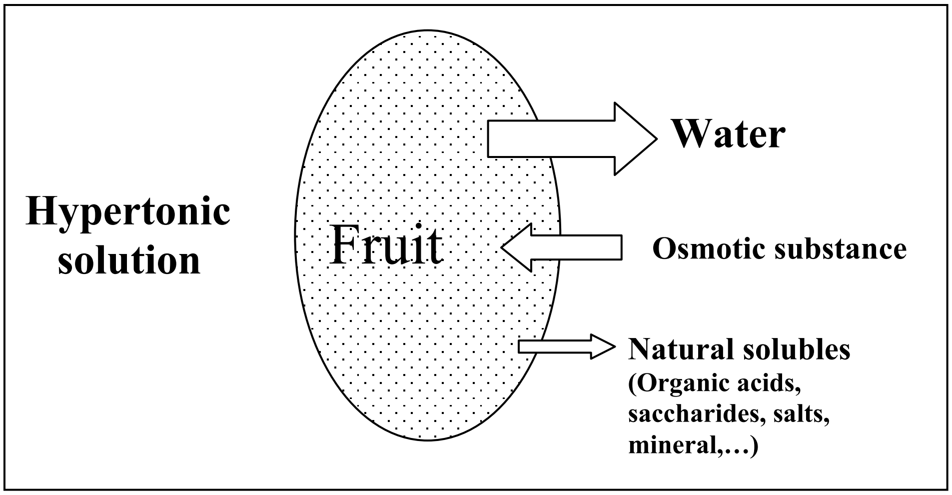

Figure 3.3 Schematic demonstration of osmotic dehydration process (adapted from Lewicki and Lenart, 1995)

Lenart (1996) deduced four main advantages of using osmotic dehydration:

1. Reduction of heat usage, hence negative changes of color and aromatic substances are diminished in subsequent drying.

2. The cell membranes are not absolutely resistant to osmotic substance, assuring a small flow of sugar into the cell, causing a sweeter taste of the dehydrated food.
3. Osmotic dehydration as a pretreatment provides shorter drying time and increases the dryer's potential.
4. Energy consumption is smaller at a rate of 20-30 % when compared to convective drying.

Venkatachalaphaty and Raghavan (1999) reported that combined osmotic-microwave dried strawberry were similar to that of the freeze-dried products in terms of rehydration characteristics and overall sensory evaluation.

3.4 Principle of microwave drying

Wavelengths of microwave range from 1mm to 1m, corresponding to a frequency range of 300 MHz to 300GHz (Sanga et al., 2000). The foundation of the electromagnetic wave theory was laid down by Maxwell in 1864 when he formulated equations describing electromagnetic phenomena. Hertz provided the first experimental proof of the existence of electromagnetic waves in 1888. Electromagnetic radiation was first used for communication (radio, radar, and television) in 1894 (Stuchly and Stuchly, 1980). Nowadays, many diversified applications of electromagnetic radiation are employed and are being studied extensively.

Since a conventional dryer is limited by heat transfer to the core of product and mass transfer of water out of the material (Mujumdar and Menon, 1995), it would be expected that microwave drying would perform more uniformly and faster due to the volumetric heating. In microwave drying, heat is generated by directly transforming electromagnetic energy into kinetic molecular energy, thus the heat is generated within the material. Microwave drying has gained popularity as an alternative drying method in the food industry because it is rapid and energy efficient compared to conventional hot-air drying (Decareau and Peterson, 1986).

During microwave heating, heat is generated by dielectric materials that absorb microwaves, but materials that are reflectors will not be heated directly. It is distinct from conventional drying which is driven by the difference in temperature between the outside and inside of the material. Microwave drying is not governed by temperature gradients but the heat arises from the oscillation of molecular dipoles and movement of ionic constituents respectively in response to alternating electric fields at high frequency. The resulting energy is absorbed throughout the volume of the wet material. The increase in internal pressure drives out the moisture from the interior to the surface of the material (Sanga et al., 2000).

The property of the materials that defines their interaction with electromagnetic fields is the electric permittivity (ε). The electric permittivity defines the material behavior in the electric field, and consists of a real part, (ε') called the dielectric constant, and an imaginary part, called the loss factor (ε'') (Stuchly and Stuchly, 1980.). This can be represented by Equations 3.1 and 3.2.

$$\varepsilon = \varepsilon' - j\,\varepsilon'' \tag{3.1}$$

$$\tan\delta = \frac{\varepsilon''}{\varepsilon'} \tag{3.2}$$

Where j = $\sqrt{-1}$, which indicates a phase shift between the real (ε') and imaginary (ε'') parts of the dielectric constant (Schiffmann, 1995). The dielectric constant (ε') governs the electromagnetic field distribution within the material and provides a measure of how easily energy can be stored by material. The loss factor (ε'') describes the loss interactions and determines how easily energy can be dissipated into the material (Sanga et al., 2000). These properties can be measured at various frequencies, and they are not constant; they are dependent on the temperature, moisture content, composition and particle density of the material. The dielectric properties of fruits and vegetables are shown in Table 3.2.

The two basic physical phenomena that contribute to large values of the loss factor and that are responsible for the heating effect at microwave frequencies are ionic conduction and dipolar rotation. At room temperature, when an electric field is applied to a material containing ions, the ions spontaneously break down and collide with other molecules, and the kinetic energy is converted into heat through those collisions. This is a two-step energy conversion process in which electric field energy is converted into a kinetic energy of the ion moving in a defined direction, and then the kinetic energy is converted into heat through multiple collisions (Stuchly and Stuchly, 1980).

Table 3.2 Dielectric properties of fruits and vegetables at 23ºC (Venkatesh and Raghavan, 2004)

Fruits / Vegetables	MC, % (w.b.)	Dielectric constant (ε') Frequency		Dielectric loss factor (ε") Frequency	
		915 MHz	2450 MHz	915 MHz	2450 MHz
Apple	88	57	54	8	10
Avocado	71	47	45	16	12
Banana	78	64	60	19	18
Cantaloupe	92	68	66	14	13
Carrot	87	59	56	18	15
Cucumber	97	71	69	11	12
Grape	82	69	65	15	17
Grapefruit	91	75	73	14	15
Honeydew	89	72	69	18	17
Kiwifruit	87	70	66	18	17
Lemon	91	73	71	15	14
Lime	90	72	70	18	15
Mango	86	64	61	13	14
Onion	92	61	64	12	14
Orange	87	73	69	14	16
Papaya	88	69	67	10	14
Peach	90	70	67	12	14
Pear	84	67	64	11	13
Potato	79	62	57	22	17
Radish	96	68	67	20	15
Squash	95	63	62	15	13
Strawberry	92	73	71	14	14
Sweet potato	80	55	52	16	14
Turnip	92	63	61	13	12

While there are a number of advantages of microwave drying over convection drying. Simultaneously, some limitations are also found in the process. The advantages and limitations of microwave drying are presented in Table 3.3. Raghavan and Orsat (1998) recommended that heat and mass transfer through conduction, convection and electro-heating each have their own advantages and disadvantages, and that new process equipments would gain from combining multiple processes, as seen in the application of microwave with convection drying (Tulasidas et al., 1993), freeze drying (Ma and Arsem, 1982), vacuum drying (Gardner and Butler, 1982), heat pump drying (Sanga et al., 2000) and osmotic dehydration (Venkatachalapaty and Raghavan 1998).

Table 3.3 Advantages and limitations of microwave drying (Sanga et al., 2000)

Advantages	Limitations
Fast and volumetric heating	High initial costs
Higher drying rate	Loss of aroma and negative sensory changes of juice powder drying
Short drying time	Physical damages
Enhance quality of the product	Specific sample size and shape may be required
Reduced energy consumption	
Lower operating costs	

3.5 Microwave vacuum drying

Since the boiling point is reduced at lower pressures, vacuum can be applied to the microwave drying environment to improve the process. Drouzas and Schubert (1996) investigated vacuum-microwave drying of banana slices. Pulse generated microwaves were applied to banana samples. The product quality in terms of taste, aroma, smell and rehydration tests were found to be excellent.

Youngsawastidigul and Gunasekaran (1996) studied microwave-vacuum drying of cranberries. The experiment was done both in the pulsed and continuous modes. The dried products were redder and had a softer texture than those dried by the conventional hot-air method.

Attiyate (1979) investigated microwave heating under vacuum to produce orange powder for a natural instant fruit drink. It showed good quality and processing advantages in terms of retention of vitamins, orange flavor, color, aroma, shorter process cycles and low process temperature.

Kubota et al. (1992) found that the temperature increased during microwave drying, and caused browning and a flavor change in potato. The temperature increase can be reduced under a vacuum operation.

Drouzas and Schubert (1996) performed microwave drying experiments on fruit gels with a vacuum (range of 30-50 mbar) at MW power rating of 640-710 W. The distribution of the electromagnetic field in the cavity was not uniform. The color of the microwave-vacuum dried fruit gel was significantly lighter than the color of the microwave-air dried product at atmospheric pressure.

Tein et al. (1998) compared carrot slices dried under microwave vacuum to air drying and freeze drying on the basis of rehydration potential, color, density, nutritional value, and textural properties. Microwave vacuum dried (MVD) carrot slices had higher rehydration potential, higher α-carotene and vitamin C content, lower density, and softer texture than those prepared by air drying. Although freeze drying of carrot slices yielded a product with improved rehydration potential, appearance, and nutrient retention, the MVD carrot slices were rated as equal to or better than freeze dried.

3.6 Quality Assessment

Quality, the summary of all characteristics of dried product is important to the food industry. Quality characteristics of a dried product may be divided into three major categories: sensory, hidden and quantitative (Salunkhe et al., 1991). The sensory characteristics are color, gloss, size, shape, defects, odor and taste. Hidden characteristics are nutritive value, presence of dangerous contaminants and poisonous materials. Quantitative parameters are those that contribute to overall fruit quality, such as yield of a dried product.

In order to determine the quality of dried fruits and vegetables, several parameters need to be examined. These parameters are water activity, skin color, textural characteristics, shrinkage, rehydration and sensory evaluation properties.

3.6.1 Moisture determination

The initial moisture content by drying in hot air oven at 70°C for 6h or by the vacuum dry method (Ranganna, 1986 and Canellas et al. 1993) were found to compare well for initial moisture content. Therefore the oven method was selected to determine initial moisture and dried sample.

3.6.2 Water activity

Water plays an important role in the stability of fresh, frozen and dried foods. It acts as a solvent for chemical, microbiological and enzymatic reactions. The water activity, a_w, is a measure of the availability of water to participate in such reactions. The water in a food will exert a vapour pressure. The extent of this pressure will depend on the amount of water present, the temperature and the composition of the food. Different food components will lower the water vapour pressure to different extents, with salts and sugars being more effective than starches or proteins. Thus two different foods with similar moisture contents may not necessarily have the same a_w. Water activity can be defined as the ratio of the vapour pressure exerted by the food to the saturated vapour pressure of water at the same temperature.

$$a_w = \frac{\text{Vapour pressure of water exerted by food}}{\text{Saturated vapour pressure of water at the same temperature}} \tag{3.3}$$

Water activity is a function of moisture content in the food and the temperature (Ratti and Mujumdar, 1996). Bound molecule of water in food can be defined by water activity (Barbosa-Cánovas and Vega-Mercado, 1996):

- Tightly bound water $a_W < 0.3$
- Moderately bound water $0.3 < a_W < 0.7$
- Loosely bound water $a_W > 0.7$
- Free water $a_W \approx 1.0$.

Most bacteria do not grow at water activities below 0.91, and most molds cease to grow at water activities below 0.80 (Leung, 1986). By measuring water activity, it is possible to predict which microorganisms will or will not be potential sources of spoilage. Lower water activity of a dried product implies better potential for storage.

3.6.3 Color determination

Color is a direct and easy method to determine for the product. Dried products are usually darker in color, but darker color does not mean better quality. Too dark may imply that the product is over dried. The advantage is that this parameter can be visually determined for assessing dryness quality.

The most common technique to assess the color is by colorimetry. There are several color scales in which the surface color can be represented. The 3-dimensional scale L^*, a^* and b^* is used in a Minolta chromameter. The L^* is the lightness coefficient, ranging from 0 (black) to 100 (white) on a vertical axis. The a^* is purple-red (positive a^* value) and blue-green (negative a^* value) on a horizontal axis. A second horizontal axis is b^*, that represents yellow (positive b^* value) or blue (negative b^* value) color (McGuire, 1992). This 3D color system can be seen in Figure 3.4. The values of L^*, a^* and b^* can be converted to hue angles (h^o) and Chroma (C^*) values, analogous to color saturation or intensity (McGuire, 1992). The color difference ΔE can be calculated if one wants to find the difference between the sample and a previously chosen standard (McGuire, 1992).

$$h^0 = \arctan \frac{b^*}{a^*} \tag{3.4}$$

$$C^* = \sqrt{(a^*)^2 + (b^*)^2} \tag{3.5}$$

$$\Delta E = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \tag{3.6}$$

Where ΔL^* is the difference between L^* of the sample and that of the standard, Δa^* is the difference between a^* of the sample and that of the standard, and Δb^* is the difference between b^* of the sample and that of the standard (McGuire, 1992).

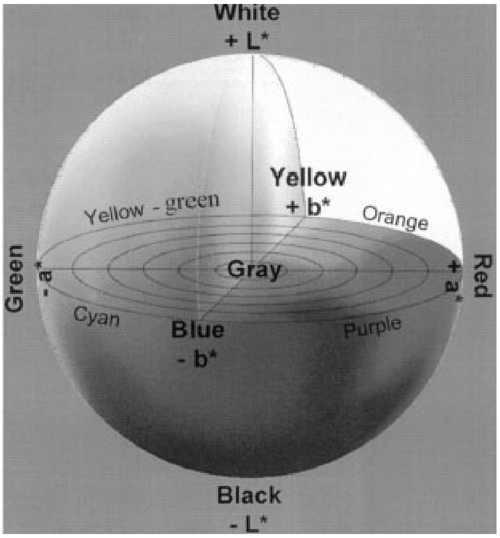

Figure 3.4 $L^*a^*b^*$ color three-dimensional system (Abbott, 1999)

3.6.4 Textural characteristics

Texture is a mechanical property of a material. The texture together with appearance and color is one of the most important and assessed properties. Mechanical tests of texture includes the familiar puncture, compression and shear tests as well as creep, impact, sonic and ultrasonic methods (Judith, 1999). The Universal Testing Machine also was widely used to determine texture. The typical curve acquired from the Universal Testing Machine is shown in Figure 3.5. The applied load (N) was plotted against deformation (mm). The slope of the Load/Deformation curve reflects elastic modulus and is often used as an index of firmness (Abbott, 1999). Some authors describe the fruit firmness using a deformation test. Displacement using a force of 10 N was measured and the pressure was calculated by the applied puncture force (Riley and Zachary, 1989). The type and direction of force applied can be different, depending on the method used, i.e. the probe element that is in contact with food. Beaudry et al. (2003) used Kramer shear to evaluate the texture of dried cranberry.

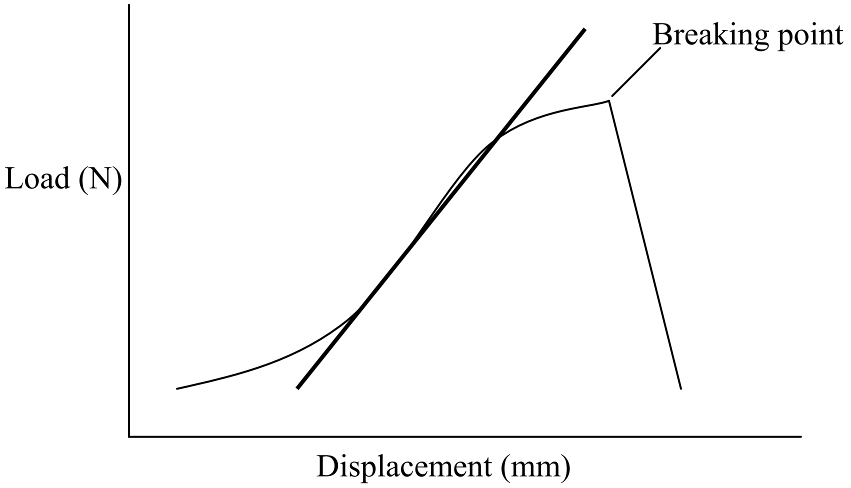

Figure 3.5 Typical diagram obtained from axial testing of a material

3.6.5 Shrinkage

The drying of a product usually results in a smaller size than the original wet form. The shrinkage in volume is dependent on the density. The shrinkage can also be a factor in rehydration, which will be mentioned in detail later. Most of the shrinkage occurs in the early drying stages, where 40 to 50 % shrinkage may occur (Okos et. al., 1992).

Lazano et al. (1983) described the bulk shrinkage coefficient by:

$$S_b = \frac{V_{b(X)}}{V_{b,o}} \tag{3.7}$$

Where S_b = Bulk shrinkage coefficient

$V_{b(x)}$ = Bulk volume m^3 at moisture content X

$V_{b,o}$ = Bulk volume m^3 at initial moisture

3.6.6 Rehydration

Not all dried products can be consumed directly. Most need to be rehydrated by soaking in water prior to consumption, for instance, in the case of mushrooms. There are several factors affecting rehydration, such as the soaking period, temperature of the water, and the rehydration capacity of the product.

The rehydration capacity can be influenced by the drying process. Drying processes that change product composition to a lesser extent are supposed to offer better rehydration ratio of finished product. For the rehydration capacity, Venkatachalapaty (1998) used equation 3.8 for calculating the coefficient of rehydration for blueberries and strawberries.

$$COR = 10 \cdot \frac{m_{rh} \cdot (100 - M_{in})}{m_{dh} \cdot (100 - M_{dh})} \tag{3.8}$$

COR = coefficient of rehydration (non-dimensional)
m_{rh} = mass of rehydrated sample (g)
m_{dh} = mass of dehydrated sample (g)
M_{in} = initial moisture content of the sample before drying (% wet basis)
M_{dh} = moisture content of the dry sample (% wet basis)

3.6.7 Sensory evaluation

Sensory evaluation is important to assess the consumers' requirements. It is difficult to classify 100% by machine because it is a subjective factor. Venkatachalapathy (1998) worked with a panel of ten or more untrained judges for his sensory analysis of dried strawberries and blueberries, whereas Rennie et al. (2001) used visual quality assessment scale ranging from 9 to 1, representing a range of excellent quality to extremely poor, respectively. Tulasidas et al. (1995) used a scoring panel of 10 judges to determine the quality attributes of MW/convective dried grapes, and the ratings was assigned on a scale of 0 to 5 points, where 0 is the highest quality and 5 the poorest.

3.7 Drying models

According to the complex components of biological products and various conditions of drying techniques, describing the drying models have never been completed. Based on the patterns of moisture change and simultaneous heat and mass transfer, the various proposed models can be classified in to three categories:

a) Diffusion model,
b) Heat and mass transfer models
c) Semitheoretical and empirical.

Since the mechanism of drying is associated with moisture movement, the application of Fick’s second law of diffusion is used to describe a moisture transport.

$$\frac{\partial m}{\partial t} = D_{eff} \nabla^2 M \tag{3.9}$$

where, M = moisture content (dry basis)
D_{eff} = moisture diffusivity (m^2/s)

The solution of this equation for a homogeneous, isotropic sphere with constant diffusion coefficient was presented by Crank (1975) as shown in the equation 3.10.

$$\frac{M - M_e}{M_0 - M_e} = \frac{6}{\pi^2} \sum_{n=1}^{n=\infty} \frac{1}{n^2} \exp\left[-\frac{n^2 \pi^2 D_{eff}}{R^2} t \right] \tag{3.10}$$

where, M_e = the equilibrium moisture content, kg/kg
M_0 = the initial moisture content, kg/kg
D_{eff} = moisture diffusivity, m^2/s
n = the integer,
R = the sphere’s radius, m.

Heat and mass transfer model is related to the phenomena that occur during the drying process. The conditions of drying which relates to the evaporation of moisture will be counted in the model. The numerical analysis and simulation will be set up to propose the model. This kind of model usually contains complicated parameters but provides the high accuracy of prediction. These are useful for scale-up or to the products which have similar properties.

The most used of drying model is semi-theoretical which assumed that the drying rate is proportional to the difference of moisture content and equilibrium moisture content of drying condition. This concept can be expressed in the form of equation 3.9.

$$\frac{dX}{dT} = -k\ (X_t - X_e) \qquad (3.9)$$

where, X_t = moisture content at any time t, kg/kg dry mass

t = time, h

k = constant rate, h^{-1}

X_e = equilibrium moisture content related to air condition, kg/kg dry mass

This equation can be solved to the simplified form leading to a well known exponential equation.

$$\mathrm{MR} = \frac{M - M_e}{M_0 - M_e} = \exp\ (-kt\ ) \qquad (3.10)$$

where, MR = Moisture ratio, dimensionless

Page (1949) developed drying model based on exponential equation. The empirical exponent was added to time, t in the equation 3.10. The modified equation is:

$$\mathrm{MR} = \frac{M - M_e}{M_0 - M_e} = \exp\ (-kt^n) \qquad (3.11)$$

where, n = empirical drying exponent

The studies of model for microwave drying have been done in a number of ways. Shivare et al. (1994) applied diffusion model to predict drying rate of corn. Since the result showed that it was inadequate to represent the microwave-drying, they proposed a modified moisture ratio based on surface moisture instead of equilibrium moisture content. The modified model provided the reasonable fits to drying curve of corn.

Tulasidas et al. (1997) developed the semi-theoretical model of microwave drying of grapes based on mass, heat transfer, energy transfer and diffusivity of vapor. The numerical procedure predicted the behavior of microwave drying of grapes very well. However, they reported that the drying rate of the developed semi-theoretical model is very similar to the result from Page's model. That means Page's model is adequate to present the drying rate of microwave drying.

Venkatachalaphaty (1998) applied exponential model to microwave drying in which the rate constant (k) was a function of microwave power level. The results showed a very good fit at the lower power level but for the higher power level the moisture was underestimated after first 45 minutes of drying.

McMinn (2006) investigated the various models to fit with the convective, microwave-convective and microwave-vacuum drying of lactose powder. He found that Page's model was good enough to predict the drying rate of those drying techniques.

3.8 Experimental design

A second-order central composite design (CCD) was widely used to find the optimum condition of multi factors in many studies due to the high precision of acquired predictive equation with less number of experiments (Ravindra and Chottopadhyay, 2000; Uddin et al., 2004 and Corzo and Gomez, 2004)

The CCD contains fractional factorial design with center points that could provide the estimation of curvature. To understand the pattern of CCD, figure 3.6 illustrates the structure of the model of CCD for two factors (Croarkin and Guthrie 2006).

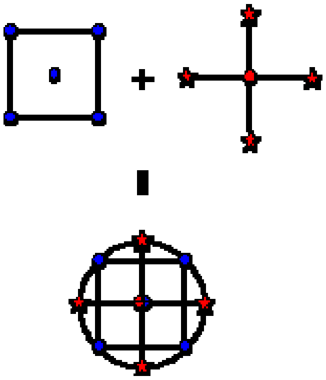

Figure 3.6 Generation of central composite design for two factors

The model contains the factorial model with center point and a group of star points. The distance of the stars from the center is ± α. According to the distance of α, the CCD can be classified to 3 types; circumscribed (CCC), face-centered (FCC) and inscribed (ICC) as shown in figure 3.7.

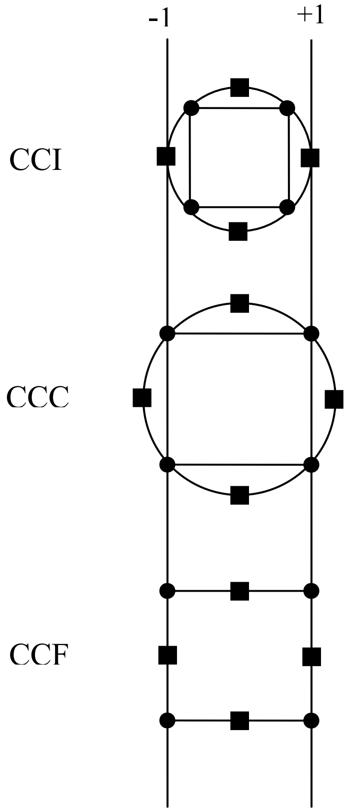

Figure 3.7 Three types of central composite designs

CCC designs are the original form of the central composite design. The star points are at some distance α from the center based on the properties desired for the design and the number of factors in the design. The star points establish for the low and high settings for all factors. These designs have circular, spherical, or hyperspherical symmetry and require 5 levels for each factor.

ICC designs are suitable for the situations in which the limits specified for factor settings are truly limits, the ICC design uses the factor settings as the star points and creates a factorial or fractional factorial design within those limits. This design also requires 5 levels of each factor. The recommended α values of ICC and CCD are $\alpha = \sqrt{k}$ where k is the number of studied factors.

In the FCC designs, the star points are at the center of each face of the factorial space, so α = ± 1. This variety requires 3 levels of each factor. The practical situations in which the region of interest and the region of operability are the same are suitable for FCC.

The replication at the center of central composite design is important to achieve a reasonable distribution of the variables. In the case of spherical designs (CCC and ICC), the number of center runs (n_c) was recommended between 3-5. In the cuboidal case of FCC, one or two center runs are sufficient to produce reasonable of variables (Myers and Montgomery, 2002).

3.9 Conclusions

In this chapter, basic knowledge and the advantage of osmotic dehydration and microwave vacuum drying were reviewed. It shows the possibility to enhance microwave drying by working with vacuum and osmotic dehydration. This study intends to apply this hybrid drying to fruits and vegetables. Strawberry will be a representative fruit and carrot will be a representative vegetable.

CHAPTER IV

MICROWAVE VACUUM DRYER SETUP AND PRELIMINARY STUDIES ON STRAWBERRIES AND CARROTS

4.1 Abstract

A Laboratory scale microwave vacuum dryer with the ability to record temporal variation of mass and temperature of a drying product was designed and built. The initial study was set up to investigate the effect of the position of a vacuum pressure control valve at two vacuum pressure levels, 6.5 and 13.3 kPa, with a fixed power input of 1.5 W/g. Then, strawberry halves and carrot cubes (10 x 10 x 10 mm) were used for a preliminary study to investigate the effect on drying product temperature and the effect of input microwave powers (1, 1.5 and 2 W/g) at a fixed level of vacuum pressure (6.5 kPa).

The position of the valve which allows air to pass through the vacuum container was found to provide shorter drying time and reduced the occurrence of vapor condensation. The product temperature at the end stage of drying was too high for both strawberry halves and carrot cubes which meant that the microwave vacuum drying protocol used could not finish drying with a single level of input power within the range of this study.

4.2 Introduction

The advantages of fast heating in microwave ovens are well established. The number of microwave appliances in North American household clearly show the advantages of this heating technique. The application of microwave in the drying process is well-known in term of faster drying time due to volumetric heating of dielectric materials. Microwave vacuum drying combines the advantages of a vacuum and the rapidity of a microwave oven. The vacuum condition imposes the low boiling temperature which reduces the damage to heat sensitive nutritional substances and vitamins in fruits and vegetables. Recently, the studies of microwave vacuum dehydration have proved it to be a rapid, energy-efficient technique which also minimizes change in characters (Drouzas and Schubert 1996; Sunjka et al. 2004).

Despite the fact that a number of studies published in research papers have shown numerous advantages of microwave technology, the application of microwave technology in drying processes is still limited in industrial application. The non-uniformity of the drying material provides the biggest resistance to its widespread use (Metaxas and Meredith, 1983). Drying product temperature is a key factor to acquire uniformity of dried product. Current drying temperature monitoring in microwave drying applications is limited due to the sparking of conventional metal thermocouple. Most microwave drying studies have relied on controlling input power instead of product temperature. The final product quality assessment is based on input power level, temperature of air flow in microwave convective drying or vacuum level in microwave vacuum drying.

This study aimed to design and setup a laboratory scale microwave vacuum drying system which is able to track mass and temperature of the drying product. In the initial test of the microwave vacuum dryer however, the problem of vapor condensation inside the container was found. There are two possible contributing causes to the observed condensation: firstly, the hot vapor reached its dew point after contact with the cold container wall. Secondly, condensation could be due to the low air circulation inside the container. Heating the container equal to the temperature of vapor could solve the first problem. The second could be solved by changing the position of the pressure control valve to improve air circulation inside the container. Since the aim of this study is to minimize energy consumption, the latter solution was selected to solve the problem of condensation inside the container.

4.3 Objectives

The objectives of this study are to determine the effect of the position of the vacuum pressure control valve and the effect of input power on mass and temperature of a drying product consisting of strawberry halves and carrot cubes which represent fruits and vegetables respectively.

4.4 Materials and methods

4.4.1 Microwave vacuum dryer setup

A schematic diagram of the microwave vacuum dryer and its photograph are shown in Figures 4.1 and 4.2 respectively. The main components of the microwave vacuum consist of i) variable power (0-750 W) microwave generator, ii) reflected power absorber, iii) microwave cavity, iv) vacuum pump, v) fiber optic thermometer sensor vi) electronic scale and vii) PC computer.

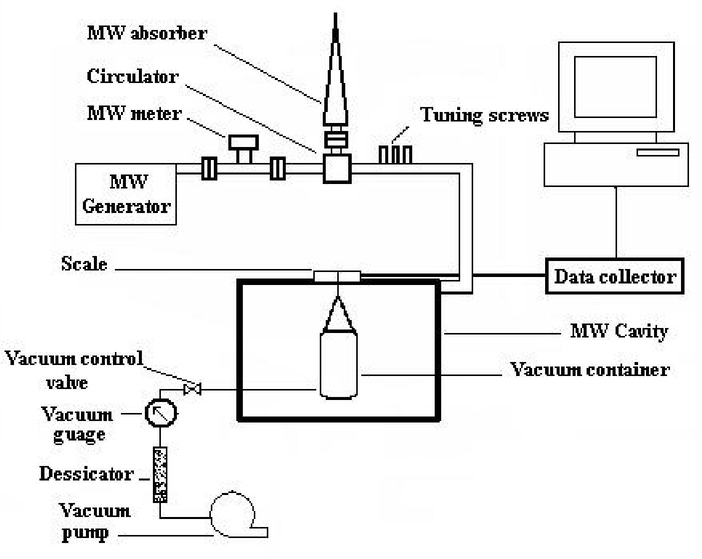

Figure 4.1 Schematic of the microwave vacuum dryer.

Figure 4.2 Photograph of the microwave vacuum dryer.

The variable power 0 - 750 W magnetron microwave generator produced microwaves at a single frequency of 2,450 MHz. A rectangular wave guide (WR 284) conveyed microwaves from the magnetron to the cavity via the three port circulator. The microwave energy was introduced in the first port while the second port was used simultaneously for the forward input energy to the cavity and backward reflected energy from the cavity. Before getting back to the circulator, reflected energy could be minimized by the three tuning screws (Pozar, 1990). After minimizing, the reflected energy will be circulated to the third port which directs it to a carbon load for energy dissipation later on. The main purpose of using three ports circulator is to protect the magnetron from too high reflected energy. Two sensors were located at the rectangular wave guide to detect input microwave power and reflected microwave power in watts.

The vacuum pump (John Scientific Inc., Canada) was used to create a vacuum in the circular (150 mm diameter) plastic container in which the vacuum level was controlled by an open-ended valve. The moisture absorber $CaSO_4$ was located between the container and vacuum pump to absorber moisture from the vapor.

4.4.2 Instrumentation, Measurement and Controls.

Ambient temperature was recorded by T-type thermocouples. The fiber optic temperature sensor was installed inside the container and the whole container was hung under the digital scale through a 6 mm diameter hole. The real time data of sample weight, sample temperature, ambient temperature, input power and reflected power were recorded by the computer via the data acquisition system (Hewlett-Packard, USA). The software HP VEE version 5.01 was used to design the program to record and control the drying process.

The interactive display of the program is shown in Figure 4.3 which shows the values of input and reflected microwave power, ambient and drying product temperature, sample mass and drying time. This program also provided the drying curve from the records of mass and drying time. The time interval for data sampling was controlled by the cycle duration. In the present drying study, data were collected every minute.

The program controlled the process by switching on/off the microwave generator by the following conditions.

1. Microwave generator will shut down when either reflected power or product temperature reaches the set point.
2. Resuming of microwave generator will be controlled by cycle duration time.

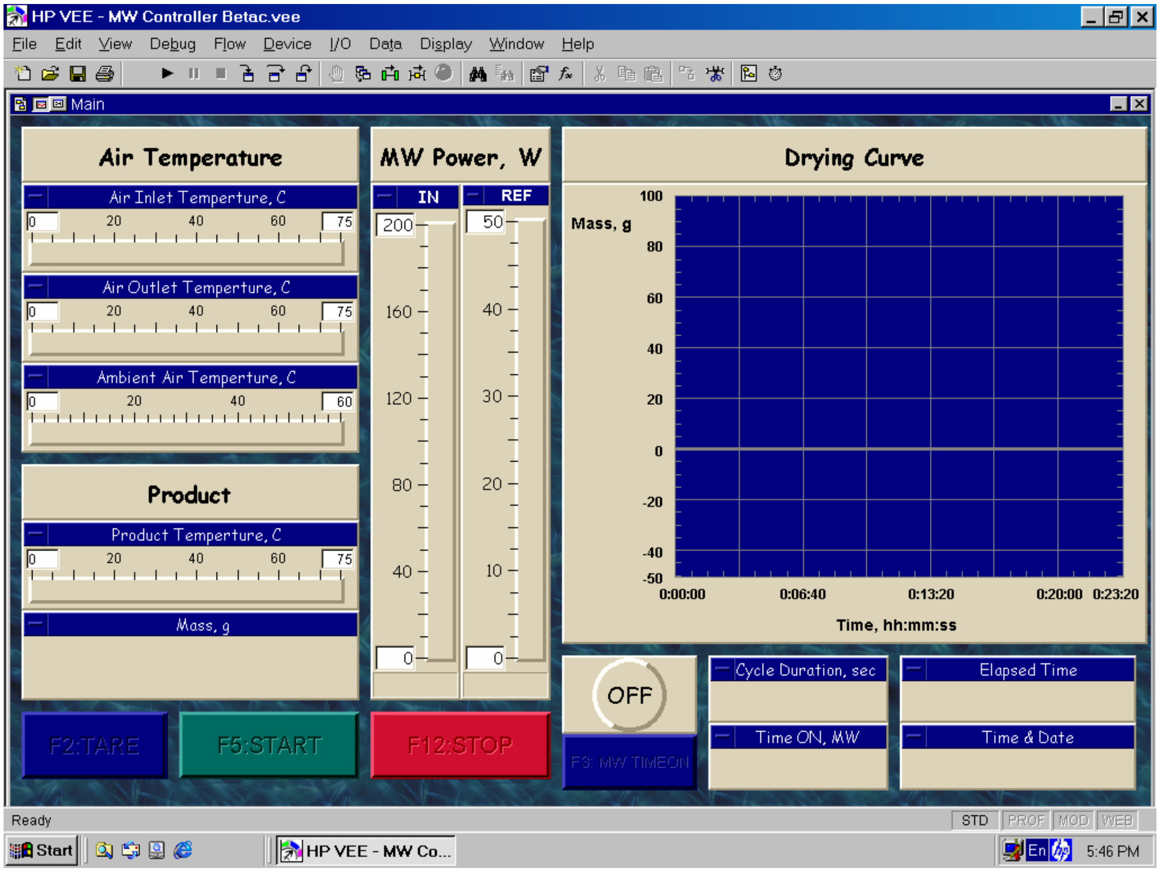

Figure 4.3 Figure showing interactive display of the developed program

4.4.3 Study of the effect of valve position in the microwave vacuum system

The setup of valves A and B shown in Figure 4.4 was used to investigate the effect of the position of the valve to the occurrence of vapor condensation. Position B will allow the ambient air to pass through the vacuum container. 10 mm carrots cubes were used to study the effect of valve position. The drying curve and the production temperature were used to compare drying performance between the two positions of the valve. The experiments were performed under the conditions of fixed microwave power levels of 1.5 W/g and two vacuum pressure levels (6.5 and 13.3 kPa).

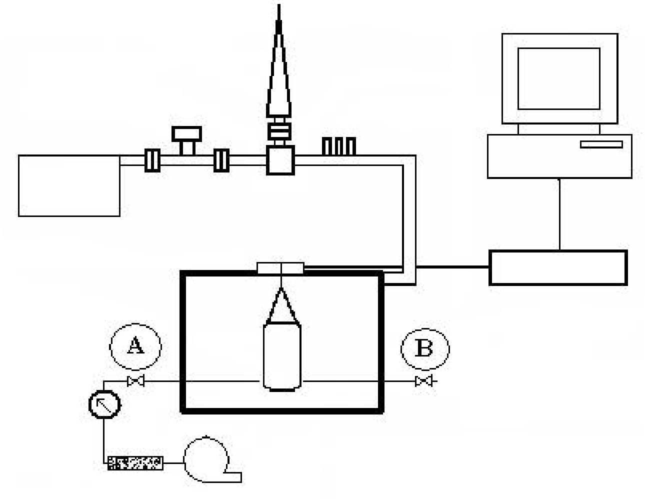

Figure 4.4 The position of valves A and B

4.4.4 Microwave vacuum drying study of strawberries in halves and carrots in cubes

The position of valve which was able to solve the problem of vapor condensation was used for microwave vacuum drying of strawberries and carrots. Unknown cultivars of strawberries and carrots were procured from a local market as representatives of fruits and vegetables respectively and stored in a cold room at 1°C. To attain room temperature, all samples were removed from the cold room two hours before the experiments. Strawberry halves and 10 mm side-carrot cubes were selected for the preliminary study with the sample size of 50±1 g. The preparation of samples for all experiments in the following chapters followed the same procedure.

Three levels of microwave power (1, 1.5 and 2 W/g) with a fixed level of vacuum pressure (6.5 kPa) were chosen for the microwave vacuum drying strawberries and carrots. The strawberry halves were dried until the moisture content was less than 10 % (wet basis) which confers resistance to microbial growth and less susceptibility to Maillard reactions (Salunkhe et al.,1991). The desired dried moisture content of carrots was 7 % (wet basis) (Dauthy, 1995). All experiments were conducted in triplicate.

4.5 Results and discussion

4.5.1 The effect of valve position

The results show that the valve at position B provided faster drying time than the valve at position A for both vacuum pressure levels as shown in Figures 4.5 and 4.6. There were no differences of drying time due to the difference of vacuum pressure in both installations. Beaudry et al. (2003) and Sunjka et al. (2004) also found little effect of vacuum pressure to drying time for microwave vacuum drying of cranberries. Even though condensation was observed with both installations, the condensed water was removed before the end of the drying process with the valve at position B while drops of water never disappeared until the end of process with the valve at position A which is able to cause rewetting of dried product. The results prove that passing air through the drying material is able to improve vapor removal in subatmospheric conditions. One remark for the effect of the position of valve was the drying product temperature. Since the valve at position B allowed the ambient air pass through the vacuum container, the drying product temperature curves showed more oscillations.

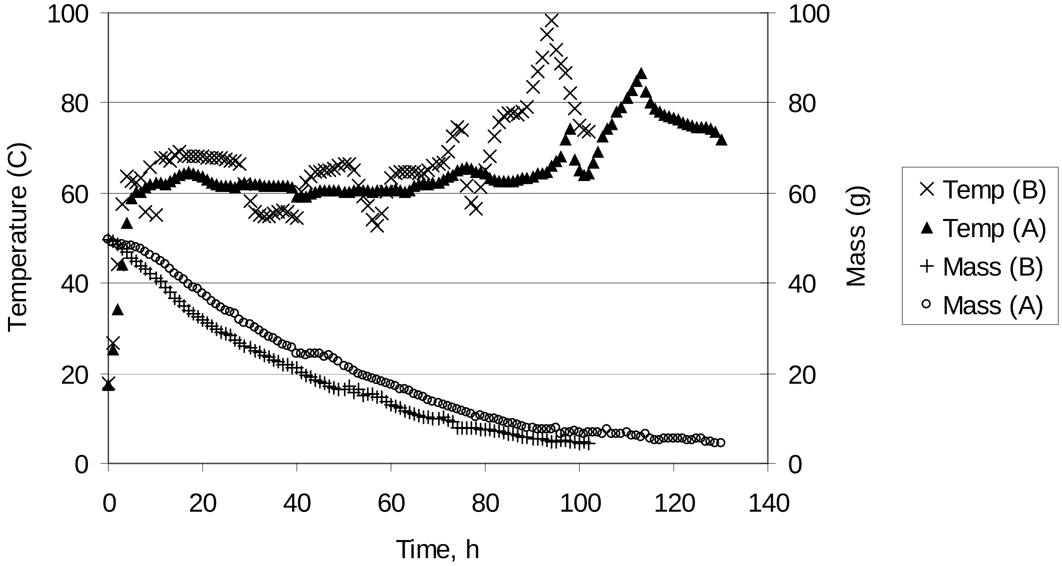

Figure 4.5 The effects of valve position on process parameters under vacuum pressure of 13.3 kPa

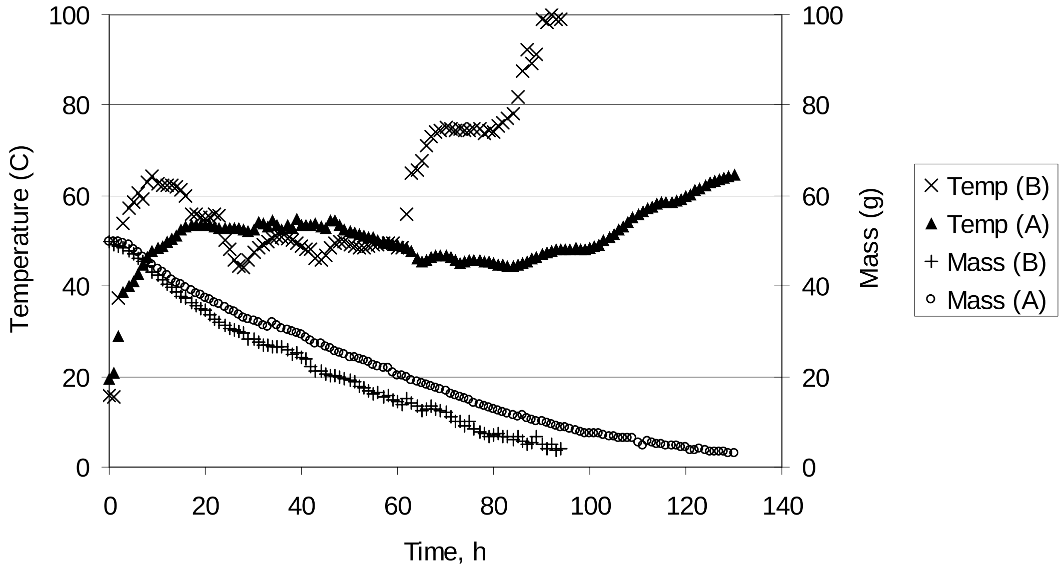

Figure 4.6 The effect of valve position on process parameters under vacuum pressure of 6.5 kPa

4.5.2 Microwave vacuum drying study of strawberry in halves

The initial moisture content of strawberries varied from 89 to 91% wet basis, which correspond to 9 to 10 dry basis (kg water/ kg dry matter). The experiments were designed to study the effect of 3 levels of input power, 1, 1.5 and 2 W/g. The results show that an input power of 1 W/g was able to carry the process until the end, but at 1.5 and 2 W/g, the input power needed to be decreased at the last stage of drying due to too high reflected power as shown in Figures 4.8 and 4.9. It was also found that the reflected power at the last stage of the process was very difficult to control for 2 W/g of input power. This could be implied that 2 W/g was too high for microwave vacuum drying of strawberries.

The results at input powers of 1 and 1.5 W/g were good for microwave vacuum drying of strawberries; however, the product temperature at the last stage was too high (Figure 4.7) which could result in quality degradation of dried product in terms of color, texture and nutritional value. Figures 4.7, 4.8 and 4.9 show the corresponding product temperature and input power for the three levels of power used; high input power always led to a high product temperature. A number of studies have proposed ways to control input power. Cheng et al. (2006) used a phase-controlled electrical power regulator to control input power. A pulse mode (on/off) of input power also was investigated to control input power (Yongsawatdigul and Gunasekaran, 1996; Gunasekaran, 1999). Sunjka et al. (2004) recommended that the pulse mode of 30 second on/ 45 second off provided better quality of color, texture and rehydration for microwave vacuum drying of cranberry. Although the pulse mode of 30 second on/ 45 second off will extend drying time, it provided more efficient energy consumption. All techniques that have been studied seem to favor the pulse mode as a simple technology. From the results of this experiment and the literature data, the proper conditions for microwave vacuum drying of strawberries could be obtained by the combination of continuous input power at the early stage of process with pulse mode at the last stage in which the input power of microwave should be between 1-1.5 W/g.

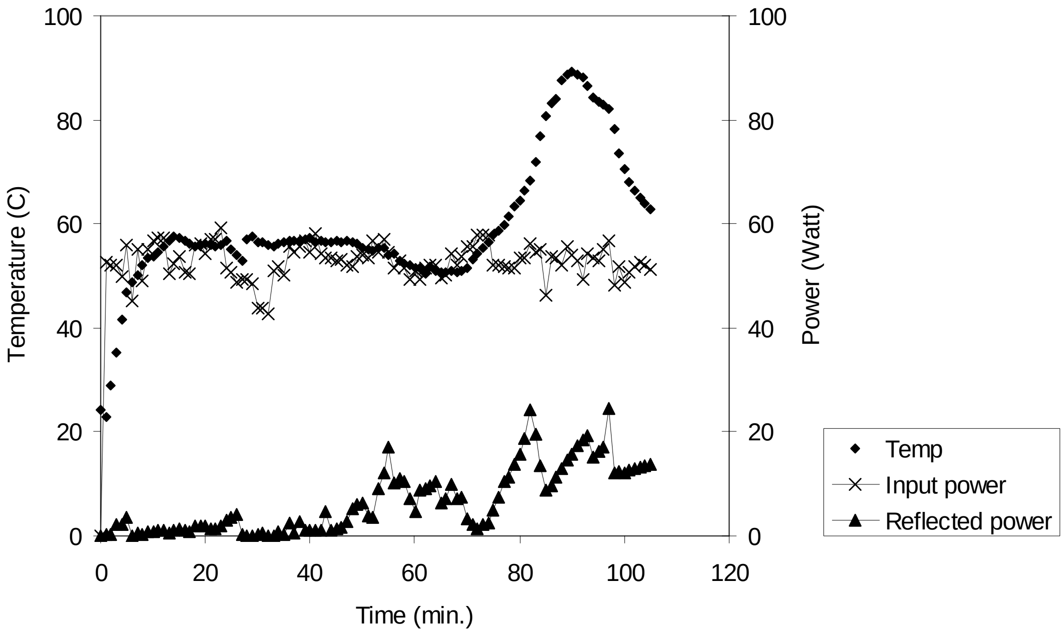

Figure 4.7 Tracking product temperature, input power and reflected power for input power of 1 W/g during strawberry drying

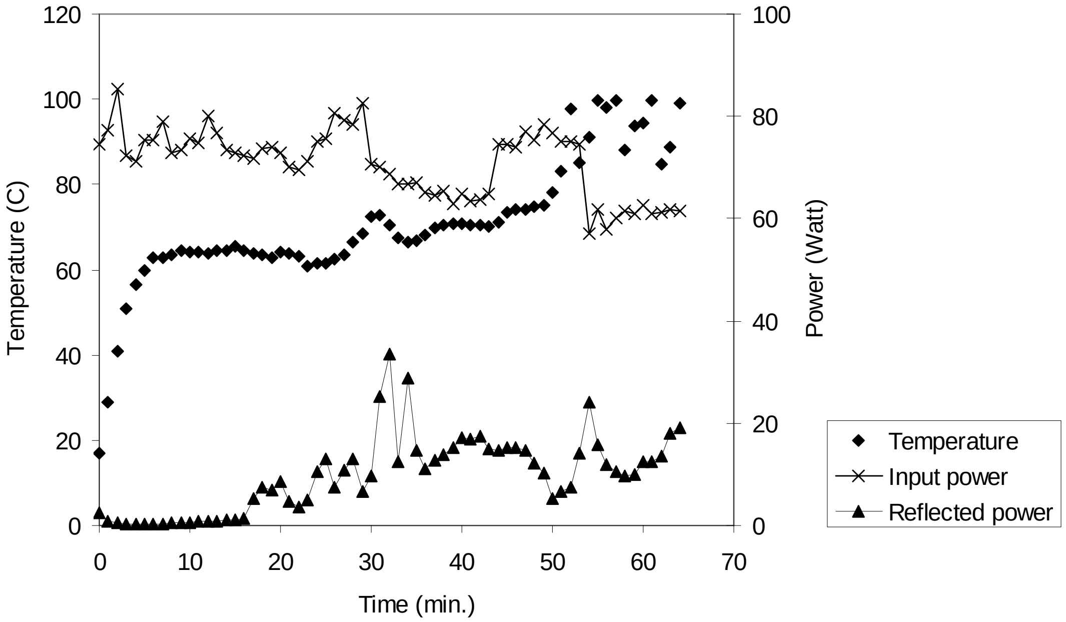

Figure 4.8 Tracking product temperature, input power and reflected power for input power of 1.5 W/g during strawberry drying

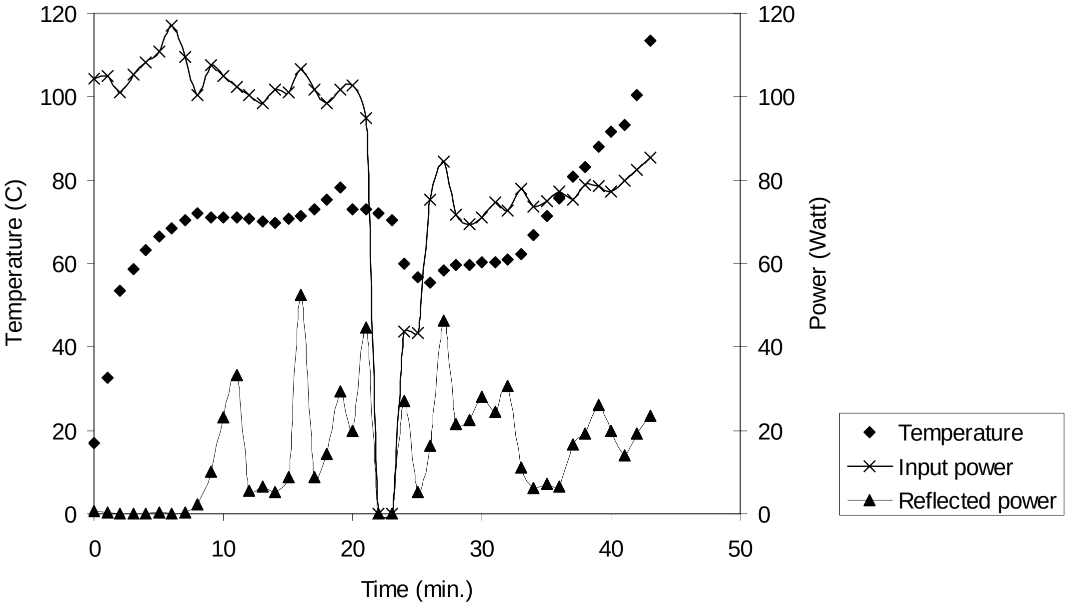

Figure 4.9 Tracking product temperature, input power and reflected power for input power of 2 W/g during strawberry drying

4.5.3 Microwave vacuum drying study of carrots in cubes

The initial moisture content of carrots varied from 88 to 90% wet basis, which corresponded to 9 to 10 dry basis (kg water/ kg dry matter).

It was found that the reflected power for the experiments at input powers of 1 and 1.5 W/g could be kept under control (Figures 4.10 and 4.11). On the other hand, it was difficult to control reflected power for input power of 2 W/g which forced a decrease of input power as shown in Figure 4.12. Finally, the experiment with an input power of 2 W/g was ended before reaching target moisture content. It was concluded that an input power of 2 W/g is too high for microwave vacuum drying of carrots.

By taking all the results in to account, it was found that the product temperature at 1 W/g input power was not too high but tended to increase at the last stage of drying. At 1.5 W/g the product temperature was high as found in drying of strawberries. The product temperature at 2 W/g could not be determined because the process was stopped before reaching the target moisture content. Since an input power lower than 1 W/g would take longer process time, the suitable input power for drying 10 mm carrot cubes and strawberries halves should be between 1-1.5 W/g and a pulse mode of input power could be applied at the last stage of process to control drying product temperature.

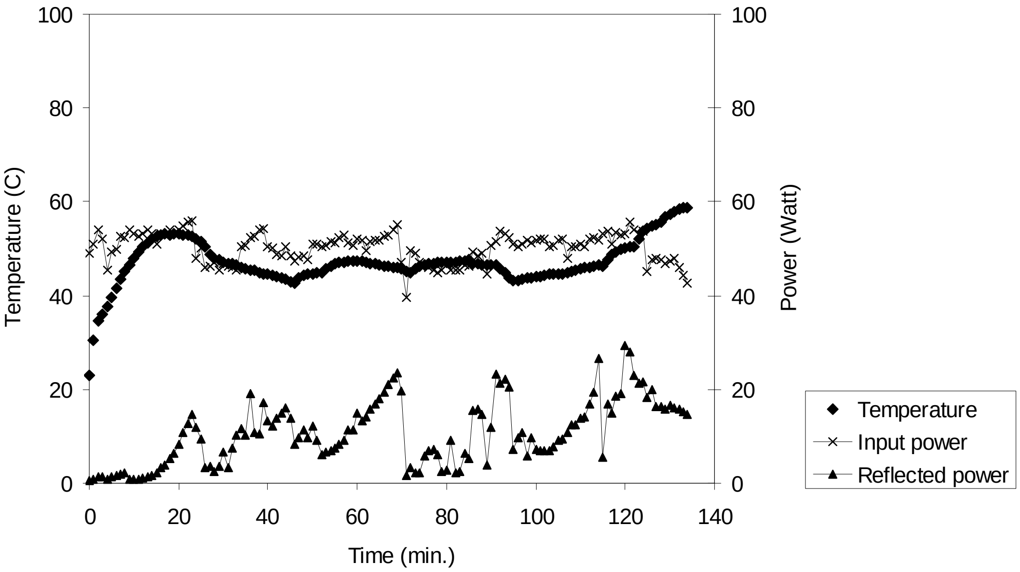

Figure 4.10 Tracking product temperature, input power and reflected power for input power 1 W/g of carrot drying

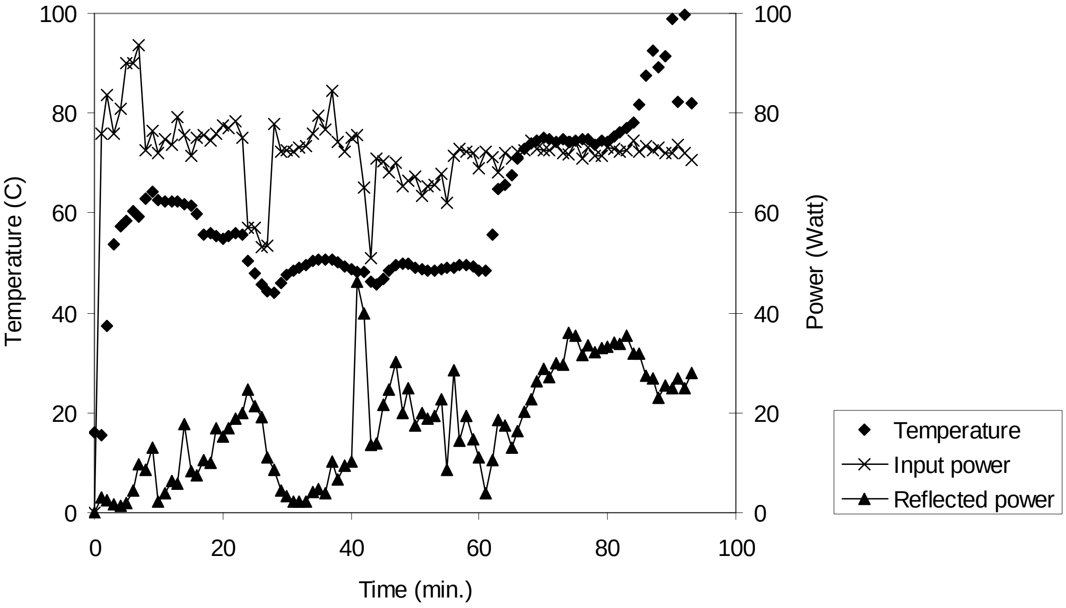

Figure 4.11 Tracking product temperature, input power and reflected power for input power 1.5 W/g of carrot drying

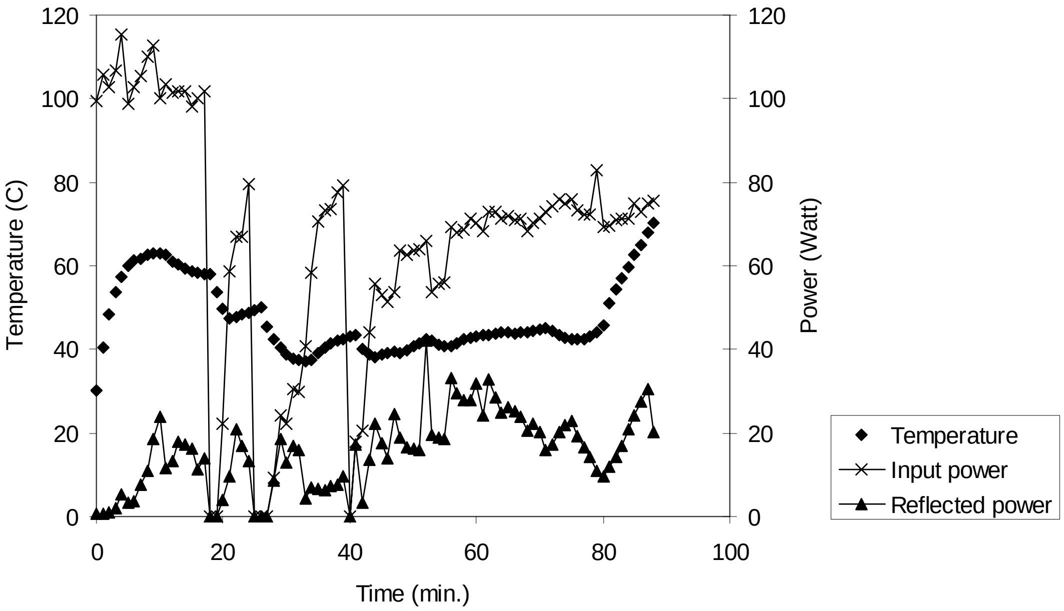

Figure 4.12 Tracking product temperature, input power and reflected power for input power 2 W/g of carrot drying

4.6 Conclusions

The positioning of the controlled pressure release valve in microwave vacuum system affects the drying time and the occurrence of vapor condensation. Passing air through the vacuum container provided reduced drying time and reduction in the occurrence of vapor condensation. The vacuum pressure did not influence the drying time. The suitable input power for microwave vacuum drying of strawberries halves and 10 mm carrot cubes was found to be between 1-1.5 W/g.

4.7 Acknowledgments

The authors are grateful to the Postgraduate Education Research and Development Project in Postharvest Technology, Chiangmai University, Thailand and the Natural Sciences and Engineering Research Council of Canada.

4.8 References

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CONNECTING TEXT

The installation and modification of a microwave vacuum dryer was presented in Chapter IV. The results of input power management will be used for the design of an experimental investigation of osmotically dehydrated microwave vacuum of carrots and strawberries in the Chapter VII and VIII.

CHAPTER V

EFFECT OF OSMOTIC DEHYDRATION ON THE DIELECTRIC PROPERTIES OF CARROTS AND STRAWBERRIES

5.1 Abstract

Osmotic dehydration can potentially be used as a pretreatment for microwave drying. Since microwave drying is dependent on the dielectric properties of the material to be dried, it is important to know if osmotic dehydration has any effect on these properties. Strawberries and carrots were used as representative fruits and vegetables, respectively, in this study. Two osmotic agents, sucrose and salt, were used for carrots but only sucrose was used for strawberries. The effects of variations in sucrose and salt concentrations, solution temperature, and length of immersion time on the dielectric constant (ε') and the loss factor (ε") were measured. A predictive model was established for the range of variation used for each of the conditions studied. In general, the ε' decreased with an increase in value of osmotic parameters. The ε" of strawberries was not affected by osmotic dehydrations. The use of salt as the osmotic agent did have a significant effect on the ε" of carrots. Predictive models of dielectric properties of strawberries and carrots were developed using response surface methodology.

5.2 Introduction

The application of microwave heating to drying processes has been investigated primarily because of its high drying rate. The better quality of microwave dried products and significant energy savings have also been noted (Prabhanjan et al., 1995; Sanga et al., 2000). The dielectric properties of materials are the key factors in microwave-assisted drying process. The dielectric constant (ε') is a measure of the ability of a material to couple with electromagnetic field. The dielectric loss factor (ε") of a material is a measure of the ability of the material to heat by absorbing energy (Datta et al., 2005). Experimental data on the dielectric properties of various foods are available in the literature (Tinga and Nelson, 1973; Venkatesh et al., 1998, Liao, 2002). To improve microwave assisted drying, there are many combinations to be considered for study. Among these combinations, researchers have shown that osmotic drying prior to microwave-assisted drying leads to lower energy consumption and better qualities of dried product (Venkatachalapathy and Raghavan, 1999; Beaudry et al., 2003).

The osmotic process is the simultaneous process of water and solute diffusion (Ponting et al., 1966; Lerici et al., 1985; Krokida and Marinos-Kouris, 2003). Moisture is known to be the main factor affecting dielectric properties, lower moisture content tends to provide low ε' (Rajnish et al., 1995). Solute diffusion could be the transfer of either osmotic agents ie. sugar and salt, or solid components of produce which also will affect the dielectric properties. To enhance performance of osmotic dehydration, increasing temperature resulted in greater water removal (Ravindra and Chattopadhyay, 2000). Changes in water removal rates due to temperature can influence dielectric properties also. Thus, it could be assumed that the osmotic process will affect the dielectric properties of the product. Since the dielectric properties are an important factor of any microwave study, data on the dielectric properties of produce after osmotic processing will be helpful to researchers to find the proper conditions for this process prior to microwave-assisted dehydration.

Most applications of microwaves in food processing in North and South America are designed for operation at the frequency of 2450 MHz (Venkatesh and Raghavan, 2004). The present study will focus on dielectric properties at this frequency. Strawberries and carrots were selected for the study as the representatives of fruits and vegetables.

5.3 Objectives

The focus of the current study is to investigate the effects of osmotic conditions on the dielectric properties of strawberries and carrots as the representatives of fruits and vegetables, at the frequency of 2,450 MHz.

5.4 Materials and Methods

5.4.1 Materials

The cultivar of strawberries and carrots used in this study were not known. Carrots were obtained from a local market and were cut into 10 mm sized cubes with a mechanical cutting device. Strawberries were cut into halves with a stainless steel knife. Strawberries and carrots were stored at 4°C and were allowed to sit at room temperature (22 ± 1 °C) one hour before the tests were started.

5.4.2 Osmotic treatments

Carrots (50g) and strawberries (4 halves) were treated by placement in an osmotic solution. The results of the study by Singh et al. (1999) showed no significant difference among the ratios of sample to solution 1:4, 1:7 and 1:10 for the osmotic dehydration of carrot. All samples in this study were kept with a ratio of sample to solution 1 : 5 (w/w). Three sugar concentrations (30, 40 and 50 %w/w) and three salt concentrations (5, 10, and 15 % w/w) were mixed to obtain an osmotic solution for carrots and three sugar concentrations (40, 50 and 60 % w/w) were used for strawberries. The temperature of the osmotic solutions was set up to 20, 30 and 40°C for both strawberries and carrots. To investigate the effect of time, carrots were placed in osmotic solution for 2, 5 and 8 hours and 12, 18 and 24 hours for strawberries. After osmotic treatment the samples were dipped in ambient temperature water (20°C) in order to remove the osmotic agents at the surface of samples and gently wiped with a soft tissue and left for 15 minutes in ambient air in order to remove surface moisture.

5.4.3 Dielectric properties measurement

After osmotic dehydration, the dielectric properties of samples were measured by an open-ended coaxial probe (Agilent-85070D, California) at a frequency of 2450 MHz. An Agilent network analyzer (Agilent-8722ES, California) was used to analyze the dielectric properties signal. The instrument was first calibrated using three different loads: (i) solid metal, (ii) air and (iii) distilled water at 20°C. The measurement was initiated by touching the samples against the flat face of open-ended probe.

5.4.4 Experimental designs

Response surface methodology (RSM) was used to estimate the main effects. A second-order central composite design (CCD) in the form of a face-centered cube (FCC) with four factors (sucrose concentration, salt concentration, and temperature and immersion time) at three levels each was used for carrots. Only three factors, sucrose concentration, temperature and immersion time at three levels each were applied for strawberries. All experiments were conducted in triplicate. The three levels of actual factor values and corresponding coded values (-1, 0, 1) for carrots and strawberries are given in Tables 5.1 and 5.2 respectively.

Table 5.1 Second-order central composite design (CCD) for carrots

Experiment No.	Sucrose concentration (%w/w)	Salt concentration (%w/w)	Temp (°C)	Time (h)
1	30 (-1)	5 (-1)	20 (-1)	2 (-1)
2	50 (+1)	5 (-1)	20 (-1)	2 (-1)
3	30 (-1)	15 (+1)	20 (-1)	2 (-1)
4	50 (+1)	15 (+1)	20 (-1)	2 (-1)
5	30 (-1)	5 (-1)	40 (+1)	2 (-1)
6	50 (+1)	5 (-1)	40 (+1)	2 (-1)
7	30 (-1)	15 (+1)	40 (+1)	2 (-1)
8	50 (+1)	15 (+1)	40 (+1)	2 (-1)
9	30 (-1)	5 (-1)	20 (-1)	8 (+1)
10	50 (+1)	5 (-1)	20 (-1)	8 (+1)
11	30 (-1)	15 (+1)	20 (-1)	8 (+1)
12	50 (+1)	15 (+1)	20 (-1)	8 (+1)
13	30 (-1)	5 (-1)	40 (+1)	8 (+1)
14	50 (+1)	5 (-1)	40 (+1)	8 (+1)
15	30 (-1)	15 (+1)	40 (+1)	8 (+1)
16	50 (+1)	15 (+1)	40 (+1)	8 (+1)
17	30 (-1)	10 (0)	30 (0)	5 (0)
18	50 (+1)	10 (0)	30 (0)	5 (0)
19	40 (0)	5 (-1)	30 (0)	5 (0)
20	40 (0)	15 (+1)	30 (0)	5 (0)
21	40 (0)	10 (0)	20 (-1)	5 (0)
22	40 (0)	10 (0)	40 (+1)	5 (0)
23	40 (0)	10 (0)	30 (0)	2 (-1)
24	40 (0)	10 (0)	30 (0)	8 (+1)
25	40 (0)	10 (0)	30 (0)	5 (0)
26	40 (0)	10 (0)	30 (0)	5 (0)

Table 5.2 Second-order central composite design (CCD) for strawberries

Experiment No.	Sucrose concentration (%w/w)	Temperature (°C)	Time (h)
1	40 (-1)	20 (-1)	12 (-1)
2	60 (+1)	20 (-1)	12 (-1)
3	40 (-1)	40 (+1)	12 (-1)
4	60 (+1)	40 (+1)	12 (-1)
5	40 (-1)	20 (-1)	24 (+1)
6	60 (+1)	20 (-1)	24 (+1)
7	40 (-1)	40 (+1)	24 (+1)
8	60 (+1)	40 (+1)	24 (+1)
9	40 (-1)	30 (0)	18 (0)
10	60 (+1)	30 (0)	18 (0)
11	50 (0)	20 (-1)	18 (0)
12	50 (0)	40 (+1)	18 (0)
13	50 (0)	30 (0)	12 (-1)
14	50 (0)	30 (0)	24 (+1)
15	50 (0)	30 (0)	18 (0)
16	50 (0)	30 (0)	18 (0)

5.4.5 Statistical analysis and model development

Data was analyzed by using the software package STATGRAPHIC Plus 5.1 (Manugistics, Inc., Rockville, MD). The model was developed from regression coefficients under a range of experimental factors. The coefficient of determination (r^2) was used to indicate how the model fits the variability of the results. The terms of second order polynomial model consist of linear, quadratic (squared) and interaction terms as shown by the following equations:

$$Y_1 = b_0 + b_1X_1 + b_2X_2 + b_3X_3 + b_4X_4 + b_{11}X_1^2 + b_{22}X_2^2 + b_{33}X_3^2 + b_{44}X_4^2 + b_{12}X_1X_2 + b_{13}X_1X_3 + b_{14}X_1X_4 + b_{23}X_2X_3 + b_{24}X_2X_4 + b_{34}X_3X_4 \quad (5.1)$$

$$Y_2 = b_0 + b_1X_1 + b_2X_2 + b_3X_3 + b_{11}X_1^2 + b_{22}X_2^2 + b_{33}X_3^2 + b_{12}X_1X_2 + b_{13}X_1X_3 + b_{23}X_2X_3 \quad (5.2)$$

where b_n are the regression coefficients; Y_1 is the response either ε' or ε" of carrots; X_1, X_2, X_3 and X_4 in Eqn. (5.1) are sucrose concentration (% w/w), salt concentration (% w/w), temperature (°C) and immersion time (h), respectively; Y_2 is the response either ε' or ε" of strawberries; X_1, X_2 and X_3 in Eqn. (5.2) are sucrose concentration (% w/w), temperature (°C) and time (h), respectively. Also note that the values of X_n correspond to the real values (uncoded values) of the variable. The response surface was developed by the same software.

5.5 Results and discussion

The initial ε' and ε" were 66.1 and 16.3 for carrots, and 69.1 and 18 for strawberries. Since the dielectric properties are significantly influenced by the presence of moisture, the higher ε' of strawberries over the ε' of carrots would be expected due to the higher initial moisture content, 93.5% and 87.7% (wet basis), respectively.

5.5.1 The influence of osmotic dehydration on dielectric constant of carrots

The results show that a decrease of ε' is attributable to an increase in immersion time, temperature and concentration of osmotic agents as shown in Figure 5.1. The main effects of osmotic dehydration on dielectric properties are a result of removed moisture and gained solid (sucrose and salt) of end product. Similar result was observed by Tulasidas, 1995 that decreasing moisture decreased ε', increasing sugar concentration decreased ε'. However, the influence of salt concentration on ε' in this study was contrary to the result of Goedeken et al., 1997 and Bengtsson and Risman, 1971 which reported the insignificant influence of salt content on ε'. Since the amount of removed water in the osmotic process increases with an increase in immersion time, temperature and concentration, decreasing of ε' in this study could be implied that the influence of water removal overcame the influence of solid gain. This confirmed that moisture plays an important role in ε' (Venkatesh and Raghavan, 2004). The highest F-value value of time in Table 5.3 means that in osmotic dehydration of carrot, time factor is the dominant one affecting ε'. However, it was found that the lowest value of ε' which was affected by time occurred within the range of this study, 2-8 h. It might be assumed that ε' will not be lower even with process time longer than 8 h.

According to the table 5.3 the result shows significant interaction correlation between sucrose and time. The response surface of these factors was selected to show in Figure 5.2. The figure clearly shows that increasing sucrose concentrations cause larger decreases of ε' which is affected by time.

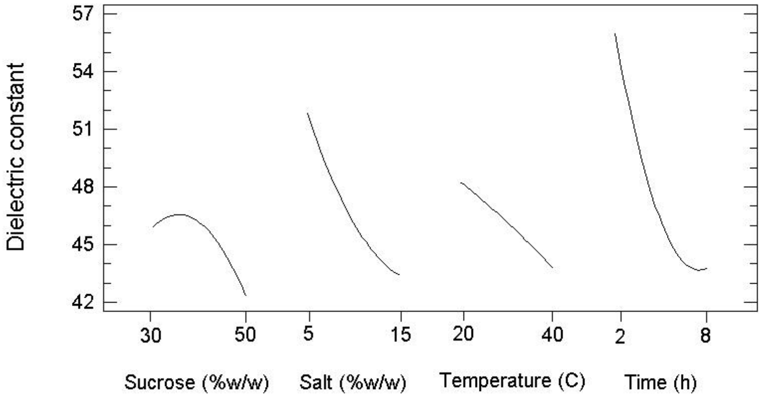

Figure 5.1 The effects of sucrose, salt, temperature and immersion time on ε' of carrot

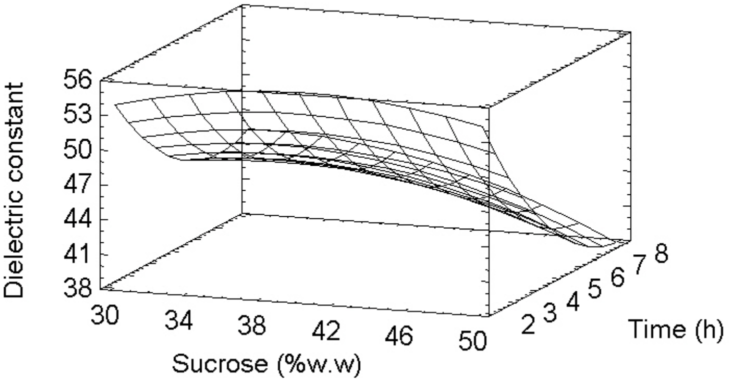

Figure 5.2 Response surface plot of the effect of sucrose and time on the ε' of carrot

5.5.2 The influence of osmotic dehydration on the loss factor of carrots

Sucrose and salt concentration were more dominant affecting on ε" than temperature and time as shown in Figures 5.3. The F-value of ε" in Table 5.3 confirms that temperature and time did not have a significant effect. As mentioned above, decreased moisture and increased sucrose and salt contents of the end product would result from osmotic dehydration. The effect of changing moisture, sucrose and salt on ε" were reported in that there was no significant effect on ε" of moisture levels between 40-80 % (wet basis) and sucrose content (Tulasidas et al., 1995) but increased salt content increased the loss factor (Goedeken et al., 1997). In this study, the effect of salt was found dominant. This means that salt gaining significantly affected the ε" of the end product of osmotic dehydration. The strength of the influence of salt is shown by the F-value in Table 5.3. The high value, 29-49, of the ε" of end product (Figure 5.3) also shows the strong influence of salt to the loss factor where the initial ε" was only 16.3.

The interaction response surface plot in Figure 5.4 shows that increasing sucrose concentration cause smaller increases of ε" which is also affected by salt.

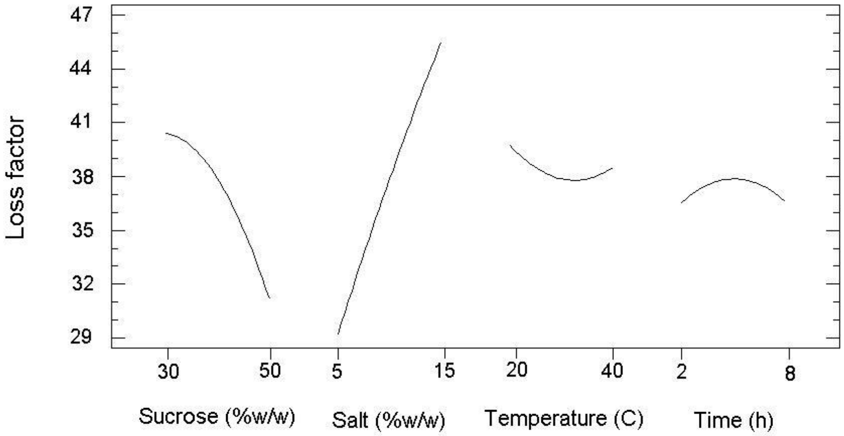

Figure 5.3 The effects of sucrose, salt, temperature and immersion time on Main effects plot for ε" of carrot

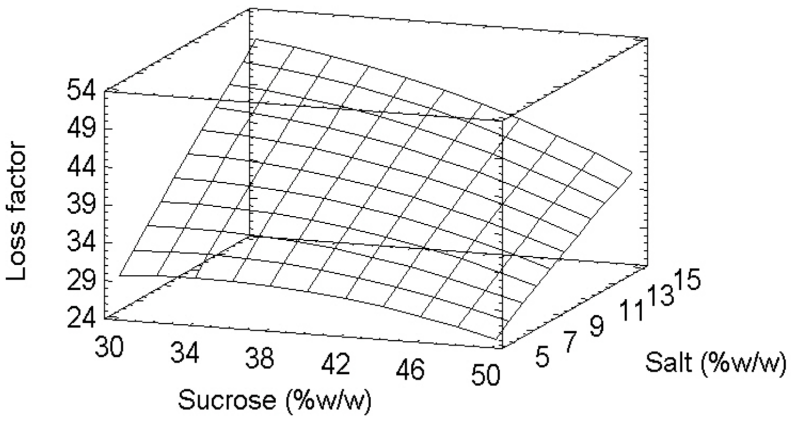

Figure 5.4 Response surface plot of the effect of sucrose and salt on the ε” of carrot

5.5.3 Predictive model for dielectric constant and loss factor of carrots

The coefficient of determination (r^2 value) of ε' and ε” of carrots were 0.97 and 0.96, respectively. Regression coefficients for ε' and ε” of carrots as shown in Table 5.3 provided the predictive equations in actual terms (uncoded) as the following:

$$\varepsilon' = 42.5479 + 1.7708(Su) - 2.5678(Sa) + .1807(T) - 2.1675(t) -.2024(Su)^2 + .0143(Su)(Sa) - .005(Su)(T) - .065(Su)(t) + .0590(Sa)^2 +.0063(Sa)(T) - .0425(Sa)(t) - .0017(T)^2 - .0325(T)(t) + .4140(t)^2 \qquad (5.3)$$

$$\varepsilon'' = -9.0091 + 1.5686(Su) + 3.8418(Sa) - .8315(T) + 4.2985(t) - .0209(Su)^2 - .0454(Su)(Sa) + .0052(Su)(T) - .0123(Su)(t) - .0195(Sa)^2 + .0098(Sa)(T) - .0613(Sa)(t) + .0126(T)^2 - .0585(T)(t) - .1431(t)^2 \qquad (5.4)$$

Where, Su = Sugar (%w/w), $30 < Su < 50$,
Sa = Salt (%w/w), $5 < Sa < 15$,
T = Temperature (°C), $20 < T < 40$ and
t = Time (hour), $2 < T < 8$.

Table 5.3 Regression equation coefficients for ε' and ε" of osmotic dehydration of carrots[a]

Coefficients	ε'	ε"
b_0	42.5479	-9.0091
Linear		
b_1 (Sucrose)	1.7708 (15.17)**	1.5686 (51.25)**
b_2 (Salt)	-2.5678 (82.03)**	3.8418 (159.44)**
b_3 (Temperature)	.1807 (23.19)**	-.8315 (0.88)
b_4 (Time)	-2.1675 (171.18)**	4.2985 (0)
Quadratic		
b_{11}	-.0202 (2.70)	-.0209 (1.49)
b_{22}	.0590 (1.43)	-.0195 (0.08)
b_{33}	-.0017 (0.02)	.0126 (0.55)
b_{44}	.4140 (9.14)*	-.1430 (0.57)
Interaction		
b_{12}	.0143 (2.09)	-.0454 (11.03)**
b_{13}	-.005 (1.03)	.0052 (0.58)
b_{14}	-.065 (15.63)**	-.0123 (0.29)
b_{23}	.00625 (0.40)	.0099 (0.52)
b_{24}	-.0425 (1.67)	-.0613 (1.81)
b_{34}	-.0325 (3.91)	-.0585 (6.61)*
r^2	0.97	0.96

*, **: F value significant at level 0.05 and 0.01, respectively

[a] Value in the parenthesis show F values.

5.5.4 The influence of osmotic dehydration on dielectric constant of strawberries

The sucrose concentration, temperature and immersion time, had strong influences on the ε' of strawberries (Figure 5.5). The ε' decreased as the values of all experimental factors increased. Changes in ε' of strawberries had agreement with the results of carrots. This means that water removal in the osmotic processing of strawberries and carrots was the dominant effect on affecting the changes in ε'. A significant interaction was found between temperature and time. The response surface plot in Figure 5.6 shows that increasing temperature causes a large decrease of ε' which is affected by time. That means the osmotic processing of strawberries at a high temperature tends to provide low ε'. If dielectric heating supposes to be performed after osmotic dehydration of strawberries, a high temperature of osmotic process should be avoided.

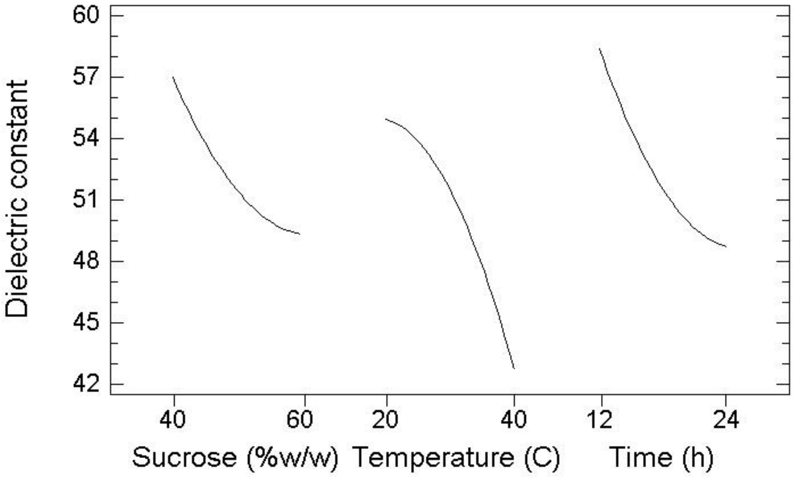

Figure 5.5 The effects of sucrose, temperature and immersion time on ε' of strawberry

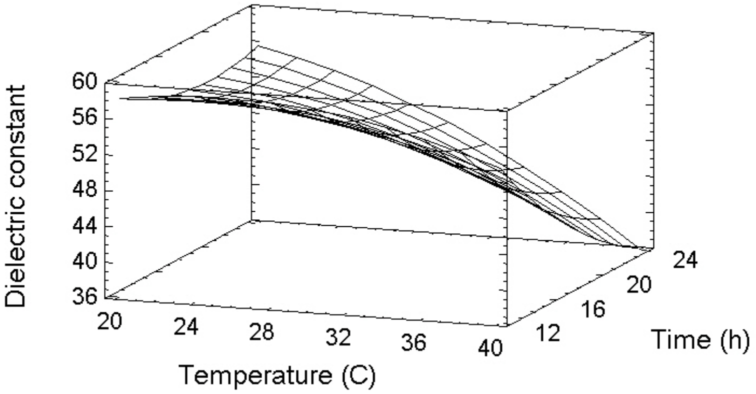

Figure 5.6 Response surface plot of the effect of sucrose and time on the ε' of strawberry

5.5.5 The influence of osmotic dehydration on loss factor of strawberries

Although Figure 5.7 shows that the experimental factors had some effects on the ε”, but only quadratic term of immersion time shows significant influence to ε” by statistic proof as seen in Table 5.4. There were no significant effects in linear term. This result was in accordance with previous studies on grape (Tulasidas et al., 1995) that changes in moisture content didn’t affect ε” when the moisture content was over 40 % (wet basis) and the different sugar solutions did not cause significant changes of ε”. It could be concluded that there was no effect on ε” due to the removal of moisture and sugar gain in osmotic dehydration of strawberries.

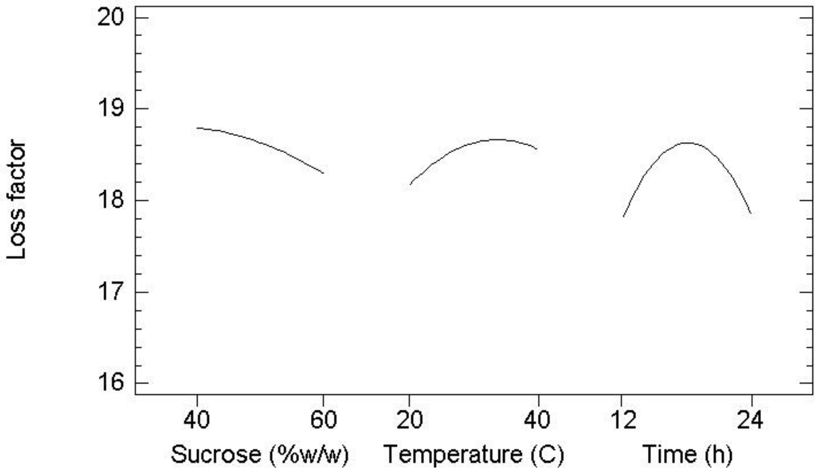

Figure 5.7 Effects of sucrose, temperature and immersion time on Main effects plot for ε” of strawberry

5.5.6 Predictive model for dielectric constant and loss factor of strawberries

The coefficient of determination (r^2 value) of ε' and ε” of strawberry were 0.94 and 0.83, respectively. Regression coefficients of Equation 5.2 for the predictive models ε' and ε” of carrots as shown in Table 5.4 provided the predictive equations in actual terms (uncoded) as the following:

$$\varepsilon' = 77.6979 - 1.4779(Su) + 2.7635(T) - .51794(t) + .01671(Su)^2 - .0133(Su)(T) - .0010(Su)(t) - .0268(T)^2 - .0613(T)(t) + .05683(t)^2 \quad (5.5)$$

$$\varepsilon'' = -1.1906 + .1875(Su) + .3963(T) + 1.0577(t) -.0009(Su)^2 - .0027(Su)(T) - .0025(Su)(t)- .0026(T)^2 - .0048(T)(t) - .0219(t)^2 \quad (5.6)$$

where, Su = Sugar (%w/w), $40 < Su < 60$,
T = Temperature (°C), $20 < T < 40$ and
t = Time (hour), $12 < T < 24$.

Table 5.4 Regression equation coefficients for ε' and ε" of osmotic dehydration of strawberries[a]

Coefficients	ε'	ε"
b_0	77.6979	-1.1906
Linear		
b_1 (Sucrose)	-1.47789 (16.74)**	0.18744 (3.09)
b_2 (Temperature)	2.76354 (42.12)**	0.39626 (1.75)
b_3 (Time)	-0.51794 (26.56)**	1.0577 (0.01)
Quadratic		
b_{11}	0.01671 (0.83)	-0.00088 (0.1)
b_{22}	-0.02679 (2.14)	-0.00263 (0.87)
b_{33}	-0.05682 (1.25)	-0.0219 (7.78)*
Interaction		
b_{12}	-0.01327 (1.59)	-0.00266 (2.69)
b_{13}	-0.00995 (0.32)	-0.0024 (0.84)
b_{23}	-0.06125 (12.22) *	-0.00477 (3.11)
r^2	0.94	0.83

*, **: F value significant at level 0.05 and 0.01, respectively

[a] Value in the parenthesis show F values.

5.6 Conclusions

It can be concluded from the results that the ε' of carrots and strawberries decreased with an increase in the concentration of the osmotic agents, temperature and immersion time. The immersion time was the most significant factor affecting the ε' of carrots. Salt was the most significant factor affecting the ε" of carrots. There was no influence of osmotic conditions on ε" during osmotic dehydration of strawberries.

5.7 Acknowledgements

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CONNECTING TEXT

The acquired predictive equation dielectric constant (ε') and the loss factor (ε") of carrots and strawberries in Chapter V will be useful in the study for the carrots and strawberries in Chapter VII and VIII. The effects of changes in dielectric properties due to osmotic pre-treatment will be further studied in hybrid drying concepts of later chapters.

CHAPTER VI

OPTIMIZATION OF OSMOTIC DEHYDRATION OF CARROTS AND STRAWBERRIES

6.1 Abstract

As osmotic dehydration can provide partial moisture removal, it can potentially be a treatment prior to conventional drying. Since water loss (WL) and solid gain (SG) are the simultaneous occurrences in osmotic process, the aim is always to maximize WL and minimize SG. The parameter of WL/SG was used to balance WL and SG. The goal of this study was to achieve the highest value of WL/SG with optimum osmotic conditions.

Carrots and strawberries were used as representatives of vegetables and fruits, respectively, in this study. Two osmotic agents, sucrose and salt, were used for carrots but only sucrose was used for strawberries. The effects of variations in sucrose and salt concentrations, solution temperature, and length of immersion time on the WL and SG were calculated. A predictive model was established for the range of variation used for each of the conditions studied. In most cases, an increase of sucrose concentration, temperature and immersion time increased WL and SG, except the increasing of sugar concentration for osmotic treatment of strawberries decreased SG. Predictive equations of WL, SG and WL/SG and optimization of strawberries and carrots were developed using a response surface methodology.

6.2 Introduction

Due to energy and quality related advantages of osmotic treatment; it is gaining popularity as a complementary process (Torreggiani, 1993). Osmotic treatment is the process that immerses whole or pieces of fruits and vegetables in hypertonic solution. At least two major simultaneous counter-current flows occur, water flow out of the food into solution and solute from the solution into food (Barbosa-Canovas and Vega-Mercado, 1996). As the 50 % of water flow out of food in osmotic process (Ponting et al., 1966) it can potentially be considered as a treatment prior to conventional drying. Osmotic dehydration before convective drying provides a flexible and fluffy structure of dried product (Lenart, 1996). Osmotic dehydration of strawberries prior to microwave drying reduces loss of aroma, flavor and color (Venkatachalapathy and Raghavan, 1999). The 50% reduction in time for rehydration was found in the study of osmotic dehydration followed by fluidized bed drying (Ravindra and Chattopadhyay, 2000). In most cases, osmotic dehydration is related to improvement of some nutritional, organoleptic and functional properties of the product (Torreggiani, 1993), the accumulation of solid gain with an increased solute concentration decreases the rate of mass transfer (Grabowski et al., 2002) and interferes with reaching an adequate moisture content for product storage (Moreira et al., 2004). When osmotic dehydration is selected as a treatment prior to conventional drying, minimum solid gain is required.

The osmotic process variables (pre-treatment, temperature, concentration of the solution, agitation, additives, immersion time, etc) have been reported to have influence on mass transfer and on the product quality (Lerici et al., 1985; Rostogi and Raghavarao, 1997; Erle and Schubert, 2001; Rostogi et al., 2004). In studying the effect of multiple variables on one or more responses in industrial investigations or any processes, response surface methodology is often used due to its effectiveness and practical utility (Corzo and Gomez, 2004). This method minimizes the number of samples, and can help in identifying the influence of various factors to the purpose of optimizing conditions to obtain the maximum or the minimum of studied factors. In this study response surface technology was used to optimize the osmotic conditions which consist of the following variables: osmotic agents concentration (sucrose and/or salt), temperature and immersion time for strawberries and carrots as representatives of fruits and vegetables, respectively. The maximum WL and minimum SG are investigated through the maximum of their ratio WL/SG.

6.3 Objectives

The objectives of this study are to provide predictive equations and optimize the osmotic conditions consisting of osmotic agents concentration, temperature and immersion time of osmotic dehydration as a pre-drying process on strawberries and carrots as representatives of fruits and vegetables, respectively. The studies aim to achieve two goals:

1. To maximize removal of water,
2. To minimize solid gain.

6.4 Materials and Methods

6.4.1 Materials, osmotic treatments and experimental designs

The materials and osmotic treatments used to perform the experiments in this study were the same as those used in the experiments on the effect of osmotic dehydration on the dielectric properties of carrots and strawberries in Chapter V. There were three replicates for all treatments.

6.4.2 Calculations

Water loss (WL) and solid gain (SG) were calculated in terms of percentage based on initial sample weight in which WL represented the net removed water and SG expressed the net solid uptake of osmotically dehydrated samples, carrots and strawberries (Le Maguer, 1988):

$$\text{WL (\%)} = \frac{m_i - m_{os}}{W_i} \times 100 \tag{6.1}$$

$$\text{SG (\%)} = \frac{s_{os} - s_i}{W_i} \times 100 \tag{6.2}$$

where m_i = moisture content of fresh sample, g
m_{os} = moisture content of osmotically dehydrated sample, g
s_i = solid content of fresh sample, g
s_{os} = solid content of osmotically dehydrated sample, g
W_i = Initial weight of fresh sample, g

Since the maximum removed moisture and minimum solid gain as a result of changes in each variable were expected to fall in different regions, the parameter of WL/SG was used to evaluate the optimized variables.

6.4.3 Statistical analysis and model development

Data was analyzed by using the software package STATGRAPHIC Plus 5.1 (Manugistics, Inc., Rockville, MD). The model was developed from regression coefficients under a range of experimental factors. The coefficient of determination (r^2) was used to indicate how the model fits the variability of the results. The terms of second order polynomial model consist of linear, quadratic (squared) and interaction terms as shown by the following equations:

$$Y_1 = b_0 + b_1X_1 + b_2X_2 + b_3X_3 + b_4X_4 + b_{11}X_1^2 + b_{22}X_2^2 + b_{33}X_3^2 + b_{44}X_4^2 + b_{12}X_1X_2 + b_{13}X_1X_3 + b_{14}X_1X_4 + b_{23}X_2X_3 + b_{24}X_2X_4 + b_{34}X_3X_4 \qquad (6.3)$$

$$Y_2 = b_0 + b_1X_1 + b_2X_2 + b_3X_3 + b_{11}X_1^2 + b_{22}X_2^2 + b_{33}X_3^2 + b_{12}X_1X_2 + b_{13}X_1X_3 + b_{23}X_2X_3 \qquad (6.4)$$

where b_n are the regression coefficients; Y_1 is the response of WL, SG and WL/SG of carrots; X_1, X_2, X_3 and X_4 in Eqn. (6.3) are sucrose concentration (% w/w), salt concentration (% w/w), temperature (°C) and immersion time (h), respectively; Y_2 is the response of WL, SG and WL/SG of strawberries; X_1, X_2 and X_3 in Eqn. (6.4) are sucrose concentration (% w/w), temperature (°C) and time (h), respectively. Also note that the values of X_n correspond to the real values (uncoded values) of the variable. The response surface graph and the optimization of the osmotic conditions; osmotic agents concentration, temperature and immersion time, were established using the same software (STATGRAPHIC Plus 5.1, Manugistics Inc., Rockville, MD).

6.5 Results and discussion

The initial moisture content of carrots and strawberries were 87.7 % and 93.5% (wet basis), respectively. The simultaneous water loss (WL) and solid gain (SG) was considered as mass exchange during osmotic treatment. The WL/SG showed a balance between WL and SG. The highest value of WL/SG expressed the maximum removed water and minimum solid gain. Predictive equations and optimization of osmotic conditions are presented in the final part of discussion of each product.

6.5.1 Mass exchange during osmotic dehydration of carrots

Increasing osmotic conditions; osmotic solution concentration, temperature and immersion time, significantly increased WL as shown in Figure 6.1 and Table 6.1. This result had agreement with previous studies (Sacchetti et al., 2001; Corzo and Gomez, 2004). The interaction effect of sucrose and salt to WL in Table 6.1 is presented in Figure 6.2. It shows that the presence of salt improved WL which was similar to the study by Uddin et al., 2004 and Telis et al., 2004. It confirmed that increasing salt concentration improves WL. It should be noted that this interaction was found at the low concentration of sucrose while a high sucrose concentration did not show the influence.

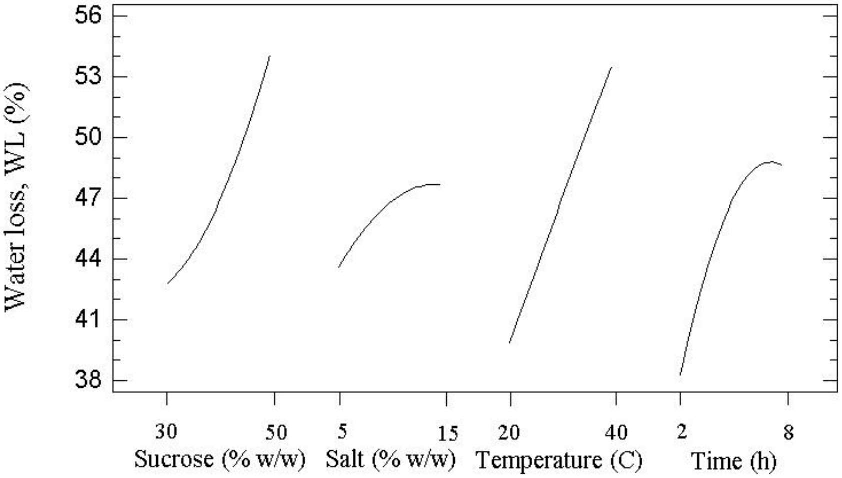

Figure 6.1 The effects of sucrose, salt, temperature and immersion time on WL of carrots

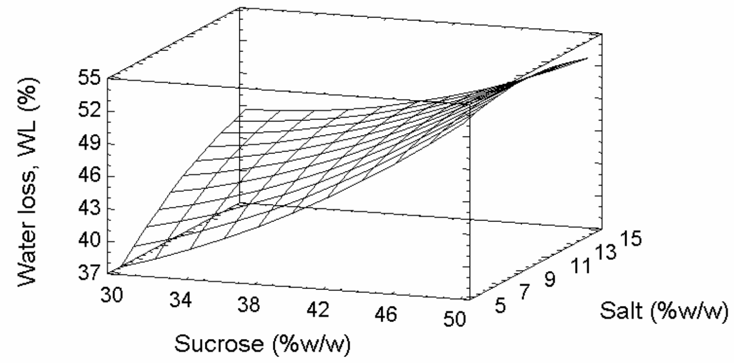

Figure 6.2 The interaction effect of sucrose and salt on WL of carrots

The effect on SG was almost the same as that found in WL except for the effect of sucrose concentration, shown in Figure 6.3. Increasing sugar resulted in an initial increased SG for a short period of time, followed by a decrease. Lazarides et al. (1997) proposed that the reason for this phenomenon is that the accumulation at the subsurface of solute resulted in decrease of solid gain in high concentration osmotic solutions. The higher sucrose concentration seemed to be in favor of osmotic treatment as a pre-drying step because it provided high WL and low SG.

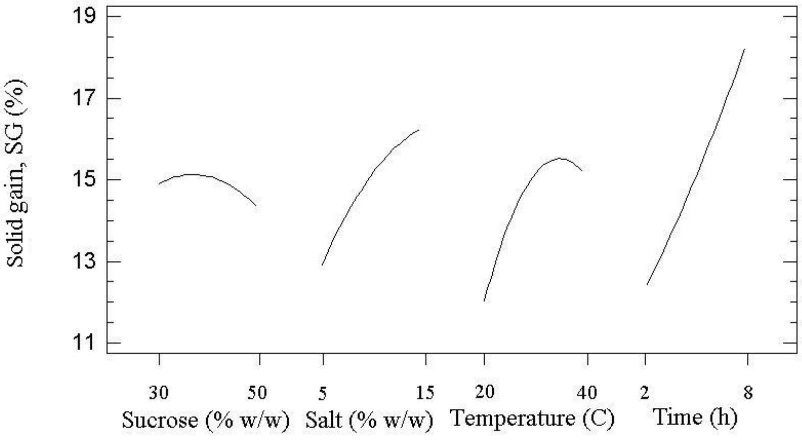

Figure 6.3 The effects of sucrose, salt, temperature and immersion time on SG of carrots

The parameter WL/SG in figure 6.4 shows balancing between WL and SG. Higher values of WL/SG will support use of osmotic treatment as a pre-drying stage. The influence of sucrose to WL was greater than the occurrence of SG. So WL/SG increased with increasing sucrose concentration. Higher SG due to increasing salt concentration was dominant over WL which resulted in a decrease of WL/SG. As a pre-drying treatment, a low salt concentration is recommended. The effect of temperature was tied between WL and SG under the range of temperature for this study. Table 6.1 shows no significant effect of temperature on WL/SG. Time affected SG more than WL. Increasing immersion time decreased WL/SG.

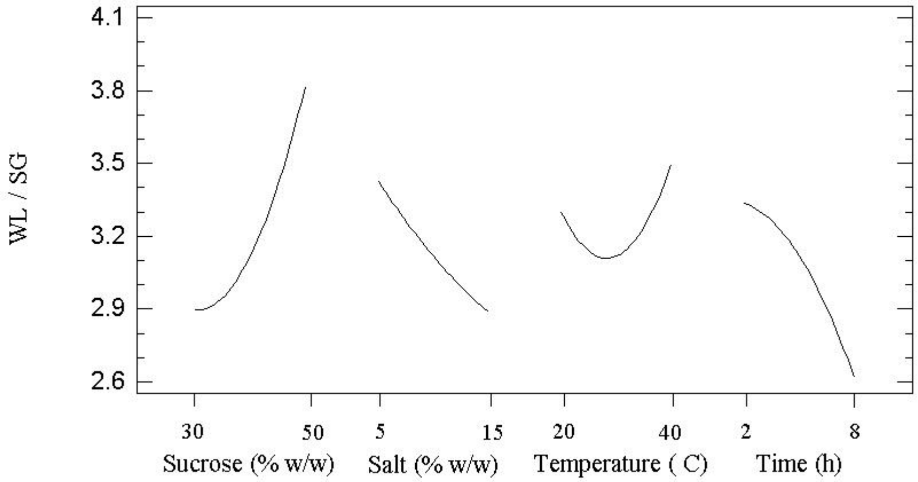

Figure 6.4 The effects of sucrose, salt, temperature and immersion time on WL/SG of carrots

Table 6.1 Regression equation coefficients of WL, SG and WL/SG of osmotic dehydration of carrots[a]

Coefficients	WL	SG	WL/SG
b_0	16.5927	-25.8851	11.2066
Linear			
b_1 (Sucrose)	-1.0384 (44.02)**	0.5871 (0.80)	-0.2017 (23.32)**
b_2 (Salt)	2.9631 (5.84)*	1.0349 (28.10)**	-0.1010 (7.98)*
b_3 (Temperature)	-0.1249 (64.97)**	1.1280 (26.06)**	-0.2613 (1.06)
b_4 (Time)	4.0807 (37.49)**	0.4989 (86.14)**	-0.0526 (14.03)**
Quadratic			
b_{11}	0.01668 (0.55)	-0.0046 (0.31)	0.0024 (0.89)
b_{22}	-0.0453 (0.26)	-0.0205 (0.39)	0.0016 (0.02)
b_{33}	-0.0008 (0.00)	-0.0146 (3.14)	0.0028 (1.22)
b_{44}	-0.3703 (2.21)	0.0264 (0.08)	-0.0157 (0.31)
Interaction			
b_{12}	-0.0426 (5.65)*	-0.0113 (2.90)	-0.001 (0.26)
b_{13}	0.0153 (2.91)	-0.0034 (1.04)	-0.0010 (2.99)
b_{14}	0.0465 (2.41)	-0.0063 (0.32)	0.0028 (0.71)
b_{23}	0.0174 (0.94)	0.001 (0.02)	0.0028 (1.95)
b_{24}	-0.0929 (2.41)	0.025 (1.29)	-0.0056 (0.69)
b_{34}	0.0140 (0.22)	0.0067 (0.37)	0.0011 (0.10)
r^2	0.94	0.94	0.84

*, **: F value significant at level 0.05 and 0.01, respectively

[a] Value in the parenthesis show F values.

6.5.2 Predictive equation of mass exchange of osmotic dehydration of carrots

The coefficient of determination (r^2) of WL, SG and WL/SG of carrots were 0.94, 0.94 and 0.84 respectively. Regression coefficients of Equation 6.3 for the predictive models WL, SG and WL/SG of carrots as shown in Table 6.1 provided the predictive equations in actual terms (uncoded) as the following:

$$WL\ (\%) = 16.5927 - 1.0384*Su + 2.9631*Sa - 0.125*T + 4.0807*t + 0.0167*Su^2 - 0.0426*Su*Sa + 0.0153*Su*T + 0.0465*Su*t - 0.0453*Sa^2 + 0.0174*Sa*T - 0.0929*Sa*t - 0.0008*T^2 + 0.014*T*t - 0.3703*t^2 \qquad (6.5)$$

$$SG\ (\%) = -25.8851 + 0.5871*Su + 1.0349*Sa + 1.128*T + 0.499*t - 0.0046*Su^2 - 0.0113*Su*Sa - 0.0034*Su*T - 0.0063*Su*t - 0.0205*Sa^2 + 0.001*Sa*T + 0.025*Sa*t - 0.0146*T^2 + 0.0067*T*t + 0.0264*t^2 \qquad (6.6)$$

$$WL/SG = 11.2066 - 0.2017*Su - 0.1010*Sa - 0.2613*T - 0.0526*t + 0.0024*Su^2 - 0.001*Su*Sa + 0.0018*Su*T + 0.0028*Su*t + 0.0016*Sa^2 + 0.0028*Sa*T - 0.0056*Sa*t + 0.0028*T^2 + 0.0011*T*t - 0.0157*t^2 \quad (6.7)$$

Where, Su = Sugar (%w/w), $30 < Su < 50$,
Sa = Salt (%w/w), $5 < Sa < 15$,
T = Temperature (°C), $20 < T < 40$ and
t = Time (hour), $2 < T < 8$.

6.5.3 Optimum condition of osmotic dehydration of carrots

The optimization of osmotic dehydration of carrots was done via the WL/SG parameter at the point of maximum WL and minimum SG. The optimization was performed by the software package STATGRAPHIC Plus 5.1 (Manugistics, Inc., Rockwille, MD) with the goal to maximize WL/SG. The resulting optimum conditions in Table 6.2 provide the highest value of WL/SG = 4.63. This means that the optimum condition for osmotic treatment as pre-drying step to provide maximum water removal and minimum solid gain was a sucrose concentration of 50 % (w/w), a salt concentration of 5% (w/w), a temperature of 40°C and an immersion time of 3 hour 20 minute.

In case of low energy input consideration, operating process under ambient temperature (20°) is ideal. The predicted optimum condition was performed as a trial. The result of the optimum condition of osmotic treatment as pre-drying at 20°C was a sucrose concentration of 50 % (w/w), a salt concentration of 5% (w/w), a temperature of 20°C and an immersion time of 2 hour 38 minute as shown in Table 6.3. It provided a WL/SG of 4.41 while the range of the study was 2.76 – 4.79. So the WL/SG of 4.41 from the optimum condition at 20°C is reasonable considering a low energy input process.

Table 6.2 Predicted optimum condition of osmotic dehydration of carrots (20° < T < 40°C)

Factor	Low	High	Optimum
Sucrose	30	50	50
Salt	5	15	5
Temp	20	40	39.99
Time	2	8	3.32

Table 6.3 Predicted optimum condition of osmotic dehydration of carrots (T = 20°C)

Factor	Low	High	Optimum
Sucrose	30	50	50
Salt	5	15	5
Temp	20	20	20
Time	2	8	2.64

6.5.4 Mass exchange during osmotic dehydration of strawberries

Mass exchange during the osmotic conditions in the study of strawberries showed the same patterns of WL and SG as found in carrots (Figures 6.5 and 6.6). The increase in sucrose concentration, temperature and immersion time increased WL and SG. The only exception is that a higher concentration of sucrose tends to hinder SG due to the accumulation at subsurface of solute as discussed early. The difference between carrots and strawberries was seen in the effect of immersion time to SG; for strawberries; treatment did not show as strongly as it was found in carrots, probably due to non presence of salt in the osmotic solution used for strawberries treatment. Molecular size of salt is smaller than sucrose. The effect of molecular size to SG was reported by Lazarides et al. (1997) that further decrease of solute size resulted in a substantially increased SG.

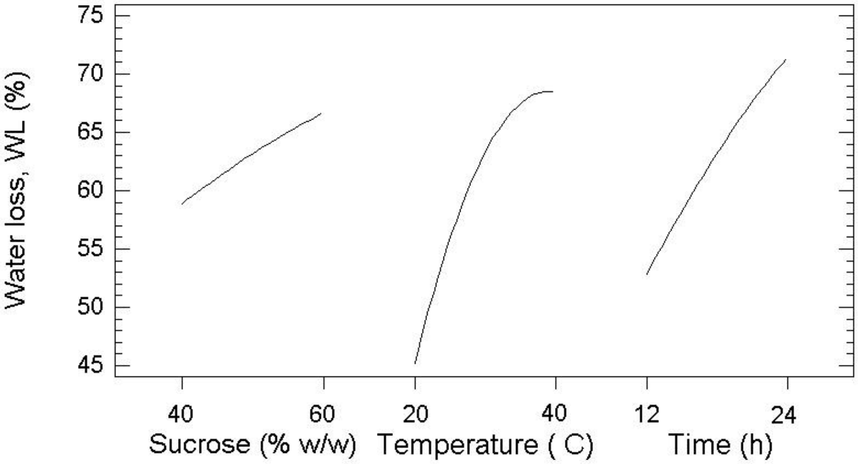

Figure 6.5 The effects of sucrose, temperature and immersion time on WL of strawberries

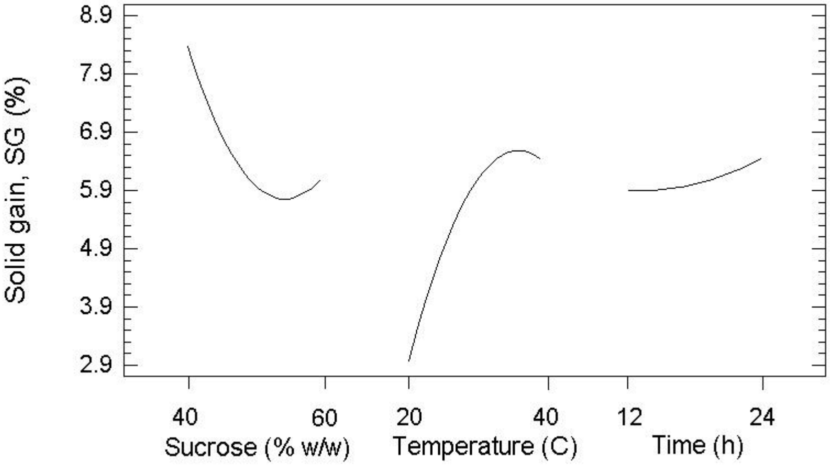

Figure 6.6 The effects of sucrose, temperature and immersion time on SG of strawberries

In general, the effect on WL/SG as seen in Figure 6.7, sucrose and temperature in the study of strawberries showed the same results as found in carrots but it was contrary for immersion time. Longer immersion time in strawberries increased WL/SG while opposite was observed in the carrots study. This was expected due to the result of low SG in the process of strawberries. The value of SG in Figures 6.3 for carrots was between 12 to18 while the SG of strawberry treatments was only from 3 to 8 (Figure 6.6). The significant interaction (Table 6.4) between sucrose concentration and immersion time, and between temperature and immersion time are shown in Figures 6.8 and 6.9, respectively. The longer immersion time increased WL/SG at the high concentration of sucrose. In contrast, the longer immersion time lowered the rate of increase of WL/SG which was affected by temperature.

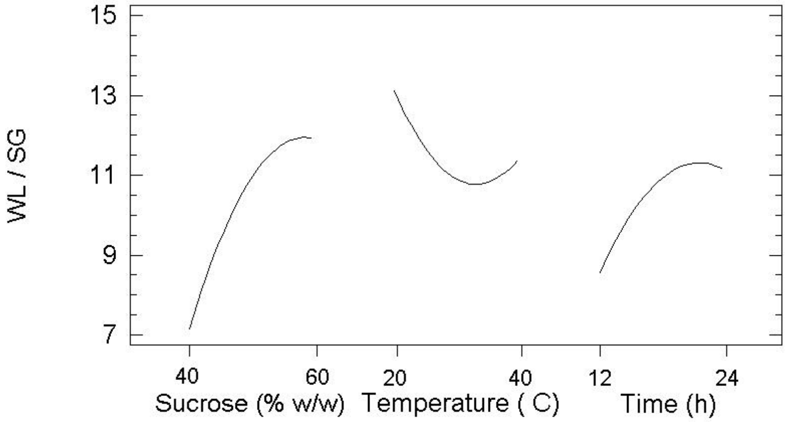

Figure 6.7 The effects of sucrose, temperature and immersion time on WL/SG of strawberries

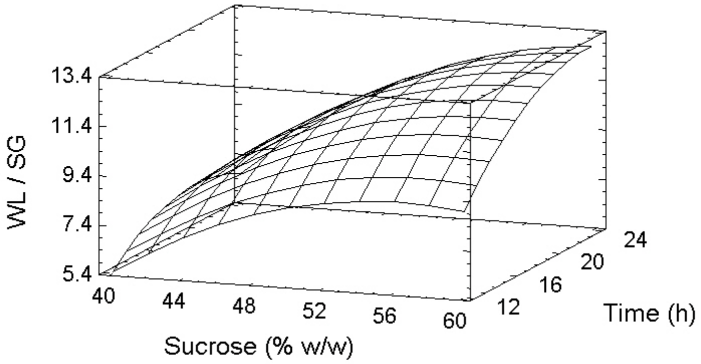

Figure 6.8 The interaction effect of sucrose and time on WL/SG of strawberries.

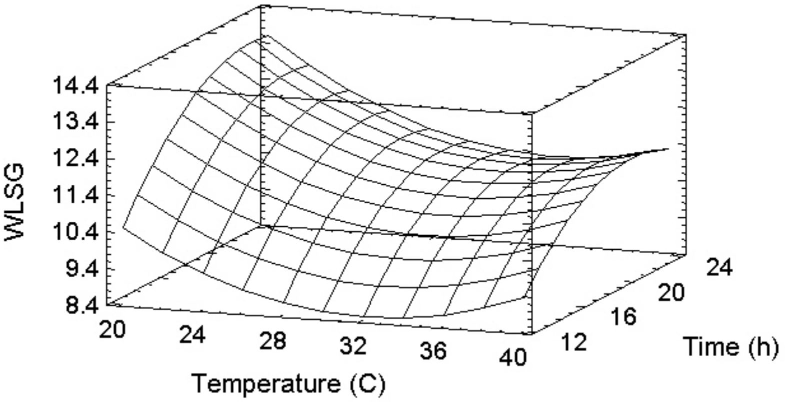

Figure 6.9 The interaction effect of temperature and time on WL/SG of strawberries.

Table 6.4 Regression equation coefficients of WL, SG and WL/SG of osmotic dehydration of strawberries[a]

Coefficients	WL	SG	WL/SG
b_0	-16.6393	7.5077	-36.4224
Linear			
b_1 (Sucrose)	0.5778 (12.26)**	-0.3694 (1.21)	1.6212 (41.75)**
b_2 (Temperature)	0.2153 (38.95)**	0.1710 (96.66)**	-0.3170 (45.91)**
b_3 (Time)	0.0598 (42.95)**	-0.0665 (58.27)**	0.5869 (54.73)**
Quadratic			
b_{11}	-0.0054 (4.18)*	0.0038 (4.56)*	-0.0151 (4.83)*
b_{22}	-0.0023 (0.76)	0.0035 (3.94)	0.0030 (0.19)
b_{33}	0.0047 (0.40)	0.0121 (6.03)*	-0.0448 (5.51)*
Interaction			
b_{12}	0.0008 (0.26)	-0.0003 (0.10)	-0.0078 (3.96)
b_{13}	-0.0006 (0.05)	-0.0005 (0.07)	0.0194 (8.74)**
b_{23}	-0.0017 (0.44)	-0.0153 (82.40)**	0.0163 (6.14)*
r^2	0.84	0.89	0.84

*, **: F value significant at level 0.05 and 0.01, respectively

[a] Values in the parenthesis show F values.

6.5.5 Predictive equation of mass exchange of osmotic dehydration of strawberries

The developed predictive models of WL, SG and WL/SG of strawberries follow the Equation 6.4. The regression equation coefficients are shown in Table 6.4. The coefficient of determination (r^2 value) of 0.84, 0.89 and 0.84 were obtained for WL, SG and WL/SG, respectively indicating good fit of experimental data and the predictive equations in actual values (uncoded) are:

$$WL = -16.6393 + 0.5778*Su + 0.2153*T + 0.0598*t - 0.0054*Su^2 + 0.0008*Su*T - 0.0006*Su*t - 0.0023*T^2 - 0.0017*T*t + 0.0046855*t^2 \quad (6.8)$$

$$SG = 7.5077 - 0.3694*Su + 0.171*T - 0.0665*t + 0.0038*Su^2 - 0.0003*Su*T - 0.0005*Su*t + 0.0035*T^2 - 0.0153*T*t + 0.012*t^2 \quad (6.9)$$

$$WL/SG = -36.4224 + 1.6212*Su - 0.317*T + 0.5869*t - 0.015*Su\hat{}2 - 0.0078*Su*T + 0.0194097*S*t + 0.003*T^2 + 0.0163*T*t - 0.0448*t^2 \quad (6.10)$$

where, Su = Sugar (%w/w), $40 < Su < 60$, T = Temperature (°C), $20 < T < 40$ and
t = Time (hour), $12 < T < 24$.

6.5.6 Optimum conditions of osmotic dehydration of strawberries

The optimization of osmotic dehydration of strawberries was performed by the same software as used for carrots. The goal of maximum WL/SG was used to determine the optimum conditions. The resulting optimum conditions in Table 6.5 provided the highest value of WL/SG = 15.68 which was higher than that found in the carrots study. The resulting optimum conditions in using osmotic treatment as a pre-drying step to provide maximum WL and minimum are: sucrose concentration of 60 % (w/w), temperature of 20°C and immersion time 24 hours.

Table 6.5 Predicted optimum condition of osmotic dehydration of strawberries

Factor	Low	High	Optimum
Sucrose	40	60	60
Temperature	20	40	20
Time	12	24	24

6.6 Conclusions

The result of water loss and solid gain for the study of strawberries and carrots showed the same tendency. In most cases, an increase of sucrose concentration, temperature and immersion time increased water loss and solid gain except that in the case of increasing sugar concentration for the process of strawberries, which decreased sugar gain.

The optimum osmotic conditions to maximize the WL/SG for carrots were: sucrose concentration of 50 % (w/w), salt concentration of 5% (w/w), temperature of 40°C and immersion time of 3 hour 20 minute.

The optimum osmotic conditions to maximize the WL/SG for carrots were sucrose concentration of 50 % (w/w), salt concentration of 5% (w/w), temperature of 20°C and immersion time of 2 hour 38 minute, in case of low input energy by working at an ambient temperature of 20°C.

The optimum conditions to maximize the WL/SG for strawberries were: sucrose concentration of 60 % (w/w), temperature of 20°C and immersion time of 24 hours.

6.7 Acknowledgements

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CONNECTING TEXT

The optimum condition of osmotic pre-drying of carrots and strawberries will be used for the study microwave vacuum process of osmotically dehydrated carrots and strawberries. The effects of solid gain, water loss and dielectric properties will be investigated.

CHAPTER VII

OSMOTICALLY DEHYDRATED MICROWAVE VACUUM DRYING OF CARROTS

7.1 Abstract

Osmotic dehydration prior to the drying process was able to remove free water which accounts for around 50% of moisture of fresh product. The advantage of microwave vacuum drying is that it provides faster drying times in a low temperature process. The combination of osmotic and microwave vacuum was investigated in this study. Since solid gain from osmotic agents might cause a decrease in diffusivity of the osmotically dehydrated product and lower qualities of dried product, it is important to know the effects of osmotic treatment prior to microwave vacuum drying. Carrots were used as representative of vegetables. Two levels of input power (1 and 1.5 W/g) and three power modes (continuous, 45s on/15s off and 30s on/30s off) were studied at the absolute pressure 8 kPa of microwave vacuum drying. Drying kinetics, energy consumption and qualities in terms of water activity, shrinkage, rehydration capacity, color characteristics and sensory evolution were studied. Empirical models were developed to fit the observed data. In general, osmotic dehydration was able to decrease drying time and energy consumption. Less shrinkage and improving appearance were the advantages in terms of quality. Page's model showed the best fit among the selected models.

7.2 Introduction

The simplest objective of drying is to remove moisture to a certain level which is good enough to avoid microbial growth. This leads to the main purpose of drying which is the extension of shelf-life while maintaining product quality. In today's context, maintaining nutrition value of fresh product and low energy consumption are also required which cannot be achieved by a single technique as it has been done before.

Carrot (*Daucus carota* L.) is a good source of β-carotene thiamine, iron, vitamin C and sugar. It is classified as a commercially significant vegetable. Drying of carrots has been studied in a number of ways i.e. sun drying (Mulet et al., 1993), solar drying (Ratti and Mujumdar, 1997), convective air drying in tunnel or on single conveyor (Grabowski and Marcotte., 2003), convective microwave drying (Prabhanjan et al., 1995), freeze drying (Lin et al., 1998). Among them, convective hot air is the most widely used technology for carrots, with a temperature of hot air around 70ºC and final moisture content of about 4-8% (w.b.) (Grabowski and Marcotte, 2003). To achieve the requirements of keeping the nutrition value of fresh carrots, low energy consumption and fast drying time, this study proposes a combination of osmotic dehydration and microwave vacuum drying.

The aim of this study is to improve microwave assisted drying, in which microwaves have shown the advantage of faster drying time. The combination of microwave technology with the low temperature processing under vacuum has been studied by a number of researchers. The results have shown that microwave vacuum drying can be a potential alternative way to improve the quality of dried products due to the low temperature in the vacuum process combined with the faster heating time of microwaves. Successful results are reported for applications on several products such as orange powder, cranberries, potatoes, bananas, and carrots (Attiyate 1979; Yongsawatdigul and Gunasekaran, 1996; Kubota et al., 1992; Drouzas and Schubert, 1996. Tein et al.,1998).

Osmotic dehydration can be used to remove water for heat sensitive products with low energy consumption at a lower temperature. Since osmotic dehydration cannot remove moisture to a level that will avoid microbial growth, it is good as a partial dehydration step. While osmotic dehydration is a simultaneous process of water flow out and solid gain from osmotic agents, the gaining of osmotic agent could be another advantage in improving nutritional, sensorial and functional properties of the dried food.

In this study the improvement of microwave assisted drying with the combination of vacuum and osmotic treatment will be investigated in term of drying kinetics, drying models, energy consumption and quality aspects.

7.3 Objectives

The objectives of this study is to determine the effect of osmotic pretreatment prior to microwave vacuum drying at different input power level and power mode (continuous, 45s on/15s off and 30s on 30s off). Carrot was selected as a representative of vegetables.

7.4 Materials and Methods

7.4.1 Materials

The cultivar of carrots used in this study was not known. Carrots were obtained from a local market and were cut into 10 mm sized cubes with a mechanical cutting device. Carrots were stored at 4°C and were allowed to sit at room temperature (20±1 °C) for one hour before the tests were started.

7.4.2 Initial properties measurement

The fresh carrots' moisture was determined by drying in a hot air oven 70ºC for 12 h (Ranganna, 1986). The dielectric properties of fresh carrots were measured by an open-ended coaxial probe (Agilent-85070D, California) at a frequency of 2450 MHz. An Agilent network analyzer (Agilent-8722ES, California) was used to analyze the dielectric properties signal. The instrument was first calibrated using three different loads: (i) solid metal, (ii) air and (iii) distilled water at 20°C. The measurement was initiated by touching the samples against the flat face of open-ended probe. The color of fresh carrots was measured by using a chroma meter (Model CR-300X, Minolta camera Co. Ltd., Japan).

7.4.3 Osmotic dehydration

In the process of osmotic pretreatment, 100 g of carrots were treated at room temperature (20ºC) by placement in a mixed osmotic solution of 50% w/w of sugar concentration and 5% w/w of salt concentration for 2 hour and 38 minute, which followed the optimum condition suggested in Chapter VI. Since the results of the study by Singh et al. (1999) showed no significant difference among the ratios of sample to solution 1:4, 1:7 and 1:10 for the osmotic dehydration of carrot, all samples in this study were kept with a ratio of sample to solution 1:5 (w/w). During each osmotic treatment, the sample (100 g) was separated into 20 g and 80 g in the osmotic solution. After osmotic treatment the samples were dipped in ambient temperature water (20°C) in order to remove the osmotic agents at the surface of samples and gently blotted with tissue paper and left for 15 minutes in ambient air in order to remove surface moisture. The part of 80 g was used in microwave vacuum drying. The rest was analyzed to calculate water loss (WL), solid gain (SG) and dielectric properties after osmotic process.

7.4.4 Microwave vacuum drying

The same microwave vacuum dryer as that studied in Chapter IV was used in this study which enabled recording of drying product temperature and mass every 1 minute. Due to the small effect to dried product of vacuum pressure in a microwave vacuum, (Cui et al., 2004) the vacuum was fixed at 27.5 inHg of gauge pressure or 8 kPa of absolute pressure. The osmotically dehydrated carrot samples and 80 g of fresh carrots were used to investigate the effect of osmotic pretreatment in microwave vacuum drying. The products were dried until the final moisture content reached 10 % (wet basis). The dried samples were cooled to ambient temperature in desiccators, packed and stored in a cold room at 3ºC for water activity, shrinkage, rehydration, color, texture and sensory evaluation studies.

7.4.5 Empirical models

The experimental moisture content data was calculated using the equation:

$$MR = \frac{X - X_e}{X_o - X_e} \tag{7.1}$$

where MR is the moisture ratio; X is the moisture content at time t (kg/kg, dry basis); X_e is the equilibrium moisture content (kg/kg, dry basis); X_o is the initial moisture content (kg/kg, dry basis). For the analysis it was assumed that the equilibrium moisture content was equal to zero due to the vacuum condition. The selected thin layer drying models used in the analysis of drying characteristics are presented in Table 7.1. They have been widely used due to their ease of use and their good fit with the observed data. The coefficient of determination (r^2) and root mean square error (RMSE) were used to evaluate the fit of each model in which RMSE was calculated using (Togrul and Pehlivan, 2003)

$$RMSE = \left[\frac{1}{N} \sum_{i=1}^{N} \left(MR_{\exp,i} - MR_{pred,i} \right)^2 \right]^{0.5} \tag{7.2}$$

where $MR_{exp,i}$ is the experimental moisture ratio; $MR_{pred,i}$ is the predicted moisture ratio; N is the number of data. The lower the calculated value of RMSE, the better the ability of the model to represent the observed data. This statistical tool has been widely used to select the best correlation between predicted curves and dried samples (McMinn, 2006; Ertekin and Yaldiz, 2004 and Ozdemir and Devres, 1999)

Table 7.1 The selected thin layer-drying models

Models	Models (reported by)
MR = exp(-kt)	Lewis model (1921)
MR = a*exp(-kt)	Henderson and Pabis model (1961)
MR = exp(-kt^n)	Page's model (1949)

7.4.6 Energy consumption

The energy consumption was calculated in term of specific energy consumption (SEC) by the following equation

$$\text{SEC, J/kg water} = \frac{P \times t_{on}\left(100 - M_f\right)}{m\left(M_i - M_f\right)} \qquad (7.3)$$

where, P = input power (W)

t_{on} = the total amount of time "on" (s)

M_f = final moisture content (%, wet basis)

M_i = initial moisture content (%, wet basis)

m = the initial mass (kg)

7.4.7 Quality evaluation

The evaluation of the quality of the dried products was based on water activity, shrinkage, rehydration capacity, texture, color and sensory.

Water activity could indicate the product safety and stability in relation to microbial growth. Measurements were made using a water activity meter (Model 3 TE Series, Meyer Service & Supply, Ont., Canada). The dried samples were measured at 24.7ºC which was the default setup of the device.

Shrinkage was calculated in terms of the percentage of volume change. Since the fresh carrot samples were cut into 10 mm cube, the volume of a piece of fresh carrot was 1 cm^3. The volumes of dried samples were measured using a displacement method in toluene (Tulasidas, 1994).

Rehydration capacity is useful to determine how the dried product reacts with the moisture because in most cases dried carrots will be consumed in their rehydrated form. In this work, rehydration tests of dried samples were performed by the method recommended by the USDA (Anon, 1944). 150 g of distilled water was boiled in a 500 ml beaker. The water was brought to boiling point for 3 minutes then 5 g of dried samples were added to the boiling water for an additional 5 min. The rehydrated sample was transferred to a 7.5 cm Buchner funnel cover with Whatman no.1 filter paper. Water was drained out by applying a gentle suction until there were no more drops from the funnel. The sample was then removed and weighed, and the rehydration ratio was calculated by using the following equation.

$$COR = \frac{m_{rh}\left(100 - M_{in}\right)}{m_{dh}\left(100 - M_{dh}\right)} \tag{7.4}$$

COR = Coefficient of rehydration
m_{rh} = Mass of rehydrated sample
m_{dh} = Mass of dehydrated sample
M_{in} = Initial MC % (wet basis) of the sample before drying
M_{dh} = MC % of the dry sample (wet basis)

Texture characteristics were measured by the Instron Universal Testing Machine (Sires IX Automated Materials Testing System 1.16). Compression tests using a 2mm diameter plunger with a crosshead speed of 25 mm/min. The texture was evaluated in terms of firmness. The applied force (N) was plotted against deformation (mm). The slope of the Force/Deformation curve reflects elastic modulus and is often used as an index of firmness (Abbott, 1999). The measurement was performed with rehydrated product because most dried carrots will be consumed after rehydration.

The surface color of dried samples was expressed in two terms, color change and redness (a/b) by the same device used to measure the color of fresh carrots. Each reading provided a value for the coordinates, L*, a* and b*. The color change (ΔE) was calculated by the following equation.

$$\Delta E = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{1/2} \tag{7.5}$$

where, $\Delta L^* = L^*_{sample} - L^*_{fresh}$

$\Delta a^* = a^*_{sample} - a^*_{fresh}$

$\Delta b^* = b^*_{sample} - b^*_{fresh}$

The ratio (a/b) is a convenient way of reducing two parameters to one. The higher a/b ratio indicates more redness of the objects.

Since the dried carrots will mostly be consumed in rehydrated form, sensory testes were performed with the rehydrated samples. Sensory evaluations were done by a panel of ten untrained judges evaluating two properties: taste and overall appearance. A rating using a Hedonic scale ranging from "Like extremely" to "Dislike extremely" were given by judges. The range was later converted to numerical values from 9 (Like extremely) to 1 (Dislike Extremely), respectively.

7.4.8 Experimental design

The experimental design was a 2x2x3 factorial, with 2 conditions of with and without osmotic treatment, 2 input power levels (1 and 1.5 w/g) and 3 power models (continuous, 45s on/ 15s off and 30s on/30s off). The data of quality studies were subjected to analysis of variance (ANOVA) and the significance or non-significance of the variables were ascertained through Tukey HSD multiple range test. All experiments were conducted in triplicate.

7.5 Results and discussion

7.5.1 Osmotic dehydration

The moisture content of fresh carrots was 87.7 % (wet basis). The initial dielectric constant (ε') and dielectric loss (ε") was 61.3 and 15.3, respectively. After the osmotic process, around 50 % of water was removed from the fresh carrots which resulted in an average moisture content of 67 % (wet basis). The average ratio of removed water and solid gain (WL/SG) of carrot after pre-treatment was 4.46 which followed the calculation by predictive equation in Chapter VI. It was 1.12 % different from the predictive equation. The average dielectric properties of osmotically dried product were 55.3 and 24.9 for ε' and ε", respectively. They were 0.5% and 1.5 % different from the predictive equation of Chapter IV. These proved that the predictive equations for removed water, solid gain and dielectric properties were good enough to predict the end properties of the product of the osmotic pretreatment with an accuracy of ± 1.5 %.

7.5.2 Drying kinetics of microwave vacuum drying (MVD)

Drying kinetics of MVD will be showed in term of the temperature of drying product, drying curve and drying time. The effects of with and without pretreatment by osmotic dehydration, the differences of input power and power mode (on/off) will be discussed.

Temperature of drying product

Figures 7.1a,b and 7.2a,b show the effect of osmotic pretreatment and power mode of microwave vacuum drying at input powers of 1 W/g and 1.5 W/g respectively. There was no significant difference in product temperature during drying between samples with and without osmotic pretreatment. It might be the balance between decreasing ε' and increasing ε" of osmotic treatment which decreased the ability to couple with electromagnetic field but increased in ability to dissipate the microwave energy. The pulse mode (on/off) clearly showed an effect on drying product temperature. The longer inactive time was able to decrease the drying product temperature which was the purpose of applying pulse mode in this study. However the pulse mode could not overcome the problem of excessive high temperatures in the process. The temperature at the end of the drying process was still high. This might be due to the heat build-up inside the material being higher than the required heat to evaporate the moisture at the last step of process. So decreasing input power at the last stage of the microwave vacuum drying could be a way to control drying product temperature.

The effect of input power shown in Figures 7.1 and 7.2 were the same in previous studies (Lu et al., 1999 and Boldor et al., 2005) in that the increased input power would increase drying product temperature. The average product temperature at input power of 1 W/g was 40-65 ºC while the average for input power of 1.5 W/g was 45-80 ºC.

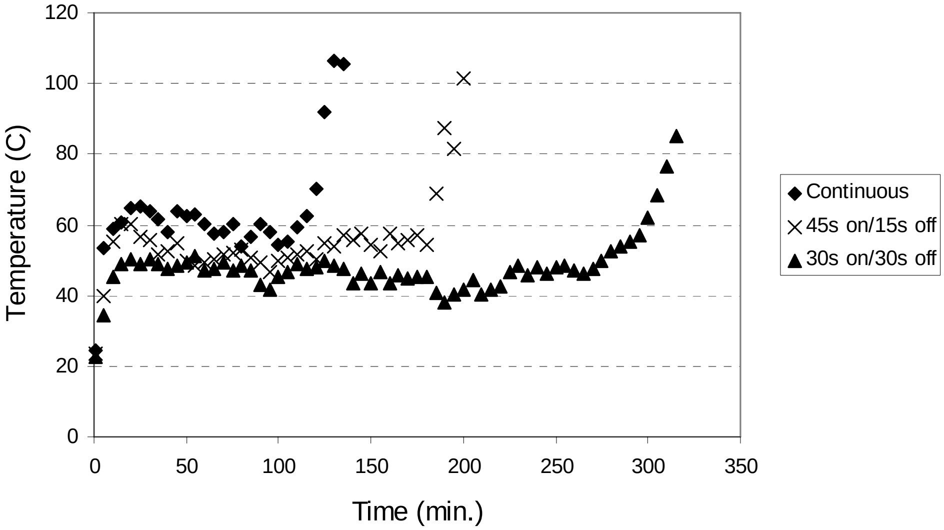

Figure 7.1a Temperature of microwave vacuum drying of carrots at 1 W/g power with different power modes

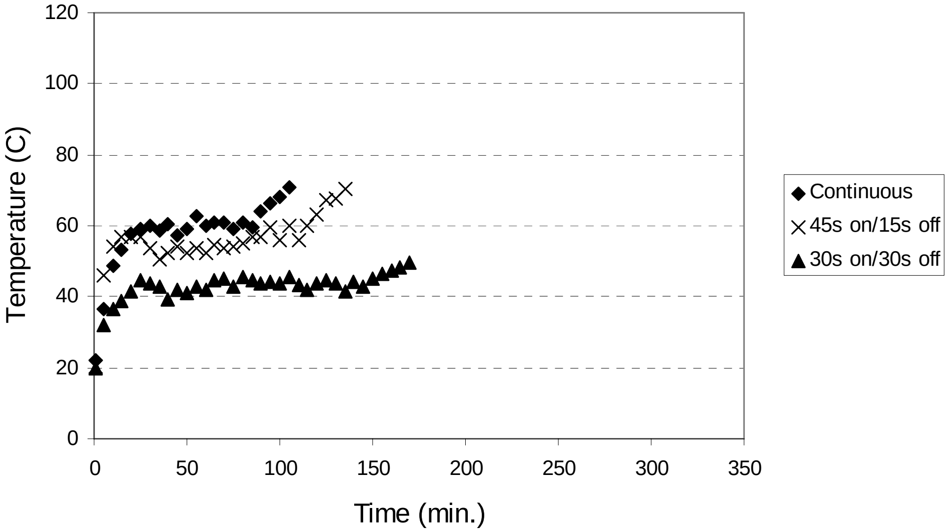

Figure 7.1b Temperature of osmotically dehydrated microwave vacuum drying of carrots at 1 W/g power with different power modes

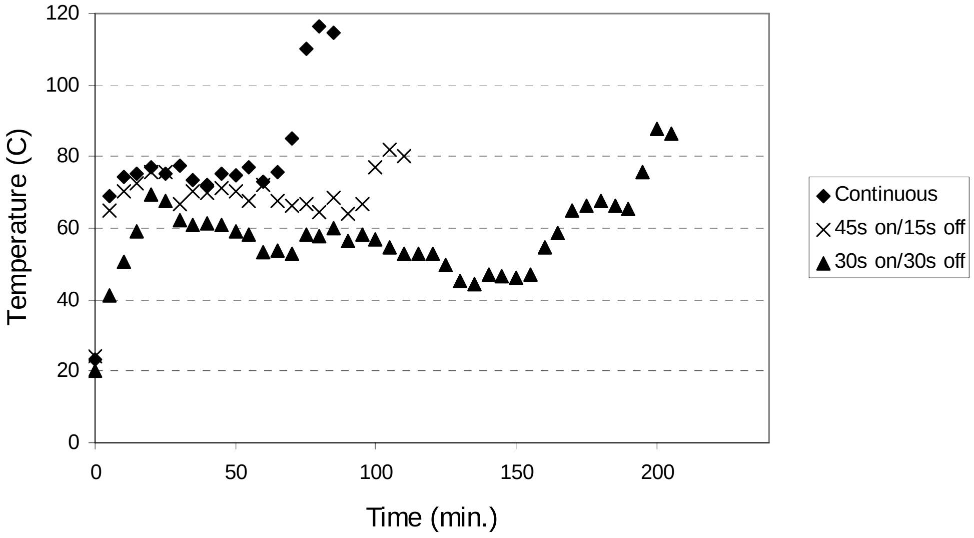

Figure 7.2a Temperature of microwave vacuum drying of carrots at 1.5 W/g power with different power modes

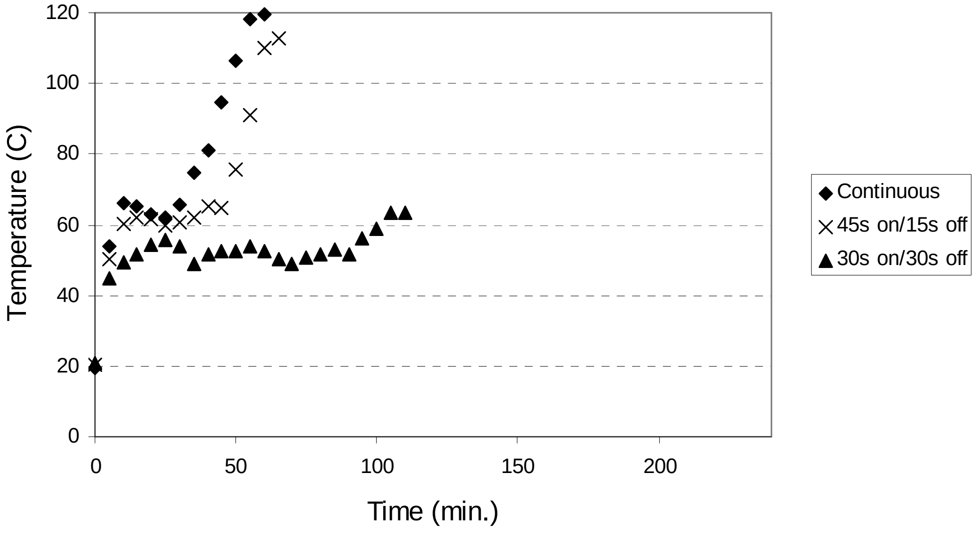

Figure 7.2b Temperature of osmotically dehydrated microwave vacuum drying of carrots at 1.5 W/g power with different power modes

Drying curves, drying time and drying rates

The osmotic process significantly affected drying curves and drying time for both cases of input power of 1 W/g as shown in Figure 7.3 and 1.5 W/g in Figure 7.4. The drying rates of microwave vacuum without osmotic pretreatment showed short typical constant but did not show for the processes with osmotic pretreatment as seen in Figure 7.5 and 7.6. These results are achieved because the water content of osmotically dehydrated product falls below the critical threshold level. Similar observation was made by Lenart (1996). Barbanti et al. (1994) also reported the absence of constant rate period for fruits following osmotic dehydration. Beaudry et al. (2004) also found the absence of constant rate period in microwave vacuum drying of osmotically dehydrated cranberries. Although the pulse mode of input power was able to decrease temperature in the process as discussed above, it took longer time for completing the drying process. So, the energy consumption and end product qualities should be considered in order to assess the appropriate conditions of the operation of osmotically dehydrated microwave vacuum drying.

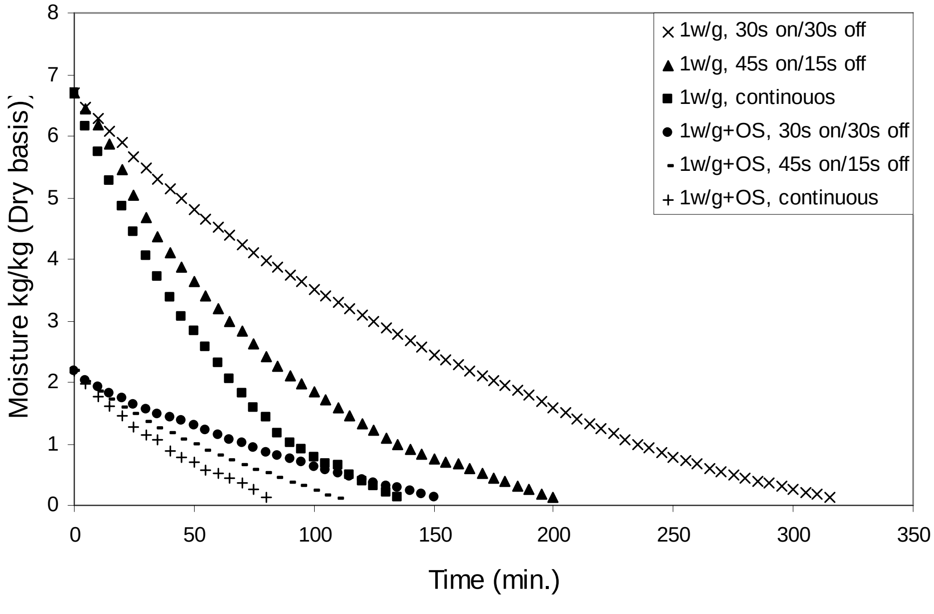

Figure 7.3 Drying curves of carrots at 1 W/g with different power modes

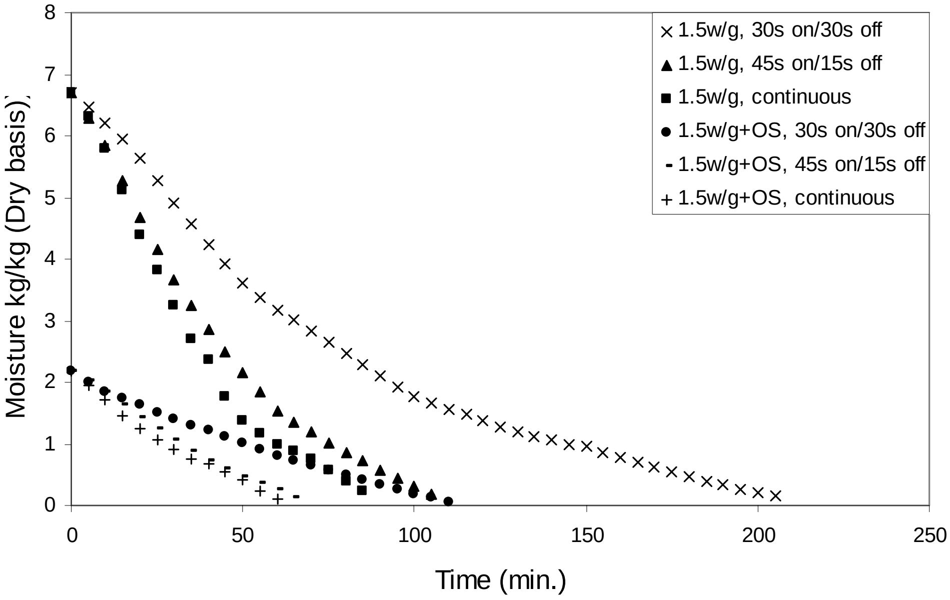

Figure 7.4 Drying curves of carrots at 1.5 W/g with different power modes

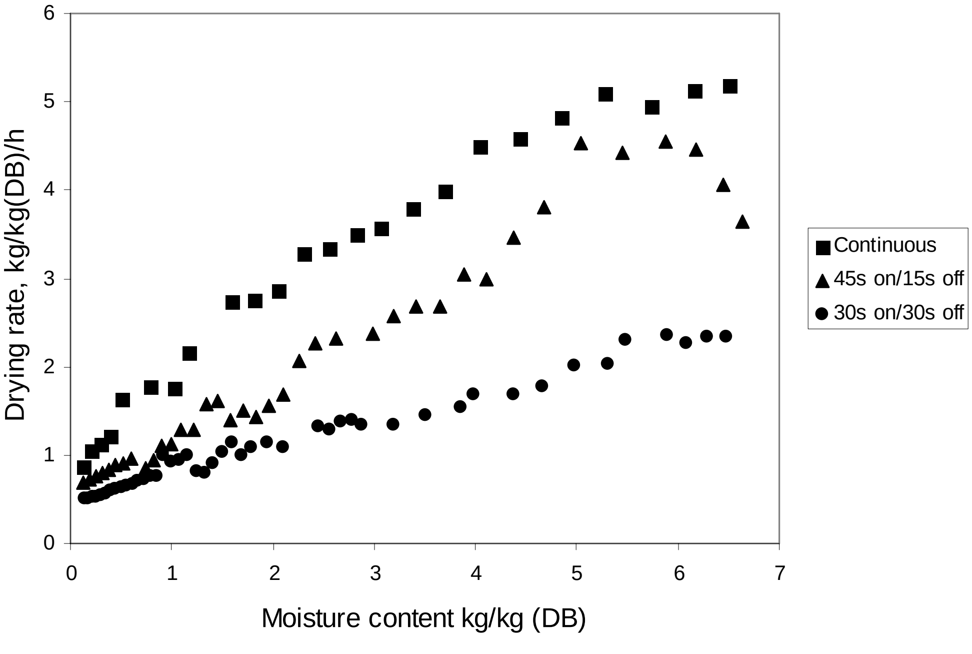

Figure 7.5 Drying rates of microwave vacuum without osmotic pretreatment of carrots at 1 W/g with different power modes

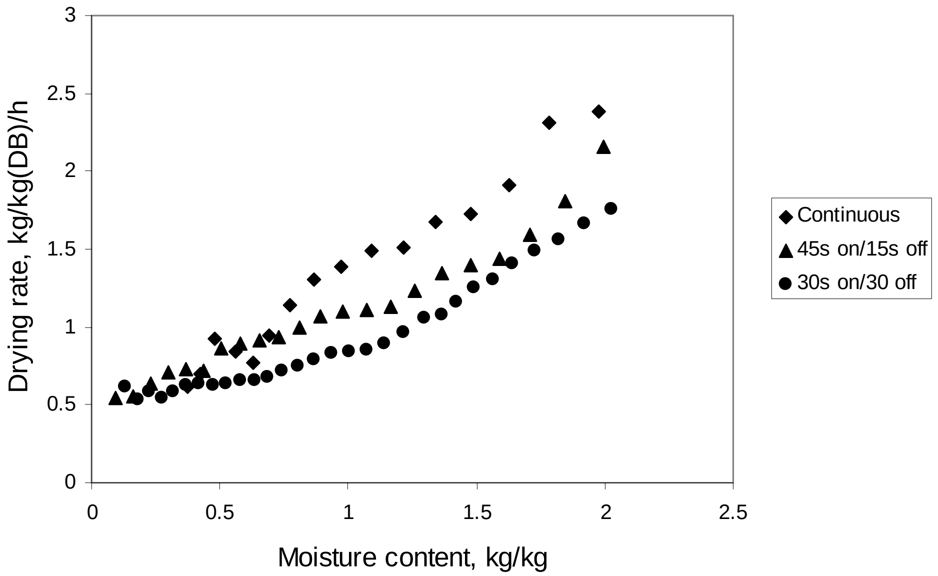

Figure 7.6 Drying rates of microwave vacuum with osmotic pretreatment of carrots at 1 W/g with different power modes

7.5.3 Empirical model of finish drying with microwave-vacuum

The wide applications of thin-layer models are due to their prediction of drying performance and to their ease of use and lesser amount of data required. The set of thin-layer models as presented in Table 7.1 which were developed from exponential equation were used to compare the observed data of microwave vacuum in this study. The constants of the models were acquired from nonlinear regression. The suitability of the models was validated by the RSME and r^2 which were calculated using the observed data and predictive model. The constant values, RMSE and r^2 of the models are presented in Tables 7.2 and 7.3 for the input powers of 1 W/g and 1.5 W/g respectively. The comparison of RMSE among the models in Figure 7.7 and 7.8 show that Page's model presented the best fit in most cases of the study including all input power levels, all power mode and with or without osmotic pre-treatment with a RSME of 0.01-0.03 and an $r^2$of 0.990-0.999. This was another confirmation of the suitability of Page's model in microwave drying which has been reported by Prabhanjan et al (1995), Tulasidas et al. (1997), Kardum et al. (2001) and McMinn (2006).

The lack of fit at the middle period of Lewis model as shown in Figure 7.9 had agreement with the study of Shivhare et al (1994) which studied microwave drying of grapes. They proposed using the surface moisture content instead of equilibrium moisture content for the calculation of moisture ratio (MR) to overcome the problem, but in this study equilibrium moisture content was assumed to be zero due to vacuum condition. So Page's model could be the alternative model to fit the observed data for microwave vacuum drying.

Table 7.2 Coefficients and statistical analysis of thin-layer models for input power 1 W/g of microwave vacuum drying of carrots

Model	Parameters	MVD			OS+MVD		
		Continuous	45-15	30-30	Continuous	45-15	30-30
Lewis	k	0.0188	0.0131	0.007	0.023	0.017	0.012
	RMSE	0.03	0.04	0.04	0.03	0.04	0.04
	r^2	0.994	0.998	0.987	0.981	0.987	0.983
Henderson & Pabis	a	1.055	1.065	1.048	1.075	1.059	1.055
	k	0.0198	0.0139	0.007	0.0246	0.018	0.0128
	RMSE	0.03	0.02	0.04	0.031	0.04	0.04
	r^2	0.991	0.996	0.984	0.985	0.983	0.979
Page's model	k	0.008	0.00628	0.003	0.009	0.007	0.004
	n	1.195	1.1619	1.196	1.241	1.228	1.246
	RMSE	0.02	0.01	0.03	0.02	0.03	0.03
	r^2	0.997	0.998	0.991	0.993	0.992	0.991

Table 7.3 Coefficients and statistical analysis of thin-layer models for input power 1.5 W/g of microwave vacuum drying of carrots

Model	Parameters	MVD			OS+MVD		
		Continuous	45-15	30-30	Continuous	45-15	30-30
Lewis	k	0.027	0.0227	0.0137	0.03	0.026	0.017
	RMSE	0.06	0.04	0.04	0.06	0.07	0.06
	r^2	0.991	0.995	0.998	0.985	0.979	0.977
Henderson & Pabis	a	1.133	1.103	1.075	1.109	1.146	1.082
	k	0.031	0.025	0.0137	0.033	0.03	0.019
	RMSE	0.04	0.03	0.02	0.04	0.06	0.05
	r^2	0.985	0.991	0.996	0.979	0.968	0.971
Page's model	k	0.006	0.007	0.0059	0.009	0.004	0.004
	n	1.40	1.295	1.173	1.339	1.538	1.344
	RMSE	0.01	0.01	0.01	0.03	0.03	0.03
	r^2	0.999	0.999	0.998	0.991	0.996	0.989

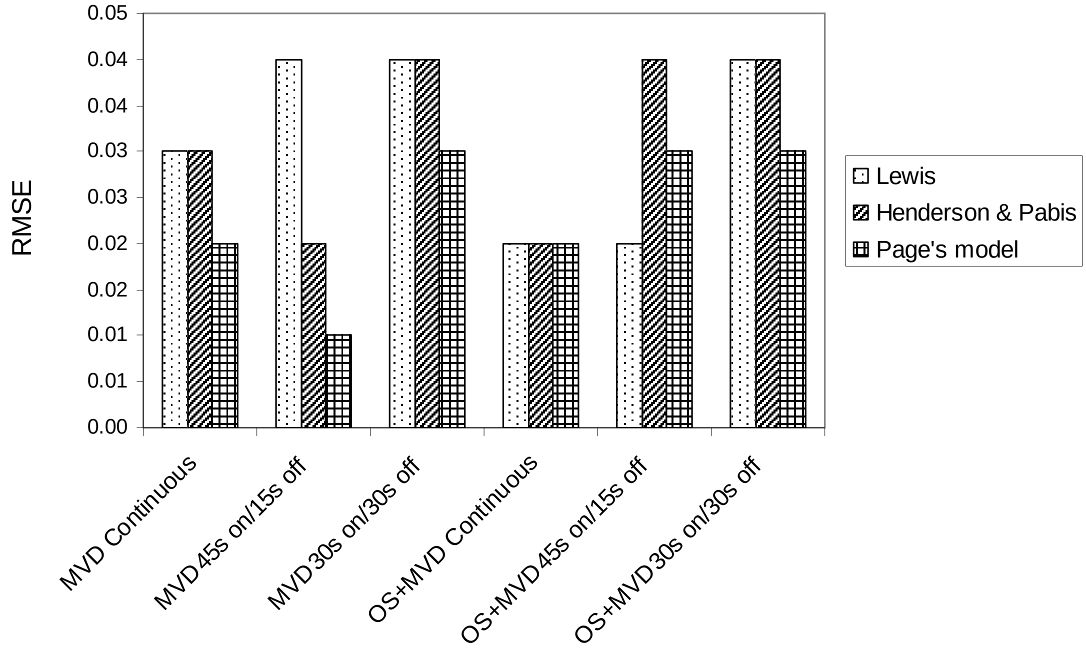

Figure 7.7 Comparison of root mean square error of the models for input power 1 W/g of microwave vacuum drying of carrots under different conditions

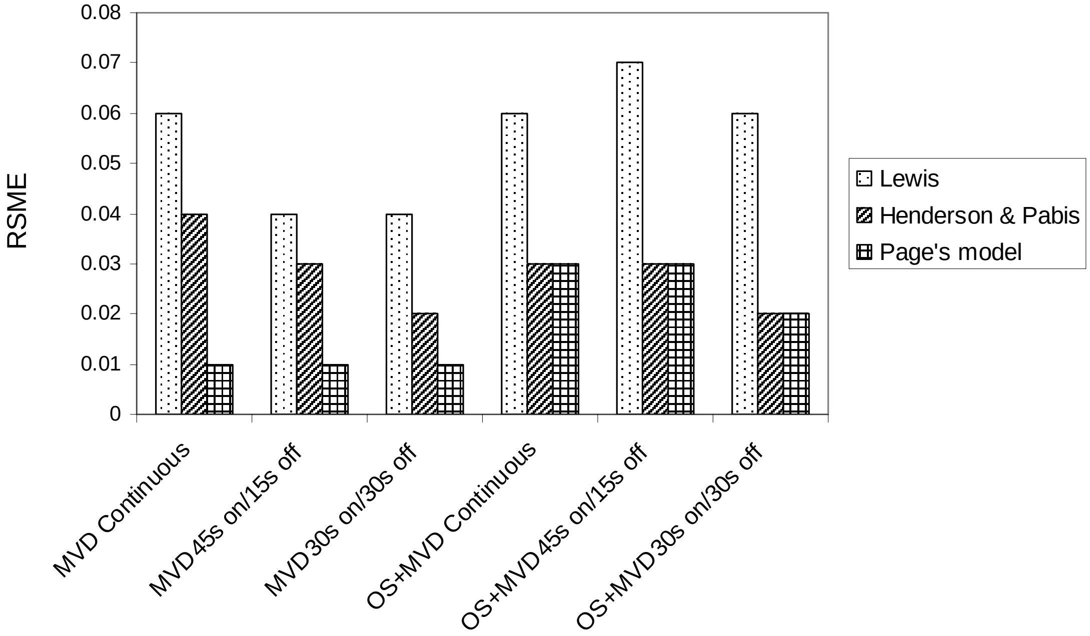

Figure 7.8 Comparison of root mean square error of the models for input power 1.5 W/g of microwave vacuum drying of carrots under different conditions

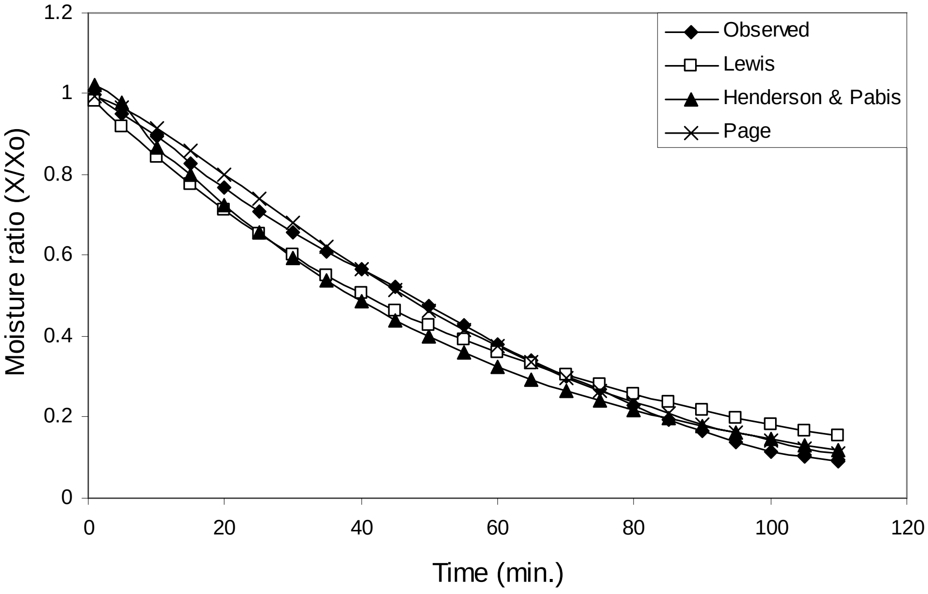

Figure 7.9 Comparison of observed MR in osmotically dehydrated microwave vacuum dried carrots with the MR predicted by various models

7.5.4 Energy aspect

Energy consumption was determined in terms of specific energy consumption (SEC), MJ/kg which is defined as energy consumption per kilogram of water evaporated. The energy demand was considered only in the use of microwave and thus did not account for the energy required to produce vacuum used in the experiments. The calculated SEC of each combination of pre-treatment, input power and power mode are shown in Table 7.4.

As presented in Table 7.4, the osmotic pretreatment clearly showed the lower SEC when matched against the process without osmotic pretreatment. It could be concluded that the osmotic process for pre-treatment of carrot drying provided a great help to remove free water and did not affect the diffusivity of the remaining drying process. So the drying time of the process with osmotic pretreatment as discussed above was shorter which resulted in lower energy demand to remove the rest of the moisture in the process. The interesting thing was that the lower input power did not mean lower energy consumption since the higher input power came with the shorter drying time. A contrast between with and without osmotic pretreatment was the effect on microwave mode. The longer time "off" in the process of osmotic pretreatment showed the lower SEC while the process without osmotic tended to show the opposite trend. This might be the result of a longer process time from longer time "off" in the process without osmotic pre-treatment. The general conclusion in terms of energy consumption of this study could be summarized in that osmotic pretreatment could help to reduce energy demand, the difference of input power levels did not affect energy consumption and the longer time "off" for the process with osmotic pretreatment was able to decrease required energy.

Table 7.4 Comparison of specific energy consumption (SEC) with and without osmotic pretreatment of microwave vacuum drying of carrots

MW Power	MW Mode	Specific energy consumption (SEC), MJ/kg	
		With Osmotic	Without Osmotic
1 W/g	continuous	0.051	0.081
	45-15	0.050	0.091
	30-30	0.045	0.095
1.5 W/g	continuous	0.056	0.081
	45-15	0.046	0.074
	30-30	0.050	0.094

7.5.5 Quality evaluation

Water activity (a_w)

The water activity of all dried samples was measured at a temperature around 24.7ºC and was found lower than 0.6. Foods having a water activity between 0.4 and 0.65 are considered to be dried foods (Raoult-Wack et al., 1992). Looking at Table 7.5, it shows no difference among all treatments. It was not surprising because the water activity is related to moisture content. The target moisture content of this study was 10 % (w.b.) which was considered for the stabilization of the end product rather than measuring differences among treatments. Since the growth rate of molds, bacteria and yeast is not activated and enzymatic reactions are not promoted when the water activity is below 0.7 (Barbosa-Canovas and Vega-Mercado, 1996), it should be noted that the moisture content of dried carrot at 10 % (w.b.) is good enough to stabilize the dried product because the water activity of the end product is in the safe range.

Shrinkage

The shrinkage is presented in term of the percentage of volume change. The results in Table 7.5 clearly show less shrinkage when the process was coupled with an osmotic pretreatment. The impregnation of sugar and salt from the osmotic agent to carrots was able to strengthen the cell structure of drying product. This study confirmed the decrease of shrinkage and collapse of cell structure which was reported by a group of researchers (Riva et al., 2005, Lozano et al., 1983 and Nieto et al., 1998)

Table 7.5 Mean values of water activity and shrinkage for different combinations of pre-treatment, input power and power mode of carrots

Treatment	Power	Mode	Water activity (A_w)	Change in volume (%)
With Osmotic	1w/g	continuous	0.55	40
		45-15	0.55	40
		30-30	0.55	40
	1.5w/g	continuous	0.55	40
		45-15	0.55	40
		30-30	0.53	40
Without Osmotic	1w/g	continuous	0.54	50
		45-15	0.52	50
		30-30	0.54	50
	1.5w/g	continuous	0.53	50
		45-15	0.53	50
		30-30	0.52	50

Rehydration capacity

The rehydration capacity was calculated through equation 7.4 in terms of a rehydration coefficient in which higher value correlates with a higher capacity of rehydration. As shown in Table 7.6, the osmotic pretreatment and the level of input power significantly affected the rehydration but there was no influence by the different power modes. In cooperation with shrinkage property, low shrinkage promises to provide higher rehydration capacity as found in freeze drying (Liapis and Bruttini, 1995 and

Beaudry et al., 2004). The result in this study was different. The occupation of solids from osmotic agents in the void space of carrot samples was the reason why the low shrinkage in this study provided lower rehydration capacity. There was no significant difference among the different types of power used.

Table 7.6 Tukey's test for mean rehydration coefficient affected by pre-treatment, input power and power mode of carrots

Treatment	Mean	Input power	Mean	Power mode	Mean
With osmotic	0.21^a	1 W/g	0.245^a	Continuous	0.250^a
Without osmotic	0.29^b	1.5 W/g	0.250^a	45s on/15s off	0.245^a
				30s on/30s off	0.245^a

Mean with the same letter in the same column are not significantly different at the 0.05 level.

Texture

The texture evaluation was performed by the Universal Testing Machine (Sires IX Automated Materials Testing System 1.16). The results of testing were plotted between the force (F) and deformation (D). The slope of the F/D plot was used to present the firmness in N/mm (Abbott, 1999). Table 7.7 shows that osmotic pretreatment had a significant effect ($P < 0.05$) on the toughness. The impregnation of solid content in osmotic process made the end product softer than the treatment without osmotic pretreatment.

Table 7.7 Tukey's test for mean firmness affected by pre-treatment, input power and power mode of carrots

Treatment	Mean	Input power	Mean	Power mode	Mean
With osmotic	8.97^a	1 W/g	11.14^a	Continuous	10.23^b
Without osmotic	14.33^b	1.5 W/g	12.14^a	45s on/15s off	11.76^a
				30s on/30s off	12.92^a

Mean with the same letter in the same column are not significantly different at the 0.05 level.

Color characteristics

The color was presented in two ways, color change and redness (a/b) of end product. Color change was calculated through the Equation 7.5. The results as seen in Table 7.8 show a significant influence ($P < 0.05$) of all factors; pretreatment, input power level and power mode. The fresh carrot was orange with the ratio a/b very close to "1". So the higher ratio a/b of end product would present more redness when compared to the fresh one. Table 7.9 shows that osmotic pretreatment, higher input power level and longer power time "on" created more redness of dried product. These effects would be expected because the temperature in the drying process directly affects color characteristics. It was found in this study that the higher input power and longer power time "on" increased the product temperature so the color would be changed due to the influence of input power level and duration of pulse power.

Table 7.8 Tukey's test for mean color change (ΔE) affected by pre-treatment, input power and power mode of carrots

Treatment	Mean	Input power	Mean	Power mode	Mean
With osmotic	25.64^a	1 W/g	26.46^a	Continuous	27.88^c
Without osmotic	28.93^b	1.5 W/g	28.10^b	45s on/15s off	27.52^b
				30s on/30s off	26.44^a

Mean with the same letter in the same column are not significantly different at the 0.05 level.

Table 7.9 Tukey's test for mean redness (a/b) affected by pre-treatment, input power and power mode of carrots

Treatment	Mean	Input power	Mean	Power mode	Mean
With osmotic	1.38^b	1 W/g	1.25^a	Continuous	1.32^c
Without osmotic	1.14^a	1.5 W/g	1.27^b	45s on/15s off	1.25^b
				30s on/30s off	1.21^a

Mean with the same letter in the same column are not significantly different at the 0.05 level.

Sensory evaluation

The sensory evaluations were studied in terms of taste and overall appearance. The product after rehydration was tasted by ten untrained judges. The score for product after drying with osmotic pretreatment was significantly lower than the others (Table 7.10). However, the whole response of tasting fell between the scale of "dislike slightly" and "neither like nor dislike". It might be assumed that all judges relatively disliked the taste of rehydrated carrots. Probably, the time of rehydration in this study was too short. The rehydrated carrots used for this test were still salty. In term of appearance, the results are shown in Table 7.11. The process with osmotic pre-treatment was significantly more appreciable than without osmotic treatment. The browning attributed to longer time "on" and higher input power stimulated less acceptability.

Table 7.10 Tukey's test for mean sensory (taste) affected by pre-treatment, input power and power mode of carrot

Treatment	Mean	Input power	Mean	Power mode	Mean
With osmotic	3.82^{a}	1 W/g	4.67^{a}	Continuous	4.69^{a}
Without osmotic	5.62^{b}	1.5 W/g	4.77^{a}	45s on/15s off	4.72^{a}
				30s on/30s off	4.74^{a}

Mean with the same letter in the same column are not significantly different at the 0.05 level.

Table 7.11 Tukey's test for mean sensory (over all appearance) affected by pre-treatment, input power and power mode of carrots

Treatment	Mean	Input power	Mean	Power mode	Mean
With osmotic	7.53^{a}	1 W/g	5.75^{a}	Continuous	5.0^{a}
Without osmotic	3.13^{b}	1.5 W/g	4.92^{b}	45s on/15s off	5.1^{a}
				30s on/30s off	5.9^{b}

Mean with the same letter in the same column are not significantly different at the 0.05 level.

7.6 Conclusions

There was no effect of osmotic pretreatment to drying product temperature while higher input power and longer time “on” had positive effects. The pulse mode was not enough to control drying product temperature, lowering input power at the last stage of drying process should be considered.

Page’s model showed the best fit with observed data for both cases of with and without osmotic pretreatment. The drying constant (k) in the models showed that osmotic conditions in this study did not affect diffusivity of moisture in the microwave vacuum drying process.

Osmotic pretreatment of microwave vacuum drying was able to decrease drying time and energy consumption in the process.

In terms of quality aspects, osmotic treatment prior to microwave vacuum drying provided less shrinkage and rehydration capacity but generated redness of the end product. Higher input power had positive effects on rehydration property and color change. A longer time “on” of pulse mode increased the color change.

7.7 Acknowledgements

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CONNECTING TEXT

The effects of osmotic treatment prior to microwave vacuum of carrots as a representative of vegetables were studied in this Chapter VII. The same regime of drying process will be used to investigate the osmotically dehydrated microwave vacuum of strawberries in the Chapter VIII.

CHAPTER VIII

OSMOTICALLY DEHYDRATED MICROWAVE VACUUM DRYING OF STRAWBERRIES

8.1 Abstract

Strawberries were osmotically dehydrated prior to microwave vacuum drying. Drying kinetics were presented in terms of the temperature of drying product, drying curve and drying time. Thin layer models: Lewis model, Henderson & Pabis model and Page's model were fitted with the observed data. The root mean square error (RSME) and the coefficient of determination (r^2) were used to evaluate the fit of the models. The effects on quality of dried strawberries of with and without osmotic treatment, input power level (1 W/g and 1.5 W/g) and power mode (continuous, 45s on/15s off, 30s on/30s off) were evaluated by a standard factorial (2x2x3) in triplicate. The quality aspects were studied through water activity, shrinkage, rehydration capacity, texture, color and sensory testing. The results showed that the osmotic pretereatment did not help in terms of drying time and energy saving but provided a better quality of dried product. Page's model presented the best fit to the observed data.

8.2 Introduction

To improve drying processes by reducing energy consumption and providing high quality with minimal increase in economic input has become the goal of modern drying (Raghavan et al., 2005). Any single technique using present technology cannot by itself achieve this target. A combination of existing drying techniques should be considered. Based on the fast drying time of microwave heating, microwave convective drying of fruit has shown success in obtaining high quality dried product with low specific energy consumption (Tulasidas et al., 1997, Raghavan and Silveira, 2001). The combination of microwaves with vacuum has been proven to acquire faster drying time with a resulting good quality of dried product due to a low process temperature (Drouzas et al., 1999; Sunjka et al., 2004).

The potential of osmotic dehydration as a pretreatment has been proven useful by a number of studies, providing not only water removal but also taste improvement. (Torreggiani, 1993 and Torringa et al., 2001). The quality of dried strawberries of osmotic pretreatment prior to microwave convective drying showed better results of dried product compared to freeze drying (Venkatachalapathy and Raghavan, 1999). In this study, osmotic pretreatment prior to microwave vacuum was setup with the assumption of improving drying time and quality of end product. Strawberries were selected to study as a representative of fruits in this study.

8.3 Objectives

The objectives of this study were to determine the effects of osmotic treatment prior to microwave vacuum drying and the influence of input power level and pulse mode of input power.

8.4 Materials and Methods

The measurement of fresh samples and methods used for the study of strawberries in this Chapter were the same as those used in the experiments on osmotically dehydrated microwave vacuum drying of carrots in Chapter VII. The materials and osmotic conditions were different from the study of carrots, so only the materials and osmotic pretreatment will be presented in this part.

8.4.1 Materials

The unknown cultivar strawberries used in this study was obtained from a local market. The uniformity of the size of strawberries was carefully selected which was around 8 strawberries per 100 g. Strawberries were taken from a 4°C cooled room and allowed to sit at room temperature (20±1 °C) one hour before the tests were started. All samples were cut into halves.

8.4.2 Osmotic dehydration

In the process of osmotic pretreatment, a 100±5 g of cut strawberries were placed in an osmotic solution of 60% w/w of sugar concentration at room temperature (20ºC) for 24 hours which followed the optimum conditions established in Chapter IV. According to the study of Erle and Schubert (2001) all samples in this study were kept with a ratio of sample to solution of 1:9 (w/w). The whole sample (100±5 g) was separated into 20±5 g and 80±5 g in the osmotic solution. After osmotic treatment the samples were dipped in ambient temperature water (20°C) in order to remove the osmotic agents at the surface of samples and gently wiped with a kitchen paper and left for 15 minutes in ambient air in order to remove the surface moisture. The part of 80±5 g sample was used for the microwave vacuum drying. The rest was analyzed to calculate water loss (WL), solid gain (SG) and dielectric properties after the osmotic process.

8.5 Results and discussions

8.5.1 Osmotic dehydration

The moisture content of fresh strawberries was 91% (wet basis) and initial dielectric constant (ε') and dielectric loss (ε") were 69.1 and 18 respectively. The average ratio of water loss and solid gain (WL/SG) of carrot after pre-treatment was 15.5 which followed the calculation by predictive equation in Chapter VI. It was 1.16 % different from the predictive equation. The water loss and solid gain caused the final moisture content after osmotic treatment to be 59 % (wet basis). The dielectric properties after osmotic pretreatment were 53.7 and 17.7 for ε' and ε" respectively. The difference from the result of the predictive equation in Chapter V was less than 1.5 %. These results proved that the predictive equations for removed water, solid gain and dielectric properties of strawberries were good enough to predict the end product with an accuracy of ± 1.5 %.

8.5.2 Drying kinetics of microwave vacuum drying (MVD)

Drying kinetics of MVD will be showed in term of the temperature of drying product, drying time and drying curve. The effects of with and without pretreatment of osmotic, input power levels and power mode (on/off) will be discussed.

Temperature of drying product

As observed in Figures 8.1a,b and 8.2a,b osmotic pretreatment, input power level and power mode influenced the drying product temperature. The temperature in the process with osmotic pretreatment was lower than the process without osmotic pretreatment. This might be due to dielectric constant which was lower after osmotic treatment. Since the lower dielectric constant product has less ability to couple with microwave energy, the drying product temperature was lower. The average drying product temperature with input power 1 W/g ranged between 40-70ºC while with 1.5 W/g it was around 45-75ºC. The higher input power increased the drying product temperature due to more energy absorption of product. For power mode, a longer time "off" was able to decrease the temperature in the process which was the purpose in this study. During the period of time "off", even if the temperature was declining, the heat was still in the product. So, a proper period of time "off" was able to maintain drying product temperature. Gunasekaran (1999) reported in his study that pulsed mode of MW drying could be more energy efficient than continuous, and shorter power-on time and longer power-off time can improve product quality and overall energy efficiency.

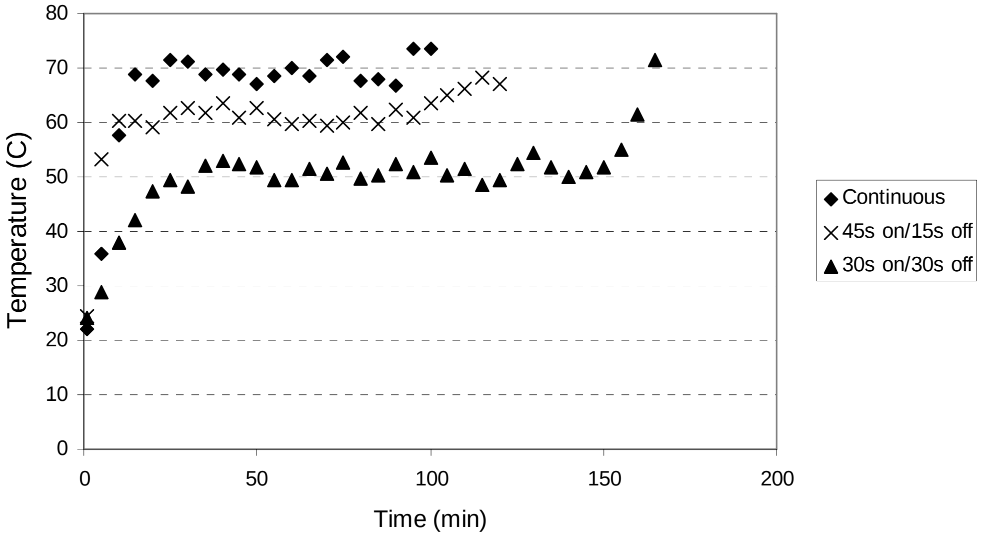

Figure 8.1a Temperature of microwave vacuum drying of strawberries at 1 W/g power with different power modes

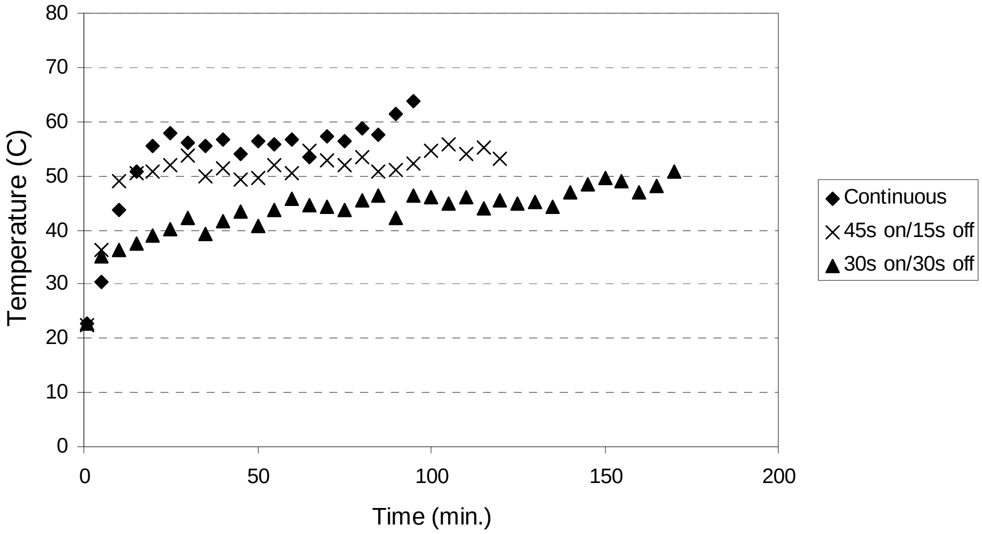

Figure 8.1b Temperature of osmotically dehydrated microwave vacuum drying of strawberries at 1 W/g power with different power modes

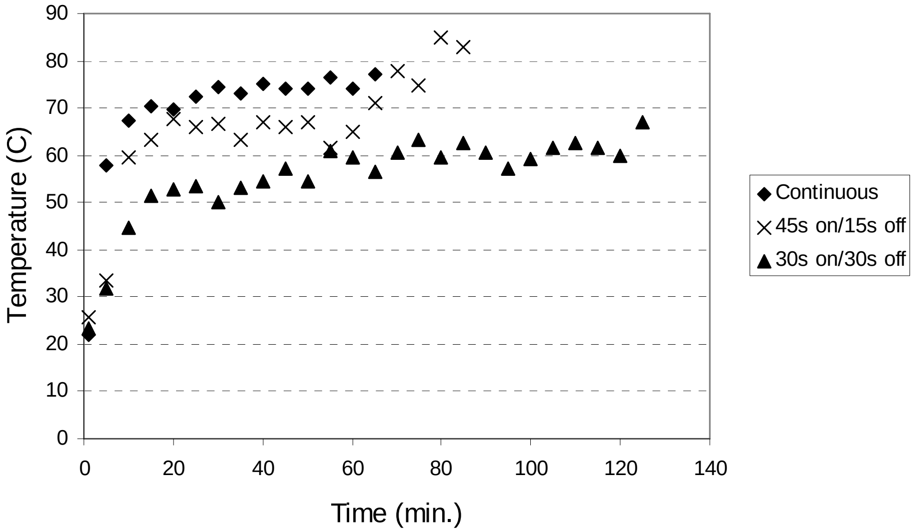

Figure 8.2a Temperature of microwave vacuum drying of strawberries at 1.5 W/g power with different power modes

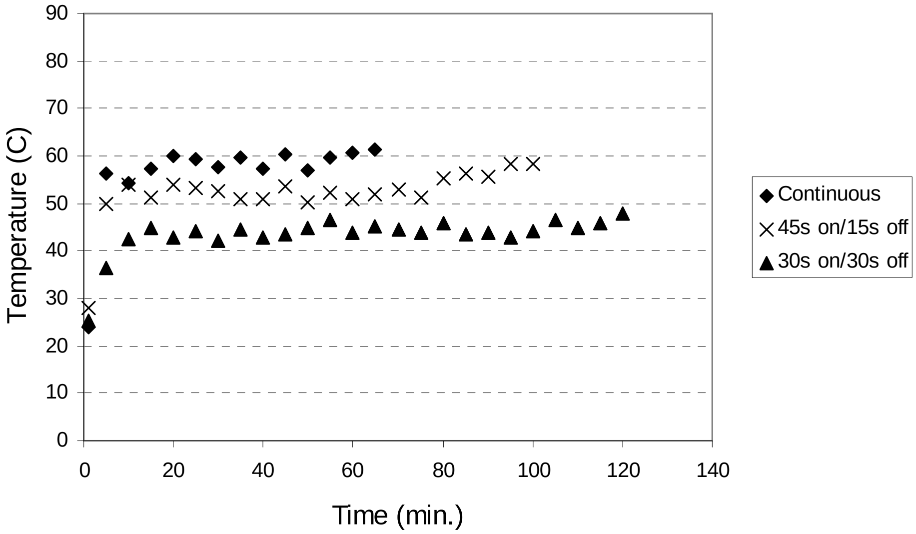

Figure 8.2b Temperature of osmotically dehydrated microwave vacuum drying of strawberries at 1.5 W/g power with different power modes

Drying rates and drying time

Drying curves of strawberries without osmotic treatment showed the typical period of constant drying rate and falling rate period (Figures 8.3 and 8.4) while the process with osmotic treatment showed only a falling rate period. This agreed with the study of carrots in Chapter VII and Beaudry et al (2004). Lewicki and Lenart (1992) explained this phenomenon in that the water content of osmotically dehydrated product falls below the critical level.

The effect on drying time of osmotically dehydrated microwave vacuum drying of strawberries (Figure 8.5) was quite different from carrots as discussed in Chapter VII. Even if the moisture content after osmotic pretreatment decreased from 91% (wet basis) to 59 % (wet basis), the drying time was the same even without osmotic pretreatment. This has agreement with the study of Grabowski et al., (2002) which reported that the osmotic pretreatment for the study of the effects of osmotic treatment of cranberries prior to various dryers (cabinet-air-through, fluid bed, pulsed fluid bed, and vibrated fluid bed dryers) reduced drying rate. In this study, the level of sucrose gained was high enough to affect the diffusion coefficient. It could be concluded that the osmotic pretreatment of strawberries drying within the conditions in this study did not help in terms of drying time.

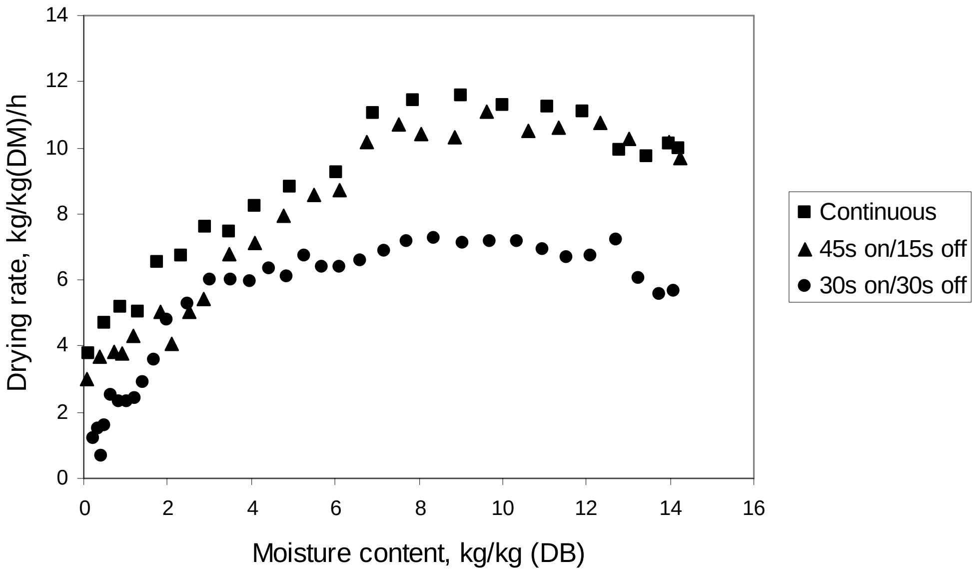

Figure 8.3 Drying rates of microwave vacuum without osmotic pretreatment of strawberries at 1 W/g with different power modes

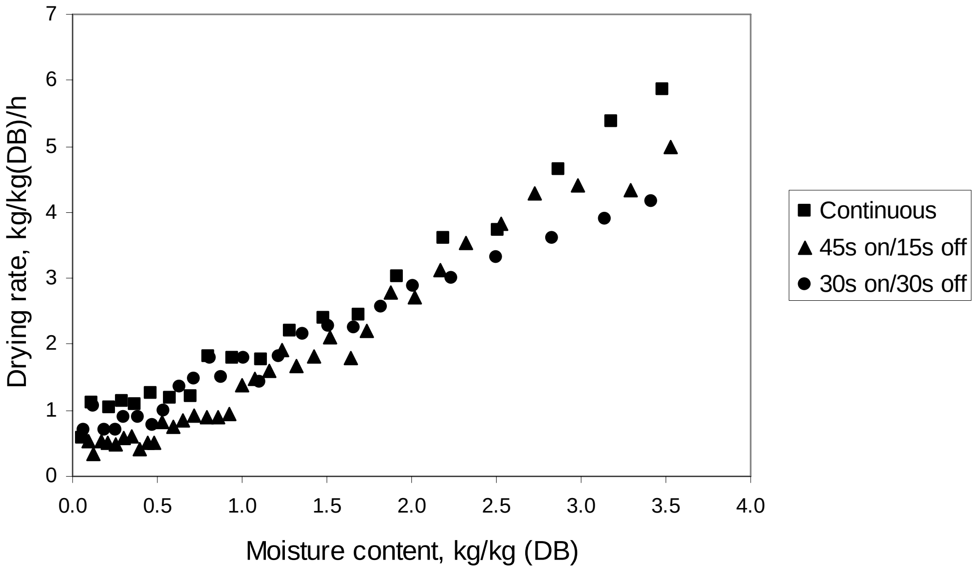

Figure 8.4 Drying rates of microwave vacuum with osmotic pretreatment of strawberries at 1 W/g with different power modes

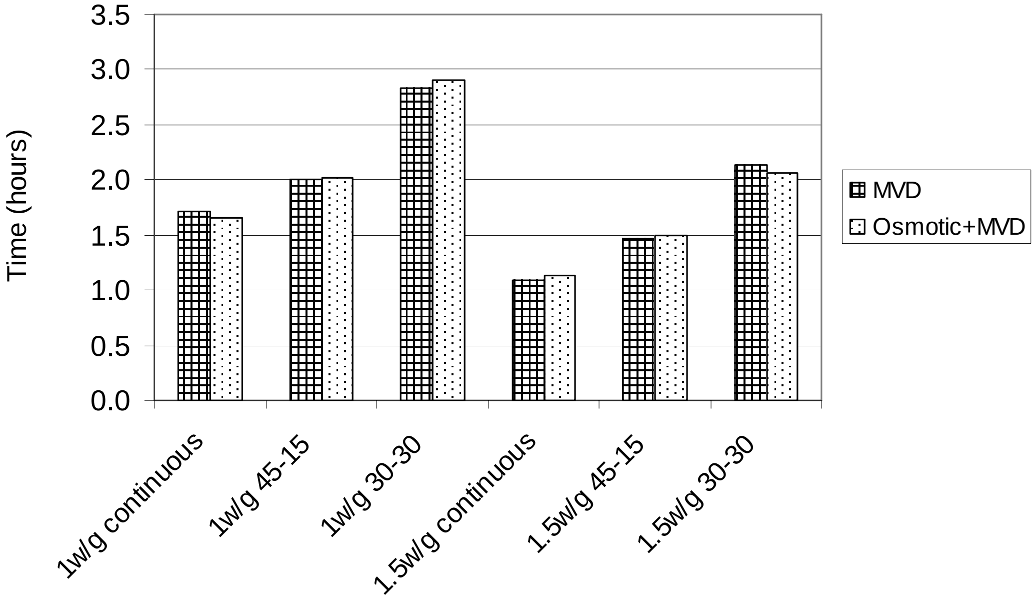

Figure 8.5 Drying time of strawberries dried by different power modes

8.5.3 Empirical model of finish drying with microwave-vacuum

The parameters in the models were evaluated through non-linear regression analysis. The RMSE and r^2 were used to assess the fit between model and experimental data. A lower calculated value of RMSE indicates better agreement of the model with the observed data. Although all models were good enough to represent the experimental data since the overall RMSE ranged from 0.02 to 0.11 (Tables 8.1 and 8.2), Page's model was relatively better than the others with the RMSE of 0.01-0.03. Tulasidas et al., (1997) also found that the empirical Page's model provided a good fit with observed data similar to their semi-theoretical model for microwave drying of grapes. The RMSE values of the model of Henderson & Pabis and Lewis in the process with osmotic pretreatment (0.02-0.03) were lower than the process without osmotic treatment (0.05-0.1). It could be hypothesized that the Henderson & Pabis model and Lewis model would rather fit with the falling rate period because the process with osmotic pretreatment did not show a constant rate period as discussed above.

Table 8.1 Coefficients and statistical analysis of thin-layer models for input power 1 W/g of microwave vacuum drying of strawberries

Model	Parameters	MVD			OS + MVD		
		Continuous	45s on/ 15s off	30s on/ 30s off	Continuous	45s on/ 15s off	30s on/ 30s off
Lewis	k	0.019	0.017	0.014	0.027	0.022	0.016
	RMSE	0.1	0.07	0.07	0.03	0.02	0.02
	r^2	0.991	0.984	0.981	0.996	0.994	0.995
Henderson & Pabis	a	1.203	1.142	1.136	1.068	0.995	0.995
	k	0.023	0.02	0.015	0.029	0.022	0.016
	RMSE	0.07	0.05	0.06	0.03	0.02	0.02
	r^2	0.970	0.974	0.971	0.993	0.995	0.995
Page's model	k	0.0008	0.002	0.0015	0.014	0.021	0.015
	n	1.8	1.482	1.494	1.180	1.013	1.007
	RMSE	0.01	0.03	0.01	0.02	0.02	0.02
	r^2	0.999	0.996	0.995	0.997	0.994	0.995

Table 8.2 Coefficients and statistical analysis of thin-layer models for input power 1.5W/g of microwave vacuum drying of strawberries

Model	Parameters	MVD			OS+MVD		
		Continuous	45s on/ 15s off	30s on/ 30s off	Continuous	45s on/ 15s off	30s on/ 30s off
Lewis	k	0.034	0.024	0.015	0.031	0.03	0.019
	RMSE	0.07	0.10	0.11	0.04	0.01	0.03
	r^2	0.987	0.977	0.948	0.993	0.998	0.995
Henderson & Pabis	a	1.172	1.232	1.215	1.078	1.019	1.066
	k	0.04	0.03	0.018	0.033	0.03	0.02
	RMSE	0.05	0.07	0.09	0.03	0.1	0.03
	r^2	0.977	0.960	0.926	0.989	0.998	0.992
Page's model	k	0.006	0.0014	0.0002	0.014	0.024	0.008
	n	1.515	1.775	2.073	1.231	1.054	1.196
	RMSE	0.02	0.02	0.02	0.02	0.01	0.02
	r^2	0.997	0.997	0.996	0.996	0.998	0.997

8.5.4 Energy aspects

The energy consumption was calculated based on input power and power time on in terms of specific energy consumption (SEC), MJ/kg water. The input power in the calculation counted only microwave input energy and did not include power consumption by the vacuum pump. There was no difference in drying time between with and without osmotic pretreatment as discussed above, so the process with osmotic pretreatment in this study did not show the advantage of energy saving. Anyway, the power mode with a longer time "off" provided lower energy consumption as seen in Table 8.3. In terms of energy saving, it could be concluded that there was no advantage from osmotic treatment.

Table 8.3 Comparison of specific energy consumption (SEC) with and without osmotic pretreatment of microwave vacuum drying of strawberries

MW Power	MW Mode	Specific energy consumption (SEC), MJ/kg water	
		With Osmotic	Without Osmotic
1 W/g	continuous	0.049	0.056
	45-15	0.050	0.047
	30-30	0.046	0.043
1.5 W/g	continuous	0.051	0.053
	45-15	0.052	0.053
	30-30	0.048	0.051

8.5.5 Quality evaluation

The quality evaluations for osmotic pretreatment prior to microwave vacuum drying in this study were examined through the criteria of water activity, shrinkage, rehydration capacity, texture, color and sensory.

Water activity was measured at a temperature of 24.7ºC for all samples.. Since water activity is related to moisture content and all samples in this study were set to reach 7% (wet basis), the results did not show any difference in water activity (Table 8.4). However, the moisture content at 7% (wet basis) of end product was considered a safe level because the water activities of all samples were around 0.52-0.57 which is recommended to avoid microbial growth and enzymatic reactions (Barbosa-Canovas and Vega-Mercado, 1996).

The change in volume was used to study the shrinkage property, calculated from the initial volume. The samples with osmotic pretreatment had low percentage of change when compared to the samples without osmotic pretreatment. This result was the same as that found in Chapter VII and the study of Riva et al., (2005) which studied osmo-air-dehydration of apricot cubes. The solid gain in osmotic process strengthens the cell structure and was assumed to be the reason of this phenomenon.

Table 8.4 Mean values of water activity and shrinkage for different combinations of pre-treatment, input power and power mode of strawberries

Treatment	Power	Mode	Water activity (A_w)	Change in volume (%)
With Osmotic	1w/g	continuous	0.52	73.1
		45-15	0.57	72.34
		30-30	0.56	75.0
	1.5w/g	continuous	0.56	76.75
		45-15	0.56	78.99
		30-30	0.55	79.44
Without Osmotic	1w/g	continuous	0.56	83.57
		45-15	0.56	83.19
		30-30	0.56	84.42
	1.5w/g	continuous	0.55	85.92
		45-15	0.56	86.91
		30-30	0.54	85.72

The effects of process variables on rehydration property, texture, color and sensory were analyzed through the analysis of variance (ANOVA) in order to see the effects of pretreatment, input power and power mode. The multiple range tests were performed by Tukey HSD to show a statistically significant difference at the 95% confidence level.

Even rehydration is a complex phenomenon affected by numerous factors. Porosity is an important factor of rehydration capacity of dried product (Marabi and Saguy, 2004). The void space of strawberries after osmotic treatment promised to decrease due to the impregnation of sucrose molecules, so it reduced the capacity of rehydration as seen in Table 8.5. Another factor that would affect the rehydration is the changing of cell structure during the drying process. In most cases, the changing of cell structure is related to drying product temperature. In this study, the higher input power showed higher firmness but the different types of power mode did not show any influence. It meant that, only the generated temperature by the power levels was high enough to affect the rehydration property.

Table 8.5 Tukey's test for mean rehydration coefficient affected by pre-treatment, input power and power mode of strawberries

Treatment	Mean	Input power	Mean	Power mode	Mean
With osmotic	0.28^a	1 W/g	0.29^a	Continuous	0.295^a
Without osmotic	0.32^b	1.5 W/g	0.31^b	45s on/15s off	0.305^a
				30s on/30s off	0.300^a

Means with the same letter in the same column are not significantly different at the 0.05 level.

The presentation of texture in this study was expressed in term of firmness. The dried samples were directly tested with the Universal Testing Machine (Sires IX Automated Materials Testing System 1.16). The applied force (N) was plotted against deformation (mm). The slope of the force/deformation curve was used to evaluate the firmness (Abbott, 1999). Solid gain by osmotic pretreatment was not high enough to affect the texture property. Only power mode affected the firmness of dried product (Table 8.6). Since the longer time "on" of power mode provided higher product temperature, the higher temperature would be the reason of greater firmness in this study. Venkatachalapathy and Raghavan (1998) also reported a significant effect of temperature on toughness for the study of blueberries.

Table 8.6 Tukey's test for mean firmness affected by pre-treatment, input power and power mode of strawberries.

Treatment	Mean	Input power	Mean	Power mode	Mean
With osmotic	9.43^{a}	1 W/g	9.15^{a}	Continuous	11.64^{b}
Without osmotic	10.02^{a}	1.5 W/g	10.3^{a}	45s on/15s off	9.02^{ab}
				30s on/30s off	8.52^{a}

Means with the same letter in the same column are not significantly different at the 0.05 level.

The color property was presented in two terms, color change (ΔE) and redness (a/b). The color change was calculated by a comparison of fresh product and dried product. The influence of power on color change was the same as that found with toughness. The higher input power and longer power time "on" provided a significant change in color (ΔE) and redness (a/b) as shown in Tables 8.7 and 8.8 respectively. The temperature was assumed to be the reason for changes in color as discussed with the toughness. That means that the drying product temperature in microwave vacuum drying is the most important factor in acquiring a good quality of dried product. The osmotic process did not affect the redness (a/b) but showed significant influence on color change (ΔE). Since the color change (ΔE) was calculated through the parameters L*, a* and b*, it could be implied that only L* was affected by osmotic pretreatment. As discussed about the drying product temperature, reduction of the dielectric constant caused a low temperature in the process with osmotic treatment. So, the process with lower temperature promised to provide lesser color change (ΔE).

Table 8.7 Tukey's test for mean color change (ΔE) affected by pre-treatment, input power and power mode of strawberries.

Treatment	Mean	Input power	Mean	Power mode	Mean
With osmotic	8.29^{a}	1 W/g	10.54^{a}	Continuous	11.01^{c}
Without osmotic	13.93^{b}	1.5 W/g	11.67^{b}	45s on/15s off	11.08^{b}
				30s on/30s off	10.63^{a}

Means with the same letter in the same column are not significantly different at the 0.05 level.

Table 8.8 Tukey's test for mean redness (a/b) affected by pre-treatment, input power and power mode of strawberries.

Treatment	Mean	Input power	Mean	Power mode	Mean
With osmotic	1.98^a	1 W/g	1.92^a	Continuous	2.42^b
Without osmotic	2.61^a	1.5 W/g	2.22^b	45s on/15s off	1.93^a
				30s on/30s off	1.88^a

Means with the same letter in the same column are not significantly different at the 0.05 level.

Sensory testing was evaluated on two aspects, taste and overall appearance. The score ranged from 1 to 9 which represented "Dislike extremely" to "Like extremely". The dried samples were tested by 10 untrained judges. The process with osmotic pretreatment showed favor over the process without osmotic treatment in both cases, taste and overall appearance (Table 8.9 and 8.10). It has agreement with an earlier study (Raoult-Wack et al., 1991) where osmotic pretreatment was able to improve quality of dried product. The result of overall appearance in Table 8.10 shows the significant low score of higher input power level and longer time "on". It could be the reason of high temperature as discussed in toughness and color. The dried strawberries with osmotic pretreatment were preferable than without pretreatment.

Table 8.9 Tukey's test for mean sensory (tasting) affected by pre-treatment, input power and power mode of strawberries.

Treatment	Mean	Input power	Mean	Power mode	Mean
With osmotic	7.06^b	1 W/g	6.11^a	Continuous	6.08^a
Without osmotic	5.44^a	1.5 W/g	6.39^a	45s on/15s off	6.25^a
				30s on/30s off	6.42^a

Means with the same letter in the same column are not significantly different at the 0.05 level.

Table 8.10 Tukey's test for mean sensory (overall appearance) affected by pre-treatment, input power and power mode of strawberries.

Treatment	Mean	Input power	Mean	Power mode	Mean
With osmotic	6.67^b	1 W/g	6.0^b	Continuous	5.08^a
Without osmotic	4.39^a	1.5 W/g	5.1^a	45s on/15s off	5.54^{ab}
				30s on/30s off	5.96^b

Mean with the same letter in the same column are not significantly different at the 0.05 level.

8.6 Conclusions

Pulse mode input power was able to decrease drying product temperature and save energy. Osmotic pretreatment of microwave vacuum drying did not help in terms of drying time and energy saving but provided a better quality of dried product. Page's model showed the best fit to osmotically dehydrated microwave vacuum drying of strawberries when compared to Henderson & Pabis and Lewis models. Temperature in the process was a critical factor which affected the quality of dried product in terms of rehydration, toughness, color and sensory appeal. Osmotic pretreatment prior to microwave treatment was more attractive to the consumers in terms of taste and overall appearance.

8.7 Acknowledgements

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CHAPTER IX

GENERAL SUMMARY AND CONCLUSIONS

9.1 General summary and conclusions

The purpose of this study was to improve a microwave-based process for drying carrots and strawberries. The laboratory scale microwave vacuum setup was designed and built and preliminary study was performed. The effects of osmotic pretreatment were experimentally studied in terms of dielectric properties, water loss and solid gain. Finally, combining of osmotic treatment prior to microwave vacuum were investigated. All experiments led to the following conclusions.

1. The laboratory scale microwave vacuum setup was able to record variation of mass and temperature of drying product in real-time. Input and reflected power were monitored to acquire the accuracy of power management.

2. The position of vacuum control valve in the microwave vacuum system has affected the drying time and occurrence of vapor condensation. Passing air through the vacuum container provided faster drying time and could reduce the occurrence of vapor condensation.

3. Halved strawberries and 10 mm cubed carrots can be dried in microwave vacuum with the input power not exceeding 1.5w/g.

4. The dielectric constant of carrots and strawberries decreased with an increase in the concentration of the osmotic agents, temperature and immersion time.

5. The immersion time was the most significant factor affecting dielectric constant of carrots while salt was found to be the most significant factor affecting the loss factor of carrots.

6. The dielectric constant after osmotic pretreatment of carrots decreased while loss factor increased.

7. The dielectric constant after osmotic pretreatment of strawberries decreased while loss factor was not affected.

8. An increase of sucrose concentration, temperature and immersion time increased water loss and solid gain for the osmotically treated carrots but increase of sucrose concentration for the osmotic treatment of strawberries decreased the solid gain.

9. Osmotic treatment prior to microwave vacuum drying of carrots decreased drying time and energy consumption. In term of quality evaluation, less shrinkage and improving appearance were found whereas the taste was not acceptable due to gaining of salt.

10. Osmotic treatment prior to microwave vacuum drying of strawberries did not help in term of drying time and energy saving but the quality of dried product was improved.

11. Temperature in the microwave vacuum drying was the critical factor to affect the quality of dried product. In this study, the temperature was able to be controlled by input power level and pulse mode.

12. Microwave vacuum with osmotic pretreatment of carrots did not show constant rate drying period while the process without osmotic pretreatment showed a short period of constant rate followed by falling rate period.

13. Microwave vacuum with osmotic pretreatment of strawberries showed only a single falling rate period while the process without osmotic pretreatment clearly showed a constant rate period followed by falling rate period.

14. Lewis and Henderson & Pabis model seemed to show a good fit for the drying process with a single falling rate period.

15. Page's model fitted well the observed data of microwave vacuum drying of carrots and strawberries in both cases of with and with out osmotic treatment and with a constant as well as falling rate period.

9.2 Contributions to knowledge

This study has made original contribution to knowledge by providing information on osmotically dehydrated microwave vacuum drying of carrots and strawberries. The main contributions are as follows:

1. Heating with microwave energy in vacuum container causes the vapor condensation. The proper positioning of valve in microwave vacuum drying system that allows air to pass through the vacuum container can reduce the occurrence of condensed vapor in the container. This information will be useful for designing a microwave vacuum dryer.

2. This study has showed that osmotic treatment can potentially be a pretreatment for microwave vacuum drying of carrots as demonstrated through the drying time, energy saving and quality improvement. In strawberries, however, the pretreatment has contributed only for the improvement of dried product quality.

3. The optimum conditions for using osmosis concept for pretreatment of carrots and strawberries were established in this study. Accordingly, the optimal osmotic conditions required highest ratio of water loss and solid gain.

4. Page's model was found to provide the best fit with the observed data for both constant rate and falling rate period. Meanwhile, Lewis and Henderson & Pabis models only fit well with the falling rate period.

9.3 Recommendations for further studies

This study revealed that osmotic dehydration as a pretreatment for drying process may or may not benefit in reducing drying time and saving energy but it was found to be certainly helpful in maintaining quality in terms of organoleptic properties.

The results in this study showed that temperature was the critical factor affecting quality of dried product. In order to control temperature in microwave drying process, input power is the key factor which affects the change in the product temperature during drying. A very high input power level will cause high reflected power which in turn may also have an effect on the microwave generator. It was found in this study that a fixed input power level results in varying temperature. Hence decreasing input power during the drying process should be studied. The pulse mode in this study resulted in more energy saving when compared to continuous mode. The combination of decreasing input power and using pulse mode should be further studied. However, it is difficult to achieve these combinations manually. Therefore new strategies should be incorporated and studied to establish a temperature driven process.

The taste of rehydrated carrots which received osmotic pretreatment was unacceptable due to the salty taste. It is felt because the duration of time given for rehydration was too short. Hence, optimization of rehydration time for osmotically dehydrated product needs to be investigated.

Desiccator being not large enough, the high suction of vacuum pump used to create pressure of 7-8 kPa leads to the contamination of oil of vacuum pump system by water vaporized from the product and consequently it reduces the efficiency. This can be solved by placing water trap along the line between vacuum pump and microwave cavity.

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APPENDICES

Appendix A

Appendix B

Appendix C

Appendix D

Appendix E

Appendix A

Table A.5.1 Analysis of variance and regression coefficients for dielectric constant of carrot

Analysis of Variance for dielectric constant of carrot

Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
A:Sucrose	59.0422	1	59.0422	15.17	.0025
B:Salt	319.202	1	319.202	82.03	.0000
C:Temp	90.2272	1	90.2272	23.19	.0005
D:Time	666.125	1	666.125	171.18	.0000
AA	10.4942	1	10.4942	2.70	.1288
AB	8.1225	1	8.1225	2.09	.1764
AC	4.0	1	4.0	1.03	.3324
AD	60.84	1	60.84	15.63	.0023
BB	5.57712	1	5.57712	1.43	.2564
BC	1.5625	1	1.5625	.40	.5392
BD	6.5025	1	6.5025	1.67	.2226
CC	.0777909	1	.0777909	.02	.8901
CD	15.21	1	15.21	3.91	.0736
DD	35.5488	1	35.5488	9.14	.0116
Total error	42.8043	63	3.8913		
Total (corr.)	1345.92	77			

R-squared = 96.8197 percent
R-squared (adjusted for d.f.) = 92.772 percent
Standard Error of Est. = 1.97264
Mean absolute error = 1.03508
Durbin-Watson statistic = 2.53264 (P=. 170)
Lag 1 residual autocorrelation = -.333569

Regression coefficients for dielectric constant of carrot

---

constant = 42.5479
A:Sucrose = 1.77082
B:Salt = -2.56779
C:Temp = .180683
D:Time = -2.16746
AA = -.0202429
AB = .01425
AC = -.005
AD = -.065
BB = .0590286
BC = .00625
BD = -.0425
CC = -.00174286
CD = -.0325
DD = .413968

Table A.5.2 Analysis of variance and regression coefficients for loss factor of carrot

Analysis of Variance for loss factor of carrot

Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
A:Sucrose	382.722	1	382.722	51.25	.0000
B:Salt	1190.72	1	1190.72	159.44	.0000
C:Temp	6.60056	1	6.60056	.88	.3673
D:Time	.008889	1	.008889	.00	.9731
AA	11.1611	1	11.1611	1.49	.2471
AB	82.3556	1	82.3556	11.03	.0068
AC	4.30563	1	4.30563	.58	.4636
AD	2.17562	1	2.17562	.29	.6001
BB	.608929	1	.608929	.08	.7805
BC	3.90063	1	3.90063	.52	.4849
BD	13.5056	1	13.5056	1.81	.2058
CC	4.08119	1	4.08119	.55	.4752
CD	49.3506	1	49.3506	6.61	.0260
DD	4.246	1	4.246	.57	.4667
Total error	82.1497	63	7.46815		
Total (corr.)	1857.42	77			

R-squared = 95.5772 percent
R-squared (adjusted for d.f.) = 89.9482 percent
Standard Error of Est. = 2.73279
Mean absolute error = 1.44093
Durbin-Watson statistic = 1.40551 (P=. 115)
Lag 1 residual autocorrelation = .288382

Regression coefficients for loss factor of carrot

constant = -9.00913
A:Sucrose = 1.56857
B:Salt = 3.84176
C:Temp = -.831526
D:Time = 4.29851
AA = -.0208762
AB = -.045375
AC = .0051875
AD = -.0122917
BB = -.0195048
BC = .009875
BD = -.06125
CC = .0126238
CD = -.0585417
DD = -.143069

Table A.5.3 Analysis of variance and regression coefficients for dielectric constant of strawberry

Analysis of Variance for dielectric constant of strawberry

```
--------------------------------------------------------------------------------
Source            Sum of Squares    Df   Mean Square   F-Ratio   P-Value
--------------------------------------------------------------------------------
A:Sucrose            147.994         1      147.994      16.74    .0064
B:Temp               372.466         1      372.466      42.12    .0006
C:Time               234.837         1      234.837      26.56    .0021
AA                   7.35863         1      7.35863        .83    .3968
AB                   14.0981         1      14.0981       1.59    .2536
AC                   2.85605         1      2.85605        .32    .5904
BB                   18.9257         1      18.9257       2.14    .1938
BC                   108.045         1      108.045      12.22    .0129
CC                   11.0328         1      11.0328       1.25    .3067
Total error          53.0556        38       8.8426
--------------------------------------------------------------------------------
Total (corr.)        963.544        47
```

R-squared = 94.4937 percent
R-squared (adjusted for d.f.) = 86.2343 percent
Standard Error of Est. = 2.97365
Mean absolute error = 1.61412
Durbin-Watson statistic = 1.65833 (P=.1813)
Lag 1 residual autocorrelation = -.0432388

Regression coefficient for dielectric constant of strawberry

```
-------------------------------------------------------------------
constant                  = 77.6979
A:Sucrose                 = -1.47789
B:Temp                    = 2.76354
C:Time                    = -.51794
AA                        = .0167069
AB                        = -.013275
AC                        = -.00995833
BB                        = -.0267931
BC                        = -.06125
CC                        = .0568247
-------------------------------------------------------------------
```

Table A.5.4 Analysis of variance and regression coefficients for loss factor of strawberry

Analysis of Variance for loss factor of strawberry

```
-----------------------------------------------------------------------------------------
Source              Sum of Squares     Df   Mean Square    F-Ratio    P-Value
-----------------------------------------------------------------------------------------
A:Sucrose                .65025          1      .65025         3.09     .1294
B:Temp                   .36864          1      .36864         1.75     .2340
C:Time                   .00169          1      .00169          .01     .9315
AA                     .0206245          1    .0206245          .10     .7649
AB                      .567112          1     .567112         2.69     .1519
AC                      .177012          1     .177012          .84     .3946
BB                      .182977          1     .182977          .87     .3872
BC                      .655513          1     .655513         3.11     .1281
CC                       1.6389          1      1.6389         7.78     .0316
Total error             1.26352         38     .210587
-----------------------------------------------------------------------------------------
Total (corr.)           7.35718         47
```

R-squared = 82.826 percent
R-squared (adjusted for d.f.) = 77.0649 percent
Standard Error of Est. = .458898
Mean absolute error = .25825
Durbin-Watson statistic = 2.10521 (P=.3146)
Lag 1 residual autocorrelation = -.0684683

Regression coefficient for loss factor of strawberry

```
-----------------------------------------------------------
constant                  = -1.19056
A:Sucrose                 = .187448
B:Temp                    = .396269
C:Time                    = 1.0577
AA                        = -.000884483
AB                        = -.0026625
AC                        = -.00247917
BB                        = -.00263448
BC                        = -.00477083
CC                        = -.0219013
-----------------------------------------------------------
```

Appendix B

Table B.6.1 Analysis of variance and regression coefficients for water loss (WL) of carrot

Analysis of Variance for WL

Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
A:Sucrose	566.722	1	566.722	44.02	0.0000
B:Salt	75.2356	1	75.2356	5.84	0.0342
C:Temperature	836.405	1	836.405	64.97	0.0000
D:Time	482.569	1	482.569	37.49	0.0001
AA	7.12195	1	7.12195	0.55	0.4726
AB	72.6756	1	72.6756	5.65	0.0368
AC	37.5156	1	37.5156	2.91	0.1158
AD	31.0806	1	31.0806	2.41	0.1485
BB	3.2839	1	3.2839	0.26	0.6235
BC	12.0756	1	12.0756	0.94	0.3536
BD	31.0806	1	31.0806	2.41	0.1485
CC	0.0173804	1	0.0173804	0.00	0.9713
CD	2.80562	1	2.80562	0.22	0.6497
DD	28.439	1	28.439	2.21	0.1653
Total error	141.606	63	12.8732		
Total (corr.)	2349.46	77			

R-squared = 93.9728 percent
R-squared (adjusted for d.f.) = 86.3019 percent
Standard Error of Est. = 3.58793
Mean absolute error = 1.8813
Durbin-Watson statistic = 2.23379 (P=0.0803)
Lag 1 residual autocorrelation = -0.124011

Regression coefficient for WL of carrot

constant = 16.5927
A:Sucrose = -1.0384
B:Salt = 2.96313
C:Temperature = -.124946
D:Time = 4.08065
AA = .0166762
AB = -.042625
AC = .0153125
AD = .0464583
BB = -.0452952
BC = .017375
BD = -.0929167
CC = -.00082381
CD = .0139583
DD = -.370265

Table B.6.2 Analysis of variance and regression coefficients for solid gain (SG) of carrot

```
Analysis of Variance for SG
-----------------------------------------------------------------------------------
Source            Sum of Squares   Df   Mean Square   F-Ratio  P-Value
-----------------------------------------------------------------------------------
A:Sucrose           1.38889         1      1.38889       0.80    0.3913
B:Salt              49.005          1     49.005        28.10    0.0003
C:Temperature       45.4422         1     45.4422       26.06    0.0003
D:Time             150.222          1    150.222        86.14    0.0000
AA                0.547527          1      0.547527      0.31    0.5865
AB                  5.0625          1      5.0625        2.90    0.1165
AC                  1.8225          1      1.8225        1.04    0.3286
AD                  0.5625          1      0.5625        0.32    0.5815
BB                0.672344          1      0.672344      0.39    0.5473
BC                    0.04          1      0.04          0.02    0.8824
BD                    2.25          1      2.25          1.29    0.2802
CC                  5.4768          1      5.4768        3.14    0.1040
CD                    0.64          1      0.64          0.37    0.5570
DD                  0.1446          1      0.1446        0.08    0.7787
Total error        19.1843         63     1.74402
-----------------------------------------------------------------------------------
Total (corr.)      298.082     77

R-squared = 93.5641 percent
R-squared (adjusted for d.f.) = 85.3729 percent
Standard Error of Est. = 1.32061
Mean absolute error = 0.685018
Durbin-Watson statistic = 2.09807 (P=0.1387)
Lag 1 residual autocorrelation = -0.0853275
```

```
Regression coefficient for SG
------------------------------------------
constant                = -25.8851
A:Sucrose                = .587127
B:Salt                  = 1.0349
C:Temperature           = 1.12798
D:Time                  = .498942
AA                      = -.00462381
AB                      = -.01125
AC                      = -.003375
AD                      = -.00625
BB                      = -.0204952
BC                      = .001
BD                      = .025
CC                      = -.0146238
CD                      = .00666667
DD                      = .0264021
------------------------------------------
```

Table B.6.3 Analysis of variance and regression coefficients for the ratio between water loss and solid gain (WL/SG) of carrot

```
Analysis of Variance for WLSG
-----------------------------------------------------------------------------------------
Source              Sum of Squares    Df   Mean Square   F-Ratio   P-Value
-----------------------------------------------------------------------------------------
A:Sucrose                3.81801       1     3.81801       23.32    0.0005
B:Salt                   1.30681       1     1.30681       7.98     0.0165
C:Temperature            0.17405       1     0.17405       1.06     0.3246
D:Time                   2.29694       1     2.29694       14.03    0.0032
AA                       0.14646       1     0.14646       0.89     0.3645
AB                      0.042025       1     0.042025      0.26     0.6224
AC                          0.49       1       0.49        2.99     0.1115
AD                        0.1156       1     0.1156        0.71     0.4186
BB                    0.00392383       1     0.00392383    0.02     0.8798
BC                      0.319225       1     0.319225      1.95     0.1901
BD                      0.112225       1     0.112225      0.69     0.4253
CC                      0.199553       1     0.199553      1.22     0.2931
CD                        0.0169       1     0.0169        0.10     0.7540
DD                     0.0508116       1     0.0508116     0.31     0.5886
Total error              1.80081      38     0.16371
-----------------------------------------------------------------------------------------
Total (corr.)            11.4196      47

R-squared = 84.2305 percent
R-squared (adjusted for d.f.) = 77.1602 percent
Standard Error of Est. = 0.404611
Mean absolute error = 0.228108
Durbin-Watson statistic = 2.54004 (P=0.0162)
Lag 1 residual autocorrelation = -0.286706

Regression coefficient for WLSG
-----------------------------------------------
constant                  = 11.2066
A:Sucrose                 = -.201675
B:Salt                     = -.101037
C:Temperature             = -.261319
D:Time                    = -.0525661
AA                        = .00239143
AB                        = -.001025
AC                        = .00175
AD                        = .00283333
BB                        = .00156571
BC                        = .002825
BD                        = -.00558333
CC                        = .00279143
CD                        = .00108333
DD                        = -.0156508
-----------------------------------------------
```

Table B.6.4 Analysis of variance and regression coefficients for water loss (WL) of strawberries

Analysis of Variance for Water loss

Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
A:Sucrose	6.84496	1	6.84496	12.26	0.0013
B:Temperature	21.7431	1	21.7431	38.95	0.0000
C:Time	23.9771	1	23.9771	42.95	0.0000
AA	2.33189	1	2.33189	4.18	0.0483
AB	0.145704	1	0.145704	0.26	0.6126
AC	0.0287042	1	0.0287042	0.05	0.8219
BB	0.423214	1	0.423214	0.76	0.3897
BC	0.246037	1	0.246037	0.44	0.5110
CC	0.225032	1	0.225032	0.40	0.5295
Total error	20.482962	38	0.558266		
Total (corr.)	77.6549	47			

R-squared = 84.1194 percent
R-squared (adjusted for d.f.) = 77.9898 percent
Standard Error of Est. = 0.747172
Mean absolute error = 0.499895
Durbin-Watson statistic = 2.43161 (P=0.0472)
Lag 1 residual autocorrelation = -0.219984

Regression coefficient for Water loss

constant = -16.6393
A:Sucrose = 0.577755
B:Temperature = 0.215343
C:Time = 0.0597663
AA = -0.00542989
AB = 0.000779167
AC = -0.000576389
BB = -0.00231322
BC = -0.0016875
CC = 0.0046855

Table B.6.5 Analysis of variance and regression coefficients for solid gain (SG) of strawberry

```
Analysis of Variance for Solid gain
-----------------------------------------------------------------------------
Source          Sum of Squares   Df   Mean Square   F-Ratio   P-Value
-----------------------------------------------------------------------------
A:Sucrose          0.298003       1    0.298003       1.21     0.2791
B:Temperature       23.8521       1    23.8521       96.66     0.0000
C:Time              14.3798       1    14.3798       58.27     0.0000
AA                  1.12521       1    1.12521        4.56     0.0396
AB                0.0247042       1    0.0247042      0.10     0.7535
AC                0.0176042       1    0.0176042      0.07     0.7909
BB                 0.971729       1    0.971729       3.94     0.0549
BC                   20.332       1    20.332        82.40     0.0000
CC                   1.4887       1    1.4887         6.03     0.0190
Total error       8.9391725      38    0.246761
-----------------------------------------------------------------------------
Total (corr.)       77.6368      47

R-squared = 88.5577 percent
R-squared (adjusted for d.f.) = 85.8477 percent
Standard Error of Est. = 0.496751
Mean absolute error = 0.331513
Durbin-Watson statistic = 1.48954 (P=0.0259)
Lag 1 residual autocorrelation = 0.250712

Regression coefficient for Solid gain
---------------------------------------------
constant                = 7.50765
A:Sucrose               = -0.369401
B:Temperature           = 0.171023
C:Time                  = -0.0664617
AA                      = 0.00377184
AB                      = -0.000320833
AC                      = -0.000451389
BB                      = 0.00350517
BC                      = -0.0153403
CC                      = 0.0120514
---------------------------------------------
```

Table B.6.6 Analysis of variance and regression coefficients for the ratio between water loss and solid gain (WL/SG) of strawberry

Analysis of Variance for WLSG

Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
A:Sucrose	155.451	1	155.451	41.75	0.0000
B:Temperature	170.933	1	170.933	45.91	0.0000
C:Time	203.789	1	203.789	54.73	0.0000
AA	17.9814	1	17.9814	4.83	0.0345
AB	14.7423	1	14.7423	3.96	0.0543
AC	32.5501	1	32.5501	8.74	0.0055
BB	0.690704	1	0.690704	0.19	0.6693
BC	22.8735	1	22.8735	6.14	0.0180
CC	20.5304	1	20.5304	5.51	0.0245
Total error	151.6137	38	3.72359		
Total (corr.)	823.545	47			

R-squared = 83.7229 percent
R-squared (adjusted for d.f.) = 79.8678 percent
Standard Error of Est. = 1.92966
Mean absolute error = 1.29351
Durbin-Watson statistic = 1.73202 (P=0.1319)
Lag 1 residual autocorrelation = 0.129663

Regression coefficient for WLSG

constant = -36.4224
A:Sucrose = 1.6212
B:Temperature = -0.31701
C:Time = 0.586927
AA = -0.0150782
AB = -0.0078375
AC = 0.0194097
BB = 0.00295517
BC = 0.0162708
CC = -0.0447542

Appendix C

Table C.7.1 Analysis of Variance for rehydration property of carrot and multiple range test by Tukey HSD

```
Analysis of Variance for Rehydration property of carrots - Type III Sums of Squares
--------------------------------------------------------------------------------
Source              Sum of Squares   Df   Mean Square    F-Ratio   P-Value
--------------------------------------------------------------------------------
MAIN EFFECTS
 A:Pretreatment          .0529         1     .0529          573.08     .0000
 B:Input power           .0004         1     .0004            4.33     .0474
 C:Power mode            .0002         2     .0001            1.08     .3533
INTERACTIONS
 AB                      .0009         1     .0009            9.75     .0044
 AC                      .0008         2     .0004            4.33     .0238
 BC                      .0014         2     .0007            7.58     .0025
RESIDUAL                 .0024        26     .0000923077
--------------------------------------------------------------------------------
TOTAL (CORRECTED) .059                35
--------------------------------------------------------------------------------
```

Multiple Range Tests for Rehydration of carrots by Pretreatment

```
--------------------------------------------------------------------------------
Method: 95.0 percent Tukey HSD
Pretreatment  Count   LS Mean      LS Sigma     Homogeneous Groups
--------------------------------------------------------------------------------
Osmotic        18      .208333     .00226455          A
No osmotic     18      .285        .00226455          B
--------------------------------------------------------------------------------
```

Multiple Range Tests for Rehydration of carrots by Input power

```
--------------------------------------------------------------------------------
Method: 95.0 percent Tukey HSD
Input power   Count   LS Mean      LS Sigma     Homogeneous Groups
--------------------------------------------------------------------------------
1.5 W/g        18      .243333     .00226455          A
1 W/g          18      .25         .00226455          A
--------------------------------------------------------------------------------
```

Multiple Range Tests for Rehydration of carrots by Power mode

```
--------------------------------------------------------------------------------
Method: 95.0 percent Tukey HSD
Power mode      Count   LS Mean     LS Sigma     Homogeneous Groups
--------------------------------------------------------------------------------
45s on/15s off   12      .245       .0027735            A
30s on/30s off   12      .245       .0027735            A
Continuous       12      .25        .0027735            A
--------------------------------------------------------------------------
```

Table C.7.2 Analysis of Variance for texture of carrots and multiple range test by Tukey HSD

Analysis of Variance for texture of carrots - Type III Sums of Squares

```
--------------------------------------------------------------------------------
Source              Sum of Squares    Df   Mean Square   F-Ratio  P-Value
--------------------------------------------------------------------------------
MAIN EFFECTS
 A:Pretreatment         256.144        1       256.144       5.41    .0280
 B:Input power            9.003        1         9.003        .19    .6663
 C:Power mode            43.9217       2        21.9608       .46    .6337
INTERACTIONS
 AB                       8.2436       1         8.2436       .17    .6798
 AC                      46.9082       2        23.4541       .50    .6147
 BC                     556.812        2       278.406       5.89    .0078
RESIDUAL                1229.91       26        47.3041
--------------------------------------------------------------------------------
TOTAL (CORRECTED) 2150.94             35
--------------------------------------------------------------------------------
```

Multiple Range Tests for texture of carrots by Pretreatment

```
--------------------------------------------------------------------------------
Method: 95.0 percent Tukey HSD
Pretreatment  Count    LS Mean      LS Sigma     Homogeneous Groups
--------------------------------------------------------------------------------
Osmotic        18        8.96961     1.62111              A
No Osmotic     18       14.3044      1.62111              B
--------------------------------------------------------------------------------
```

Multiple Range Tests for texture of carrots by Input power

```
--------------------------------------------------------------------------------
Method: 95.0 percent Tukey HSD
Input power   Count    LS Mean      LS Sigma     Homogeneous Groups
--------------------------------------------------------------------------------
1.5 W/g        18       11.1369      1.62111              A
1 W/g          18       12.1371      1.62111              A
--------------------------------------------------------------------------------
```

Multiple Range Tests for texture by Power mode

```
--------------------------------------------------------------------------
Method: 95.0 percent Tukey HSD
Power mode     Count    LS Mean      LS Sigma     Homogeneous Groups
--------------------------------------------------------------------------
Continuous       12       10.2271      1.98545             A
45s on/15s off   12       11.7597      1.98545             A
30s on/30s off   12       12.9243      1.98545             A
--------------------------------------------------------------------------
```

Table C.7.3 Analysis of Variance for color changing (ΔE) of carrots and multiple range test by Tukey HSD

```
Analysis of Variance for color changing (ΔE) - Type III Sums of Squares
--------------------------------------------------------------------------------
Source            Sum of Squares    Df   Mean Square   F-Ratio   P-Value
--------------------------------------------------------------------------------
MAIN EFFECTS
 A:Pretreatment         97.3044      1     97.3044     1295.42    .0000
 B:Input power          24.2655      1     24.2655      323.05    .0000
 C:Power mode            13.468      2     6.73402       89.65    .0000
INTERACTIONS
 AB                     101.204      1     101.204     1347.33    .0000
 AC                      5.8492      2     7.92458      105.50    .0000
 BC                     11.1875      2     5.59376       74.47    .0000
RESIDUAL                1.95297     26    .0751144
--------------------------------------------------------------------------------
TOTAL (CORRECTED) 265.231           35
--------------------------------------------------------------------------------
```

Multiple Range Tests for color changing (ΔE) by Pretreatment

```
--------------------------------------------------------------------------------
Method: 95.0 percent Tukey HSD
Pretreatment  Count    LS Mean      LS Sigma     Homogeneous Groups
--------------------------------------------------------------------------------
Osmotic          18     25.6369     .0645989            A
No osmotic       18     28.925      .0645989            B
--------------------------------------------------------------------------------
```

Multiple Range Tests for color changing (ΔE) by Input power

```
--------------------------------------------------------------------------------
Method: 95.0 percent Tukey HSD
Input power   Count    LS Mean      LS Sigma     Homogeneous Groups
--------------------------------------------------------------------------------
1 W/g         18       26.4599      .0645989            A
1.5 W/g       18       28.1019      .0645989            B
--------------------------------------------------------------------------------
```

Multiple Range Tests for color changing (ΔE) by Power mode

```
--------------------------------------------------------------------------------
Method: 95.0 percent Tukey HSD
Power mode     Count    LS Mean      LS Sigma     Homogeneous Groups
--------------------------------------------------------------------------------
30s on/30s off   12     26.4407      .0791172            A
45s on/15s off   12     27.5231      .0791172            B
Continuous       12     27.879       .0791172            C
--------------------------------------------------------------------------------
```

Table C.7.4 Analysis of Variance for color redness (a/b) of carrots and multiple range test by Tukey HSD

```
Analysis of Variance for color redness (a/b) - Type III Sums of Squares
--------------------------------------------------------------------------------
Source              Sum of Squares    Df   Mean Square   F-Ratio   P-Value
--------------------------------------------------------------------------------
MAIN EFFECTS
 A:Pretreatment       .492949          1     .492949      1336.60   .0000
 B:Input power        .00317507        1     .00317507       8.61   .0069
 C:Power mode         .0795341         2     .0397671      107.83   .0000
INTERACTIONS
 AB                   .000698883       1    .000698883       1.89   .1804
 AC                   .0072572         2    .0036286         9.84   .0007
 BC                   .00611772        2    .00305886        8.29   .0016
RESIDUAL              .00958899       26    .000368807
--------------------------------------------------------------------------------
TOTAL (CORRECTED)  .599321            35
--------------------------------------------------------------------------------
```

Multiple Range Tests for color redness (a/b) by Pretreatment

```
--------------------------------------------------------------------------------
Method: 95.0 percent Tukey HSD
Pretreatment   Count   LS Mean     LS Sigma      Homogeneous Groups
--------------------------------------------------------------------------------
No osmotic      18      1.14357     .00452651            A
Osmotic         18      1.3776      .00452651            B
--------------------------------------------------------------------------------
```

Multiple Range Tests for color redness (a/b) by Input power

```
--------------------------------------------------------------------------------
Method: 95.0 percent Tukey HSD
Input power    Count   LS Mean     LS Sigma      Homogeneous Groups
--------------------------------------------------------------------------------
1 W/g           18      1.25119     .00452651            A
1.5 W/g         18      1.26997     .00452651            B
--------------------------------------------------------------------------------
```

Multiple Range Tests for color redness (a/b) by Power mode

```
--------------------------------------------------------------------------------
Method: 95.0 percent Tukey HSD
Power mode      Count   LS Mean     LS Sigma      Homogeneous Groups
--------------------------------------------------------------------------------
30s on/30s off   12      1.21142     .00554382            A
45s on/15s off   12      1.24642     .00554382            B
Continuous       12      1.32391     .00554382            C
--------------------------------------------------------------------------------
```

Table C.7.5 Analysis of Variance for sensory taste of carrots and multiple range test by Tukey HSD

```
Analysis of Variance for Taste - Type III Sums of Squares
--------------------------------------------------------------------------------
Source             Sum of Squares    Df   Mean Square   F-Ratio   P-Value
--------------------------------------------------------------------------------
MAIN EFFECTS
 A:Pretreatment          29.3403      1       29.3403     198.20     .0000
 B:Input power           .100278      1       .100278        .68     .4180
 C:Power mode           .0155556      2     .00777778        .05     .9489
INTERACTIONS
 AB                     .0336111      1      .0336111        .23     .6377
 AC                     .0955556      2      .0477778        .32     .7270
 BC                   .00222222       2     .00111111        .01     .9925
RESIDUAL                 3.84889     26       .148034
--------------------------------------------------------------------------------
TOTAL (CORRECTED) 33.4364            35
--------------------------------------------------------------------------------
```

Multiple Range Tests for Sensory Taste by Pretreatment

```
--------------------------------------------------------------------------------
Method: 95.0 percent Tukey HSD
Pretreatment  Count   LS Mean     LS Sigma    Homogeneous Groups
--------------------------------------------------------------------------------
Osmotic         18     3.81667     .0906869          A
No osmotic      18     5.62222     .0906869          B
--------------------------------------------------------------------------------
```

Multiple Range Tests for Sensory Taste by Input power

```
--------------------------------------------------------------------------------
Method: 95.0 percent Tukey HSD
Input power   Count   LS Mean     LS Sigma    Homogeneous Groups
--------------------------------------------------------------------------------
1 W/g           18     4.66667     .0906869          A
1.5 W/g         18     4.77222     .0906869          A
--------------------------------------------------------------------------------
```

Multiple Range Tests for Sensory Taste by Power mode

```
--------------------------------------------------------------------------
Method: 95.0 percent Tukey HSD
Power mode     Count   LS Mean     LS Sigma    Homogeneous Groups
--------------------------------------------------------------------------
30s on/30s off   12     4.69167     .111068           A
45s on/15s off   12     4.725       .111068           A
Continuous       12     4.74167     .111068           A
--------------------------------------------------------------------------
```

Table C.7.6 Analysis of Variance for overall appearance of carrots and multiple range test by Tukey HSD

```
Analysis of Variance for Overall Appearance - Type III Sums of Squares
--------------------------------------------------------------------------------
Source             Sum of Squares    Df   Mean Square    F-Ratio    P-Value
--------------------------------------------------------------------------------
MAIN EFFECTS
 A:Pretreatment          174.24        1       174.24      11921.68     .0000
 B:Input power             6.25        1         6.25        427.63     .0000
 C:Power mode              5.84        2         2.92        199.79     .0000
INTERACTIONS
 AB                         .49        1          .49         33.53     .0000
 AC                         .42        2          .21         14.37     .0001
 BC                         .56        2          .28         19.16     .0000
RESIDUAL                    .38       26     .0146154
--------------------------------------------------------------------------------
TOTAL (CORRECTED) 188.18              35
--------------------------------------------------------------------------------
```

Multiple Range Tests for Overall Appearance by Pretreatment

```
--------------------------------------------------------------------------------
Method: 95.0 percent Tukey HSD
Pretreatment  Count    LS Mean      LS Sigma     Homogeneous Groups
--------------------------------------------------------------------------------
No osmotic     18      3.13333      .028495            A
Osmotic        18      7.53333      .028495            B
--------------------------------------------------------------------------------
```

Multiple Range Tests for Overall Appearance by Input power

```
--------------------------------------------------------------------------------
Method: 95.0 percent Tukey HSD
Input power   Count    LS Mean      LS Sigma     Homogeneous Groups
--------------------------------------------------------------------------------
1.5 W/g        18      4.91667      .028495            A
1 W/g          18      5.75         .028495            B
--------------------------------------------------------------------------------
```

Multiple Range Tests for Rehydration by Power mode

```
--------------------------------------------------------------------------------
Method: 95.0 percent Tukey HSD
Power mode     Count    LS Mean      LS Sigma     Homogeneous Groups
--------------------------------------------------------------------------------
Continuous      12        5.0        .0348991           A
45s on/15s off  12        5.1        .0348991           A
30s on/30s off  12        5.9        .0348991           B
--------------------------------------------------------------------------------
```

Appendix D

Table D.8.1 Analysis of Variance for rehydration capacity of strawberries and multiple range test by Tukey HSD

```
Analysis of Variance for Rehydration - Type III Sums of Squares
--------------------------------------------------------------------------------
Source               Sum of Squares   Df   Mean Square   F-Ratio   P-Value
--------------------------------------------------------------------------------
MAIN EFFECTS
 A:Pretreatment            .0169       1        .0169        43.08      .0000
 B:Input power             .0049       1        .0049        12.49      .0016
 C:Power mode              .0006       2        .0003          .76      .4757
INTERACTIONS
 AB                        .0036       1        .0036         9.18      .0055
 AC                        .0014       2        .0007         1.78      .1879
 BC                        .0026       2        .0013         3.31      .0522
RESIDUAL                   .0102      26    .000392308
--------------------------------------------------------------------------------
TOTAL (CORRECTED) .0402               35
--------------------------------------------------------------------------------
```

Multiple Range Tests for rehydration capacity by Pretreatment

```
--------------------------------------------------------------------------------
Method: 95.0 percent Tukey HSD
Pretreatment   Count   LS Mean      LS Sigma      Homogeneous Groups
--------------------------------------------------------------------------------
Osmotic          18     .278333      .0046685            A
No osmotic       18     .321667      .0046685            B
--------------------------------------------------------------------------------
```

Multiple Range Tests for rehydration capacity by Input power

```
--------------------------------------------------------------------------
Method: 95.0 percent Tukey HSD
Input power    Count   LS Mean      LS Sigma      Homogeneous Groups
--------------------------------------------------------------------------
1 W/g            18     .288333      .0046685            A
1.5 W/g          18     .311667      .0046685            B
--------------------------------------------------------------------------
```

Multiple Range Tests for rehydration capacity by Power mode

```
--------------------------------------------------------------------------
Method: 95.0 percent Tukey HSD
Power mode      Count   LS Mean      LS Sigma      Homogeneous Groups
--------------------------------------------------------------------------
Continuous        12     .295         .00571772           A
30s on/30s off    12     .3           .00571772           A
45s on/15s off    12     .305         .00571772           A
--------------------------------------------------------------------------
```

Table D.8.2 Analysis of Variance for texture of strawberries and multiple range test by Tukey HSD

```
Analysis of Variance for texture - Type III Sums of Squares
--------------------------------------------------------------------------------
Source              Sum of Squares    Df   Mean Square    F-Ratio    P-Value
--------------------------------------------------------------------------------
MAIN EFFECTS
 A:Pretreatment          3.11346       1      3.11346          .39      .5388
 B:Input power           11.8876       1      11.8876         1.48      .2345
 C:Power mode            67.3652       2      33.6826         4.20      .0263
INTERACTIONS
 AB                      5.71449       1      5.71449          .71      .4065
 AC                      7.30999       2      3.65499          .46      .6392
 BC                      11.6439       2      5.82196          .73      .4937
RESIDUAL                 208.688      26      8.02647
--------------------------------------------------------------------------------
TOTAL (CORRECTED315.723               35
--------------------------------------------------------------------------------
```

Multiple Range Tests for texture by Pretreatment

```
--------------------------------------------------------------------------------
Method: 95.0 percent Tukey HSD
Pretreatment   Count    LS Mean      LS Sigma      Homogeneous Groups
--------------------------------------------------------------------------------
Osmotic          18      9.43111     .667769             A
No osmotic       18      10.0193     .667769             A
--------------------------------------------------------------------------------
```

Multiple Range Tests for texture by Input power

```
--------------------------------------------------------------------------------
Method: 95.0 percent Tukey HSD
Input power    Count    LS Mean      LS Sigma      Homogeneous Groups
--------------------------------------------------------------------------------
1 W/g            18      9.15056     .667769             A
1.5 W/g          18      10.2998     .667769             A
--------------------------------------------------------------------------------
```

Multiple Range Tests for texture by Power mode

```
--------------------------------------------------------------------------------
Method: 95.0 percent Tukey HSD
Power mode      Count    LS Mean      LS Sigma      Homogeneous Groups
--------------------------------------------------------------------------------
30s on/30s off    12      8.51567      .817846            A
45s on/15s off    12      9.02242      .817846            AB
Continuous        12      11.6375      .817846            B
--------------------------------------------------------------------------------
```

Table D.8.3 Analysis of Variance for color changing (ΔE) of strawberries and multiple range test by Tukey HSD

```
Analysis of Variance for color changing (ΔE) - Type III Sums of Squares
--------------------------------------------------------------------------------
Source              Sum of Squares    Df   Mean Square    F-Ratio    P-Value
--------------------------------------------------------------------------------
MAIN EFFECTS
 A:Pretreatment          285.744          1      285.744         3190.26     .0000
 B:Input power           11.4804          1      11.4804          128.18     .0000
 C:Power mode            5.83888          2      2.91944           32.59     .0000
INTERACTIONS
 AB                      2.1319           1      2.1319            23.80     .0000
 AC                      4.36239          2      2.18119           24.35     .0000
 BC                      1.31858          2      .659292            7.36     .0029
RESIDUAL                 2.32876         26      .0895676
--------------------------------------------------------------------------------
TOTAL (CORRECTED) 313.205                35
--------------------------------------------------------------------------------
```

Multiple Range Tests for color changing (ΔE) by Pretreatment

```
--------------------------------------------------------------------------------
Method: 95.0 percent Tukey HSD
Pretreatment  Count    LS Mean      LS Sigma     Homogeneous Groups
--------------------------------------------------------------------------------
Osmotic         18        8.29087     .0705406            A
No osmotic      18        13.9255     .0705406            B
--------------------------------------------------------------------------------
```

Multiple Range Tests for color changing (ΔE) by Input power

```
--------------------------------------------------------------------------------
Method: 95.0 percent Tukey HSD
Input power   Count    LS Mean      LS Sigma     Homogeneous Groups
--------------------------------------------------------------------------------
1 W/g           18        10.5435     .0705406            A
1.5 W/g         18        11.6729     .0705406            B
--------------------------------------------------------------------------------
```

Multiple Range Tests for color changing (ΔE) by Power mode

```
--------------------------------------------------------------------------------
Method: 95.0 percent Tukey HSD
Power mode     Count    LS Mean      LS Sigma     Homogeneous Groups
--------------------------------------------------------------------------------
30s on/30s off   12       10.6292     .0863943            A
45s on/15s off   12       11.0808     .0863943            B
Continuous       12       11.6146     .0863943            C
--------------------------------------------------------------------------------
```

Table D.8.4 Analysis of Variance for color redness (a/b) of strawberries and multiple range test by Tukey HSD

```
Analysis of Variance for Rehydration - Type III Sums of Squares
--------------------------------------------------------------------------------
Source             Sum of Squares    Df   Mean Square   F-Ratio   P-Value
--------------------------------------------------------------------------------
MAIN EFFECTS
 A:Pretreatment          .31574       1      .31574         3.80     .0622
 B:Input power           .83177       1      .83177        10.01     .0039
 C:Power mode           2.14388       2     1.07194        12.90     .0001
INTERACTIONS
 AB                     .279371       1      .279371        3.36     .0782
 AC                     3.47641       2     1.73821        20.91     .0000
 BC                     1.98072       2      .990358       11.91     .0002
RESIDUAL                2.16117      26      .0831221
--------------------------------------------------------------------------------
TOTAL (CORRECTED) 10.12              35
--------------------------------------------------------------------------------
```

Multiple Range Tests for color redness (a/b) by Pretreatment

```
--------------------------------------------------------------------------------
Method: 95.0 percent Tukey HSD
Pretreatment  Count    LS Mean      LS Sigma     Homogeneous Groups
--------------------------------------------------------------------------------
Osmotic         18      1.98252      .0679551            A
No osmotic      18      2.16982      .0679551            A
--------------------------------------------------------------------------------
```

Multiple Range Tests for color redness (a/b) by Input power

```
--------------------------------------------------------------------------------
Method: 95.0 percent Tukey HSD
Input power   Count    LS Mean      LS Sigma     Homogeneous Groups
--------------------------------------------------------------------------------
1 W/g           18     1.92417      .0679551             A
1.5 W/g         18     2.22817      .0679551             B
--------------------------------------------------------------------------------
```

Multiple Range Tests for color redness (a/b) by Power mode

```
--------------------------------------------------------------------------------
Method: 95.0 percent Tukey HSD
Power mode     Count    LS Mean      LS Sigma     Homogeneous Groups
--------------------------------------------------------------------------------
45s on/15s off   12      1.88152     .0832276            A
30s on/30s off   12      1.92669     .0832276            A
Continuous       12      2.4203      .0832276            B
--------------------------------------------------------------------------------
```

Table D.8.5 Analysis of Variance for sensory taste of strawberries and multiple range tests by Tukey HSD

```
Analysis of Variance for sensory taste - Type III Sums of Squares
--------------------------------------------------------------------------------
Source              Sum of Squares    Df   Mean Square   F-Ratio   P-Value
--------------------------------------------------------------------------------
MAIN EFFECTS
 A:Pretreatment         23.3611        1       23.3611        4.33     .0474
 B:Input power          .694444        1       .694444         .13     .7226
 C:Power mode           .666667        2       .333333         .06     .9402
INTERACTIONS
 AB                     4.69444        1       4.69444         .87     .3594
 AC                     4.22222        2       2.11111         .39     .6800
 BC                     .888889        2       .444444         .08     .9211
RESIDUAL                140.222       26       5.39316
--------------------------------------------------------------------------------
TOTAL (CORRECTED) 174.75              35
--------------------------------------------------------------------------------
```

Multiple Range Tests for sensory taste by Pretreatment

```
--------------------------------------------------------------------------------
Method: 95.0 percent Tukey HSD
Pretreatment  Count   LS Mean    LS Sigma    Homogeneous Groups
--------------------------------------------------------------------------------
No osmotic     18     3.44444    .547376            A
Osmotic        18     5.05556    .547376            B
--------------------------------------------------------------------------------
```

Multiple Range Tests for sensory taste by Input power

```
--------------------------------------------------------------------------------
Method: 95.0 percent Tukey HSD
Input power   Count   LS Mean    LS Sigma    Homogeneous Groups
--------------------------------------------------------------------------------
1.5 W/g        18     4.11111    .547376            A
1 W/g          18     4.38889    .547376            A
--------------------------------------------------------------------------------
```

Multiple Range Tests for sensory taste by Power mode

```
--------------------------------------------------------------------------------
Method: 95.0 percent Tukey HSD
Power mode     Count   LS Mean    LS Sigma    Homogeneous Groups
--------------------------------------------------------------------------------
Continuous      12     4.08333    .670396            A
45s on/15s off  12     4.25       .670396            A
30s on/30s off  12     4.41667    .670396            A
--------------------------------------------------------------------------------
```

Table D.8.6 Analysis of Variance for overall appearance of strawberries and multiple range test by Tukey HSD

```
Analysis of Variance for overall appearance - Type III Sums of Squares
--------------------------------------------------------------------------------
Source              Sum of Squares    Df   Mean Square   F-Ratio   P-Value
--------------------------------------------------------------------------------
MAIN EFFECTS
 A:Pretreatment          46.6944        1      46.6944     65.48      .0000
 B:Input power           8.02778        1      8.02778     11.26      .0024
 C:Power mode            4.59722        2      2.29861      3.22      .0562
INTERACTIONS
 AB                          .25        1          .25       .35      .5589
 AC                      .263889        2      .131944       .19      .8322
 BC                     .0972222        2     .0486111       .07      .9343
RESIDUAL                 18.5417       26      .713141
--------------------------------------------------------------------------------
TOTAL (CORRECTED)  78.47               35
--------------------------------------------------------------------------------
```

Multiple Range Tests for overall appearance by Pretreatment

```
----------------------------------------------------------------------------
Method: 95.0 percent Tukey HSD
Pretreatment  Count  LS Mean    LS Sigma     Homogeneous Groups
----------------------------------------------------------------------------
No osmotic     18     4.38889     .199045          A
Osmotic        18     6.66667     .199045          B
----------------------------------------------------------------------------
```

Multiple Range Tests for overall appearance by Input power

```
----------------------------------------------------------------------------
Method: 95.0 percent Tukey HSD
Input power   Count  LS Mean    LS Sigma     Homogeneous Groups
----------------------------------------------------------------------------
1.5 W/g        18     5.05556      .199045         A
1 W/g          18     6.0          .199045         B
----------------------------------------------------------------------------
```

Multiple Range Tests for overall appearance by Power mode

```
----------------------------------------------------------------------------
Method: 95.0 percent Tukey HSD
Power mode  Count  LS Mean    LS Sigma     Homogeneous Groups
----------------------------------------------------------------------------
Continuous     12     5.08333     .243779          A
45s on/15s off 12     5.54167     .243779          AB
30s on/30s off 12     5.95833     .243779          B
----------------------------------------------------------------------------
```

APPENDIX E

E1. Derivation of specific energy consumption (SEC) equation

The specific energy consumption to evaporate water of materials in this study was calculated by dividing the energy consumption by the removed moisture.

The energy consumption = $P \times t_{on}$

where, P = Microwave power input, W

t_{on} = Total time of MW power-on, s

The removed water was derived as shown below:

where, m_1 = Initial mass, kg

m_2 = Final mass, kg

M_i = Initial moisture content, % wet basis

M_f = Final moisture content, % wet basis

Δw = Removed moisture, kg water

then,

$$\text{Initial moisture } (W_1) = \frac{M_i}{100} * m_1 \qquad (1)$$

$$\text{Final moisture } (W_2) = \frac{M_f}{100} * m_2 \qquad (2)$$

the removed moisture is $W_1 - W_2$:

$$\Delta w = \left(\frac{M_i}{100} * m_1\right) - \left(\frac{M_f}{100} * m_2\right)$$

$$\Delta w = \left(\frac{M_i}{100} * m_1\right) - \left(\frac{M_f}{100} * (m_1 + \Delta w)\right)$$

$$\Delta w = m\left(\frac{M_i - M_f}{100 - M_f}\right)$$

so,

$$\text{the specific energy consumption (SEC), J/kg water} = \frac{P \times t_{on}(100 - M_f)}{m(M_i - M_f)}$$

E2. Sensory evaluation form used for the taste of carrots and strawberries

Name……………………… Date……………………..

Taste the samples and check how much you like or dislike. Use the appropriate scale given to show your attitude by checking at the point (X).

	No__	No__	No__	No__	No__	No__
1-Like extremely						
2-Like very much						
3-Like moderately						
4-Like slightly						
5-Neither like nor dislike						
6-Dislike slightly						
7-Dislike moderately						
8-Dislike very much						
9-Dislike extremely						

	No__	No__	No__	No__	No__	No__
1-Like extremely						
2-Like very much						
3-Like moderately						
4-Like slightly						
5-Neither like nor dislike						
6-Dislike slightly						
7-Dislike moderately						
8-Dislike very much						
9-Dislike extremely						

E3. Sensory evaluation form used for the overall appearance of carrots and strawberries

Name……………………… Date……………………..

Look at the samples and check how much you like or dislike. Use the appropriate scale given to show your attitude by checking at the point (X).

	No__	No__	No__	No__	No__	No__
1-Like extremely						
2-Like very much						
3-Like moderately						
4-Like slightly						
5-Neither like nor dislike						
6-Dislike slightly						
7-Dislike moderately						
8-Dislike very much						
9-Dislike extremely						

	No__	No__	No__	No__	No__	No__
1-Like extremely						
2-Like very much						
3-Like moderately						
4-Like slightly						
5-Neither like nor dislike						
6-Dislike slightly						
7-Dislike moderately						
8-Dislike very much						
9-Dislike extremely						