MICROWAVE AND CONVECTIVE DRYING OF POTATO SLICES

By

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Abstract

Potato slices were dried using microwave drying, combined microwave and convective drying, and convective drying. Drying conditions included several slice thicknesses, power levels and air temperatures. The profiles of temperature, moisture content and relative humidity, as well as shrinkage data were generated. Dried products were rehydrated and rehydration kinetics were determined.

In this study, drying characteristics of the different drying methods are discussed and microwave drying is compared with convective drying. Microwave drying has a potential for producing better quality dried products while reducing considerably drying duration.

In addition, moisture diffusivity profiles were calculated by solving Fick's diffusion model using the solution proposed by Crank (1975). Multiple regression analysis shows that calculated diffusivity correlates well with the internal temperature and moisture content of the product.

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Chapter 1

INTRODUCTION

Drying of solids has been conducted since ancient times. Drying of foods, for example, was achieved by natural energies such as the sun and wind. New drying methods have developed quickly in the second half of this century. The main objective of food drying is to preserve it by reducing water activity. In addition, reducing product weight and volume results in reduced transport and storage costs. Drying can, however, cause deterioration of the quality of the dried product. Despite this, dried foods are gaining popularity especially with the growing resistance to the chemical preservation of foods. There is also a growing demand for a wider variety of dried foods offering considerable convenience to the consumers. Therefore extensive research on drying techniques has been conducted to improve product quality and energy utilization.

In convective drying, moisture is removed initially from the surface of the product thus creating a moisture gradient. This moisture gradient is the main mechanism responsible for outward moisture flow. As the surface dries out, it poses an increasing resistance to heat and moisture transfer. As such, drying duration is generally quite long and surface overheating could occur. All this could bring about case hardening, solute migration, as well as other damages to the sensory and nutritional characteristics of the product.

Microwave drying involves the conversion of electromagnetic energy into heat. Microwaves heat the product volumetrically with selective heating of the liquid components. This results in the rapid internal vaporization of moisture. The resulting gas

pressure gradient removes moisture from the product without overheating the atmosphere or the surface (Schiffman, 1987). Microwave drying produces a more even moisture profile and thus a better quality dried product. Furthermore, it reduces energy and maintenance costs and can also be combined with convective drying.

This study investigates the performance of drying potato slices by microwave, convective, and combined microwave and convective processes. The main objectives of the work are to:

1. Generate such data as the profiles of temperature, moisture, relative humidity, and shrinkage for different drying modes and conditions.
2. Determine the rehydration properties and kinetics of the dried products.
3. Explore the heat and mass transfer mechanisms that govern microwave drying.
4. Compare microwave drying with convective drying.
5. Investigate the characteristics of moisture diffusivity.

Chapter 2

LITERATURE REVIEW

Thermal drying is the application of heat in order to remove moisture from a product. It involves simultaneous heat and mass transfer in a multiphase system (Chen and Pei, 1989). By reducing water activity, drying allows a longer preservation of foods due to the limitation of microbial growth and enzyme activity. Another objective of drying is reduction of weight and volume which cuts down transport and storage costs. Drying is also frequently used to create the proper texture and flavour of such foods as raisins, prunes, etc. Drying could also offer more variety and convenience to the consumer.

Hayashi (1989) indicated that humankind has been drying food since the old stone age. Natural energies such as sunlight and wind were used. These methods are slow and unreliable especially as they depend upon the weather. Since the end of World War II, mechanical drying has developed quickly. Early methods included trucked-tray drying, drum drying, and transfer ventilation drying. Nevertheless, such problems as protein denaturation, fat oxidation, destruction of vitamins, browning reaction by aminocarbonyls, and "off" taste can occur (Hayashi, 1989) resulting in deterioration of eating quality and nutritive value of the food. In order to improve the quality of dried foods and the energy utilization, new drying methods were developed; spray drying, flash drying, fluidized drying, vacuum drying, vacuum freeze drying, and microwave drying (Hayashi, 1989). Because foods constituents have different sensitivities to heat, the appropriate drier has to be carefully selected if good quality dried product is to be

obtained. Porter et al. (1973) cited nineteen types of driers that may be used to handle eight types of materials. A more recent classification of drying processes was done by Hayashi (1989).

Rockland (1969) indicated that three types of bound water may exist in food products, namely:

1. Water molecules which are bound to ionic groups such as carboxyl and amino groups (the most difficult to remove);
2. Water molecules which are hydrogen-bonded to hydroxyl and amide groups, and
3. Unbound free water found in interstitial pores (the easiest to remove).

Hot air drying and microwave drying will be described in this chapter.

2.1 Drying using heated air

When hot air is blown over a product, the outer layer is heated by convection while conduction heats the remainder of the product (Buono and Erickson, 1985). Knowledge of drying mechanisms is indispensable when predicting methods for increasing the drying rate or for improving product quality (Chirife, 1983). Van Arsdel and Copley (1963) indicated some mechanisms that govern air drying. However, little work has been done to clarify which of the mechanisms prevail under different circumstances (King, 1977). Fellows (1988) suggested that water moves to the surface by the following mechanisms:

1. Liquid movement by capillary forces;
2. Diffusion of liquids, caused by differences in the concentration of solutes in different regions of the food;

3. Diffusion of liquids which are absorbed in layers at the surfaces of solid components of the food, and
4. Water vapor diffusion in air spaces within the food caused by vapor pressure gradients.

The convective drying process may be classified into two main categories: the constant-rate period and the falling-rate period.

2.1.1 Constant-rate period

In this period, water moves from the interior of the food at the same rate as it evaporates from the surface and the surface remains wet. Moisture content at which the constant-rate period ends is termed critical moisture content. Internal moisture transfer is mainly attributable to capillary flow of free water, which is caused by the moisture gradient. The constant drying rate depends on such external conditions as temperature, humidity and flow rate of the convective medium (Chen and Pei, 1989). Labuza and Simon (1970), Chirife and Cachero (1970), Vaccarezza et al. (1974) and Alzamora et al. (1979) did not find a constant-rate period during air drying of apples, tapioca, sugar beet root, and avocado slabs, respectively. It can be deduced that the constant-rate period may be only important in cases where, for instance, the drying potential of air is very low or the moisture content of the food is very high (Chirife, 1983).

2.1.2 Falling-rate period

When the moisture content of a product falls below the critical moisture content, the falling-rate period starts. The rate of moisture movement to the surface falls below the rate of water evaporation to the surrounding air. Hence, the surface dries out.

Fellows (1988) indicated that non-hygroscopic materials (materials having a constant water vapor pressure at different moisture contents) have a single falling-rate period. Conversely, hygroscopic materials (materials in which the partial pressure of water vapor varies with the moisture content) have two falling-rate periods.

The suggested transport mechanisms in the first falling-rate period were principally capillary flow, liquid diffusion and vapor-phase diffusion (Chirife, 1983). The plane of evaporation moves inside the food, and water diffuses through the dry solids to the drying air (Fellow, 1988). Chirife (1983) stated that Fick's law in terms of moisture gradient constitutes a good model for describing the drying characteristics of most foods in the initial phase of the falling-rate period.

The Fick's diffusion model for unidimensional flow is (Yusheng, 1988):

$$\frac{\partial W}{\partial t} = D \frac{\partial^2 W}{\partial x^2} \quad (2.1)$$

where:

W = Average moisture content (kg. water/kg. dry solid)

D = Diffusivity (m^2/s)

t = time (s)

x = Linear coordinate (m)

Assuming uniform initial moisture distribution and negligible external resistance, the solution expressed in terms of the average moisture content of the slab is (Crank, 1975):

$$\frac{W - W_e}{W_0 - W_e} = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \exp\left[-(2n+1)^2 \pi^2 \frac{Dt}{L^2}\right] \quad (2.2)$$

where:

W_0 = Initial moisture content (kg. water/kg. dry solid)

W_e = Equilibrium moisture content (kg. water/kg. dry solid)

L = Solid thickness (m).

The second falling-rate period occurs when the partial pressure of water is below the saturated water vapor pressure (Fellows, 1988). The surface moisture content reaches its maximum sorptive value, no free water exists and a receding evaporation front appears dividing the system into a wet region and a sorption region (Chen and Pei, 1989). Inside the evaporation front, the material is wet, i.e. the voids contain free water and the main mechanism of moisture transfer is capillary flow. Outside the front, no free water exists. All water is in the sorptive or bound water state and the main mechanisms of moisture transfer are the movement of bound water and vapor transfer (Chen and Pei, 1989). King (1968) suggested that water vapor pressure is the driving force for moisture transport. Chirife (1983) mentioned that if vapor pressure is the driving force, Fick's law should be written as follows:

$$\frac{\partial W}{\partial t} = \frac{b}{\rho} \frac{\partial^2 p}{\partial x^2} \quad (2.3)$$

where:

b = vapor-space permeability (kg. / Pa. m. sec.)

ρ = dry solid density (kg/m³)

p = vapor pressure of water in food (Pa.)

2.1.3 Disadvantages of hot-air drying

Fellows (1988) stated that the main disadvantages of hot air drying are:

1. Low rates of heat transfer due to the low thermal conductivity of dry foods, which results in long drying duration;
2. Damage to sensory characteristics and nutritional properties caused by long drying times and overheating at the surface;
3. Oxidation of pigments and vitamins by hot air, and
4. Case hardening (formation of a hard impermeable skin) due to high moisture gradient between the interior and the surface of the food and to the solutes migration from the interior of the food to the surface.

2.2 Microwave heating

Microwave energy is an electromagnetic radiation, the frequency of which is defined as being between 500 and 5000 MHz (Jones, 1986.). Microwave food heating usually employs specific frequency bands (2450 MHz, sometimes 896 MHz in Europe and 915 MHz in the USA) (Fellows, 1988). The microwave energy can be generated from a magnetron. Knutson et al. (1987) defined a magnetron as a cylindrical diode with the cathode located in the center and the anode around the circumference. When power is supplied, an electron emitting material at the cathode becomes excited and emits electrons into a vacuum space between the cathode and the anode. The magnetic field is created by a magnet surrounding the magnetron. The energy of the electrons becomes entrapped in the field and travels as waves through the magnetron to the antenna. The antenna transmits the oscillating waves to the wave guide (a hollow tube) in which they

travel to the oven cavity (Knutson et al., 1987). A wave stirrer can disperse the waves and improve wave distribution uniformity (Ringle and David, 1975). Dielectric materials such as foods can react to an electric field because they contain charge carriers which can be displaced (Von Hippel, 1966). The two main mechanisms that govern microwave heating of dielectric materials are dipole rotation and ionic polarization. As an alternating field is applied, molecules carrying dipolar electrical charges such as water rotate as they attempt to align their dipoles with the rapidly changing electric field. The resultant friction creates heat which gets transferred to neighboring molecules. On the other hand, charged ions such as chloride(-) and sodium(+) flow toward the alternating electric field (Best, 1987). Ions collision converts kinetic energy into heat (Decareau and Peterson, 1986). Microwave heating depends on the physical state of the material. In ice, for example, the movement of water molecules in a microwave field is restricted and, therefore, ice is a poor microwave absorber (Decareau and Peterson, 1986). Mudgett (1985) cited the literature relevant to food dielectric properties. He indicated that the basic dielectric properties of foods are related to their chemical composition, modified by physical structure, and are highly frequency and temperature dependent. A better understanding of the relationship of food dielectric properties to food microwave heating characteristics is needed for the design, analysis and the development of new applications in microwave food processing (Mudgett, 1985). The dielectric permittivity ϵ^* is a macroscopic parameter characterising the behavior of a material in a microwave field (Goyette et al. 1990).

$$\epsilon^* = \epsilon' - j\epsilon'' \quad (2.4)$$

where:

$$j^2 = -1$$

ϵ'' = dielectric loss factor (which determines the absorbed power)

ϵ' = dielectric constant (which is related to the amount of energy that can be stored in a material in the form of electric fields (Komolprasert and Ofoli, 1988)).

The dielectric constant and the dielectric loss factor of foods are primarily determined by free water and salt contents and are also related to other electrical properties that affect the coupling of microwave energy and its distribution within the product (Mudgett, 1985).

2.2.1 Power dissipated

Microwave heating involves the conversion of electromagnetic energy into heat. Metaxas and Meredith (1983) indicated that the heat transferred to each unit volume of material placed in the path of microwaves is given by (Decareau and Peterson, 1986):

$$P = 55.61 * 10^{-14} f E^2 \epsilon'' \quad (2.5)$$

where:

P = power absorbed by unit volume, W/m^3

f = frequency, Hz

E = electric field strength, V/m

ϵ'' = dielectric loss factor

2.2.2 Penetration depth

The depth of penetration of microwaves into a product is given by (Fellows, 1988):

$$x = \frac{\lambda}{2\pi\sqrt{\epsilon' \tan \delta}} \quad (2.6)$$

where:

- x = depth of penetration, m
 λ = wavelength (in vacuum), m
 ϵ' = dielectric constant
 $\tan \delta = \tan \frac{\epsilon''}{\epsilon'} = \text{loss tangent.}$

2.2.3 Rate of rise of temperature

The power required to raise the temperature of a material, subject to microwave energy, from T_0 to T (deg.C) in t seconds is given by (Metaxas and Meredith, 1983):

$$P = \frac{\rho C_p (T - T_0)}{t} \quad (2.7)$$

where:

- P = power absorbed, W/m³
 C_p = Specific heat of the material, J/kg deg.C
 ρ = density of the material, kg/m³.

Hence,

$$\frac{(T - T_0)}{t} = \frac{P}{\rho C_p} \quad (2.8)$$

2.2.4 Electric field strength

Metaxas and Meredith (1983) mentioned that the electric field strength can be determined through calorimetry:

$$P = 55.61 * 10^{-14} f E^2 \epsilon'' = \frac{\rho C_p (T - T_0)}{t} \quad (2.9)$$

Therefore,

$$E = \sqrt{\frac{\rho C_p (T - T_0)}{55.61 * 10^{-14} f \epsilon'' t}} \quad (2.10)$$

Jones (1986) reported that microwave heating is widely found in textile and paper-based industries where it is used for drying, and in the polymer industry where it is used for preheating granules or blocks of polymer prior to moulding as well as for welding PVC and similar materials. The lack of understanding of how microwaves interact with materials during heating, and the cost present major barriers to wider use of microwaves (Jolly and Turner, 1990). Still, the high rates of heating and the reduced damage to product quality increased the applicability of microwave heating in the food industry. Mudgett (1985) classified food microwave processes as follows,

1. Dehydration: to reduce moisture content
2. Blanching: to inactivate spoilage enzymes
3. Pasteurization: to inactivate vegetative microbes
4. Sterilization: to inactivate microbial spores
5. Cooking: to modify flavor and texture
6. Tempering: to raise temperature below freezing

Products and packages suitable for use in domestic microwave ovens has been developed (Anon, 1987a,b). The most important industrial applications are thawing, tempering, dehydration and baking. These were reviewed by Rosenberg and Bogl

(1987). Fellows (1988) pointed out that applications involving foods with high moisture contents (for example blanching and pasteurization) are less successful. He attributed this to the low depth of penetration in large pieces of food and to evaporative cooling at the surface, which results in the survival of large numbers of micro-organisms. Lin et al. (1989) reported that food microwave heating may cause uneven cooking of large sized products, lack of browning, overheating, boil over, volcano effects due to steam build-up, among other problems. They attributed the occurrence of those problems to the lack of knowledge of the simultaneous heat transfer, moisture migration, chemical reactions and biological changes occurring during microwave heating. They used a finite element method to describe temperature distribution in slab and cylinder-shaped solid food products of high moisture contents during microwave heating. Datta (1990) stated that the three characteristic parameters determining the temperature profile are: the sample size in relation to microwave penetration depth, the boundary conditions (surface evaporation, convection, and radiation), and the sample shape. Ofoli and Komolprasert (1988) reviewed three modeling approaches used for the analysis of energy deposition in materials in a microwave environment: analysis of the heating potential, analysis of the power absorbed, and solution of the general energy equation. They discussed the importance of the electric field strength in the thermal modeling of microwave systems, and outlined a procedure for its mapping. They also suggested the inclusion of moisture transfer terms in the analysis of food microwave heating. Dimensional analysis was employed to develop a predictive mathematical model for microwave heating analysis (Komolprasert and Ofoli, 1988). This model is limited, however, to water and other materials with similar physical, thermal and electromagnetic properties. Jolly and Turner (1990) developed a model for describing the power and temperature distributions in materials with varying dielectric properties. They solved numerically a non-linear system by finite difference method. The use of a dielectric layer, such as

teflon, placed between the metal backing and material, allowed the control of the heat transfer and the associated temperature gradients (Jolly and Turner, 1990).

2.3 Microwave drying

Microwave heating can heat even thick materials rapidly throughout their volume. Besides, microwaves heat selectively the areas with high liquid content. Those properties, among others, brought about the commercial acceptance of the application of microwave heating in the drying of a number of products in the food, textile, wood and chemical industries (Chen and Schmidt, 1990). When a wet solid is exposed to microwave heating, its temperature may reach the boiling point of the liquid. The accompanying generation of vapor due to internal evaporation of moisture brings about a gas pressure gradient which can rapidly expel the moisture from the interior of the solid (Metaxas and Meredith, 1983). This process leads to very rapid drying without overheating the atmosphere or the surface (Schiffman, 1987), and prevents case hardening since little solute migration in the liquid phase occurs (Knutson et al. 1987). Richard et al. (1990) found that in microwave drying most of the moisture could be rapidly expelled while the product temperature remains close to the boiling point temperature of water.

As far as food processing is concerned, microwave drying is mostly used for finishing operations of partly dried or low-moisture foods. Commercial applications include pasta drying, finish drying of potato chips, and grain drying (Decareau, 1985). Mudgett (1989) reported the use of microwave heating for the drying of condiments, tomato paste, wild rice, snack foods, and bacon pieces. Bouraoui and Richard (1991)

reviewed the utilization of microwave drying for the rapid moisture content determination in foods. Despite the multitude of advantages that microwave drying has over the other drying methods, it is still not sufficiently applied in the food industry because of economic constraints and because of the lack of knowledge of the heat and mass transfer characteristics of microwave drying of foods. Perkin (1979) discussed the advantages and limitations of microwave drying. Several studies have been conducted in order to investigate the characteristics of microwave drying. Kudra et al. (1990) prepared a bibliography covering publications on dielectric drying. Lyons and Hatcher (1972) measured local temperatures, moisture content, and pressure within a wet porous material (wet cotton) heated by microwaves. They found a very small mass concentration gradient. Temperature gradients were also small. An analytical model of internal transport characteristics of a textile material during microwave drying was developed by Hatcher et al. (1975). Roussy et al. (1984) proposed a simple model for the microwave drying of wet spherical particles of paper. The model was based on a first order kinetics law, the constant coefficient of which depended linearly on the square of the applied electric field. Bergman et al. (1987) studied the combined microwave and convective drying of a non-hygroscopic porous beds consisting of glass beads of different sizes. In beds of small bead sizes, drying rates were increased because of more uniform moisture distribution due to capillary effects. Dielectric drying of particulate materials in a fluidized bed improved the quality of the material being dried because of the uniform temperature maintained throughout the bed and because of the slow (as compared to dielectric drying alone) temperature increase in the course of drying (Kudra, 1989). Chen and Schmidt (1990) developed an integral model for simulation of dielectrically-enhanced convective drying behavior in hygroscopic (activated alumina spheres) and nonhygroscopic materials (glass beads). The model effectively estimated drying rates and internal temperature histories. This model was also used by Chen

and al. (1990) to simulate microwave drying of hardwood veneer. The accuracy of the model for predicting drying times was satisfactory. Perkin (1990) used simplified modeling for the drying of non-hygroscopic capillary porous materials with dielectric and convective drying. This researcher also examined qualitatively the additional internal moisture flow mechanisms arising as a result of the volumetric heating. Experiments and simulations for dielectrically-assisted drying of a nonhygroscopic material that exhibits negligible capillary moisture transfer (water-saturated packed bed of glass beads) have been conducted by Grolmes and Bergman (1990). Garcia et al. (1988) studied the drying of bananas with microwave and air ovens. The drying data was fitted to a variable diffusion model. Product temperature was not monitored, however.

So far there is little research reported on moisture diffusion determinations during microwave drying. Such research is necessary for modeling development of microwave drying processes.

Chapter 3

MATERIALS AND METHODS

3.1 Experimental apparatus

Figure 3.1 depicts the experimental apparatus of this work. A modified 700 Watt household microwave oven with a mode stirrer was used. The oven cavity contained a nylon basket suspended from a top mounted balance (Electronic Analytical Sortorius Balance) for continuous monitoring of weights. During each drying test, the internal and surface temperatures of a potato slice were continuously measured by means of three Luxtron Fluoroptic temperature probes (Model 755). These are fibre-optic probes with a temperature sensitive phosphor mounted at the end of each probe. When excited with blue-violet light, the phosphor responds with a deep red fluorescence, which varies with temperature (Anonymous, 1988). Temperature and weights were recorded in a personal computer (I.B.M.-compatible Campus 386) using a data acquisition system. Air flow could be supplied to the sample from a duct in the top of the microwave oven. Electrical resistances allowed the heating of the air. The temperature and the velocity of the air were controlled. A Humeter was used to measure the relative humidity of the air leaving the microwave oven. Also, circulating water was introduced to protect the magnetron from the reflection of microwaves when the sample was dry.

Side View of the Apparatus.

Figure 3.1: Side View of the Drying Apparatus.

Table 3.1: Drying types and conditions.

Parameter	Number	Description
Heating	4	Hot air, Microwave, Microwave and hot air, and Microwave and cool air
Thicknesses	3	1 cm, 1.5 cm, and 2 cm
Power settings	2	10 and 5
Air temperatures	2	18°C and 65°C
Air flow rate	1	0.032m ³ /sec.

3.2 Tests

Four types of drying were used:

1. Microwave drying
2. Combined microwave and hot air (65°C) drying
3. Combined microwave and cool air (18°C) drying
4. Hot air (65°C) drying

Two microwave power levels were employed; 5 and 10. Power level 10 was full power. Microwave energy was emitted for only half the drying time when the microwave was set at power level 5. For each test, transverse potato slices (*Russet potatoes*, *Solanum tuberosum*) with thicknesses of 1 cm, 1.5 cm, and 2 cm were used. Potato was chosen because it is inexpensive, easily available, has a convenient geometry, and its drying characteristics have been well documented. Only one slice was dried at a time. Initial and final slice dimensions were measured. For every drying test, three replications were made. Table 3.2 summarizes the drying tests of this study.

Once dried, sample rehydration in boiling water was undertaken. Sample weight was measured at selected time intervals (around two minutes for microwave and combined tests, and in the range of ten minutes for samples dried by convective drying).

3.3 Analysis

Knowing the sample mass variation with time, the moisture content profiles and the drying rate profiles were calculated.

In order to determine the diffusivity variation during drying tests, Fick's diffusion model for unidimensional flow (neglecting the radial diffusion) was used:

$$\frac{\partial W}{\partial t} = D \frac{\partial^2 W}{\partial x^2} \quad (3.11)$$

where:

- W = Average moisture content (kg. water/kg. dry solid)
- D = Diffusivity ($m^2/sec.$)
- t = time (sec.)
- x = linear coordinate.

The solution proposed by Crank (1975) was:

$$\frac{W - W_e}{W_0 - W_e} = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \exp\left[-(2n+1)^2 \pi^2 \frac{Dt}{L^2}\right] \quad (3.12)$$

W_0 = Initial moisture content (kg.water/kg. dry solid)

Where: W_e = Equilibrium moisture content (kg. water/kg. dry solid)

L = solid thickness (m)

Simplifying this solution by taking only the first term of the series and by assuming that $W_e = 0$, gives:

$$\theta = \frac{8}{\pi^2} \exp\left[-\pi^2 \frac{Dt}{L^2}\right] \quad (3.13)$$

Where $\theta = \frac{W}{W_0}$

Deriving the last equation with respect to time gives:

$$\frac{\partial \theta}{\partial t} = -\frac{\pi^2 D}{L^2} \theta \quad (3.14)$$

Hence at given intervals of time, and knowing $\frac{\partial \theta}{\partial t}$ and the average θ , the diffusivity values can be determined using the following equation:

$$D = \left(-\frac{\partial \theta}{\partial t}\right) \left(\frac{L^2}{\pi^2 \theta}\right) \quad (3.15)$$

Multiple regression analysis was also conducted in order to correlate the calculated diffusivity to such properties as the internal sample temperature, T and the sample moisture content, W (dry basis). The relationship used was:

$$D = T^a W^b \quad (3.16)$$

A statistical package (Systat) was used in order to determine the constants a and b of equation 3.16. Systat was also used to undergo an analysis of variance so as to test the variations of a and b for different drying conditions such as drying methods, power levels and slice thicknesses. A completely random design was employed.

Chapter 4

RESULTS AND DISCUSSION

4.1 Typical results

Typical results of potato slice drying using different methods are presented and discussed in this section.

4.1.1 Microwave drying

The results of microwave drying, at full power, of a 1.5 cm-thick potato slice are shown in Figure 4.2 and Figure 4.3 for temperature and moisture profiles respectively.

Figure 4.2 shows the profiles of surface temperatures (from the probe placed just into the surface) and profiles of internal temperatures (from the two other probes located deeper into the slice). The figure shows that in the beginning, sample temperature increased rapidly above 100°C and then stabilized at the boiling point temperature of water. When the boiling point of water was reached, moisture removal started. Most of moisture removal occurred while the temperature remained close to 100°C . This temperature stabilization can be attributed to evaporative cooling caused by internal evaporation. In the beginning product temperature exceeded 100°C because internal evaporation was not enough to stabilize the temperature. At low moisture levels, product temperature rose again because the remaining water was too little to stabilize the temperature. It can be deduced from temperature profile that vapor flow is the major

Temperature profiles

Microwave drying

Figure 4.2: Temperature profiles for drying of a 1.5 cm-thick potato slice at full microwave power.

Figure 4.3: Moisture profile for drying of a 1.5 cm-thick potato slice at full microwave power.

mechanism of moisture removal. Moreover, surface temperatures were generally lower than internal temperatures except at low moisture levels. This is due to the cooling effect of the surrounding cooler air. Drying duration was about ten minutes.

Drying rate profile is shown in Figure 4.4. High drying rate values were observed when the product temperature was near the water boiling point temperature. Then drying rates decreased with decreasing moisture contents.

Diffusivity profile is shown in Figure 4.5. Diffusivity values increased with time. However, diffusivity values calculated at very low moisture contents should not be considered. This is because calculated diffusivity is inversely proportional to moisture content (see equation 3.15) and hence very small values of moisture content give values of diffusivity that are too high to be accepted.

Figure 4.6 shows that relative humidity in the chamber increased up to 70 %. It decreased again when most of moisture was removed.

4.1.2 Combined microwave and cool air drying

The results of combined microwave (at full power) and cool air (18°C at $0.032\text{m}^3/\text{sec.}$) drying of a 1.5 cm- thick potato slice are shown in Figures 4.7 to 4.10 for the profiles of temperatures, moisture content, drying rate, diffusivity, and relative humidity respectively. These results are very similar to those of microwave drying with the exception that relative humidity did not exceed 45%. For the same power level (full power) and slice thickness (thickness=1.5 cm), analysis of variance (using a statistical package, Systat) showed that drying times did not differ significantly (0.05 was the chosen significance level) from those of microwave drying alone ($P=0.624$). The maximum drying rates did not differ significantly either ($P=0.823$).

Figure 4.4: Drying rate profile for drying of a 1.5 cm-thick potato slice at full microwave power.

Figure 4.5: Diffusivity profile for drying of a 1.5 cm-thick potato slice at full microwave power.

Figure 4.6: Relative humidity profile for drying of a 1.5 cm-thick potato slice at full microwave power.

Temperature profiles

Microwave and cool air drying

Figure 4.7: Temperature profiles for combined microwave and cool air drying of a 1.5 cm-thick potato slice.

Figure 4.8: Moisture profile for combined microwave and cool air drying of a 1.5 cm-thick potato slice.

Figure 4.9: Drying rate profile for combined microwave and cool air drying of a 1.5 cm-thick potato slice.

Figure 4.10: Relative humidity profile for combined microwave and cool air drying of a 1.5 cm-thick potato slice.

4.1.3 Combined microwave and hot air drying

The results of combined microwave (at full power) and hot air (65°C at $0.032\text{m}^3/\text{sec.}$) drying of a 1.5 cm-thick potato slice are presented in Figures 4.11 to 4.14. Figure 4.11 shows that the duration of temperature stabilization was shorter than that in the case of microwave drying. For unknown reasons, irregularities were observed in the temperature profiles at the end of drying. Figure 4.13 and Figure 4.12 show that drying rates were higher and that drying duration was a little shorter when compared with microwave drying alone. From analysis of variance (0.05 was the chosen significance level), these differences were not significant ($P=0.182$ for drying rates and $P=0.079$ for drying times). Diffusivity profile is shown in Figure 4.14. Relative humidity values remained close to 14%.

4.1.4 Hot air drying

The results of hot air (65°C at $0.032\text{m}^3/\text{sec.}$) drying of a 1.5 cm-thick potato slice are shown in Figures 4.17 to 4.18. Drying duration was longer than 900 minutes. A constant rate period was observed. Drying rates were generally more than sixty times lower than those of microwave drying (see Figure 4.17 and Figure 4.16). Figure 4.15 shows that surface temperatures were, most of the time, higher than internal temperatures. Most of moisture is thought to be removed in liquid form because most of the drying occurred while sample temperatures were below 50°C (well below the boiling point of water). The calculated diffusivities are shown in Figure 4.18.

Temperature profiles

Microwave and hot air drying

Figure 4.11: Temperature profiles for combined microwave and hot air drying of a 1.5 cm-thick potato slice.

Figure 4.12: Moisture profile for combined microwave and hot air drying of a 1.5 cm-thick potato slice.

Figure 4.13: Drying rate profile for combined microwave and hot air drying of a 1.5 cm-thick potato slice.

Figure 4.14: Diffusivity profile for combined microwave and hot air drying of a 1.5 cm-thick potato slice.

Figure 4.15: Temperature profiles for hot air drying of a 1.5 cm-thick potato slice.

Figure 4.16: Moisture profile for hot air drying of a 1.5 cm-thick potato slice.

Figure 4.17: Drying rate profile for hot air drying of a 1.5 cm-thick potato slice.

Figure 4.18: Diffusivity profile for hot air drying of a 1.5 cm-thick potato slice.

4.2 Effects of variables

4.2.1 Effect of sample thickness

Results of microwave drying (at full power) of a 2 cm-thick potato slice are discussed. The following figures show the profiles of moisture content, drying rate, and temperatures. When compared with microwave drying of thinner slices, the following conclusions were drawn:

1. The thicker the slice, the longer the drying duration.
2. The thicker the slice, the lower the drying rate.
3. At low moisture level, the thicker the slice the higher the temperatures reached.

These conclusions are also valid for combined microwave and convective drying.

4.2.2 Effect of microwave power

The results of microwave drying (power setting 5) of a 1.5 cm-thick potato slice were as follows. Figure 4.22 shows jagged temperature profiles due to the fact that at power setting 5, the magnetron was on for only half the drying time. In comparison with microwave drying at full power, microwave drying at power setting 5 is characterized by (see Figure 4.23, Figure 4.24, and Figure 4.22):

1. Longer drying duration
2. Lower drying rates
3. Lower product temperatures at low moisture levels

These characteristics were also observed in the combined microwave and convective drying tests.

Figure 4.19: Temperature profiles for drying a 2cm-thick potato slice at full microwave power.

Figure 4.20: Moisture profile for drying a 2cm-thick potato slice at full microwave power.

Figure 4.21: Drying rate profile for drying a 2cm-thick potato slice at full microwave power.

Figure 4.22: Temperature profiles for microwave drying (power 5) of a 1.5 cm-thick potato slice.

Figure 4.23: Moisture profile for microwave drying (power 5) of a 1.5 cm-thick potato slice.

Figure 4.24: Drying rate profile for microwave drying (power 5) of a 1.5 cm-thick potato slice.

4.2.3 Effect of air flow

When cool air flow was combined with microwave heating, the results were very similar to those of microwave drying alone. The values of relative humidity, however, were more limited. On the other hand, the combination of hot air with microwave heating resulted in a reduction of temperature stabilization period and in the stabilization of relative humidity in the chamber.

4.2.4 Effect of probe location

Except at low moisture levels, surface temperatures were lower than the internal ones during microwave and combined drying tests. At low moisture levels, even internal temperatures were quite different. This was thought to be due to the nonhomogeneity of the product and probably to the change in the positions of the temperature probes caused by the product shrinkage.

4.3 Rehydration

Rehydration tests were undertaken as an indicator of dried product quality. Microwave and combined microwave and convective dried potato slices were rapidly and almost completely rehydrated. This is thought to be due to the fact that the pressure build up during microwave drying caused opening of pores and allowed complete rehydration. Rehydration kinetics following microwave and combined drying tests were very similar. Figure 4.25 and Figure 4.26 show the profiles of moisture and diffusivity, respectively, during the rehydration of a microwave dried, 1.5 cm thick potato slice. Diffusivity decreased with time as opposed to diffusivity profiles in microwave drying, which increased with time. This was due to differences in the mechanisms of moisture diffusion between drying and rehydration. In contrast, the rehydration of hot air dried

Table 4.2: Shrinkage data of 1.5 cm thick potato slices dried by different techniques (Average of three replications).

Drying tests	Radial shrinkage (%)	Thickness shrinkage (%)
Microwave (Full power, 1.5 cm-thick slice)	16.2* (3.032**)	22.2 (3.811)
Microwave (Power 5, 1.5 cm-thick slice)	13.6 (0.48)	17.8 (3.851)
Hot air (1.5 cm-thick slice)	14.6 (3.466)	44.45 (3.851)

* Mean.

** Standard deviation.

potato slices did not exceed 80% (see Figure 4.27 and Figure 4.28) and was much slower. This was thought to be due to case hardening and closing of surface pores brought about by hot air drying.

4.4 Shrinkage data

Table 4.2 presents typical results of shrinkage (values are averages of three replications). The degree of shrinkage that occurred during microwave drying was very close to that occurring during combined microwave and convective drying. Furthermore, slice shrinkage in microwave drying at power setting 5 was less than that at full power. More thickness shrinkage took place during hot air drying alone despite lower temperatures. Therefore, in comparison with convective drying, microwave drying allowed better rehydration while causing less product shrinkage.

4.5 Regression analysis

A statistical package (Systat) was used in order to correlate the calculated diffusivities, D with the internal sample temperature, T (deg.C) and the sample moisture

Figure 4.25: Moisture profile during the rehydration of a microwave dried (full power) 1.5 cm-thick potato slice.

Figure 4.26: Diffusivity profile during the rehydration of a microwave dried (full power) 1.5 cm-thick potato slice.

Figure 4.27: Moisture profile during the rehydration of a hot air dried 1.5 cm-thick potato slice.

Figure 4.28: Diffusivity profile during the rehydration of a hot air dried 1.5 cm-thick potato slice.

content, W (dry basis).

The model used is:

$$D = T^a W^b \quad (4.17)$$

Where:

- . a and b are constants
- . Diffusivity unit is ($m^2 \times 10^{10}/sec.$) for microwave and combined drying tests. It is ($m^2 \times 10^{10}/min.$) for convective drying tests.

Table 4.3 summarizes the multiple regression results of this model for different drying tests. R^2 is the squared multiple regression coefficient. P_a indicates the significance of temperature (if P_a is very small, then temperature has a significant effect on the model). P_b indicates the significance of moisture (if P_b is very small, then moisture has a significant effect on the model).

The values of R^2 indicate that diffusivity correlates very well with the temperature and moisture. Moreover, the values of P_a and P_b were very small (generally less than 0.05, the chosen significance level), which means that both the temperature and moisture have significant effect on the model.

Table 4.3: Multiple regression analysis to correlate diffusivity to internal temperature and moisture.

Drying tests	a	b	R^2	P_a	P_b	n
Microwave (full power, 1 cm-thick slice)						
1	1.466	-0.293	0.998	0.000	0.000	19
2	1.347	-0.500	0.985	0.000	0.002	23
3	1.389	-0.404	0.988	0.000	0.002	22
Microwave (Power 5, 1 cm-thick)						
1	1.300	-0.403	0.988	0.000	0.000	34
2	1.227	-0.531	0.989	0.000	0.000	40
3	1.264	-0.432	0.995	0.000	0.000	41
Microwave (full power, 1.5 cm-thick)						
1	1.576	-0.400	0.997	0.000	0.001	19
2	1.545	-1.025	0.988	0.000	0.002	20
3	1.475	-0.205	0.995	0.000	0.159	21
Microwave (Power 5, 1.5 cm-thick)						
1	1.388	-0.943	0.983	0.000	0.000	37
2	1.393	-1.039	0.990	0.000	0.000	40
3	1.422	-1.147	0.985	0.000	0.000	39
Microwave (full power, 2 cm-thick)						
1	1.776	-1.427	0.991	0.000	0.015	18
2	1.857	-2.156	0.991	0.000	0.000	21
3	1.682	-0.994	0.996	0.000	0.000	21
Microwave (Power 5, 2 cm-thick)						
1	1.450	-1.380	0.977	0.000	0.000	49
2	1.487	-0.864	0.987	0.000	0.000	43
3	1.503	-0.705	0.990	0.000	0.000	45

Table 4.3 (continued)

Drying tests	a	b	R^2	P_a	P_b	n
Microwave (full power, 1 cm-thick) and hot air						
1	1.410	0.179	0.996	0.000	0.237	15
2	1.434	-0.341	0.993	0.000	0.074	17
3	1.443	-0.794	0.969	0.000	0.003	16
Microwave (Power 5, 1 cm-thick) and hot air						
1	1.346	-0.736	0.986	0.000	0.000	28
2	1.291	-0.746	0.980	0.000	0.003	26
3	1.344	-0.439	0.983	0.000	0.003	29
Microwave (full power, 1.5 cm-thick) and hot air						
1	1.561	-0.363	0.988	0.000	0.076	19
2	1.532	-1.017	0.973	0.000	0.015	18
3	1.538	-0.488	0.979	0.000	0.035	18
Microwave (Power 5, 1.5 cm-thick) and hot air						
1	1.477	-0.289	0.992	0.000	0.009	35
2	1.459	-0.182	0.994	0.000	0.046	36
3	1.474	-0.507	0.993	0.000	0.000	35
Microwave (full power, 2 cm-thick) and hot air						
1	1.626	-0.648	0.977	0.000	0.007	23
2	1.623	-0.665	0.991	0.000	0.002	24
3	1.661	-0.660	0.988	0.000	0.034	19

Table 4.3 (continued)

Drying tests	a	b	R^2	P_a	P_b	n
Microwave (Power 5, 2 cm-thick) and hot air						
1	1.508	-0.589	0.992	0.000	0.000	46
2	1.504	-0.609	0.993	0.000	0.000	47
3	1.468	-0.623	0.982	0.000	0.000	50
Microwave (full power, 1 cm-thick) and cool air						
1	1.684	-0.322	0.996	0.000	0.001	20
2	1.392	-0.428	0.982	0.000	0.009	21
3	1.425	-0.249	0.991	0.000	0.007	22
Microwave (Power 5, 1 cm-thick) and cool air						
1	1.311	-0.391	0.983	0.000	0.001	32
2	1.261	-0.375	0.985	0.000	0.000	38
3	1.241	-0.211	0.983	0.000	0.068	37
Microwave (full power, 1.5 cm-thick) and cool air						
1	1.574	-1.408	0.984	0.000	0.004	19
2	1.524	-0.366	0.996	0.000	0.004	21
3	1.593	-0.385	0.998	0.000	0.000	21
Microwave (Power 5, 1.5 cm-thick) and cool air						
1	1.426	-0.646	0.985	0.000	0.000	36
2	1.363	-0.788	0.976	0.000	0.000	42
3	1.360	-0.482	0.988	0.000	0.000	43

Table 4.3 (continued)

Drying tests	a	b	R^2	P_a	P_b	n
Microwave (full power, 2 cm-thick) and cool air						
1	1.607	-0.373	0.991	0.000	0.013	28
2	1.588	-0.649	0.994	0.000	0.002	23
3	1.702	-0.599	0.993	0.000	0.000	21
Microwave (Power 5, 2 cm-thick) and cool air						
1	1.499	-1.287	0.987	0.000	0.000	47
2	1.412	-1.071	0.977	0.000	0.000	44
3	1.626	-2.204	0.976	0.000	0.000	44
Hot air (1 cm-thick slice)						
1	1.300	-0.115	0.999	0.000	0.000	89
2	1.685	-0.109	0.999	0.000	0.000	108
3	1.208	-0.036	0.999	0.000	0.443	74
Hot air (1.5 cm-thick)						
1	1.351	0.225	0.998	0.000	0.000	112
2	1.228	-0.194	0.998	0.000	0.000	109
3	1.522	-0.265	0.998	0.000	0.000	109
Hot air (2 cm-thick slice)						
1	1.318	0.906	0.998	0.000	0.000	122
2	1.319	0.932	0.995	0.000	0.000	130
3	1.389	0.258	0.998	0.000	0.000	126

Systat was also used to undergo an analysis of variance for the determined values of the constants a and b.

4.5.1 Microwave drying tests

For the same thickness, a- values of full microwave power tests significantly differed from those of power 5 tests (p-values less than 0.05), contrarily to b-values (p-values greater than 0.05).

For full microwave power tests, a-values of three thicknesses (1, 1.5 and 2cm) were significantly different ($P=0.002$). Significant difference ($P=0.034$) was also found between b-values of the three thicknesses.

4.5.2 Combined microwave and hot air tests

For the same thickness, a-values of full microwave power tests significantly differed from those of power 5 tests. Except for 2cm thick slices ($p=0.01$), b-values of full microwave power tests were not significantly different from those of power 5 tests.

For the three thicknesses, and for full microwave power tests, a-values were significantly different ($P=0.000$) whereas b-values were not ($P=0.464$).

4.5.3 Combined microwave and cool air tests

Except for a-values of 1.5 cm thick slices ($P=0.004$), a-values of full microwave power tests did not differ significantly from those of power 5 tests. Also, for the same thickness b-values of full microwave power tests were not significantly different from those of power 5 tests.

For the three thicknesses, and for full power tests, a-values were not significantly different ($P=0.344$) and neither were b-values ($P=0.464$).

4.5.4 Hot air tests

For the three thicknesses, a-values were not significantly different ($P=0.924$) whereas b-values were significantly different ($P=0.018$).

4.5.5 Comparisons

At full microwave power and for the same thicknesses, microwave tests results were compared to combined microwave and cool air tests results. a-values were not significantly different. Except for 2 cm thick slices ($P=0.048$), b-values were not significantly different.

At full microwave power and for the same thicknesses, microwave tests results were compared to combined microwave and hot air results. No significant difference was found between the a-values. Except for 1 cm thick slices ($P=0.000$), b-values were not significantly different.

Chapter 5

CONCLUSIONS

Experiments on microwave drying, combined microwave and convective drying, and convective drying were undertaken. These experiments generated profiles of temperature, moisture content and relative humidity, as well as shrinkage data.

Fick's diffusion model was solved in order to calculate moisture diffusivity profiles during drying tests and during rehydration tests.

Multiple regression analysis was used to relate the calculated diffusivities to the product temperature and moisture content.

From the results of this study, the following conclusions can be drawn:

1. Results of microwave drying were very similar to those of combined microwave and convective drying, in contrast to convective drying alone.
2. During microwave drying and combined drying most of the moisture was expelled while product temperatures remained close to the boiling point of water. This temperature stabilization was attributed to evaporative cooling. The stabilization period was shorter in the case of combined microwave and hot air drying.
3. In microwave drying and in combined drying, vapor flow is thought to be the principal mechanism of moisture removal, whereas liquid flow is thought to be the major mechanism of moisture transfer in convective drying.
4. In contrast to convective drying, in microwave drying and in combined drying internal temperatures were generally higher than surface temperatures.

5. Drying rates in microwave drying and in combined drying were more than sixty times higher than those in convective drying. This resulted in much shorter drying times.
6. The lower the microwave power setting, the longer the drying time and the lower the product temperatures reached at low moisture levels.
7. The thicker the product, the longer the drying duration and the higher the internal temperatures of the product.
8. In microwave drying and in combined drying, no case hardening was observed.
9. The shrinkages were less than that in convective drying.
10. Results suggest that products dried by microwave or combined drying can be completely rehydrated. Generally, less than 80% rehydration occurred following convective drying.
11. Good correlation was found between calculated diffusivities and product temperature and moisture content.

For future studies, it is suggested that Fick's law be solved considering vapor pressure gradient as the driving force of moisture removal in microwave drying. Moreover, product nonhomogeneity and shrinkage should be considered in microwave drying modeling.

Microwave drying has potential to produce better quality products with reduced drying time. Further work is required to explore taste and microstructure of dried foods.

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