COMPARISON OF MICROWAVE DRYING
AND
MICROWAVE MIXED-BED DRYING OF RED PEPPERS

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ABSTRACT

COMPARISON OF MICROWAVE DRYING AND MICROWAVE MIXED-BED DRYING OF RED PEPPERS

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The main objective of this work is to investigate whether the time required to dry red peppers in the diffusion controlled period can be reduced. For this purpose, the possibility of microwave drying in this period was studied. As comparison parameters the drying rates and color of the products were selected.

The conventional drying was conducted under constant external drying conditions with air at 60 ^{0}C and 3.5 % RH and 1.0 m/s velocity in a batch dryer. For the microwave drying a domestic microwave oven with three power levels, 286, 397 and 560 W was used.

Pre-experiments were done to obtain an insight on the possibility of moisture distribution within the structure of the red peppers and electrical field distribution inside the oven cavity. The non-uniformity due to the latter effect was tried to be overcome by designing and installing a six blade impeller into the bed having the symmetrical pair of blades fixed at three levels.

Samples for the microwave drying experiments were prepared by drying the peppers from approximately 90% of moisture to 20% in 7 hours in the conventional dryer at 60^0C and then cutting them into pieces about 1x1 cm. Thus prepared samples were dried further in the microwave oven to 14% moisture content without and with the agitator.

To compare the results, the effective diffusivity coefficients were calculated for all of the methods and parameters to enable the aimed comparison. These indicated that by using microwave drying, the drying time can be reduced by about 120 times. Further, by mixing the uniformity of drying and the drying rate could be improved.

Considering color of the product, there was no significant difference with respect to the fresh samples after all operations.

Keywords: Red peppers, Drying, Microwave, Mixing, Drying rate, Color.

ÖZ

KIRMIZI BİBERİN MİKRODALGA İLE VE MİKRODALGADA KARIŞTIRILARAK KURUTULMASININ KARŞILAŞTIRILMASI

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Bu çalışmanın ana amacı, kırmızı biberlerin kurutulması sürecinde yayınma denetimli kuruma bölgesinde kurutma süresinin kısaltılabilmesidir. Bu amaçla bu bölgede mikrodalga ile kurutmanın yararlılığı araştırılmıştır. Yöntemlerin karşılaştırılmasında sağladıkları kuruma hızları ve ürün rengi ölçüt olarak seçilmiştir.

Yaygın yönteme göre kurutma değişmeyen koşullu ortamda 60^0C ve %3.5 göreli nemi olan havanın 1.0 m/s hızda beslendiği kurutma bölgesinde yapılmıştır. Mikrodalga ile kurutma için ise ev tipi, 286, 397 ve 560 W, üç güç ayarlı bir mikrodalga fırın kullanılmıştır.

Çalışmanın ilk bölümünde, biberin yapısı içerisindeki nem ve mikrodalga fırın içerisindeki elektriksel alan dağılımını incelemek için ön deneyler yapılmıştır. Bunlardan ikincisinin eşit olmadığı saptanması üzerine, eşit yararlanma

sağlayabilmek amacı ile yatak içerisine yerleştirilebilen altı kanatlı, çiftlerin bitişik olarak üç yükseklikte olduğu, bir karıştırıcı tamamlanmış ve kullanılmıştır.

Mikrodalga fırında kurutmanın daha ekonomik olması ve biberlerin pişmemesi için önce yaygın kurutucu bölmesinde 60 derecedeki hava ile 7 saatte nem içeriği %90 dan %20'ye düşürülen kırmızı biberler yaklaşık 1x1 cm boyutlarında kesilerek mikrodalga fırında karıştırılmadan ve karıştırılarak kurutularak nem içeriği %14'e getirilmiştir.

Sonuçların değerlendirilmesi ve karşılaştırma için tüm yöntemlere ve koşullara göre elde edilen kuruma hızı eğrilerinde yayınma katsayıları bulunmuştur. Bulunan değerler mikrodalga ile kurutmada elde edilen kurutma hızının yaygın yöntemden yaklaşık 120 kat daha büyük olduğunu göstermektedir. Karıştırma ile bu oran artmakta ayrıca ürün içinde nem dağılımı azalmaktadır.

Renk bakımından incelendiğinde, metotların taze biberlere göre renge etkisinde belirgin bir değişiklik gözlenmedi.

Anahtar kelimeler: Kırmızı biber, Kurutma, Mikrodalga, Karıştırma, Kurutma hızı, Renk

To my parents.......

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LITERATURE SURVEY

I. 1. INTRODUCTION

I. 1. 1. DRYING

Drying is one of the oldest methods known for the preservation of vegetables, with a wide production potential. Drying fruits, spices and vegetables is of great technological interest and has a long tradition as a conservation method in Turkey. Longer shelf-life, product diversity and substantial volume reduction are the main advantages for its popularity and this could be expanded further with improvements in product quality and process applications.

'Drying technology has evolved from the simple use of solar energy to current technology that includes, among others, kiln drying, tray drying, tunnel drying, spray drying, drum drying, freeze dehydration, osmotic dehydration, extrusion, fluidization, and the use of microwaves, radio frequency (RF)' (Vega-Mercado et al, 2001).

Drying process is one of the thermal processes that require higher process time and high-energy consumption in the industry. That's why new methods are aimed to decrease drying time and energy consumption with lower quality degradation. Microwave drying is a relatively newer addition to the family of traditional dehydration techniques. Other recent techniques include impingement drying, spouted bed drying, microwave halogen combination drying and microwave-vacuum drying, etc.

In this study drying of red pepper as one of the highly consumed spices is investigated with the aim to shorten the drying time especially in the diffusion controlled period. For this purpose, utilization of microwave energy is considered.

I. 1. 2. RED PEPPER (*Capsicum annum L.*)

The genus Capsicum belongs to the family Solanaceae, which also includes tomato and potato. Its fruits are used as a pungent spice or condiment (red, chilli or cayenne peppers) and as a non-pungent vegetable or source of colour and flavour (sweet or bell peppers, paprika, pimentos). The fruits are used fresh or processed, which usually involves drying and grinding (Macrea et al, 1993).

Capsicum contains about 20 species. The large-fruited, non-pungent bell peppers, paprikas and pimentos, together with the small-fruited, extremely pungent bird peppers, as well as most of the Mexican chillies are all included in *C. annuum*. This is the most widespread, and economically the most important, of all the cultivated species of *Capsicum* (Macrea et al, 1993).

In all Capsicum fruits, an inner cavity containing the seeds is surrounded by an outer wall (pericarp), which varies in both thickness and moisture content. In its fresh state the fruits have a thick pericarp, which becomes thinner, with fewer layers of cells and reduced water content when dried or ground. A highly, impermeable outer cuticle retards water loss. The seeds are attached to a spongy tissue called the placenta. The middle layer (mesocarp) of the *Capsicum* fruit wall is responsible for the color of fruits (Macrea et al, 1993).

Spice paprika is used for its strong color and contains little or no pungency. When processed carotenoids, which give red color to the paprika, are isolated and are vulnerable to the effects of heat, light and high oxygen tension. Since the activity of water in a sample of paprika depends on the manufacturing procedure used, it is clear that the drying system, including its pre-processing steps, will have an influence on pigment stability (Ramesh et al, 2001). All compositions of the red pepper are listed in Table A. 1. 1.

I. 1. 3. RED PEPPER DRYING IN TURKEY

In the recent years, rapidly increasing national and international market conditions and demand in Europe, Middle East, and Central Asia has been encouraging Turkey’s fresh and dry agricultural crop export. Grapes, apricots, black tea, figs, red pepper, and a large variety of aromatic plants are the major exported agricultural crops, contributing annually 35 to 40 millions of USD$ to Turkey’s economy. However, from the quality point of view, proper drying of special crops still is an important topic for the agricultural sector (Oztekin et al, 1999).

Traditionally used drying methods and especially sun-drying have many drawbacks. High and uncontrolled air temperatures and relative humidity changes during the drying season promote the insect and mold development in harvested crops. Also, the intensive solar radiation causes appreciable quality reductions like vitamin losses or color changes in dried crops. Thus, the conventional drying methods do not meet the particular requirements of the related standards. To overcome these problems, producers should be made well aware of the fact that the high quality dried products can be marketed at three or four fold prices. Moreover, utilization of low cost and locally manufactured dryers offer a promising alternative to reduce the excessive post-harvest losses and also improve the economical situation of the farmers (Oztekin et al, 1999).

The production of fresh red pepper (*Capsicum annum L.*) is approximately 25000 tons per annum in Turkey. The major part is consumed in ground form. In the traditional production method red pepper is laid on the plastic sheets and sun dried. The first harvest red peppers are dried to 10 to 14 % moisture content within 6 to 10 days. The second harvest is usually dried in the mid September, with longer drying periods. For the production of high quality peppers a high drying rate is required (Oztekin et al, 1999).

During storage, shelf life of the product is highly and dangerously limited by the presence of microorganisms. In addition to microbial growth, chemical and physical processes may occur in foods during storage and damage quality. Close and sufficient control of water content through water activity affects the rate of these processes and may contribute to extension of storage life (Fennema, 1975). However, in the traditionally used drying methods, relative humidity during the drying season promotes the insect and mold development in red pepper. Certain molds growing on spices produce mycotoxins, which may be acutely toxic, carcinogenic to consumers. Aflatoxin B1 is the most carcinogenic of many kinds of mycotoxins and is produced by *A. flavus* and *A. parasiticus*. Red pepper is the one of the best substrates for aflatoxin production even when it is cooked. (Ito et al, 1994)

Red pepper drying studies have been accelerated for last five years and these studies are about conventional methods and change in the quality of the red peppers during the drying processes (Turhan et al, 1997; Kaymak, 2002; Shin et al, 2001). Owing to the reasons explained above, development of new methods of drying for such perishable vegetables is essential for food preservation which can save time and energy and minimize quality degradation.

I. 1. 4. OBJECTIVES OF THE STUDY

The main objective of this study is to shorten the drying time at the conventional dryer in the diffusion controlled drying period. For this purpose microwave drying was used as an alternative method in this zone. Further, by introducing a suitable mechanical agitator microwave drying and microwave agitated-bed drying were to be compared on the basis of drying rate and color of red pepper. It was also aimed to determine the effects of microwave power on drying rates.

As independent variables of the study, in addition to the conventional drying two microwave methods (without and with mixer) were selected where also the power levels of the microwave oven were to be used for each. Dependent variables were color and the drying rate.

To compare the results, the effective diffusivity coefficients for the studied parameters were calculated and compared.

Pre-experiments were done to find out moisture distribution within the structure of the red pepper and electrical field distribution within the microwave oven cavity.

Samples were dried from approximately 90% of moisture to 20% by conventional drying especially to avoid cooking. Thus prepared samples were dried further in the microwave oven by one of the two methods and at two power values to about 14% moisture content.

I. 2. MICROWAVE DRYING

I. 2. 1. MICROWAVES AND THEIR PROPERTIES

Microwaves are part of the electromagnetic waves propagating between 300 MHz and 300 G Hz. being an electromagnetic wave, microwaves have electric and magnetic components, acting perpendicularly to each other and are highly polarized (Owusu-Ansah, 1991). Microwaves are also differing from other electromagnetic radiation as light waves and radio waves primarily in wavelength and frequency. Microwaves are between radio waves and infrared radiation with wavelengths in the range of about 0.025 to 0.75 meters. The relationship between wavelength and frequency is expressed by the simple equation $\lambda_0=c/f$, where λ_0 is the wavelength in free space in meters/second and f is the microwave frequency in cycles/second. Hertz (Hz) is the unit for frequency and for food applications the approved and most commonly used microwave frequencies are 2450 MHz. and 915 MHz. Thus for a typical microwave oven frequency (2450 MHz) the wavelength is (Decareau, 1992):

$$(30x10^7 \text{ meters/second}) / (2.45x10^9 \text{ cycles/second}) = 0.1225 \text{ m/cycle.}$$

Microwaves are reflected, transmitted and absorbed. They are reflected from metal surfaces and the oven cavity being basically a metal box, the waves bounce around. Many materials including glass, ceramics, plastics and paper nearly fully where as some materials only partially transmit microwaves. In the letter materials a fraction of the incident energy is absorbed and is converted into heat. (Decareau, 1992)

I. 2. 2. MECHANISM OF MICROWAVE HEATING AND DRYING

Only ionic conduction and dipolar rotation are of primary interest in microwave heating of foods (Owusu-Ansah, 1991).

The basic premise associated with microwave heating is that it involves the interaction of microwaves with a non-homogeneous food product, which contains materials which are highly affected by the electrical component of the electromagnetic field. In foods, it is the polar molecules that for the most part interact with microwaves to produce heat. Water is the most common polar molecule and is a major component in most foods.

In the case of dipolar rotation, due to having a strong dipole or non-uniform charge distribution, water molecule attempts to line up with the field in much the same manner iron fillings line up with the field of a magnet in the presence of a microwave electric field. Since the microwave field is reversing its polarity, millions of times each second, the water molecule, because it is constrained by the nature of the food of which it is a part, only begins to move in one direction when it must reverse itself and move in the other direction. In doing so, kinetic energy is extracted from the microwave field and heating occurs by internal molecular friction. In addition, the contribution of microwave absorbing components is also a function of their state, i.e., whether they are “free” or “bound”. Consequently, bound water exhibits much lower microwave absorptivities. (Decaurau, 1992; Ramaswamy & Van de Voort 1990)

Ionic conduction is another important microwave heating mechanism. Ions, being electrically charged, are influenced by microwave fields. Ions present in a solution flow first in one direction then in the opposite direction as the field is reversed and ionized compounds randomly collide with non-ionized groups when subjected to an electric field. The kinetic energy of these ions are transmitted as heat during such collisions. Ionic conduction occurs in cellular fluids when animal or vegetable tissues are exposed to microwave energy (Decaurau, 1992; Owusu-Ansah, 1991).

The long drying periods of conventional methods is due to the their mechanism which involves the heating of the outside of the food by convection of heated oven air. The interior of the food is heated by conduction from surface. The thermal conductivity of foods is not high; thus with this method of heating, quite a long time is required for the interior of food to reach required temperatures. Other major problems are the early hard surface formation and shrinkage of the product that leads to decreasing mass and heat transfer rate, yielding low value products (Mudgett, 1989).

Compared with conventional drying, microwave drying could greatly reduce the drying time of biological materials. When microwave energy is used for the heating of the food, food is heated up primarily by the generation of heat within the food and thus the time for the food to reach cooking temperature is reduced. Air in the oven and the food container is warmed only when they receive heat from the food. Thus, microwaves provide an energy efficient process. The increased pore size, due to puffing effect, provides easy diffusion of moisture through the sample resulting with higher mass transfer rate (Mudgett, 1989).

Microwave drying, like conventional drying, is caused by water vapor pressure differences between interior and surface regions, which creates a driving force for moisture transfer, and it is most effective at product moisture contents below 20%, as used in a number of drying processes (Mudgett, 1989).

I. 2. 3. MICROWAVE PROPERTIES OF FOODS

In the design of microwave processes, not only thermal properties of foods, which are relatively insensitive to temperature differences, but also a number of interrelated electrical properties, which vary extensively with the processing frequency, and with product time-temperature profiles are considered. At microwave frequencies, the most basic of these electrical properties are the dielectric constant and dielectric loss factor (Mudgett, 1986).

The dielectric constant is a measure of a material's ability to store electrical energy, while the dielectric loss is a measure of its ability to dissipate electrical energy to heat. By determining the dielectric constant and dielectric loss factor for a material, one can calculate the complex permittivity of biological materials using the following relation (Ramasvamy & Van de Voort, 1990; Mudgett, 1982):

$$\varepsilon = \varepsilon' - j\varepsilon'' \qquad \text{(II. 1)}$$

where: ε = relative complex permittivity

ε' = relative dielectric constant

ε'' = relative dielectric loss factor

$j = \sqrt{-1}$

The amount of power that can be absorbed by a substance is expressed by the relationship (Decareau, 1992):

$$P = \sigma E^2 \text{ (watts/cm}^3\text{)} \qquad \text{(II. 2)}$$

where,

P = the power absorbed in watts/cm^3

σ = the equivalent dielectric conductivity

E =the electric field gradient in volts/cm

with the dielectric conductivity, given by

$$\sigma = 2\ \pi\ \varepsilon_0\ \varepsilon'' f \qquad \text{(II. 3)}$$

where,

f = the frequency of the energy source

ε_0 = the dielectric constant of vacuum (8.85 x 10^{-12} farads/m)

ε'' = the dielectric loss factor of the substance

The penetration depth is that depth in a material at which the microwave power level is 37% of the surface value (or 1/e). The equation for converting dielectric property data into penetration depth (dp) is (Decareau, 1992):

$$dp = \frac{1}{2\alpha_e} \qquad \text{(II. 4)}$$

where α_e = the attenuation constant given by,

$$\alpha_e = \frac{2\pi}{\lambda_0}\sqrt{\frac{\varepsilon'}{2}\left(\sqrt{1+\frac{\varepsilon''}{\varepsilon'}}-1\right)} \qquad \text{(II. 5)}$$

I. 2. 4. PARAMETERS AFFECTING MICROWAVE HEATING

Heating of materials by microwaves is affected by a number of properties of the equipment and the material being heated. The impact of each of these must be considered in the design of a processing system. These parameters are (Schiffmann, 1986):

- **Frequency:** There are two available frequencies for microwave heating- 915 and 2,450 MHz with the wavelengths of 0.33 and 0.122 m, respectively. The frequency affects the depth of penetration into a material as given in Eq. (II. 4) and (II. 5).

- **Microwave Power:** The higher the power output, the faster the heating for a given mass. Varying the power output usually controls the speed of microwave heating. Speed is usually the most attractive feature of microwave heating. This is a double-edged sword, since it is possible to heat the material too rapidly in a microwave oven. Food processes are complex physicochemical systems requiring the input of heat to initiate and accelerate reactions. However, these reactions must occur in a proper order and rate, be given the proper time to occur. In a drying process, heating faster than the food can keep up with it can cause higher rate of generation of internal steam pressure than it can be relieved. In such a case it is possible to observe over-expansion, rupture, or even explosion of the material.

  Another problem that can arise from rapid heating is non-uniform temperature distribution. This occurs because the local heating may be so fast as to prevent the effectiveness of thermal conductivity in transferring heat to the cooler portions. This is particularly a problem with unusually shaped pieces or pieces with sharp corners.

- **Mass:** There are two considerations here, (i) the total mass being heated at one time, and (ii) the mass of an individual piece. As for the total mass, there is a direct relationship between the mass and the amount of microwave power, which must be applied to achieve the desired heating. When the total mass is small, this might be done in a batch oven, whereas for a larger throughput a conveyorized system may be better. Such conveyorized systems have the added advantage of providing greater heating uniformity by moving the product through the microwave field. The effect of mass of an individual particle will be explained under physical geometry and density (Schiffmann, 1986).

- **Moisture content:** Water is usually the major influence in how well materials, particularly foods, absorb microwave energy. Usually, the more water present, the higher the dielectric loss factor and, hence, the better is the heating. As a product becomes dry, very often-wetter areas absorb the microwave energy preferentially and a moisture-leveling effect is seen; this effect can be very useful in drying operations. At very low moisture level, the water is bound and not free to be affected by the rapidly alternating microwave field. As the moisture level exceeds the critical moisture content m_c, the loss factor increases and the product become more receptive to microwave heating (Schiffmann, 1986).

- **Density:** The density of a product affects its dielectric constant. The dielectric constant of air is 1.0, and for all practical purposes, it is completely transparent at the industrial heating frequencies. Thus, air inclusions will reduce a material's dielectric constant. Hence, as a material's density increases, so does its dielectric constant, often in an almost linear fashion.

- **Temperature:** Temperature of the material plays a role in microwave heating in several ways (Schiffmann, 1986):

1. The dielectric loss may increase or decrease with temperature, depending upon the material. Since temperatures and moisture levels change during heating, they may have a profound effect upon the dielectric constant, dielectric loss factor, and it is important to know what functional relationships exist between these parameters in any material.

2. Freezing has a important effect upon a material's heating ability because of the vastly different dielectric properties of ice and water. Whereas water is highly absorptive and heats well, where as ice is highly transparent and does not heat well at all.

3. The starting temperature of food products being heated by microwaves should either be controlled or known, so the microwave power can be adjusted to obtain uniform final temperatures.

- **Physical Geometry:** The physical geometry of the product exerts its influence mainly in two ways (Schiffmann, 1986):

  1. **Size**. If the size of each individual piece is very large in comparison to the wavelength and, more importantly, to the depth of penetration, the heating will not be uniform. In other cases where the size is closer to the penetration depth heating will be uniform.

  2. **Shape**: Heating is more uniform in regularly shaped bodies. Presence of sharp edges and corners result in overheating at these locations, i.e., sphere is better than square.

- **Conductivity:** This describes the ability of a material to conduct electric currents by the displacement of electrons and ions, however dipolar rotation is the more frequently discussed means of generating heat in microwave systems where ionic conduction plays a major role in many cases, especially in foods containing salts (Schiffmann, 1986).

- **Thermal conductivity:** This may have an important effect when heating large materials where the depth of penetration is not sufficient enough to heat uniformly up to the center or when the microwave heating time is long. In cases where the time is short, thermal conductivity will play a secondary role, and it may be necessary to extend the heating time to achieve its benefits (Schiffmann, 1986).

- **Specific heat:** This is an often-neglected parameter in microwave heating, but one, which can have an overriding influence on the heating. It is this property, which can cause a material with a relatively low dielectric loss to heat well in a microwave field. (Schiffmann, 1986).

I. 2. 5. THE MICROWAVE OVEN

The components of a microwave oven responsible for the transfer of energy to a food product are: microwave generator (magnetron), transformer, rectifier and the device for controlling the supply of microwave energy to the food.

The most important component of the microwave oven is the magnetron. It is a generator or power tube that converts electrical power to microwaves. This occurs at the frequencies of $2.45x10^9$ cycles per second (2450 MHz) or $9.15x10^8$ cycles per second (915 MHz). A small antenna at the top of the magnetron tube picks up these high frequency oscillations and transmits them to the wave guide, a metallic conduit that serves as the coupling system between the magnetron and the oven cavity (Annis, 1980).

The magnetron requires direct current to operate, which is provided by the transformer and the rectifier. The transformer transforms the mains electricity at a voltage of usually 220 V to 1000-10000 V AC and the rectifier changes the current from alternating (AC) to direct (DC).

The components of a domestic oven except for those that are responsible for energy transfer and mentioned above are oven cavity, turntable, oven door, control panel.

Oven cavity is the enclosure where the food is placed and where energy is directed and reflected to cook it. Cavity size and shape must be carefully chosen so that the operating parameters of the wave generator is matched in order to provide uniform energy distribution for uniform load heating (Annis, 1980).

The turntable inside the domestic microwave oven, which can reduce the effects of the variations in field by moving the food continuously through high and low electric fields, is one of the most effective and less expensive approaches to improve uniformity of heating (Datta & Anantheswaran, 2001).

The doors used in microwave ovens are opaque to microwaves but visually transparent to provide for viewing the oven contents. The door seal is a very important safety consideration, which is required for the prevention of radiation leakage. There are safety regulations concerning the radiation leakage through the door seal (Annis, 1980).

The control panel of a domestic oven enables the adjustment of wattage for heating and includes a timer for the user to set the processing time.

I. 2. 6. MICROWAVE DRYING OF FOODS

Microwave drying employs a completely different mechanism. Because of the internal heat generated by the microwave field, there is an internal pressure gradient, which effectively pumps water to the surface. When judiciously applied, this water is easily removed by hot air. In fact, the hot air now serves a different purpose-to transport the water outside the dryer-so it can be maintained at a much lower temperature instead of above the dew point temperature (Datta & Anantheswaran, 2001).

The usual means of applying microwaves to a drying process is at the end of the falling rate period, in which case this is referred to as finish drying (Datta & Anantheswaran, 2001).

Usually, drying is combined with conventional heating. The first commercial application of microwave energy in food processing was finish drying of potato chips. Microwave drying is also used for condiments, tomato paste, wild rice, snack foods, and bacon pieces. There are significant differences in the mechanisms of microwave and conventional drying processes, since microwaves are able to penetrate dry food solids to reach unevaporated moisture (Mudgett, 1989).

In combination ovens, microwaves are used to achieve internal heating, and conventional heat sources are used to produce the desired surface browning or crispness as well as reduction of microbial counts at product surfaces. The most highly developed commercial applications include dehydration of pasta (Mugett, 1989).

A disadvantage of microwave heating is non-uniformity within the drying cavity, which can lead to scorching in the particulate products despite the presence of a turntable. This can be overcome by keeping the product in constant motion within the microwave cavity, e.g. by use of a fluidized bed, so that all parts of the material can receive the average radiation (Mermelstein, 1998).

The combination of fluidized and microwave heating has been studied for drying of wheat and blueberries, but coarse food particles such as diced dehydrated apples are difficult to fluidize, especially when their moisture content is relatively high and the surface is relatively sticky. For such materials special designs are reported (Mermelstein, 1998).

Thus to achieve uniform treatment of the particulate materials in microwave oven, agitation of the material by some means, pneumatic or mechanical, has to be practiced (Chen et al, 2001).

For the pasta hot air-microwave drying application, the product enters the pre-dyer at a nominal moisture of 30% and is reduced to about 18% in 35 min. It then enters the microwave-hot air stage and the moisture content is dropped from 18% to about 13% in about 12 min. The introduction of the microwave at the moisture content of 18% is strategic. At this point microwave penetration depth is not seriously affected by the moisture content. Secondly, the drying seem to be approaching the falling range where conventional system perform poorly. The microwaves, therefore, enhance the drying by accelerating moisture movement within the product to the surface. (Owusu-Ansah, 1991)

Generally, microwave drying of foods or food ingredients at high moisture content (over 20% moisture) is not comparatively economical. At high moisture contents conventional heating methods more effectively remove water than microwaves. This is because although water has high dielectric constant and would absorb microwaves easily, it also has very high specific heat. Therefore, considerable amount of microwave energy would be needed to significantly raise the temperature for dehydration if the bulk of water is high (Owusu-Ansah, 1991). Thus, the introduction of the microwave at the moisture content of about 20% is strategic and necessitates application of a pre-drying process if moisture content of the material to be dried is above this value.

An inherent problem associated with microwave drying is non-uniform heating caused by an uneven spatial distribution of the electromagnetic field inside the drying cavity. Non-uniform heating may cause partial scorching in high sugar products. Fluidization provides pneumatic agitation for particles in the drying bed. It also facilitates heat and mass transfer due to a constantly renewed boundary layer at the particle surface (Tang & Yang, 2002). Combination of fluidization and microwave heating as an intermediate stage of a fluidization system for grain increased the drying rate by 50% compared to conventional hot air drying (Feng & Tang, 1998).

Microwave drying under vacuum conditions has been demonstrated to produce high quality dehydrated fruits and vegetables. The food industry is however, slow to adopt this technology, possibly due to a lack of understanding of the microwave and vacuum drying, inexperience in the process control, and relatively high capital investment (Tang & Yang, 2002). Researches on microwave vacuum drying of banana slices (Mausa & Farid, 2002) and drying of chilli in a combined microwave-vacuum-rotary drum dryer (Kaensup, et al., 2002) have been done, recently.

There are quite a number of reports on experimental studies on different methods of drying of vegetables with both heat and mass transfer aspects and quality parameters. In several studies, microwave-assisted hot-air drying of vegetables, fruits, herbs and spices such as apple, garlic, mushroom, black pepper, ginseng roots, kiwifruits were also investigated (Funebo and Ohlsson, 1998; Sharma and Prasad, 2001; Ren & Chen, 1998; Maskan, 2001; Feng & Tang, 1998).

I. 2. 7. SIZE REDUCTION AND MICROWAVE DRYING WITH MIXING

As mentioned before, decreasing sample size is an advantage for uniform microwave drying due to the relationship between sample size and penetration depth. In a study, cutting the paprika before drying process accelerated the drying and improved the initial extractable color levels, probably by reducing pigment degradation, and that is reduced the degree of color loss, probably by reducing antioxidant loss during faster drying (Krajayklang et al, 2001). The drying increases with increasing the surface area exposed to heated air, peppers dry faster if they are sliced prior to drying. Based on the results of one study for sliced peppers, drying time was decreased by 418% for peppers that were sliced together with an increase in color values (L, a, b values) (Doymaz & Pala, 2002). Cutting increases retention of vitamin C in the solid. Vitamin C being highly water soluble and as there is no extractive contact with water, most of the vitamin C is retained (Ramesh et al., 2001).

Foods are usually non-homogeneous: therefore, temperature differences occur in microwave heating. The non-uniform distribution of the heat is also due to the fact that the electrical field intensity is not homogeneous over the entire field of application, depending on the strength of reflection of the waves at the walls of the equipment (Rosenberg and Bogl, 1987).

The intensity of the electric field inside a food material depends on several factors, including the dielectric constant and loss factor of the food, the design of the oven and the placement of the food inside, and the packaging materials covering the food. Because of the standing wave pattern of the electric field, the spatial distribution of the field inside the cavity is fundamentally non-uniform. The electric field is zero at the position of the nodes, and no heat is generated in the food material at that location. At the antinodes, the electric field is maximum and the rate of heat generation is maximum (Datta, 1990).

The two most common methods used to improve the uniformity of heating are moving the food and using mode stirrers. By moving the food, all locations in the food material can be made to encounter both the nodes and antinodes of the standing microwave pattern. A mode stirrer is generally a multiblade rotating metallic reflector that continually changes the direction at which the microwaves are introduced into the cavity. This continuously perturbs the field distribution, which changes the location of the nodes and antinodes and produces more uniform heating. The extent of uniformity provided by either moving the load or using mode stirrers has been too complex to model mathematically (Datta, 1990).

It has generally been difficult to either measure or predict the value of the electric field inside the food material in a cavity. Sensors to measure the field intensity directly are currently being developed. Predicting the field intensity inside the oven is complicated because the governing electromagnetic wave equations for specific cavities with specific food loads must be solved numerically. An exponential variation in the field intensity from the boundary of the material to its interior is generally assumed (Datta, 1990).

$$E = E_0 \; e^{\alpha_e x} \qquad \text{(II. 6)}$$

where,

E_0 = electric field at the surface of the food material

α_e = the attenuation constant, defined in Eq. II. 5.

x = the distance inside the food from the boundary

It is not possible to provide a uniform electric field in a stationary microwave chamber or bed. To eliminate dead zones effect, mixing the particles should be adopted. By this means particles can be exposed evenly to microwave energy and enables a more uniform product. Furthermore, the moisture expelled in the drying process can easily leave the product resulting in shortened drying time and no hot spots. (Kaensup et al, 2002)

I. 3. HEAT AND MASS TRANSFER IN MICROWAVE PROCESSING OF FOOD

I. 3. 1. HEAT TRANSFER

For microwave heating, the governing energy equation includes a heat-generation term (Datta, 1990):

$$\frac{\partial T}{\partial t} = \alpha \nabla^2 T + \frac{Q}{\rho C_p} \qquad \text{(II. 7)}$$

where,

T= temperature as a function of time (t)

α = thermal diffusivity

ρ = density

c_p = specific heat of the material

Q = the heat generated per unit volume of material

Q represents the conversion of electromagnetic energy. Its relationship to the electrical field intensity (E) at that location can be derived from Maxwell's equations of electromagnetic waves (Eqs. (II. 2) and (II. 3):

$$Q = 2\, \pi\, f\, \varepsilon_0\, \varepsilon''\, E^2 \qquad \text{(II. 8)}$$

where the magnetic losses in the food material have been ignored and,

E = the electric field intensity

f = frequency

ε_0 = the dielectric constant of free space

ε''= dielectric loss factor of the food

The generalised boundary conditions for microwave heating can be written as (Datta, 1990):

$$-k\frac{\partial T}{\partial n} = h(T - T_{\infty}) + \sigma\varepsilon(T^4 - T_s^4) + m_w\lambda \qquad \text{(II. 9)}$$

where,

n = the direction normal to the boundary

k = the thermal conductivity of the material

h = convective heat-transfer coefficient

T_{∞} = convective air temperature

T_s = the temperature of the packaging surface facing the food material

m_w = rate of evaporation

λ = latent heat of vaporisation

σ = the Stefan-Boltzman constant

ε = surface emissivity

Radiative heat transfer is important when the surfaces of the packaging material act as susceptors. Susceptors are materials that absorb microwave energy and efficiently turn it into heat. Evaporation (m_w) at the surface is more important in microwave heating than in conventional heating because more moisture moves from the interior (Datta, 1990).

I. 3. 2. MASS TRANSFER

When heated in a microwave oven, moisture inside evaporates, migrates within, and eventually moves out of a food material through the surface. This occurs regardless of whether the primary purpose is drying or simply heating. Treating the food material as a capillary porous body, the governing equation for the internal moisture transport process can be written in accordance with Luikov parameters (Datta, 1990):

$$\frac{\partial M}{\partial t} = \alpha_m \nabla^2 M + \alpha_m \delta_p \nabla^2 P + \alpha_m \delta_T \nabla^2 T \qquad \text{(II. 10)}$$

where,

M = the total moisture content (liquid and vapour phase)

α_m = the moisture diffusivity

δ_p, δ_T = the pressure and thermal gradient coefficients

P = pressure gradient

M = Concentration gradient

T = thermal gradient

The swelling and shrinking of the food matrix are ignored and isotropy is assumed. The three terms on the right represent moisture movement due to the concentration, pressure, and temperature gradients, respectively. Contribution due to the thermal gradient, Soret effect, is generally ignored. Thus, moisture movement during the microwave heating of solid, moist food materials is considered to result from the pressure and concentration gradients. Because the mass of water vapor and air in the capillaries is always small compared to that of the liquid, their gradient can be ignored. Under these assumptions, the entire generated vapor contributes to the pressure gradient developed due to resistance to the filtrational flow of vapor and Eq. II. 10. can be condensed as:

$$\in \rho_0 \frac{\partial X}{\partial t} = k_p \nabla^2 P \qquad \text{(II. 11)}$$

where,

$\in$ = the fraction of vapor diffusivity relative to the total diffusivity

ρ_0 = the density of bone dry body

k_p = the filtrational transfer coefficient of the moisture in vapour form

X = moisture concentration as ratio, (g water/ g bds)

Under such conditions, and ignoring contribution of heat and molecular transport fluxes, Eqs. (II. 10) and (II. 11) can be combined by using an effective diffusivity term.

$$\frac{\partial X}{\partial t} = \frac{\partial}{\partial z}\left(D_{eff} \frac{\partial X}{\partial z} \right) \qquad \text{(II. 12)}$$

Compared to conventional heating, moisture flows due to concentration and pressure gradients are uniquely and significantly altered during microwave heating. The extent to which each of these is affected in a particular processing situation is often difficult to extract from the literature. Relatively larger amounts of interior heating results in increased moisture vapor generation inside of a solid food material, which creates significant interior pressure and concentration gradients. Positive pressures generated inside of a food material increase the filtrational flow of the vapor and liquid through the food material to the boundary. When the vapor concentration is small, they attributed the mass transfer to pressure gradients created by rapid vapor generation throughout the sample (Datta, 1990).

‘As mentioned earlier, moisture movement due to the concentration and pressure gradient is sometimes combined with an effective diffusivity value to avoid complexities. In one of the study, moisture transfer because of the thermal gradient was neglected, and moisture transfer caused by filtration was included in an effective diffusivity value (Tong & Lund, 1989). Increasing the electric field intensities inside of the oven increased the rate of heating, which increased the rate of moisture removal as measured by the average moisture content’ (Datta, 1990).

I. 3. 3. EFFECTIVE DIFFUSION COEFFICIENTS

The transport of water in solids is usually assumed to be controlled by molecular diffusion, i.e. the driving force is a concentration gradient (dC/dz) or the equivalent moisture content (dX/dz). For simplified analysis and calculations, one-dimensional diffusion is considered, and the Fick's diffusion equation Eq. (II.12) is applied.

The diffusion coefficient *D* of water in solids is usually defined as the effective moisture diffusivity, which is an overall transport property, incorporating all transport mechanisms (Saravacos and Maroulis, 2001).

The mechanism of moisture transport within a solid is often complex. Transport phenomena are usually classified as resulting from pressure diffusion, thermal diffusion, forced diffusion, and ordinary diffusion with net transport of material without fluid movement. A diffusion transport mechanism is assumed and the rate of moisture movement is described by an effective diffusivity value, D_{eff}, no matter which mechanism is really involved in moisture movement.

Alternatively, Fick's law is often written in the form below to describe the moisture diffusion process.

$$\frac{\partial X}{\partial t} = D_{eff} \nabla^2 X \qquad \text{(II. 13)}$$

where,

X: local moisture content on a dry basis

t: time

Once the shape of the food product is determined, the corresponding solution of Fick's law is used to obtain the effective diffusion coefficient. The solutions to Equation (II. 13) for a slab is, (Heldman and Lund, 1992 & Treybal, 1980)

$$\Gamma = \frac{(X - X_s)}{(X_0 - X_s)} = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \exp\left[-(2n+1)^2 \frac{\pi^2}{4} \frac{D_{eff} t}{L^2} \right] \qquad \text{(II. 18)}$$

where, F_0 (Fourier number) = D_{eff} x t / L^2

X = moisture content

X_0 = initial moisture content

X_s = surface moisture content

D_{eff} = effective diffusion coefficient (m^2/s)

L= thickness of the slab in the direction of transfer (m)

t = time (s)

At sufficiently large times, $F_0 > 0.1$, only the leading term in the series expansion need to be taken. Then the solution to Fick's Law simplifies to (Heldman and Lund, 1992):

$$\ln \Gamma = \ln \frac{X - X_s}{X_0 - X_s} = \ln \frac{8}{\pi^2} - \frac{\pi^2}{4} \frac{D_{eff} t}{L^2} \qquad \text{(I. 19)}$$

where a plot of ln Γ versus time will give a slope of $-2.467D_{eff} / L^2$.

This simplification is strictly valid only for constant values of D_{eff} , hence, it should be used to predict the drying curves only for small changes in moisture, since D_{eff} changes with moisture and shrinkage. However, in most studies it is employed with average D_{eff} values as a good approximation to predict the drying curve (Yasar, 1999; Okmen, 1998).

I. 4. QUALITY OF DRIED PRODUCTS

During thermal processing, the food material may be exposed to temperatures that have an adverse effect on quality and making these products susceptible to color deterioration.

The first quality judgement made by a consumer on a food at the point of sale is its visual appearance. Color is one of the most important appearance attribute for most food materials, since it influences consumer acceptability. Therefore, many food producers utilize the psychological effect of color to enhance their products. (Ramesh, 2001)

Selection of proper drying conditions is necessary for minimising thermal stress, over-drying and maintenance of relevant compounds (carotenoids, vitamin C, tocopherols, capsaicin), which determine the quality of the product. Loss of red color is caused by autoxidation of the carotenoids. It is reported that the stability of the main carotenoids of paprika during storage is dependent on drying conditions and the degradation rate increases as the drying temperature increases. Carotenoids are very stable when they are present in intact plant tissue, but when processed, carotenoids are isolated and are vulnerable to the effects of heat, light and high oxygen tension (Ramesh, 2001).

Breakdown of the red pigments is not prevented by blanching, so is not due to enzyme action, but is retarded by antioxidants. Two processes seem to be involved: an autoxidative degradation, which is accelerated by heat, and an autocatalytic destruction in light, which involves direct absorption of light energy (Macrea et al, 1993).

The color measurements can be used in an indirect way to estimate color change of foods, since it is simpler and faster than chemical analysis. Hunter color parameters (L, a, b) have previously proved valuable in describing visual color deterioration and providing useful information for quality control. These parameters expressed as L (whiteness or brightness/darkness), a (redness/greenness) and b (yellowness/blueness) at any time respectively. There is another parameter derived from Hunter L-, a-, b-scale: the total color difference (ΔE) which was used to describe the color change during drying (Maskan, 2001).

$$\Delta E = \sqrt{(L_0 - L)^2 + (a_0 - a)^2 + (b_0 - b)^2} \qquad \text{(II. 20)}$$

In one of the studies, microwave assisted air dehydration of apple (Funebo, Ohlson, 1998), it was stated that the microwave-dried products were more influenced by browning reactions than the hot-air dried products. Uneven heating in microwave ovens is a well-known problem. Variations in the power density over the volume in a microwave oven make heating uniformity difficult to achieve. The different moisture and temperature profiles in microwave-assisted drying compared to hot air drying may be of importance for the browning reactions. The influence of low air velocity is seen in the ‘a’ value, which is an indicator of browning for apples. The ‘a’ value is correlated with the air temperature, and that the lightness (L) is inversely correlated with the food temperature, that is, the higher the microwave power, the lower the lightness, L.

Maskan (2001) in his study on kinetics of color change of kiwifruits to compare hot air and microwave drying reported that the microwave drying technique strongly affected the color quality of kiwifruits and produced more brown compound(s). Introduction of microwave increased the rate of color deterioration.

CHAPTER II

EXPERIMENTAL

I. 5. MOISTURE DISTRIBUTION ANALYSIS WITHIN THE RED PEPPER

Owing to the botanical structure variations in plants it is required to observe if there are variations in moisture contents within the pepper. The fleshy part of the fresh pepper obtained from a local market was divided into three, about 5 cm length, parts, calyx which is the upper, mid and the bottom parts of the pepper. The moisture content of each part was determined gravimetrically by infrared drying method.

I. 1. 5. MATERIALS

II. 1. 1. 1. Red Pepper

Red peppers (*Capsicum annum L.*) were obtained from a local market. They were stored at 0^0C and 84% RH for 4-5 days and they were washed and then blotted with a paper towel. The stalk, placenta and seeds were removed manually. Fleshy parts of peppers were cut into two half parts as a flat shape. A half part was sliced into 10 grams of three pieces such as calyx, which is the upper part, the mid and the bottom.

II. 1. 1. 2. Moisture Determination Balance

A moisture determination balance (Ohaus Scale Corporation, U.S.A., model no: 6010H) was used throughout the experiments for moisture determination analysis of red pepper pieces. The balance had an infrared heater lamp to heat the sample and the power of heater lamp could be adjusted between 0 to 10 W. The time scale could be adjusted between 0-60 minutes. In this experiment, the moisture distribution analyses were performed at 4W. Percent moisture and the weight (in grams) could be measured as reported by the balance reading.

I. 1. 6. METHODS

After the balance was set to zero, about 10 grams of each piece from three parts of the sample were put on the plate. The power was adjusted to 4W and the samples were dried by the aid of heater lamp. The weight of the sample was recorded in every 10 minutes. Drying was carried for about 3 hours until the weight of the sample reached to constant weight. Upon attaining the constant weight, the percent moisture was read from the balance.

I. 6. ELECTRICAL FIELD DISTRIBUTION ANALYSIS

In the microwave oven, uneven electrical field distribution may cause non-uniformity of moisture content and inconsistent product quality. To observe the electrical field distribution in the microwave oven employed for the study, filter paper moistened with a solution of cobalt chloride was used. The method is based on the change in $CoCl_2$ from red to blue with the amount of incident energy and hence heating, as the paper dries thus leaving a picture of the oven heating pattern (Decareau, 1992).

II. 2. 1. MATERIALS

II. 2. 1. 1. Microwave oven

A domestic microwave oven (Vestel Goldstar, Model No: ER-5053T, Turkey) operating at 2450 MHz with a turntable (5 rev / min, diameter 20 cm) was used throughout the experiments. The oven is equipped with knobs for setting times; 0-35 min and three power levels (286W, 397W, 560W; Power I, II, III). The power levels were determined by IMPI 2-L test (Buffler, 1993). The procedure of the test and the data are in Appendix A.2. From the calculated maximum power value and entering power value (980 W), the efficiency of the microwave oven was calculated as about 57%.

II. 2. 1. 2. Cobalt Chloride Solution

A cobalt chloride solution was prepared by dissolving 50 grams of Cobalt Chloride Crystals in 1 liter of distilled water. Dark red solution was obtained in a few minutes after mixing by a stirrer.

II. 2. 1. 3. Filter Paper

A white ordinary filter paper was cut into dimensions of 20 cm by 15 cm that was suitable for the dimensions of glass support placed into the microwave oven cavity to carry the paper.

II. 2. 1. 4. Glass Support

A support to hang the filter paper wetted with the indicator is constructed from 6 mm glass tube in the form of an inverted U having arms 170 mm and length 210 mm. To keep it in upright position, two pieces of the same pipe were fixed to the end of the arms at 90^0 and foots suitably designed for placing on the turntable. The arrangement is shown in Figure. II. 2. 1. 1.

II. 2. 2. METHODS

Filter paper was dipped into the prepared cobalt chloride solution. It was waited for the paper to became pink. The wet pink filter paper was fixed on the glass support by using an electric insulating tape, that is suitable for microwave oven. The support with the fixed filter paper was put on the turntable vertically in the microwave oven. Foots of the support were fixed with the tape to prevent movement and being tipped over.

The microwave oven was adjusted to 397 W (Power II) and it was turned on for 30 seconds. After it stopped, the door was opened and the distribution of the color change was shot by a camera. The distribution and the intensity of blue color reflected the electrical field distribution in the microwave oven. This procedure was repeated for 0.5, 1, 1.5, 2, 2.5, 3, 3.5 and 4 minutes of on-times and in duplicate. The results are shown in Appendix B.

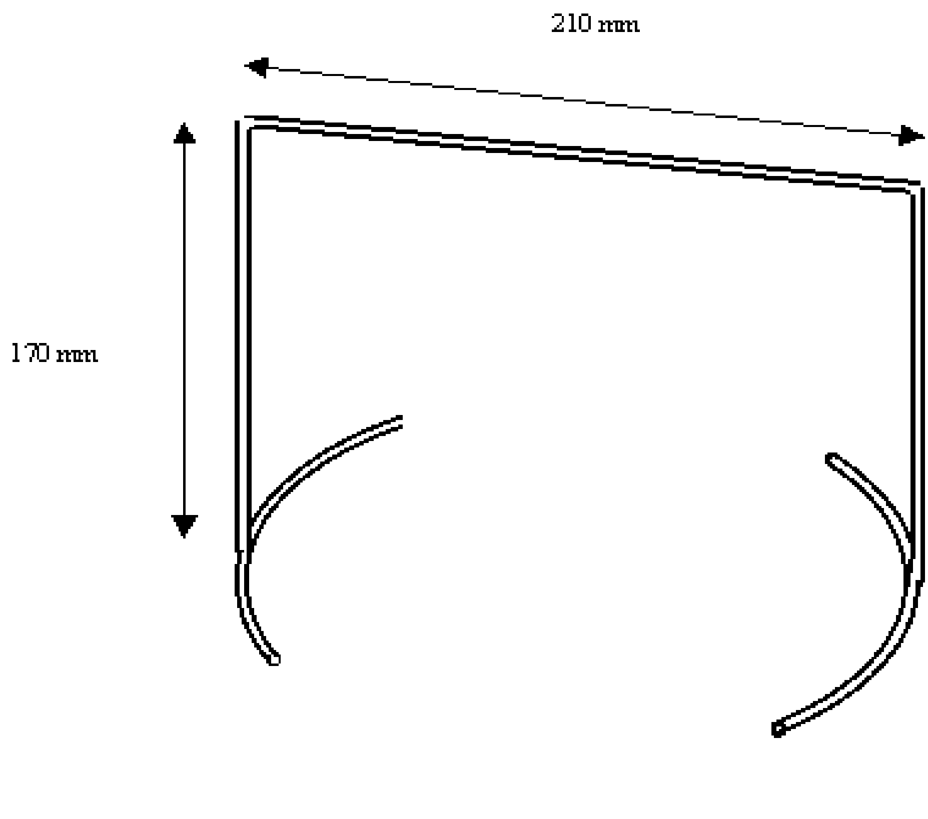


Figure. II. 2. 1. 1. The arrangement of the glass support.

I. 7. DRYING IN A CONVENTIONAL DRYER

II. 3. 1. MATERIALS

II. 3. 1. 1. Conventional dryer

A tray dryer (Armfield Limited, D.27412, England) with air flow and temperature controller was used for the conventional pre-drying of the red peppers. To the drying compartment of the dryer two parallel positioned metal hangers were installed instead of its racks.

The drier was equipped with an electrical heater, a fan, as well as temperature and flow indicators. Temperature and airflow could be adjusted to the levels of 2, 4, 6, 8, 10. Corresponding to the ^{0}C and m/s combinations given in Table A. 3. 1., all of the pre-drying runs were performed at 60^{0}C and 1.0 m/s.

II. 3. 1. 2. Balance

For weight measurements of samples during conventional drying, a portable electronic balance with 250 g ± 0.01 g (Sartorius, GMBH, Göttingen, type: PT120, made in Germany) was used.

II. 3. 1. 3. Turbo Meter

Superficial air velocity was measured by a turbo meter (Electronic Wind Speed Indicator, Davis Instruments, USA) as m/s with an accuracy of ± 0.1 m/s. It is used to check the air velocity in the conventional drier if it is operating at the set value.

II. 3. 1. 4. Thermometer

A thermometer (Tellung 1 gro. Labortherm-N, GDR) with the maximum value of 420 ± 1^0C was used to check the temperature of conventional drier.

II. 3. 1. 5. Oven for moisture determination

A lab oven (Dedeoglu, 1S-5050) operated at 100^0C ± 2 ^{0}C was used for gravimetric moisture determination (AOAC 930.04, 1995). 2 grams of sample was weighed and put into the dried petri plate. The dry weights of the samples were determined by heating at 100^0C ± 2 ^{0}C for approximately 5 hours till the constant weight was attained. These experiments were done in three replicates from different parts of the samples. The average initial moisture contents of red peppers were determined from the difference in weight of the samples.

II. 3. 1. 6. Red peppers

A sufficient number of red peppers were taken and the stalk, placenta and seeds were removed manually. Fleshy parts of peppers with a thickness of about 4 mm ± 0.4 were cut into slices of 1.5 x 10 cm (±0.4) to render a slab shape.

Approximately 20 flat pieces about 10 g each as prepared above were hung on the metal hanger individually from top by using sewing thread to allow them swing loosely in the current of hot air. This prevented them from direct contact with any metal surface as well as each other. The direction of airflow was perpendicular to the samples. 10 pieces of samples were hung to each metal support.

II. 3. 2. METHODS

The temperature and air flow levels in the dryer were adjusted and it was waited for 30 minutes to attain uniform condition (60^0C and 1.0 m/s). Then, the sliced samples were hung as described above and dried in the conventional hot-air dryer at 60 ^{0}C and 3.5 %RH. Recordings of weight data were taken at various time intervals, ranging from 15 min at the beginning extending to 60 min during the final stages of the drying process. For the equilibrium weight measurements, weight data were taken till the constant weight was attained. The experiments were repeated twice and the average of each weight data was used for drawing the drying curves (Table C. 1. 1.).

From the analysis of the data, it was determined that samples for the microwave oven experiments were to be dried in the conventional dryer for about 7 hours to attain 20% moisture content. Thus, for the pre-drying experiments, the drying process was stopped when the moisture content decreased to about 20%. The product was packed in sealed polyethylene (PE) pouches and stored in the refrigerator at +4 ^{0}C.

I. 8. DRYING IN THE MICROWAVE OVEN

I. 2. 8. MATERIALS

II. 4. 1. 1. Container

As the container for the samples, a borosilicate glass bowl diameter 15 cm and height 10 cm was used (Fig. II. 4. 1. 2.). Weight of the container was 238 g ±0.1.

II. 4. 1. 2. Mixing Apparatus

For agitation of the bowl contents a six-blade impeller constructed from 6 mm glass tube was used (Figure II. 4. 1. 1.). The agitator was fixed into the microwave oven chamber by a support rod quite similar to that used in the power distribution experiments.

The impeller blades were about 60 mm long 6 mm glass tubes. These were attached to the vertical glass shaft-tube fixed to the mid-point of the overhead support rod. The blades were placed around the shaft-tube as two in a line and horizontally 15 mm apart and 60^0 between each blade. The bottom line had a clearance of 5 mm from the base of the bowl and the overall diameter of the agitator was 120 mm. The agitation was effected by rotation of the turntable.

II. 4. 1. 3. Electronic Balance

For weight measurements of red peppers during drying, an electronic balance 8 kg ± 0.1 g (Avery Berkel, Model: CC081-10ABAAGA, England) was used.

II. 4. 1. 4. Red pepper

Flat shaped pre-dried red peppers with moisture content about 20% were cut into 10 mm ± 0.4 pieces by a knife. The cut samples were stored in a refrigerator at +4 ^{0}C in a sealed glass jar.

I. 2. 9. METHODS

For this part of the experiments, red peppers brought to about 20% ±1.5 moisture content in the conventional drier were subjected to further drying in the domestic-type microwave oven under mixing and without mixing conditions chosen to 14% moisture content. Weight versus time data were taken in both cases.

For this part of the experiments, 150 g of the cold red pepper particles as prepared above were taken. The container, with half of the volume occupied by the samples, was placed on the turntable. The power and the drying time interval of the oven were adjusted. The power levels used in the experiments were power II and I. At 30 sec time intervals, weight of sample in the container was recorded.

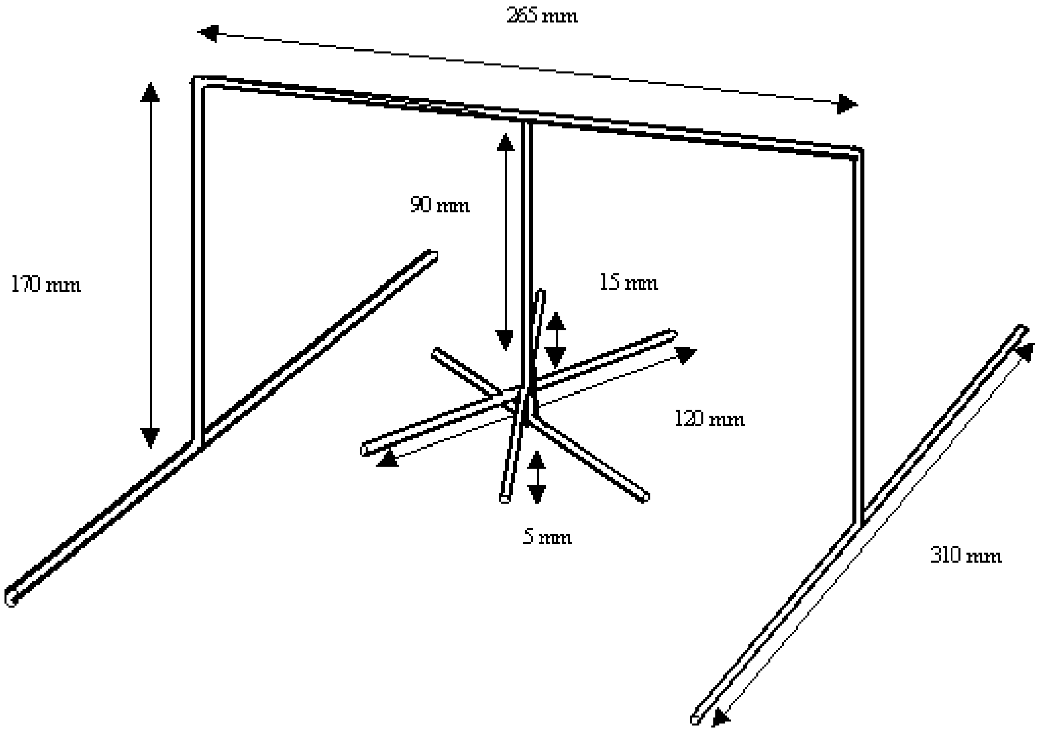


Figure II. 4. 1. 1. The glass agitator


Figure II. 4. 1. 2. The view of design

To compare the drying rates and the effective diffusion coefficients the red pepper samples were also dried by using the mixing apparatus. The experiments were repeated for the same power settings to compare the effects of the power levels. All experiments were performed in duplicate.

I. 9. FINAL MOISTURE MEASUREMENTS

To understand the effectiveness of mixing in a mass of particulate samples, the distribution of a dependent variable according to the position had to be checked. For the final moisture distribution analysis, 2 grams of samples were taken from four different positions after termination of each operation of microwave drying and moisture contents determined by using lab oven as described above. Two of these, were taken from surface of the load, center and edge, and the other two were from the bottom of the load. These positions, representing roughly the r and z-directions, are shown in Fig. II. 5. 1.

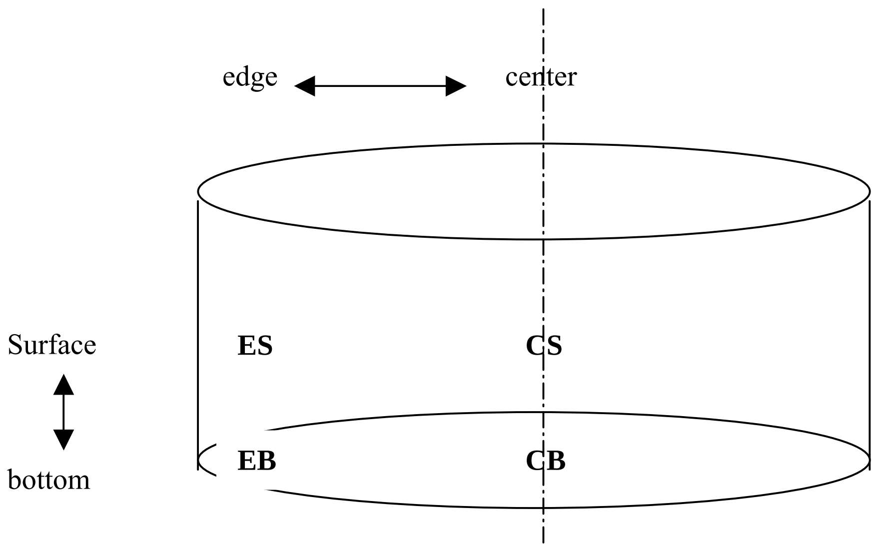


Figure II. 5. 1. The four positions for the final moisture distribution analysis (CS: Center-surface, ES: Edge-surface, EB: Edge-bottom, CB: Center-bottom).

In this comparative plot, center position of the load was taken as the radial reference point and the percent difference of the edge position was calculated according to the reference. For comparing the axial difference, bottom was taken as a axial reference and the percent difference of the surface position was calculated . The final moisture data according to the positions are tabled in Appendix-Table C. 2. 1.

I. 10. COLOR MEASUREMENTS

Color of the samples, taken from fresh, conventionally dried, microwave dried and agitated microwave dried samples, were measured by Minolta (model: CR10, Japan) color reader. The color values expressed as L (whiteness or brightness/darkness), a (redness/greenness) and b (yellowness/blueness) for the respective samples were determined. The total color difference (ΔE) that is defined in Eq. (I. 20.) was also calculated.

$$\Delta E = \sqrt{(L_0 - L)^2 + (a_0 - a)^2 + (b_0 - b)^2} \qquad \text{(I. 20.)}$$

The L, a, b values of the fresh and the dried samples were read from the surface of the sample by color reader. 10 data were taken and average values were calculated for each data. Fresh sample data values were chosen as the reference in calculation of ΔE values (L_0, a_0, b_0). Average data values are tabulated in Appendix C. 3.

CHAPTER III

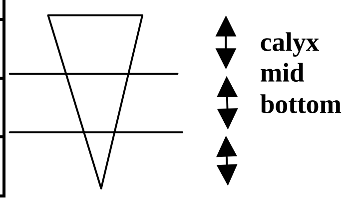
RESULTS AND DISCUSSION

III. 1. MOISTURE DISTRIBUTION ANALYSIS

Water present in cellular materials like fruits and vegetables may be located in certain zones of the structure and hence can show a distribution. To check this possibility in the red peppers, primarily determination of the moisture content distribution on the fleshy part was aimed. For this purpose, a triangular slab shaped pepper was halved along the major axis and divided into three parts corresponding to calyx, mid and bottom parts of the pepper. Then, moisture contents were determined by the infrared drying method.

Table 3. 1. 1. Moisture contents of three parts of the half-red pepper

Part of the pepper	Moisture Content (%)
Calyx	90.6 ± 0.1
Mid	90.5 ± 0.1
Bottom	90.2 ± 0.2



The results shown in Table 3. 1. 1. indicates that there is no significant difference between the moisture contents of calyx, mid and bottom parts of the red pepper. Thus, initial moisture content of the pepper can be assumed to be uniformly distributed within the pepper. Hence, by cutting the pepper into pieces does not bring non-uniformity in initial moisture distribution in the batch of cut samples subjected to microwave drying.

III. 2. ELECTRICAL FIELD DISTRIBUTION ANALYSIS

As mentioned in Chapter I, the non-uniform distribution of energy in the microwave oven is due to the fact that the electrical field intensity is not homogeneous over the entire field of application and depends on the strength of reflection of the waves at the walls of the equipment (Rosenberg, and Bogl, 1987). It has generally been difficult to either measure or predict the magnitude of the electric field inside the food material in a cavity.

In this part of the experiment, it was aimed to observe the non-uniformity in the electrical field distribution. For this purpose, filter paper was wetted with a solution of cobalt chloride, which turns from red to blue as it reaches elevated temperatures.

Figures in Appendix B. show non-uniform electric field distribution on the filter paper at different time intervals (0.5, 1, 1.5, 2, 2.5, 3, 3.5 and 4 min) of drying applications in the microwave oven at Power II (397 W). At the locations where sufficient energy is absorbed, the light pink color of the cobalt chloride solution on the paper turned to blue. Distribution of blue color shows the dried parts at the moment after microwave application corresponding to the distribution of electric field at that time instant.

White or light pink areas on the paper represent the wetted parts and also the nodes at which electrical field is zero. On the other hand, blue areas represent the antinodes at which the electrical field is maximum and the rate of heat generation is maximum. According to the figures, non-uniformity of the field distribution can be observed in spite of using the turntable.

As a result, movement of samples is important to achieve uniform final product due to this non-uniform energy distribution. Movement of the sample particles inside the cavity makes particles to act as both nodes and antinodes. Unless an efficient mixing is provided it is not possible to overcome this problem especially when particulate solids are the targets.

III. 3. DRYING OF THE RED PEPPERS

I. 1. 7. CONVENTIONAL DRYING OF THE RED PEPPERS

Drying under constant external conditions is the key study to gain an insight into the behavior of a material subjected to drying. Qualitatively and quantitatively data reflecting the possibilities of zones of drying, change of shape and size, equilibrium moisture content, effective diffusivity in the diffusional control zone can all be obtained from the kinetic weight data (Keey, 1972).

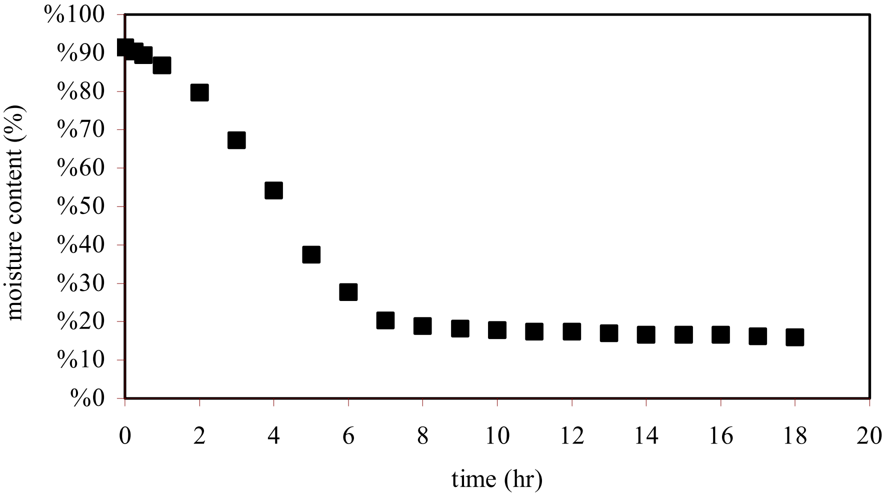


Figure. III. 3. 1. % Moisture versus time curve for red peppers dried in the conventional drier at 60°C & 3.5 %RH.

Accordingly, in the first part of the drying experiment the drying rate data for the red peppers were obtained at 60 ^{0}C and 3.5 %RH (Table C. 1. 1.) as the average of two runs using ten slabs for each. Further, this raw weight data were converted to percent moisture content and dimensionless moisture content. The former representation (given in Fig. III. 3. 1.) was used to determine, (i) the equilibrium moisture content of the peppers at the experimental conditions and (ii) the time required for the moisture content to be reduced to 20% to prepare the samples to be supplied for the microwave drying experiments. As can be seen from the data and the plot after the 7^{th} hour of drying including the initial adaptation period, the moisture content hence the rate of drying showed a sharp change at about 20.3%. This indicates that the peppers, excluding the adaptation period, exhibit two drying periods. The observed value of this second point, i.e., 20.3 % is a highly common point for most materials as reported by many researchers and known as the second critical moisture content point (Owusu-Ansah, 1991; Mudgett, 1989; Keey, 1972).

Subsequent drying below this point is essentially by a diffusion-controlled mechanism (Keey, 1972). In the light of this phenomena and the data microwave drying below the second critical point seems highly promising as comparatively after about 70% decrease in the moisture content within 7 hours, additionally only 5% can be affected in 10 hours.

On the other hand, the dimensionless moisture content values to be used in Eqn. I. 19., were calculated from the initial moisture content. The initial moisture content of the pepper was determined gravimetrically in a lab oven. The constant weight was attained after about 5 hours. The average result indicated an initial moisture content of 91.4%, which is in good agreement with the reported values (Table A. 1.). The dimensionless moisture content data were used to predict the effective diffusivity below 20% moisture content in conventional drying discussed in III. 4. 1.

Due to the mechanism of the conventional drying, surface structure of the material is very important before and during drying processes. 'Fruits are naturally covered with a cuticle composed of the biopolymer cutin and embedded wax, with epicuticular waxes on the outer surface, and this is the major barrier to water loss in the Capsicum fruit' (Krajayklang et al, 2001). There are some chemical and physical studies to overcome this retardation effect of cuticle (Krajayklang et al, 2001; Doymaz & Pala, 2002; Ade-Omowaye et al, 2001). However, due to mechanism of microwave drying, internal heating, there is no need to apply any treatment to overcome this problem.

After 7 hours of conventional pre-drying, %20 moisture content level defined as the strategic point below which continuing with microwave drying could be providing advantage. The reasons of this are (1) being more economical due to energy saved and time, (2) providing rapid drying at lower moisture contents (below %20) by avoiding any pre-treatment for demand on minimally processed foods with less degradation.

III. 3. 2. MICROWAVE DRYING OF THE RED PEPPERS

III. 3. 2. 1. EFFECT OF MICROWAVE POWER LEVEL ON THE BURNING TIME OF THE RED PEPPERS

Due to non-uniform electrical field heating, local overheating and consequent burning of particulate samples subjected to drying in a microwave oven is inevitable. According, in this study also appearance of the black colored spots on the samples was observed which started from the center of the bed.

Provided the water can absorb sufficient electromagnetic energy, the temperature of a wet solid particle could be rapidly raised to the boiling point of the water (usually greater than 100 ^{0}C due to the dissolved salts). When the wet solid material reaches such a temperature, enhancement of some chemical reactions due to polar or denaturing substances may as well happen. Also, non-enzymatic browning due to oxidation of the ascorbic acid, which is present in relatively a high amount in red pepper, might have occurred (Maskan, 2001; Ramesh, 2001).

With regard to these factors, during the experiments microwave heating was stopped at the time the initial burning sign at the center was seen. This switch of times at power I was at the 6th minute and at power II was at the 4th minute. Obviously, with the increasing power level, the time burning started was earlier. The same observation was valid also for the microwave drying with mixing. The results for microwave drying are given in Table 3. 3. 2. 1. 1. and as plotted in Fig. III. 3. 2.

1. 1. As can be seen experiments at power I and power II were terminated at the 5.5th and 3.5th minutes, respectively when mixing was applied. This study was done to avoid the presence of burnt particles.

In conjunction with the burning phenomena the final moisture content of the peppers was chosen as 14% rather than 11% because they started to burn before achieving 11%. In Table 3. 3. 2. 1. 1 it can be seen that samples could not reach 14% final moisture in microwave drying without mixing at power II. For this reason the highest power level, 560W (power III) of the microwave oven used was not included in the studies since in the preliminary trials application of this power level resulted with a very rapid burning of the samples at about 2.5th minute, which was not enough for drying the material down to 14% final moisture.

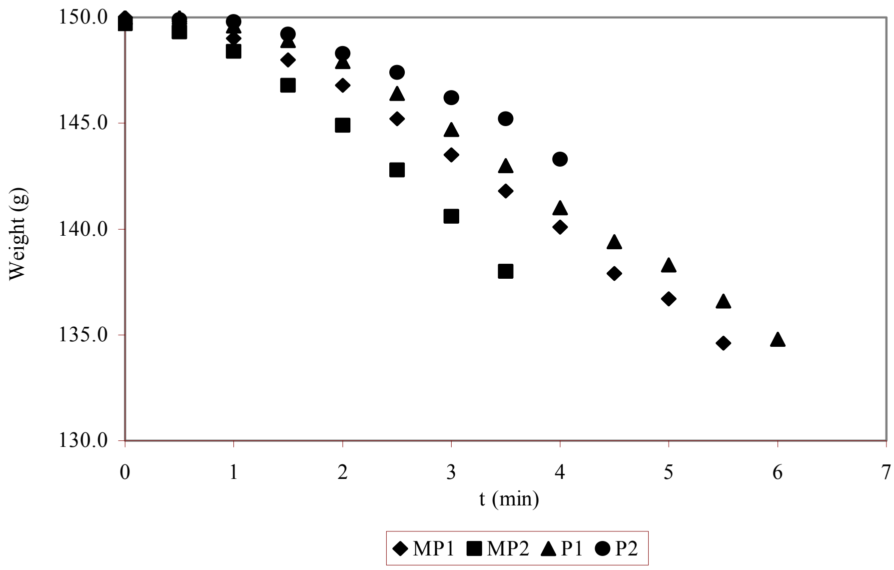


Figure III. 3. 2. 1. 1. Weight vs. time data for microwave drying and microwave drying with mixing at the two power levels used. (MP1 & MP2; microwave drying with mixing at power I, power II; P1 & P2; microwave drying without mixing at power I, power II)

Table 3. 3. 2. 1. 1. The time at which red peppers started to burn in microwave drying and microwave drying with mixing and corresponding % moisture content (on wet basis).

I. 2. 10. Met hod of drying	**Power Level**	**Time (min)**	**Final Moisture content (%w/w)**
With Mixer	Power I	5.5	12.5
	Power II	3.5	13.8
Without Mixer	Power I	6.0	11.0
	Power II	4.0	15.2

Figure III. 3. 2. 1. 1 indicates that, red peppers dried in the microwave oven without mixing at power II shows slightly lower drying rate than those dried at power I. This difference may be attributed to the relative rates of energy generated locally and that is dissipated or used for vaporization. Thus, because the former was greater, to avoid the peppers to start burning locally sufficient time for the latter process was not allowed. On the other hand, red peppers dried in microwave oven with mixing at power II shows higher drying rate than dried at power I. This result was expected since as drying rate increases with the power applied and this time by mixing the undesirable effect of local rapid heating is highly eliminated to have a more uniform temperature distribution.

Further, this effect of the power levels (about 2 min) on the burning hence the treatment time shows power level I is more suitable to reach the desired moisture levels, such as 11% and 12%, before burning starts when mixing is not applied.

Another consequence of the mixing was on the burning time. Mixing shortened the burning time about 0,5 min for the both power levels. This again can be attributed to better distribution and more effective and efficient utilization of the energy.

III. 3. 2. 2. EFFECT OF MICROWAVE POWER LEVEL ON THE DRYING TIME OF THE RED PEPPERS

To observe the effect of microwave power level on the drying time of red peppers, about 150 g of the pepper particles dried in the conventional oven to about 20% moisture content (as described in II. 4. 1.) were subjected to microwave drying to 14% final moisture in the glass bowl (II. 4. 1. 1.) under no mixer and with mixer conditions at two microwave power levels.

From weight loss of the sample data in the bowl, the percent moisture contents were calculated (Table C. 1. 2 to Table C. 1. 5). The average times of the duplicate runs at which samples in the bed achieved approximately 14% final moisture level were determined as listed in Table 3. 3. 2. 2. 1 below.

Table 3. 2. 2. 1. The average time at which the red peppers achieved about 14% (on wet basis) moisture content in the microwave drying and microwave drying with mixer studies.

Method of drying	Power Level	Treatment time (min)	Moisture content (%w/w)		Initial weight (gr)
			initial	final	
With Mixer	Power I	5	21.5	13.9	150
	Power II	3.5	20.5	13.8	149.7
Without Mixer	Power I	4.5	20	13.9	150
	Power II	4	19	15.2	150.1
Conventional drying		~600	20.3	15.8	1.13

A qualitative and quantitative evaluation of table reveals that the most remarkable result is implied by the magnitude of the treatment times of the conventional and the microwave drying processes. That is in the diffusion-controlled range the microwave drying offered about 120 to 171 times less treatment time compared to the conventional method.

On the other hand, by using the mixer an unexpected result about %10 increase in the drying time compared to the unmixed case was seen in the treatment at power I. The reason for this may be due to the slightly higher initial moisture content of the samples when mixer was used as well as timing. Also, it is equally possible that due to the non-uniform energy distribution some locations might have over dried to render the average moisture content lower. However, the positive effect of mixing can be seen from the results at power II.

Finally, it appears that the microwave drying at power II with the mixer is the best among the cases (Fig. III. 3. 2. 1. 1). In this respect, since moisture content did not reach the target value before burning has started, drying without mixer at power II was not a good indicator.

III. 4. EFFECT OF THE MIXER ON THE MICROWAVE DRYING

Although effect of the power increase on the drying rate without the mixer could not be seen clearly due to burning, with the mixer increase in the power accelerated the drying rate. According to Table 3. 2. 2. 1., when mixer was used, the drying time to reach the target final moisture at power I and power II differed by about 1.5 minutes The same difference was by about 0.5 min when the mixer was not present. Therefore, roughly it appears that introduction of the mixer to the microwave drying process of the red peppers increased the effect of the power difference on the treatment time about 3 times.

The main objective of this study was to minimize the drying process of the red peppers. The results pertaining to the effects of microwave power and mixing on drying time and drying rate of the red peppers can be considered as sufficient to have a clear idea. However, it is still needed to formulate or find the optimum conditions of these variables. These include the rotational speed of the turntable, improved agitator design, other possible microwave powers, particle size and shape on the efficiency of the operation and uniformity and consistency of the product.

Of these, especially the intensity of mixing is governed by the speed of the turntable. That is the speed of the turntable should be sufficient to release the water vapor entrapped in the space between the products, and also enable heat generated to be transferred quickly. This crucial effect of rotational speed on elimination of the dead zone effect was reported in the study on combined microwave-vacuum-drum drying of chili (Kaensup et al, 2002).

Other than drying time, uniformity of final product was roughly obtained by introduction of mixing to the microwave drying. This can be seen clearly from the results of experiments, operated at power I.

Through the microwave drying at power II with the mixer appeared to be the best operational condition among the cases studied, contribution of the agitation and the agitator designed has to be considered. At the first place for drying pepper or a solid particle in a bed placed in the cavity in a cylindrical bowl, the moisture content, $X= f(t, r,\theta, z)$, depends on time, the position in the cavity as r, θ and z. When no agitator is used the built in turntable can provide only θ–component of the motion in the cavity as r and z are fixed with respect to the fixed coordinates.

The speed of turntable was about 5 rev/min. This means for the microwave oven used the axially and radially fixed particle can pass through the same point 5 times per minute. Considering the non-uniform energy distribution within the cavity, the probability of this particle to intercept the incident energy is from zero to 100%.

On the other hand, with the agitator designed at least the particles are forced to change their position in the three dimensions twice per rotation. The impellers being cylindrical in shape force the particles to flow around the cylinder displacing them in θ and z-directions. Those particles, which are normal to the axis of the cylinder, are pushed ahead to provide mixing in r and θ directions within the bowl. Thus, the system now enables not selective but a high percentage of the particles to benefit from the incident energy and hence render the system more uniform with respect to the energy and mass transport mechanisms reducing the effect of space variables. This merely shows that by improving the agitator design and/or increasing the rotational speed of the turntable, higher degree of mixing with less treatment times can be found.

In this study agitation was provided mechanically by a fixed six-rod blade placed in the turntable rotating in the microwave oven. The design, compared to fluidization need no extra energy for agitation which was already provided by rotation of the turntable in the microwave oven onto which the material to be dried was placed in the container.

III. 5. THE EFFECTIVE DIFFUSION COEFFICIENTS

Regardless of the mechanism of moisture transport the effective diffusion coefficient, D_{eff}, is used to describe the rate of moisture movement. A high effective diffusion coefficient means that the moisture transport will be easier, hence the rate of drying will be high and vice versa. Therefore, a comparison of the effective diffusion coefficients for the conventional drying, microwave drying and microwave drying with mixing is a good indicator of the process that provides easier removal of moisture and hence faster drying.

The solution of the Fick's law for an infinite slab and at long times, $F_0 > 0.1$, is used to evaluate the effective diffusion coefficients for red peppers in the diffusional control zone (Eq. I.19). The Fourier numbers were checked for all operations are shown in Table C. 3. 1.

The equation from which the effective diffusion coefficient could be determined involves the characteristic dimension term (L), which is the half-thickness of the slab. Use of the characteristic dimension term for the calculation of effective diffusion coefficients necessitates the use of the linear segments of the curve. This is because during drying, as a result of shrinkage of the sample and changes in pore sizes the characteristic dimension may change continuously. Therefore, except at the very initial stages of drying, it is practically not possible to determine the effective diffusion coefficient from any linear segment, since the true characteristic dimension is not known at every instant during drying. Owing to the high wrapping and shrinkage of the red peppers, during drying, calculation and comparison of the D_{eff}/L^2 values seemed to be a more valid approach as they reflected the rates.

III. 5. 1. CONVENTIONAL DRYING

The D_{eff}/L^2 values are calculated for red peppers that are dried in the conventional drier at 60 ^{0}C. The plot of ln Γ versus time for the conventional drying experiments is given in Figure III. 5. 1. 1.

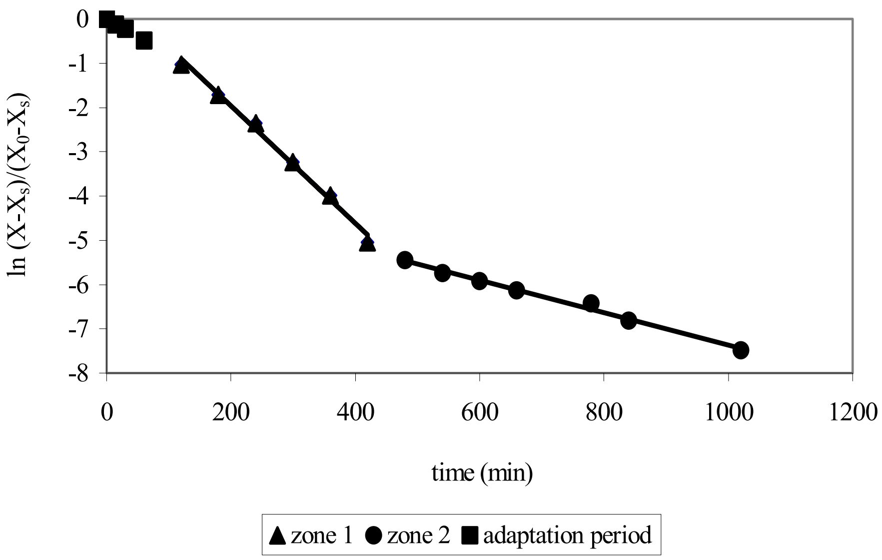


Figure III. 5. 1. 1. Dimensionless moisture analysis in the conventional drying at 60 ^{0}C & 3.5%RH of the red peppers.

The slopes of the linear segments of the curve is to be used for the calculation of D_{eff}/L^2 values. As seen in Fig. III. 5. 1. 1., two zones were identified after the adaptation period. Zone 1 is up to 7th hour corresponding to moisture content 20.3% and the zone 2 from 8th hour to 18th hour where the equilibrium moisture was approached. The slopes of the linear expressions fitted by regression (Excel, MS 95) were used to calculate the D_{eff}/L^2 values.

The calculated D_{eff}/L^2 values for zone 1 and zone 2 are 8.92 x 10^{-5} sec^{-1} and 2.50 x 10^{-5} sec^{-1}, respectively. Therefore drying rate in zone 1 is approximately 3.6 times greater than that of zone 2. The slower drying rate in zone 2 might be due to the wrapping of edge of the samples, which is generally covered with an impermeable cuticle as well as shrinkage causing contraction of the pores.

III. 5. 2. MICROWAVE DRYING AND MICROWAVE DRYING WITH MIXING

The equilibrium moisture content is defined as the moisture content attained by the solid after exposure to drying air for sufficiently long times and under the specified humidity and temperature of air in contact with the material. So, equilibrium moisture content depends on the air temperature and humidity. For the microwave oven experiments also, it was aimed to find a constant weight of the samples near the end of the drying process, to enable comparison with the conventional drying. However, it was observed that there is difference between drying in a microwave oven and drying in a conventional drier in that the mechanisms are highly different and the drying in microwave oven can be extended beyond the equilibrium weight as higher inner temperature is reached.

In a study on microwave drying of green peppers Yasar (1999) reported that upon removal of all the moisture in the sample, charring rapidly began within the sample. This was because, although water was completely driven off, other polar compounds present in the structure continued to absorb microwaves, resulting in local overheating and consequent charring. This was also observed in this study.

In the microwave drying of the red peppers beginning of burning reactions that were mentioned in the previous sections impeded us to assume all the moisture is driven off and so equilibrium moisture content in dry basis was assumed zero.

For the aimed comparison the D_{eff}/L^2 values were obtained for microwave drying of the red peppers containing about 20% moisture without and with mixer and at different power levels. The same approach of conventional drying was used for the calculations. The plots of ln versus time at different microwave power levels within the fitted lines are given in Figure III. 5. 2. 1. and Figure III. 5. 2. 2.

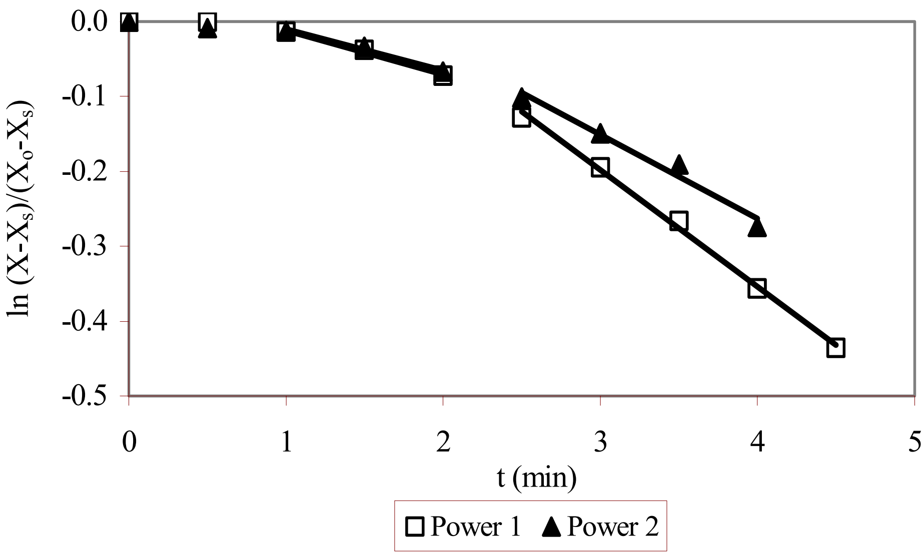


Figure III. 5. 2. 1. Dimensionless moisture analysis in microwave drying without mixing of the red peppers at power II & I.

As can be seen, contrary to the single linear regression of the conventional drying below 20%, the microwave drying cases showed two distinct zones excluding the initial part. Therefore, in the regression analysis it is assumed there are two zones during microwave drying of the red peppers. This also gave the linearity with higher correlation coefficients than one zone correlation. The D_{eff}/L^2 values of two zones for the four cases are given in Table 3. 5. 2. 1. together with that of the conventional drying.

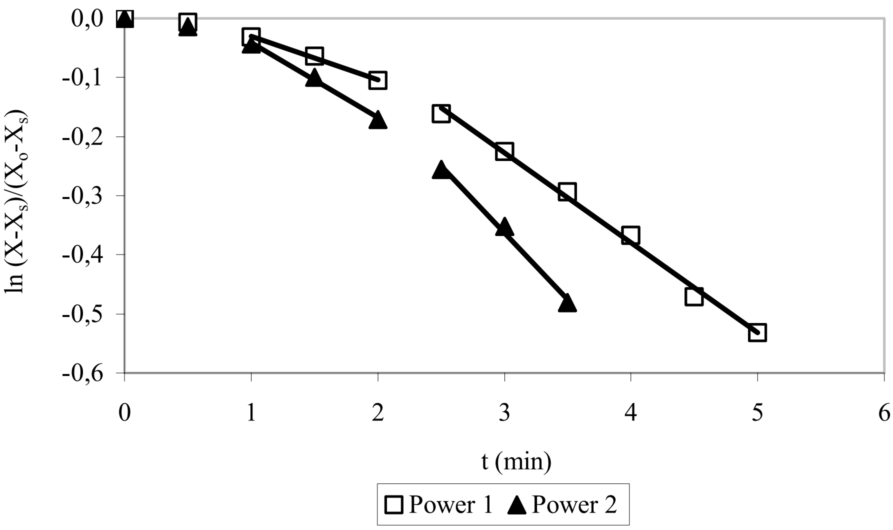


Figure III. 5. 2. 2. Dimensionless moisture analysis in microwave drying with mixing of the red peppers at power II & I.

Table 3. 5. 2. 1. The D_{eff}/L^2 values and correlation coefficients of two zones for the four cases of microwave drying and of the conventional drying.

Method of drying	Power level	II. 2. 1. 5. Zone 1			Zone 2		
		Slope	D_{eff}/L^2 (sec^{-1})	R^2	Slope	D_{eff}/L^2 (sec^{-1})	R^2
Without mixer	I	-0.0591	3.99E-04	0.9880	-0.1557	1.05E-03	0.9967
	II	-0.0546	3.69E-04	0.9851	-0.1120	7.57E-04	0.9723
With mixer	I	-0.0730	4.93E-04	0.9961	-0.1521	1.03E-03	0.9943
	II	-0.1268	8.57E-04	0.9955	-0.2254	1.52E-03	0.9936
Conventional		-0.0132	8.92E-05	0.9930	-0.0037	2.50E-05	0.9909

As well as shrinkage of the sample and changes in pore sizes hygroscopic capillary-porous materials show three zones in the falling rate period (Keey, 1972). In these zones, firstly totally free water, then partially bound and finally totally bound water leaves from the material during drying. In microwave drying below 20% moisture content presence of the two zones may be attributed to this behavior.

From Figure III. 5. 2. 1., red peppers dried in microwave oven without mixing at power II shows slightly lower drying rate than those dried at power I. As mentioned before, this slight difference may be negligible since red peppers started burning earlier and had higher accuracy in initial moisture contents.

In Table 3. 5. 2. 1. and Figure III. 4. 2. 3., the calculated values of D_{eff}/L^2 for the possible cases are shown with the power applied. This simply indicates the red peppers dried in the microwave oven with mixer at power II had the highest drying rate among the studied cases. This result was expected as drying rate was found to be proportional with the power applied. Further, second zone of the conventional drying, below 20% moisture content, is the most inferior drying application.

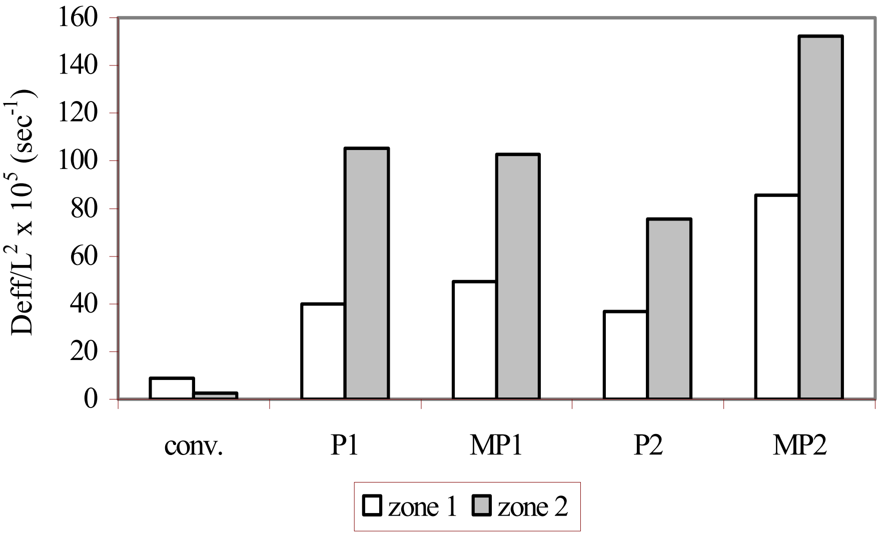


Figure III. 5. 2. 3. D_{eff}/L^2 values of two zones for both methods of microwave drying at Power II & I and the conventional drying at 60 ^{0}C.

However, at power I, there does not seem a significant difference between D_{eff}/L^2 values of the both microwave methods. More quantitatively, when mixing was applied, drying rate increased by 1.24 times in zone 1 and 0.98 times (about 1) in zone 2. On the contrary, at power II, mixing during microwave drying increased the drying rate by 2.32 times in zone 1 and 2.01 times in zone 2. Therefore, mixing appeared to be more effective on the drying rate of zone 1 rather than of zone 2. As power increased, the effect of mixing was about doubled. According to these results, again the superiority of microwave drying with mixing at power II is justified.

III. 6. FINAL MOISTURE DISTRIBUTION

To understand the effect of mixing in a mass of particulate samples, the distribution of a dependent variable according to the position had to be checked. For the final percent moisture distribution analysis (on wet basis), four samples, in 2 grams, were taken after termination of each operation of microwave drying. Of these, two were taken from surface of the load, center and edge, and the other two were from the bottom of the load. Positions of these four samples are shown in Section II. 5. (CS: Center-surface, ES: Edge-surface, EB: Edge-bottom, CB: Center-bottom). Results of this study are shown in Table C. 2.

In this comparative plot, center position of the load was taken as the reference point and the percent difference of the edge positions, (E/C) surface and (E/C) bottom, were calculated according to the reference. As can clearly be seen from the graph mixing decreases the difference between the center and the edge in both the surface and bottom parts of the batch. The results are in plotted in Figure III. 6. 1 below.

Other than r-direction, for the final moisture difference in z-direction, bottom part of the load was taken as the reference and percent change at the corresponding surface positions were calculated, S/B center and S/B edge. At power I, application of mixing decreased the moisture difference in the z-direction. However, at power II, higher moisture content of surface with mixing was not in accordance with the results of the power I. Since no mixing at power II was not a good indicator due to higher final moisture than others, this result also is not significant enough to show the advantage of mixing at power II, in contrast to power I.

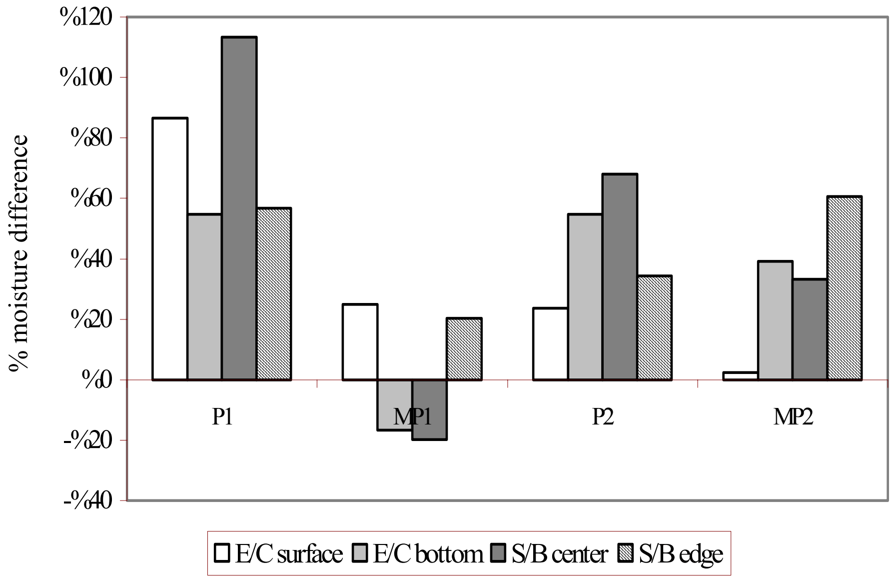


Figure III. 6. 1. Percent final moisture distribution analysis of edge with respect to radial reference position as center and of surface with respect to axial reference position as bottom in microwave dried red peppers (MP1 & MP2; microwave drying with mixing at power I, power II; P1 & P2; microwave drying without mixing at power I, power II).

Thus, to reach a valid conclusion on the effect of mixing more sampling points including the bed interior should be selected and a suitable sampling method should be developed.

III. 7. CONVENTIONAL DRYING VERSUS MICROWAVE DRYING

Drying of the red pepper samples having 20% moisture to the final moisture content, about 14%-15%, took 4.5 min at power I and 4 min at power II in a microwave oven. In conventional drying process, the drying of pepper samples to the equilibrium moisture, 15.8%, took 600 minutes (10 hours) at 60 ^{0}C. Drying by microwave energy at power I is about 120 times faster than drying in the conventional oven.

The reason why higher drying rates and consequent lower drying times are obtained by the utilization of microwave energy depends on the mechanism of microwave heating. With microwave oven, food is heated primarily by the generation of heat within the food itself. Thus the time for the food to reach elevated temperatures is reduced. Air in the oven and the food container is warmed only as they receive heat from the food (Harrison, 1980). Thus, microwaves provide an energy efficient process. On the other hand, conventional heating mechanism depends on the conduction from the heated surface and the thermal conductivity of foods is not high; thus with this method of heating, quite a long time is required for the interior of food (Curnutte, 1980).

Another factor involved in microwave processing, which provides quick drying, is the increase in pore size. When the interior of the food reaches the boiling point of water, free moisture evaporates inside the product, which causes a vapor pressure gradient that expels moisture from the sample. The vapor pressure developed within the food sample leads to an increase in pore size, which is known as the puffing effect. The increased pore size provides easy diffusion of moisture throughout the sample (Mudgett, 1989).

III. 8. EFFECT OF DRYING METHOD AND POWER LEVEL ON COLOR OF THE PRODUCT

Color of the dried red peppers is the one of the quality attributes. The data of the fresh samples were chosen as the reference in the total color difference (ΔE) measurements (L_0, a_0, b_0). The total color difference values of the 5 products corresponding to the five methods used were calculated by Eq. I. 20. The average of the L, a, b values, data of 10 replications, were used for the difference. The results are shown in Table 3. 8. 1.

Table 3. 8. 1. The averages of color values (L, a, b) and calculated ΔE values (L: Lightness/darkness, a: redness/greenness, b: yellowness/blueness).

Color values	**Fresh Sample**	**Conv. drying at 60 ^{0}C**	**Microwave drying without mixer**		**Microwave drying with mixer**	
			Power I	**Power II**	**I. 11.** Po wer I	**Power II**
L	31.5	28.3	30.9	31.6	30.9	30.6
a	35.4	35.7	43.1	41.6	36.5	36.2
b	12.1	9.3	13.3	12.6	12.2	12.5
ΔE	-	4.3	7.8	6.2	1.3	1.3

As can be seen, although there is not a significant difference between the 'L' values (lightness), the 'a' and 'b' values representing the redness and the yellowness of the samples, respectively, shows an increase after the microwave drying operations. Only the 'b' value decreased in the average result of conventional drying. Increase in the redness and the yellowness may be attributed to the increase in concentration of the color pigments due to the decrease in moisture content.

The total color difference values, ΔE, with respect to the fresh sample show these differences more clearly. Increase in the value of the microwave drying without mixer is higher than with mixing cases. Effect of power values of the microwave oven on the color values is not significant.

As to conclude, there does not seem a significant effect of drying by any one of the methods used on the color of red peppers.

CHAPTER IV

I. 12. CONCLUSIONS AND RECOMMENDATIONS

IV. 1. CONCLUSIONS

The results for the rate of drying showed that utilization of microwave drying in the diffusional rate period can significantly shorten the drying time, but may cause insignificant color change in the product with respect to the fresh samples.

Introduction of mixing provided more moisture uniformity in final products and increases the reducing effect of the power on the treatment time. Also, the design, compared to fluidization need no extra energy for agitation which was already provided by rotation of the turntable.

Contrary to the conventional drying below 20%, the microwave drying cases show two distinct linear drying zones. Mixing appears to be more effective in zone 1 according to drying rate and microwave drying with the mixer at a medium power around 350-400W is suitable operational condition.

As to conclude, substitution of microwave drying offers the second critical point in a conventional drying process with a well designed mixer seems to be an attractive alternative over conventional methods according to the drying time and quality of final product.

IV. 2. RECOMMENDATIONS

As a recommendation that can be helpful in future studies in the area of microwave processing, the characteristics of the food of concern should be well understood and the interactions of the microwaves with the food should be estimated before bringing the studies to intensive experimental work.

As a continuation of this work the optimum combination of the variables, the improved agitator design, other possible microwave powers, vacuum, coupling conventional methods with microwaves, particle size, sample load and shape on the efficiency of the operation and uniformity and consistency of the product can be studied.

Also, the microwave-dried red peppers should be evaluated for other quality parameters, vitamin C and texture being the most important.

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APPENDIX A

A. 1. COMPOSITION OF RED PEPPERS

Table A. 1. 1. The composition of sweet red pepper (*Capsicum Annum L.*)*

I. 13. Nutrient	Units	Value per 100 grams of edible portion
Proximates		
Water	g	92.19
Energy	kcal	27
Energy	kj	113
Protein	g	0.89
Total lipid (fat)	g	0.19
Ash	g	0.30
Carbohydrate, by difference	g	6.43
Fiber, total dietary	g	2.0
Minerals		
Calcium, Ca	mg	9
Iron, Fe	mg	0.46
Magnesium, Mg	mg	10
Phosphorus, P	mg	19
Potassium, K	mg	177
Sodium, Na	mg	2
Zinc, Zn	mg	0.12
Copper, Cu	mg	0.065
Manganese, Mn	mg	0.116
Selenium, Se	mcg	0.3

Table A. 1. 1. (continued)

Vitamins		
Vitamin C, total ascorbic acid	mg	190.0
Thiamin	mg	0.066
Riboflavin	mg	0.030
Niacin	mg	0.509
Pantothenic acid	mg	0.080
Vitamin B-6	mg	0.248
Folate, total	mcg	22
Folate, food	mcg	22
Folate, DFE	mcg_DFE	22
Vitamin A, IU	IU	5700
Vitamin A, RAE	mcg_RAE	285
Vitamin E	mg_ATE	0.690
Tocopherol, alpha	mg	0.68

*(Table adapted from USDA National Nutrient Database for Standard Reference, Release 15 -August 2002) (http://www.nal.usda.gov/fnic/cgi-bin/list_nut.pl)

A. 2. POWER MEASUREMENT OF MICROWAVE OVEN

A. 2. 1. Power measurement Test Procedure-IMPI 2-Liter Test

Operate the oven at its rated line voltage with oven set on high with a load of 2000 ± 5 g water placed in two 1-L beakers. The beakers should initially be at room ambient temperature. Initial water temperature should be $20^0C \pm 2^0C$, measured after water is placed in beakers and before placing in the microwave oven. The beakers are placed in the center of the oven, side by side in the width dimension of the cavity, and touching each other. The oven is turned on for 2 min and 2 s. The beakers are removed from the oven, and the final temperatures are measured and recorded.

The power is calculated from the following formula:

$$P\ (W) = 70 \times \frac{\Delta T_1(^0C) + \Delta T_2(^0C)}{2} \qquad \text{(A. 1.)}$$

where ΔT_1 and ΔT_2 are the temperature rises of the water in the two beakers, calculated by subtracting the initial water temperature from the final temperature.

The power measurement should be run three times, with the oven power the average of the three readings. If any individual measurement is more than 5% from the average, the complete test should be repeated (Buffler, 1993).

The oven should be pre-warmed by heating 2L of water for 5 minutes, then wiping the shelf with a cold wet rag. The water in each vessel should be well stirred by plastic or wooden spoon before measuring the starting and final temperatures. The temperature should be measured with a thermometer with 0.1 ^{0}C resolution.

Table. A. 2. 1. Power measurement test data

I. 14. Replicate		**Power III**		**Power II**		**I. 1. 8. Power I**	
		T_1	**T_2**	**T_1**	**T_2**	**T_1**	**T_2**
1	**I. 15. Ti=**	19	19	21.5	21.5	20.5	20.5
	Tf=	27	27	27	27	24.5	24.5
	ΔT=	8	8	5.5	5.5	4	4
2	**Ti=**	19	19	20	20	21	20.5
	Tf=	27	27	26	25.5	25	25
	ΔT=	8	8	6	5.5	4	4.5
3	**Ti=**	20	21	20	20	19.5	19.5
	Tf=	28	29	26	25.5	23.5	23.5
	ΔT=	8	8	6	5.5	4	4
Average Power (W)		**560**		**397**		**286**	

3. TEMPERATURE WITH RESPECT TO AIR VELOCITY AT THE INDICATED KNOB SETTINGS OF THE CONVENTIONAL DRIER

Table. A. 3. 1. Temperature and air flow adjustment table

Air Flow knob setting (m/s)		I. 16. Temperature (^{0}C)				
		2	**4**	**6**	**8**	**10**
2	0.3	38	48	58	68	78
4	0.7	38	45	52	58	65
6	1.0	37	44	50	55	60
8	1.3	38	42	46	50	54
10	1.7	35	38	42	45	48

APPENDIX B

B. 1. Figures showing non-uniform electric field distribution on the filter paper at different time intervals (0.5, 1, 1.5, 2, 2.5, 3, 3.5 and 4 min) of drying applications in the microwave oven at Power II (397 W).

Fig. B. 1. 1. Distrinution at time zero

Fig. B. 1. 2. Distribution at the 0.5th min

Fig. B. 1. 3. Distribution at the 1st min

Fig. B. 1. 4. Distribution at the 1.5th min

Fig. B. 1. 5. Distribution at the 2^{nd} min

Fig. B. 1. 6. Distribution at the 2.5^{th} min

Fig. B. 1. 7. Distribution at the 3^{rd} min

Fig. B. 1. 8. Distribution at the 3.5^{th} min

Fig. B. 1. 9. Distribution at the 4^{th} min

APPENDIX C

C. 1. DATA FOR CALCULATION OF EFFECTIVE DIFFUSION COEFFICIENTS

Table C. 1. 1. Calculations for the effective diffusion coefficient of red peppers in conventional drying at 60 ^{0}C from average weight measurements in duplicate runs. (w: weight of the sample, M%: percent moisture on wet basis, X_0: initial moisture concentration (g water/g bds), X_s: equilibrium moisture concentration; 0)

t (min)	w_1 (g)	w_2 (g)	w_{ave} (g)	M% (w/w)	X_t	$\ln((X_t-X_s)/(X_0-X_s))$
0	10.53	10.4	10.47	91.4	10.622	0.000
15	9.4	9.39	9.40	90.4	9.434	-0.121
30	8.55	8.55	8.55	89.5	8.496	-0.228
60	6.88	6.78	6.83	86.8	6.585	-0.489
120	4.56	4.32	4.44	79.7	3.931	-1.025
180	2.92	2.58	2.75	67.3	2.054	-1.721
240	2.1	1.83	1.97	54.2	1.182	-2.351
300	1.5	1.38	1.44	37.5	0.599	-3.234
360	1.3	1.19	1.25	27.7	0.383	-3.981
420	1.14	1.12	1.13	20.3	0.255	-5.049
480	1.12	1.1	1.11	18.9	0.233	-5.452
540	1.12	1.08	1.10	18.1	0.222	-5.737
600	1.11	1.08	1.10	17.8	0.216	-5.917
660	1.1	1.08	1.09	17.4	0.211	-6.137
780	1.1	1.07	1.09	17.0	0.205	-6.420
840	1.09	1.07	1.08	16.6	0.199	-6.816
1020	1.09	1.06	1.08	16.2	0.194	-7.480
1080	1.08	1.06	1.07	15.8	0.188	

Table. C. 1. 2. Calculations for the effective diffusion coefficient of red peppers in microwave drying without mixer at power I.

t (min)	**w_{ave} (g)**	**M% (w/w)**	**X_t**	**$\ln((X-X_s)/(X_0-X_s))$**
0	150	%20.0	0.250	0.000
0.5	150	%20.0	0.250	0.000
1	149.6	%19.8	0.247	-0.013
1.5	148.9	%19.4	0.241	-0.037
2	147.9	%18.9	0.233	-0.073
2.5	146.4	%18.0	0.220	-0.128
3	144.7	%17.1	0.206	-0.194
3.5	143	%16.1	0.192	-0.266
4	141	%14.9	0.175	-0.357
4.5	139.4	%13.9	0.162	-0.436

Table. C. 1. 3. Calculations for the effective diffusion coefficient of red peppers in microwave drying without mixer at power II.

t (min)	**w_{ave} (g)**	**M% (w/w)**	**X_t**	**$\ln((X-X_s)/(X_0-X_s))$**
0	150.1	%19.0	0.235	0.000
0.5	149.9	%18.9	0.233	-0.009
1	149.8	%18.8	0.232	-0.012
1.5	149.2	%18.5	0.227	-0.034
2	148.3	%18.0	0.220	-0.067
2.5	147.4	%17.5	0.212	-0.101
3	146.2	%16.8	0.202	-0.149
3.5	145.2	%16.3	0.194	-0.190
4	143.3	%15.2	0.179	-0.274

Table. C. 1. 4. Calculations for the effective diffusion coefficient of red peppers in microwave drying with mixer at power I.

t (min)	**w_{ave} (g)**	**M% (w/w)**	**X_t**	**$\ln((X-X_s)/(X_0-X_s))$**
0	150	%21.5	0.274	0.000
0.5	149.8	%21.4	0.272	-0.007
1	149	%21.0	0.265	-0.032
1.5	148	%20.4	0.257	-0.064
2	146.8	%19.8	0.247	-0.105
2.5	145.2	%18.9	0.233	-0.162
3	143.5	%17.9	0.219	-0.226
3.5	141.8	%17.0	0.204	-0.294
4	140.1	%16.0	0.190	-0.367
4.5	137.9	%14.6	0.171	-0.471
5	136.7	%13.9	0.161	-0.532

Table. C. 1. 5. Calculations for the effective diffusion coefficient of red peppers in microwave drying with mixer at power II.

t (min)	**w_{ave} (g)**	**M% (w/w)**	**X_t**	**$\ln((X-X_s)/(X_0-X_s))$**
0	149.7	%20.5	0.258	0.000
0.5	149.3	%20.3	0.255	-0.014
1	148.4	%19.8	0.247	-0.044
1.5	146.8	%18.9	0.233	-0.100
2	144.9	%17.9	0.218	-0.171
2.5	142.8	%16.7	0.200	-0.255
3	140.6	%15.4	0.181	-0.352
3.5	138	%13.8	0.160	-0.481

C. 2. FINAL MOISTURE DISTRIBUTION DATA OF MICROWAVE DRYING

Table C. 2. 1. % Moisture of final moisture contents of four samples from different positions (CS: center surface, ES: edge surface, CB: center bottom, EB: edge bottom).

I. 17. Method of drying	Power level	% Moisture on wet basis			
		CS	ES	CB	EB
With Mixing	I. 18. I	11.1	13.9	13.9	11.5
	II	13.3	13.6	6.3	8.7
Without Mixing	I	8.5	15.8	6.4	9.9
	II	9.3	11.4	5.5	8.5

Table C. 2. 2. % Moisture difference of final moisture contents of edge with respect to radial reference position as center and of surface with respect to axial reference position as bottom (E/C surface: % change of edge with respect to center at the surface, E/C bottom: % change of edge at the bottom, S/B center: % change of surface with respect to bottom at the center, S/B edge: % change of surface at the edge).

Method of drying	% Moisture difference				
	Power level	E/C surface	E/C bottom	S/B center	S/B edge
With Mixing	I. 19. I	25.00	-16.76	-19.84	20.37
	I. 20. II	2.27	39.13	33.24	60.63
Without Mixing	I	86.53	54.71	113.33	56.82
	II	23.69	54.78	68.06	34.30

C. 3. FOURIER NUMBERS

Table C. 3. 1. The calculated Fourier numbers in the experiments.

Method of drying	Power level	Fourier Number
Without mixer	**I**	0.11
	II	0.09
With mixer	**I**	0.15
	II	0.18
Conventional		1.62