# INFRARED-ASSISTED MICROWAVE DRYING IN THE PRODUCTION OF BREAD CRUMBS

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Approval of the Graduate School of Natural and Applied Sciences

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This is to certify that we have read this thesis and that in our opinion it is fully adequate, in scope and quality, as a thesis and for the degree of Master of Science.

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# ABSTRACT

## INFRARED-ASSISTED MICROWAVE DRYING IN THE PRODUCTION OF BREAD CRUMBS

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This study is aimed to investigate the possibility of using halogen lamp-microwave combination oven for production of bread crumbs and to determine the drying conditions in this oven to produce bread crumbs with the highest quality.

Bread crumb dough was dried from about 40.9% to 8% moisture content by conventional oven, microwave, infrared and infrared-assisted microwave drying. In the experiments 30%, 50% and 70% halogen lamp and/or microwave powers were used. As a control, conventional oven drying at 75°C was used.

Conventional drying time was reduced significantly with the usage of infrared, microwave and infrared-assisted microwave drying. Percent reduction in the drying time was found as 96.5-98.6% for microwave, 80.2-94.0% for infrared and 96.8-98.6% for infrared-assisted microwave drying. Contribution of microwave drying was about nine fold of that of infrared drying in infrared-assisted microwave drying. In conventional drying moisture content decayed exponentially with time whereas in microwave drying it showed a linear decrease. Infrared and infrared-assisted microwave drying fitted the same non-linear model.

Total color change values were lower in microwave and higher in infrared drying with respect to the conventional drying. When drying was done by infrared-assisted microwave drying similar color values with the conventionally dried bread crumbs were encountered. Microwave, infrared and infrared-assisted microwave drying methods were effective in increasing water binding capacity.

As long as time and energy reduction and high quality were considered, the optimum condition in infrared-assisted microwave drying for production of bread crumbs can be selected as 50% microwave and 30% halogen lamp power.

Keywords: Bread crumbs, Drying, Microwave, Infrared, Infrared-assisted microwave drying.

# ÖZ

## KAPLAMA MALZEMESİ ÜRETİMİNDE KIZIL ÖTESİ DESTEKLİ MİKRODALGA KURUTMA

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Bu çalışmanın amacı halojen lamba-mikrodalga kombinasyonlu fırının kaplama malzemesi üretiminde kullanılma olasılığının araştırılması ve bu fırındaki yüksek kaliteli kaplama malzemesi üretimini sağlayan kurutma koşullarının belirlenmesidir.

Konvansiyonel fırın, mikrodalga, kızıl ötesi ve kızıl ötesi destekli mikrodalga kurutma ile kaplama malzemesi hamuru yaklaşık %40.9 nem içeriğinden %8 ‘e kadar kurutulmuştur. Deneylerde %30, %50 and %70’lik halojen lamba ve/veya mikrodalga güçleri kullanılmıştır. Kontrol olarak, 75°C’de yapılan konvansiyonel fırın kurutma kullanılmıştır.

Kızıl ötesi, mikrodalga ve kızıl ötesi destekli mikrodalga kurutma yöntemleri kullanılarak konvansiyonel kurutma zamanı önemli derecede kısaltılmıştır. Kurutma zamanındaki yüzde azalmalar mikrodalga için %96.5-98.6, kızıl ötesi için %80.2-94.0 ve kızıl ötesi destekli mikrodalga kurutma için %96.8-98.6 olarak bulunmuştur. Kızıl ötesi destekli mikrodalga kurutmada mikrodalga kurutmanın katkısı kızıl ötesi kurutmaya göre dokuz kat olmuştur. Nem içeriği zamana göre konvansiyonel fırın kurutmada üstel olarak azalırken, mikrodalga kurutmada doğrusal olarak azalış göstermiştir. Kızıl ötesi ve kızıl ötesi destekli mikrodalga kurutma aynı doğrusal olmayan modele uymuştur.

Konvansiyonel kurutmaya göre, mikrodalga kurutmada toplam renk değişimi daha düşük, kızıl ötesi kurutmada daha yüksek olmuştur. Kurutma kızıl ötesi destekli mikrodalga kurutma ile yapıldığında konvansiyonel fırında kurutulan kaplama malzemesinin renk değerlerine benzer renk değerleriyle karşılaşılmıştır. Mikrodalga, kızıl ötesi ve kızıl ötesi destekli mikrodalga kurutma yöntemleri su tutma kapasitesini arttırmada etkili olmuştur.

Zaman ve enerji azaltma ve yüksek kalite düşünüldüğünde, kızıl ötesi destekli mikrodalga kurutmada kaplama malzemesi üretimi için %50 mikrodalga ve %30 halogen lambası güçleri en uygun koşul olarak seçilebilir.

Anahtar kelimeler: Kaplama malzemesi, Kurutma, Mikrodalga, Kızıl ötesi, Kızıl ötesi destekli mikrodalga kurutma.

To My Family

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# INTRODUCTION

## 1.1 Drying

Drying is one of the oldest and the most cost-effective way of preservation of grains, crops and foods in all varieties (Mujumdar, 2000). Karel (1975) defines drying as a simultaneous heat and mass transfer operation in which the water activity of a material is lowered by the removal of nearly all the water normally present by evaporation into an unsaturated gas stream.

Large quantities of food products are dried to improve shelf life, reduce packaging costs, lower shipping weights, enhance appearance, encapsulate original flavour and maintain nutritional value in many agricultural countries (Chou and Chua, 2001).

Okos et al. (1992) stated the aims of drying process research in food industry as three-fold:

a) Economic aspects: To lower cost and to improve capacity per unit amount of drying equipment, to develop simple and reliable drying equipment requiring minimum labour, to minimize off-specification product and to develop a stable process being capable of continuous operation.

b) Environmental aspects: To minimize energy consumption during the drying process and to reduce environmental impact by reducing product loss in waste streams.

c) Product quality aspects: To control the moisture content of the product precisely at the end of the drying operation, to minimize chemical degradation reactions, to reduce the change in product texture and structure, to have the desired product colour, to control density of the product and to develop a flexible drying operation yielding products with different physical structures for various end-users.

Guu (2003) categorizes drying processes as: 1) hot-air drying, such as tunnel or kiln drying, spray drying, and fluidized-bed drying, etc. where hot air is the thermal medium and moisture carrier; 2) direct-contact drying, such as drum or pan drying, where thermal conduction is the mechanism to convey heat for drying; 3) freeze drying, where food materials are first frozen, and then followed by sublimation under negative pressure; and 4) electromagnetic drying such as microwave and infrared drying, etc.

## 1.2 Conventional Drying

Moisture transport in solids is usually assumed to be controlled by molecular diffusion. In order to describe the moisture diffusion process, Fick's second law of diffusion is often written in the form given in Equation 1.1.

$$\frac{\partial X}{\partial t} = D_{eff} \nabla^2 X \tag{1.1}$$

where $X$ is the moisture content (dry basis), $t$ is time and $D_{eff}$ is the effective moisture diffusivity. $D_{eff}$ is an overall transport property incorporating all transport mechanisms (Saravacos and Maroulis, 2001).

One dimensional diffusion is considered since the thickness of the bread crumb dough is small rendering it as one dimensional. Under the conditions of constant moisture diffusivity, neglecting shrinkage and considering the diffusion in z direction only the solution to Equation 1.1 is (Crank, 1979):

$$\frac{X_t - X^*}{X_o - X^*} = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \exp\left[ -(2n+1)^2 \frac{\pi^2}{4} \frac{D_{eff}\, t}{L^2} \right] \tag{1.2}$$

where, $X_t$ is the moisture content at time t, $X^*$ is the equilibrium moisture content, $X_o$ is the initial moisture content, $L$ is the thickness of the bread crumb dough and $\frac{D_{eff}t}{L^2}$ is the Fourier number for the mass transfer.

At sufficiently large times, Fourier number is greater than about 0.1, only the leading term in the series expansion need to be taken. Then the solution of Fick's second law simplifies to:

$$\frac{X_t - X^*}{X_o - X^*} = \frac{8}{\pi^2}\exp\left[-\frac{\pi^2}{4}\frac{D_{eff}t}{L^2}\right] \tag{1.3}$$

## 1.3 Microwave Drying

### 1.3.1 Microwaves and Microwave Heating

Microwaves are high frequency, electromagnetic waves in the 1 mm to 1 m waveband, corresponding to frequencies between 300 MHz and 30 GHz. They are generated by magnetrons and klystrons and consist of electric and magnetic fields (Decareau, 1985; Khraisheh et al., 1997).

Heating, communication, navigation and radar are included in some important applications of microwaves (Schiffmann, 1987). It is unique to microwaves that when they travel through a lossy medium, a rise in temperature throughout the medium can be observed. This has led to many applications in the food industry and microwave heating has been used in the food industry since 1950s (Schiffmann, 1986; Schiffmann, 1995). Microwaves in 2450 MHz or 915 MHz frequency, corresponding to wavelengths of 12 cm or 34 cm are used in the food industry for the purpose of heating (Ohlsson and Bengtsson, 2002). Drying, thawing, tempering, sterilization, pasteurization, cooking, baking, heating, stabilization, thermal treatment, roasting, ready meals heating and other applications such as oil emulsion melting, scallop shales removing, deep penetration in margarine and honey containers emptying are the examples of microwave heating applications in the world food industry today (http://www.romill.cz).

The interactions of microwaves with food materials are generally described in terms of the dielectric properties of the material which are dielectric constant $\varepsilon'$ and dielectric loss factor $\varepsilon''$. Dielectric constant is analogous to capacitance owing to the fact that it is a measure of the material's ability to store microwave energy and the dielectric loss factor $\varepsilon''$ is analogous to a resistance because it represents the material's ability to dissipate absorbed energy as heat. Mentioned properties can be measured at various frequencies and they are dependent on the temperature, moisture content, composition and the particle density of the material. Materials can be classified as high loss or low loss. Water is the greatest absorber and dissipator of microwave energy ($\varepsilon'$=78 and $\varepsilon''$=12) among the substances associated with foods and is the most responsible component for the dielectric properties of a complex substance as a whole. Dipolar liquids and monomeric constituents interact with microwaves to a greater extent than do polymers like cellulose and lignin. The basis for estimating important values such as the heat generation rate and the penetration depth is the dielectric properties (Venkatachalapathy, 1998). The ratio of $\varepsilon''$ to $\varepsilon'$ is called the (dielectric) loss tangent (tan δ) or dissipation factor.

Principal mechanisms of energy dissipation as heat are due to frictional effects of dipolar rotation and ion migration resulting from the response to the alternating electric field (Rosenberg and Boegl, 1987). Dipolar rotation is the basic phenomena responsible for heating of foods at microwave frequencies (Schiffman, 1987). In dipolar rotation, the randomly orientated dipolar compounds undergo alignment and disorientation cycles at a rate equal to the frequency of the applied electric field. This builds up and decay of orientation generates kinetic energy that is converted to heat. Dipolar rotation is dependent on temperature and frequency. In the case of ion migration, ionized compounds randomly collide with non-ionized groups if they are subjected to an electric field. Kinetic energy of these ions is transmitted as heat during such collisions (Khraisheh et al., 1997; Buffler 1993).

Power absorption (specific absorption rate) of a material depends on various factors including frequency, temperature, magnitude of electric field in tissue, density, and dielectric constants of free space and tissue (Rosenberg and Boegl, 1987). Equation 1.4 gives the microwave power absorption by a material.

$$P_v = 2\pi f \varepsilon_0 \varepsilon'' E^2 \tag{1.4}$$

where, $P_v$ is the power absorbed per unit volume (W/m$^3$), $f$ is the frequency of the microwave system (Hz), $E$ is electric field strength within the product (V/m), $\varepsilon_0$ is the permitivity of free space (F/m) and $\varepsilon''$ is dielectric loss factor for the food sample. The electric field within the product is determined by the dielectric properties, the geometry of the product, and by the oven configuration (Buffler, 1993).

A penetration depth can be calculated from the dielectric properties in order to gain a better practical understanding of the meaning of the dielectric properties. The penetration depth $d_p$ (or power penetration depth) is defined theoretically as the depth below a large plane surface of a substance at which the power density of a perpendicularly impinging, forward propagating plane electromagnetic wave has decayed by 1/e from the surface value (1/e is about 37%). If tan δ is smaller than about 0.5, the following simplified equation gives 97% to 100% of the correct value (Risman, 1991a):

$$d_p = \frac{\lambda_0 \sqrt{\varepsilon'}}{2\pi \varepsilon''} \tag{1.5}$$

where $\lambda_0$ is free space wavelength.

The absorbed power density near the surface of an infinite inhomogeneous slab is, accordingly, approximately proportional to $\varepsilon''$ when $\varepsilon'$ does not vary very much. If tan δ is greater than 0.5, the more exact equation should be used (Risman, 1991a):

$$d_p = \frac{\lambda_0}{2\pi\sqrt{2}}\left(\varepsilon'\left[\sqrt{1+\left(\varepsilon''/\varepsilon'\right)^2}-1\right]\right)^{-1/2} \tag{1.6}$$

From Equation 1.5 and 1.6, it is obvious that materials with high dielectric constants and dielectric loss factors will have smaller penetration depths than those with lower values (Venkatachalapathy, 1998).

The heating rate of a material is also a function of the dielectric loss factor and is expressed below:

$$\frac{\Delta T}{\Delta t} = \frac{kfE^2\varepsilon''}{\rho C_p} \tag{1.7}$$

where $\rho$ is the density, $C_p$ is the specific heat and $k$ is $2\pi\varepsilon_0$. Equation 1.7 is an extension of that for power dissipated within the material as given by Metaxas and Meredith (1983) and it is valid only at the initial stages of microwave heating at which there is initial heat generation (initial absorption) and conduction has not started yet (Venkatachalapathy, 1998).

In conventional heating, heat is applied to the outside of the material, and it is transferred to the center of the material, principally by conduction. Conventional heating is relatively slow since foods are good heat insulators. The surface is the hottest area of the product and the centre the coolest (Rosen, 1972; Ryynänen, 2002). In microwave heating, material is heated primarily by the generation of heat within the material itself. This is referred to as volumetric heating, as its effect is throughout the product (Decareau, 1968; Copson, 1975). Air in the microwave oven and material container is warmed only as they receive heat from the material (Harrison, 1980). The use of microwave energy has been considered to be a suitable approach for coping with certain drawbacks of conventional heating methods of foods (Decareau and Peterson, 1986). Microwave heating have several advantages when compared to conventional heating methods. These are:

- Heating is instantaneous as the energy transfer is radiative. Furthermore, internal temperature gradients tend to be smaller due to the fact that heat is generated within the material and not just conducted towards the centre.
- Microwave energy couples directly to the material being heated. The energy transfer to the air, oven walls, conveyor or other parts is minimal as their dielectric constants are very small. This can lead to significant energy savings.
- As the moisture flow is partly pressure-driven from the interior, there is no receding moisture front as in convection, which eliminates case hardening. This favourable for some applications, but considered as a disadvantage in cooking or baking because crust formation and surface browning do not occur.
- Heat generation by microwaves promotes many chemical and physical reactions, leading to drying, puffing, melting, protein denaturation, starch gelatinization.
- Due to the rapid energy dissipation throughout the material, minor migration of water soluble constituents can be seen (Venkatachalapathy, 1998; Askari et al., 2004).

### 1.3.2 Microwave Drying

In conventional drying methods, heat supplied from the surroundings conducts into the material and increases the vapor pressure within the material. As long as the vapor can diffuse to the surface of the material and the surrounding air is not saturated, this moisture is taken up and carried away convectively. The vapor-pressure difference between the air and the surface of the material can cause outflow of liquid flow to some extent. The heat may be supplied to the material surface by convection or conduction, from where it is conducted to the interior (Ratti and Mujumdar, 1996). The most common traditional drying method used for foods to date was hot air drying which is often found as the simplest and the most economical method (Jayaraman and Das Gupta, 1995; Feng and Tang; 1998). In this type of system, main mode of heat transfer is convection. The physical properties of the food (particle size and geometry), the physical arrangement of the food with air, the physical properties of the air (temperature, humidity, velocity), and the design characteristics of the drying equipment are the main factors that can affect the rate and the total drying time (Jayaraman and Das Gupta, 1995; Grabowski et al, 2003). The main disadvantages of hot air drying are: long drying durations, the nonuniformity obtained in the dried sample, and the inferior quality of the resulting product. These are mainly damage to nutritional properties and sensory characteristics of foods, oxidation of pigments and vitamins by hot air, and migration of solutes from the interior of the food to the surface (Bouraout et al., 1994; Yongsawatdigul and Gunasekaran, 1996; Venkatachalapathy and Raghavan, 1998).

It has been recognized that microwave drying can lead to potentional economic, engineering and social benefits over the last few decades (Sanga et al, 2000). According to Feng (2000), it is the disadvantages of the conventional drying methods that provide microwave heating vast opportunity as a new drying method for improving both energy efficiency and product quality.

The physical mechanisms involved in microwave drying are distinctly different from those of conventional means. As stated in the previous section, microwaves can penetrate into dielectric materials and generate internal heat (Jia et al., 1993). Generated internal heat establishes a vapor pressure within the material and ‘pumps’ the moisture to the surface gently. Due to this moisture pumping effect, the moisture is forced to the surface of the material (Turner and Jolly, 1991). Unlike conduction, convection, or radiation, thermal energy supplied at the surface does not have to be conducted into the interior as limited by Fourier’s law of heat conduction (Strumillo and Kudra, 1986).

Feng (2000) stated that the advantages of microwave drying arise from the volumetric heating and internal vapor generation. As a consequence, an internal total gas pressure gradient builds up and most of the moisture leaves the material as vapor resulting in a significant reduction in drying time. Prabhanjan et al. (1995) reported a reduction in drying time up to 25-90% and Bruin and Luyben (1980) mentioned an increase in drying rate of 4 to 8 times in microwave drying of foods when compared to convective drying. Advantages of microwave drying can be summarized below:

- Internal heat generation leads to an increase in internal vapor generation, which promotes liquid flow towards the surface, and also leads to higher internal temperatures, both of which increase the drying rate.
- High energy efficiency in the falling rate period can be achievable. It is partially owing to the fact that the energy is directly coupled into the moisture eliminating the need to transfer heat from the low moisture surface into the interior. It is also the consequence of an increased driving force for moisture transfer due to the elevated internal vapor pressure generation.
- In microwave drying, there is great potential for energy savings because of the speed of drying and lower specific energy needs in the case of high loss materials.
- Drying times can be shortened by 50% or more depending on the product being dried and the drying conditions such as power levels and temperature.
- An improvement in product quality can also be achieved as long as microwave drying is properly applied and in some cases microwave drying eliminates case hardening, internal stresses and other problems like cracks. Case hardening may be avoided or lessened due to the surface moisture accumulation and even the liquid pumping phenomena. The unique surface moisture concentration in microwave drying has been widely reported (Turner et al., 1998; Ni et al., 1999). The favorable moisture profiles produced in microwave drying provide a high possibility to reduce the surface moisture depletion and the case hardening encountered in conventional drying. Better aroma retention (Prabhanjan et al., 1995; Drouzas and Schubert, 1996; Feng and Tang; 1998), better color (Tulasidas et al., 1995; Feng and Tang, 1998), and higher porosity (Torringa et al., 1996) have been reported for microwave dried foods. Moreover, reduction of migration can also be seen in microwave drying as solvent often mobilized as a vapor thereby not transporting other materials to the surface and this contributes to the quality of dried food product.
- Microwave drying equipment occupies less floor space and reduces the handling time.
- Cost savings may be realized through energy savings, increased throughput, labour reduction, reduced heat load in the plant, increased efficiency and lessened maintenance costs (Venkatachalapathy, 1998; Feng 2000; Schiffmann 2001; Wang et al., 2004).

Potential disadvantages of microwave drying that may adversely affect product quality (e.g. scorching of high sugar content products, over heating, or charring and uneven temperature distribution) include: (1) Nonuniformity in heating and so non-uniform product temperature distribution because of the uneven microwave field in the cavity caused by the superposition of the sinusoid microwaves, which is an inherent characteristics of microwaves. The temperature distribution is also affected by the composition and the dielectric properties of the food material and location of the food in the oven. (2) Difficulty in the control of the mass transfer rate. In some cases, the mass transfer rate is too high, causing puffing and even disintegration of the product. (3) Difficulty in controlling product final temperature at low moisture contents when compared to conventional means of drying (Khraisheh et al., 1997; Drouzas et al., 1999; Lu et al, 1999; Feng 2000; Feng et al., 2002; Sanga et al., 2002; Secmeler 2003).

Another drawback of microwave drying is the historically high investment cost and low life-span of the magnetron. However, today, both capital equipment costs and operating costs have been reduced to a level comparable to conventional drying methods (Schiffmann, 1995).

As stated earlier heating nonuniformity is a major factor causing potential problems in microwave drying. Various field-averaging methods have been developed in order to achieve heating uniformity (Feng and Tang, 1998). In such methods, the material being dried is in constant movement within the microwave cavity so that different parts of the material will receive a microwave radiation of about the average of the spatial electromagnetic field intensity over a period of time. The microwave energy averaging can be accomplished by either mechanical means (Allan, 1967; Huxsoll and Morgan, 1968; Torringa et al., 1996) or through pneumatic agitation (Salek-Mery, 1986; Kudra 1989). “The remaining obstacles for the application of microwave drying could be a lack of understanding of the microwave interaction with product, a lack of dielectric property data, and a lack of an effective means to predict the moisture and temperature history and distribution during microwave drying” (Feng, 2000).

The usual way of applying microwave energy to a drying process is in the falling rate period or at a low moisture content (where conventional drying takes a long time). The reason for this is essentially economic. Due to its high cost, microwave drying can not compete with conventional drying methods at high moisture contents (over 20% moisture content). This is because despite water has high dielectric constant and can absorb microwaves easily, it also has a very high specific heat. Therefore, considerable amount of microwave energy would be required to significantly raise the temperature for drying if the bulk of the water is high (Mudgett, 1989; Maskan, 2001; Schiffmann 2001; Wang et al., 2004). According to Beaudry et al (2004), an advantage of using microwave technology is the possibility of combining diverse drying methods with microwaves. Microwave heating is generally combined with convection or vacuum to reduce the energy consumption. Combination with conventional drying may be done in several steps or simultaneously by conducting hot or cold air along the surface of the product during microwave drying (Rosenberg and Bogl, 1987). Mujumdar (2004) states that microwave vacuum drying and microwave freeze drying are among the commercial drying technologies that have so far found some applications. Numerous laboratory and pilot scale studies have been reported on microwave drying at atmospheric as well as vacuum conditions. According to Mujumdar (2004), it is also possible to pipe microwave energy in various dryer configurations, such as fluidized bed, spouted bed, vibrated bed, or tray dryers, in order to enhance convective drying rates. Unfortunately, the initial and operating costs are such that the enhancement obtained does not offset the added cost although all the mentioned techniques do provide significant enhancement of the drying time required (Mujumdar, 2004). Furthermore, combinations with infrared irradiation have also been described (Rosenberg and Bogl, 1987).

The earliest example of microwave drying process is the finish drying of potato chips, actually it was the first great industrial microwave heating success (Shiffmann, 1986; 2001). Microwave drying has been used in drying of pasta (Anonymous, 1972a; b; 1974; Fredrickson, 1975; Al-Duri and McIntyre, 1991), fruit powder, fruit and vegetable concentrates and extracts, model fruit gels (Aref et al., 1969; Bhartia et al., 1973; Bolin, 1972; Bricout et al., 1971; Brygidyr et al., 1977; Elias, 1979; Drouzas and Saravacos, 1999), milk and milk products (Al-Duri and McIntyre, 1991; 1992; Kim and Bhowmik, 1995), meat products (Armour and Co., 1969; Brighenti et al. 1982), cereal products such as rice, maize, wheat, barley (Aref et al., 1969; Calderwood, 1971; 1972; Elias, 1979; Fanslow and Saul, 1971), potato (Bouraout et al., 1994), potato chips (Davis et al., 1965), macaroni beads (Goksu, 2003), various substances containing animal and vegetable fat (Archieri et al., 1971; Guerga, 1972), raisins (Tulasidas et al., 1993; 1996; Kostaropoulos and Saravacos, 1995), apple and mushroom (Funebo and Ohlsson, 1998), diced apples (Feng and Tang, 1998), carrots (Prabhanjan et al., 1995; Litvin et al., 1998; Lin et al., 1998; Sumnu et al., 2005), peppers (Yasar 1999; Secmeler 2003), herbs (Giese, 1992), tomato (Chin et al., 1985), strawberry (Hemphill and Martin, 1992), banana (Drouzas and Schubert, 1996; Maskan, 2000), cranberries (Yongsawatidigul and Gunasekaran, 1996), egg yolk paste (Faillon et al., 1977; 1978), fish protein (Rosenberg and Bogl, 1987) and American ginseng roots (Ren and Chen, 1998).

An increasing number of processes such as drying of pasta, potato chips, onions, snack foods, cereals and finish drying of biscuits and crackers have become commercially successful (Decareau and Peterson, 1986; Schiffmann, 2001). Drying of cereal and grains, pasta and macaroni, rice, seasoning, fruits and vegetables, tea , tobacco, instant food, coconuts, sago, flour, fruit pectin, sugar coated anised blocks, mango cubes (vacued), meat, onion, seafood, rock sugar, animal feeds, prawn/fish crackers, herbs and spices, snack and biscuits are the examples of microwave drying applications in the world industry today (http://www.ansatechno.com/products-food.htm; www.romill.cz).

## 1.4 Infrared (Halogen Lamp) Drying

Infrared radiation is the part of electromagnetic spectrum of the sun that is predominantly responsible for the heating effect of the sun. Infrared radiation can be divided into three different categories: near-infrared radiation, mid-infrared radiation and far-infrared radiation. Infrared radiation lies in the wavelength range between 0.78 and 1000 μm and in the frequency range of $3*10^{11}$ and $4*10^{14}$ Hz (Hall, 1962; Modest, 1993; Ohlsson and Bengstsson, 2002).

When radiation is used to heat or dry moist materials, the radiation impinges the exposed material, penetrates it and the radiation energy is converted into heat

(Ginzburg, 1969). Because a material is heated intensely, the temperature gradient in the material reduces within the short period. Therefore, energy consumption in infrared drying is relatively lesser. Infrared energy is transferred from the heating element to the product surface without heating the surrounding air (Jones, 1992).

Infrared heating is especially suitable to dry thin layers of material with large surface exposed to radiation. Application of infrared heating to food drying is recently of special interest due to the progress in radiator construction. Their efficiency is between 80% and 90%, the emitted radiation is in narrow wavelength range and they are miniaturized (Sandu, 1986; Nowak and Lewicki, 2004).

Food products usually contain large amount of water. Therefore, absorption of infrared energy by water is an important variable affecting drying kinetics. Generally, solid materials absorb infrared radiation in a thin surface layer. However, moist porous materials are penetrated by radiation to some depth and their transmissivity depends on the moisture content (Lampinen et al., 1991). During drying, radiation properties of the material are changing because of decreasing water content. As a result, its reflectivity increases and the absorptivity decreases (Nowak and Lewicki, 2004).

Infrared radiation is transmitted through water at short wavelength, while at long wavelength, it is absorbed on the surface (Sakai and Hanzawa, 1994). Therefore, drying of thin layers seems to be more efficient at far-infrared radiation, while drying of thicker bodies should give better results at near-infrared (Nowak and Lewicki, 2004).

Heat and mass transfer during drying of food material with infrared energy is not well described in the literature. The heat transfer differs substantially with respect to convective heating. The radiation energy is absorbed by the surface layers and converted to heat. The highest temperature occurs under the irradiated surface layer and depends on the extinction coefficient in wet bodies. The smaller the extinction coefficient, the larger the distance from the surface at which maximum temperature occurs (Ginzburg, 1969). Hence, heat generated in a layer under the surface is conducted towards the center of the material as well as to its surface. Heat from the surface to the surrounding air is transferred by convection. On the other hand, water flux is transported all the time from the center of the material to its surface. As a result, in the part of the material, heat and mass fluxes are countercurrent and in layers close to the surface are cocurrent. At the surface, both fluxes are cocurrent and the concentration and temperature profiles in the air should be different than those occuring during convective drying (Nowak and Lewicki, 2004).

Hasatani et al. (1988) have developed a model of drying by infrared energy. Their model assumes that the energy is absorbed on the surface and divides drying into three parts. The first part accounts for heating up the material and constant drying rate period. It is assumed that internal mass transfer resistance is negligible and water is evaporated from the surface. Water vapor pressure on the surface is equal to the saturated vapor pressure at the surface temperature. The second part occurs at the beginning of the falling rate drying period. Dry patches occur on the surface and drying rate begins to decrease. Further drying leads to a dry surface layer and the zone of water evaporation retreats towards the center. Water is transported as vapor through the dry layer and this period of drying is treated as the third part. Heat absorbed by the material being dried is taken into account, but the external heat transfer resistance is omitted in the energy balance. Ratti and Mujumdar (1995) developed energy and mass balance accounting for the shrinkage of the heated particle and absorption of infrared energy. According to theoretical calculations, intermittent infrared drying with energy input 10 kW/$m^2$ becomes equilavalent to convective drying in which heat transfer coefficient would be as high as 200 W/($m^2$ K).

Several researchers have demonstrated the advantages of infrared drying as:

- Heat transfer coefficients are high, the process time is short and the cost of energy is low.
- It is easy to direct the heat source to drying surface.

- Response times are quick, which allows easy and rapid process control (if needed). This is especially crucial due to fast heating and possibilities of overheating of the material.
- The process can be done at ambient air temperature as air is transparent to infrared radiation and necessity for air flow across the product is reduced.
- Incorporating infrared radiation into an existing dryer is simple and capital cost is low.
- High quality finished products are achievable (decreased chance of flavor loss, preservation of vitamins, absence of solute migration from the inner to the outer regions).
- Temperature in the product is uniform while drying.

(Dostie et al., 1989; Navari et al., 1992; Afzal and Abe, 1994; Sakai and Hanzawa, 1994; Mongpreneet et al. 2002)

Halogen lamp heating provides near-infrared radiation and has a wavelength range between 0.7 and 5 μm. Near infrared has a penetration depth of several millimeters in many foods. Hence, it can be used to about the same effect as microwaves or high frequency for thin materials (Ohlsson and Bengstsson, 2002).

Earlier attempts by Ginzburg (1969) and Yagi and Kunii (1951) to apply infrared radiation to drying process of agricultural materials have been reported in the literature. Combined infrared radiation and convection or vacuum drying has also been reported (Hasatani et al., 1983; 1986; Abe and Afzal, 1997; Dontigny et al., 1992). In intermittent infrared and continuous convection heating of a thick porous material, the drying time was 2-2.5 times less with respect to convection alone while keeping good surface quality and high energy efficiency (Dostie et al., 1989). Far infrared drying of potato achieved high drying rates with infrared heaters of high emissive power (Masamura et al., 1988). Far infrared and near infrared drying using three types of granular bed and their quantitative comparison to hot air drying from the view point of the heat transfer has been studied by Hashimoto et al. (1991). Tan et al. (2001) have investigated the effect of drying conditions on color changes of potato and pineapple with a combination of intermittent infrared and continous convection heating. 'Intermittent infrared heating reduces drying time in convective drying of osmosed products. However, depending on the product, intermittent infrared heating may or may not reduce color degradation, compared to continuous infrared heating' was one of the main findings of their study. Datta and Ni (2002) reported the application of combined infrared, microwave and hot air heating food materials. Energy and quality aspects were studied during combined far infrared and convective drying of barley (Afzal et al., 1999). Hebbar et al. (2004) have developed a combined infrared and hot air heating system for drying of vegetables. Thin layer infrared radiation drying of onion slices was studied by Sharma et al. (2005) and their study have showed that drying time reduced by about 2.25 times on increasing power from 300 to 500W. The drying of apple slices and carrots by near infrared radiation has been studied by Nowak and Lewicki (2004) and Sumnu et al. (2005). Infrared drying found also application in the food analysis for the purpose of measuring moisture content in food products (Hagen and Drawert, 1986; Anon, 1995).

Drying of low moisture foods such as bread crumbs, flour, grains, malt and tea are the main applications of infrared heating in the food industry (Ohlsson and Bengstsson, 2002). Furthermore, drying of seaweed, vegetables, fish flakes and pasta is done in tunnel infrared dryers (Nowak and Lewicki, 2004).

## 1.5 Infrared-assisted Microwave Drying

Infrared-assisted microwave drying is a new technology, which is the combination of two different heating mechanisms: microwave heating and infrared heating. Infrared-assisted microwave drying combines the time saving advantages of microwaves with surface moisture removal advantages of infrared heating. Datta and Ni (2002) showed how the excess moisture that may accumulate on the food surface from microwave drying can be removed by combining microwave heating with infrared power of small penetration depth. The studies on infrared-assisted microwave drying are limited in scientific literature. Sumnu et al. (2005) studied drying of carrots in microwave and halogen lamp-microwave combination ovens. The effects of different drying methods on quality of carrots were compared. Microwave drying at the highest power and halogen lamp-microwave combination drying reduced the drying time significantly. Carrots dried in microwave and halogen lamp-microwave combination oven had significantly less color deterioration and higher rehydration ratio. Hence, these methods of drying can be recommended for drying of carrots in the instant soups and snack foods industry. Furthermore, halogen lamp-microwave combination oven can be advised to be used when the product moisture content is required to be reduced to very low values (Sumnu et al., 2005).

Infrared-assisted microwave heating technology is used for the purpose of baking, broiling, grilling and roasting (with no preheating) of foods like chicken, potatoes and steak more often. Halogen lamp-microwave combination oven providing near infrared-assisted microwave heating is preferred owing to the following advantages:

- It is up to eight times faster than a conventional oven.
- Oven has the ability of increasing the surface temperature and removing the surface moisture build up.
- It produces surface browning and crispiness.
- It gives even heat to the oven cavity due to the presence of turn table and fan.
- It provides maximum space efficiency.
- Preheating is not needed as it is needed for conventional ovens.

(www. kitchenquest. com/ critique/ advantium; www. geappliances. com/ advantium/ home. htm).

## 1.6 Bread Crumbs

**Figure 1.1** Bread Crumb

The word bread crumb (Figure 1.1) or breading (breader) is a general term that refers to a large group of flour based, ground coatings (Dyson, 1990). Breading is defined as:

- A flour based bread crumb or cracker meal that is applied to a food in a dry form primarily to create a desired coating texture, and
- A dry food coating made from flour, starch, seasonings, etc., that is coarse in nature and is applied over moistened or battered food products; the coating can be fine to coarse in particle size (Suderman and Cunningham, 1983).

Bread crumbs have been used by numerous sectors of the food preparation industry for as long as foods have been fried; however, the use of bread crumbs to manufacture prefried convenience foods began only in the middle 1950s. The still burgeoning convenience food and franchise supply industries had their origins at that time, primarily in the frozen fish area with the introduction of the fish stick or fish finger (Dyson,1990).

Four broad groups of bread crumbs meet the definition of "thermally processed cereal particles". These are:

- Cracker Meal, Traditional Bread Crumbs
- Home-Style Bread Crumbs
- Japanese-Style Bread Crumbs
- Extruded Bread Crumbs

Their manufacturing processes are given in Figure 1.2.

**Cracker Meal, Traditional Bread Crumbs** are widely used, particularly on fish products.

The manufacture of traditional bread crumb uses variations on the following scheme.

The flour, reducing sugars, salt and any color are intensively blended and mixed with water in a continuous mixer to form a dough, which is then forced through a series of paired rollers with decreasing clearance between them. Rolling action forms the dough into a sheet of approximately 1 in. thick, which is then conveyed onto a moving band for the purpose of rapid baking. The amount of effective cooking is adjusted not only by the baking time and temperature, but also the dough thickness and the water-solids ratio in the dough. The degree of cooking (extent of cook) is determined by various cereal chemisty methods.

The endless sheet of baked dough, approximately 35% moisture content (wet basis), is then crumbled through a granulating mill or a slow-speed grinder. It is then dried to a final moisture content of approximately 8% (wet basis). This moisture level ensures the long-term stability of the bread crumb and contributes to its absorptive capacity. The dried coarse particles are then roller milled, sifted, and blended as required to arrive at the appropriate mesh specification.

In the manufacturing process, fermentation is not involved and crumbs are predust. Predust term refers to fine, dry material that is dusted onto a food first. Predusts can be unprocessed flours or blends of starch, egg whites, and gums of particle sizes similar to those of flour. These types of materials may be used in a dry form as predusts or in water suspensions as batters.

Traditional bread crumbs are not porous and are very tolerant to longer cooking times. Generally, their particle size is very fine.

**Home-Style Bread Crumbs** are produced in a wide variety of ways, centered about a traditional baking system. The flour is formed into a dough with water, yeast and shortening, with appropriate levels of sugar and salt as required to meet the criteria of the final processor.

Both batch and continuous mixing systems are used, but the procedures follow the mature technology of breadmaking. The dough is divided, proofed and baked into loaves. These loaves are allowed to cool and then shredded, dried and sifted to meet mesh specifications. This type of bread crumb is tender, has a porous structure and intolerant to long cook times.

**Japanese-Style Bread Crumbs**, also called Oriental style or Panko type, are made using standard dough mixing methods; however, the dough is proofed in special baking pans that permit a unique heat treatment during baking. This method of baking gives bread that is essentially free of brown crust particles.

An alternate method of baking utilizes electrical resistance, which allows the proofed dough to be cooked rapidly in 10 minutes or less. The pans are unloaded, and the loaves are cooled, shredded, dried and sifted. These crumbs are crust-free, very porous, light in density, usually of a very large particle size, and has a splintery or needle-like shape.

**Extruded Bread Crumbs** can be made on a wide variety of continuous mixers or cooker-extruders. These machines have also been used to manufacture pregelled starches, low density snacks and crispbread crackers. In this system, flour is continuously mixed under highly turbulent and intensive conditions; steam is injected; and the resulting slurry of cooked flour is pumped through an orifice. This continuous "rope" of cooked dough is then shredded, dried and sifted (Dyson, 1990; Sunderland, 1993).

According to Sunderland (1993), extrusion cooking sytems provide excellent organoleptic characteristics in the production of bread crumbs.

Bread crumbs are used for coating foods, topping casseroles, stuffing poultry, thickening stews and adding inexpensive bulk to meatloaves, hamburgers and fish cakes. In addition, they give long-lasting crunch to fried cheese, prawns, mushrooms and other appetizers. Due to these usages, people make their own bread crumbs at home by roasting, drying and grinding stale bread. Spices and/ or flavorings may be blended into the bread crumbs (www. foodsubs.com; www. kikkoman. com).

In Turkey, there is only one company (Undano, Ankara) that produces bread crumbs. Dough consisting of wheat flour, yeast, salt, fat, water and preservative is both baked and dried in tunnel ovens. Baked and dried dough having small thickness is then ground. Two types of bread crumbs with different particle size are obtained after grinding. Bread crumbs are used for coating meat, frozen vegetables nowadays and they are expected to be used for coating different products in the near future such as cheese.

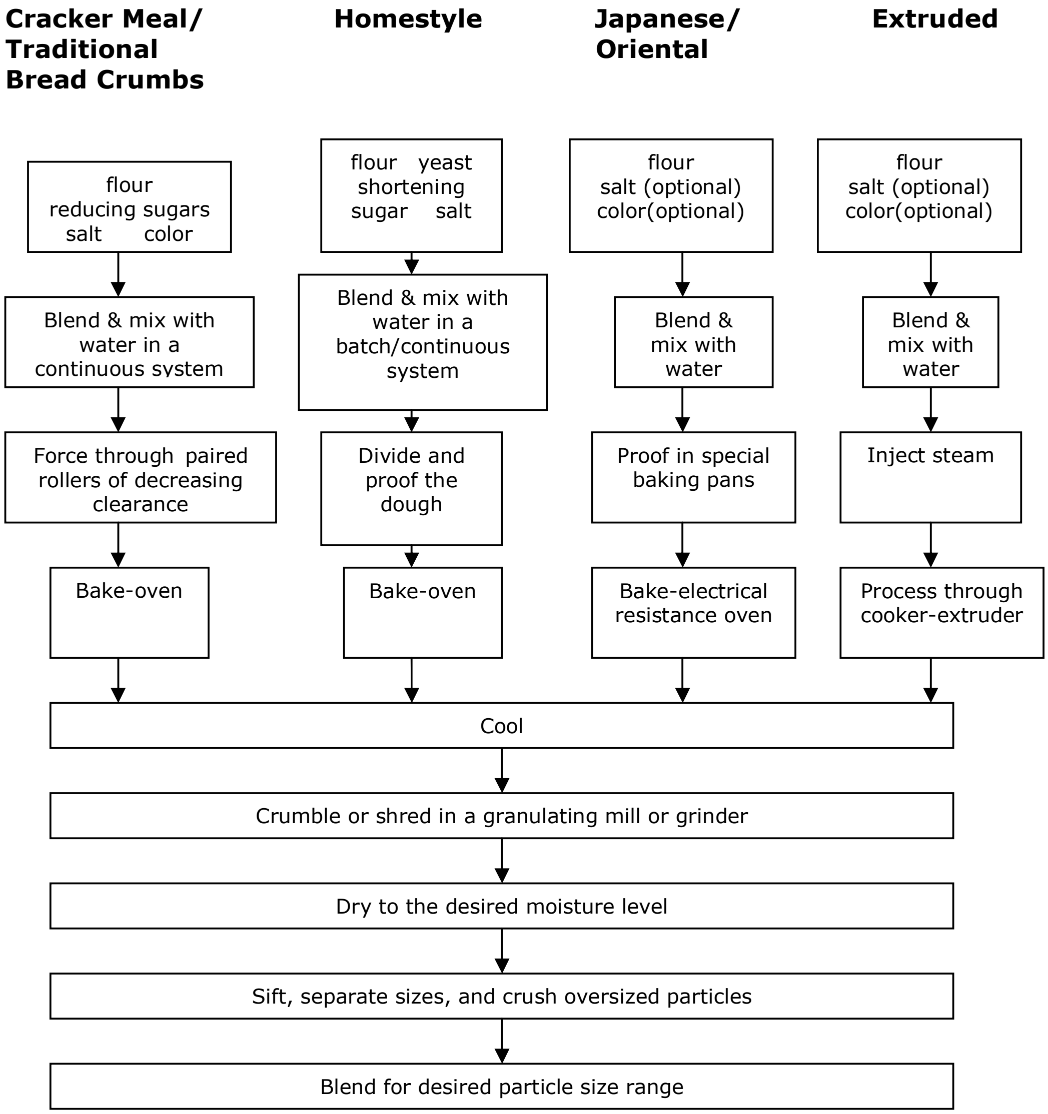

**Figure 1.2** Processing steps for bread crumb manufacture (Dyson, 1990).

## 1.7 Objectives of the Study

The main objective of this study was to investigate the possibility of using halogen lamp-microwave combination oven, which can provide microwave, infrared and infrared-assisted microwave heating, for production of bread crumbs and to determine the drying conditions in halogen lamp-microwave combination oven in order to produce bread crumbs with the highest quality.

Accumulation of moisture on the food surface is the main drawback of microwave drying method. Therefore, it was aimed to remove moisture from surface and to prevent sogginess of the dried product by using halogen lamp-microwave combination oven which has the advantages of two heating modes.

Halogen lamp-microwave combination oven is a new technology and there is only one study available in the scientific literature about drying by using this new technology. Hence, it was aimed to compare infrared-assisted microwave drying with microwave drying, infrared drying and conventional oven drying. While a number of studies has been conducted to determine the influence of different processing conditions in microwave ovens on various individual food components and drying rates, there is comparatively little research in the area of effects of processing on finished product quality. In addition, there is no information about bread crumbs although bread crumb production has been a fertile ground for research. Therefore, in the first part of the study, it was aimed to obtain drying curves of different drying methods (conventional oven drying, microwave drying, infrared drying and infrared-assisted microwave drying). It was also aimed to reduce conventional drying time by using halogen lamp-microwave combination oven. In the second part of the study, the effects of different processing conditions such as halogen lamp power and microwave power on the quality (color and water binding capacity) of the bread crumbs were investigated.

# CHAPTER 2

# MATERIALS AND METHODS

## 2.1 Materials

Flour was supplied from Ankara Un, Turkey. It contains 32% wet gluten, 13.1% moisture and 0.55% ash. All the other ingredients were obtained from a local market.

## 2.2 Bread Crumb Production

Processing steps for the production of bread crumb is given in Figure 2.1. The processing scheme given in Figure 2.1 is a modified cracker meal / traditional bread crumb manufacturing process.

The composition of the crumb dough was 100% flour, 4.3% sugar, 1.9% salt and 64.4% water (Flour weight basis).

The flour, sugar and salt were mixed for 2 minutes by a mixer at 58 rev/min (Kitchen Aid, 5K45SS, St. Joseph, USA). Then, water was added to the dry mixture and mixed again for 2.5 minutes with the same mixer at the same speed. At the end of second mixing, the dough was punched in order to make the dough be ready for the rolling step and to have an efficient moulding process. Punched dough was then rolled into a sheet having a thickness of 3.02±0.009 mm with the help of a pasta machine (Otello, Italy) shown in Figure 2.2. Additional flour (on dough basis; 100 % dough, 0.8% additional flour) was used to avoid sticking of dough sheet to the equipment. Moulding was done by cutting the dough sheet to have a circular shape with a diameter of 8.9±0.01 cm and weight of 20.8 g. Prior to drying step, initial moisture content of the dough was determined by weighing 10 g of dough sheet with an electronic balance

(Adventurer™ OHAUS, China), and drying in 100°C oven (Dedeoğlu, TS-5050, Turkey) until a constant weight value was reached. Initial moisture content was determined as 40.925±0.0250% (wet basis). Cut dough sheets were dried by using conventional oven, microwave, infrared and infrared-assisted microwave drying methods up to a final moisture content of 8% (wet basis). Weight and time data were recorded during the drying process and time intervals were adjusted according to the drying method. Finally, dried cut dough sheets were blended with a coffee mill (Moulinex Super Junior S, France) for 2.5 minutes.

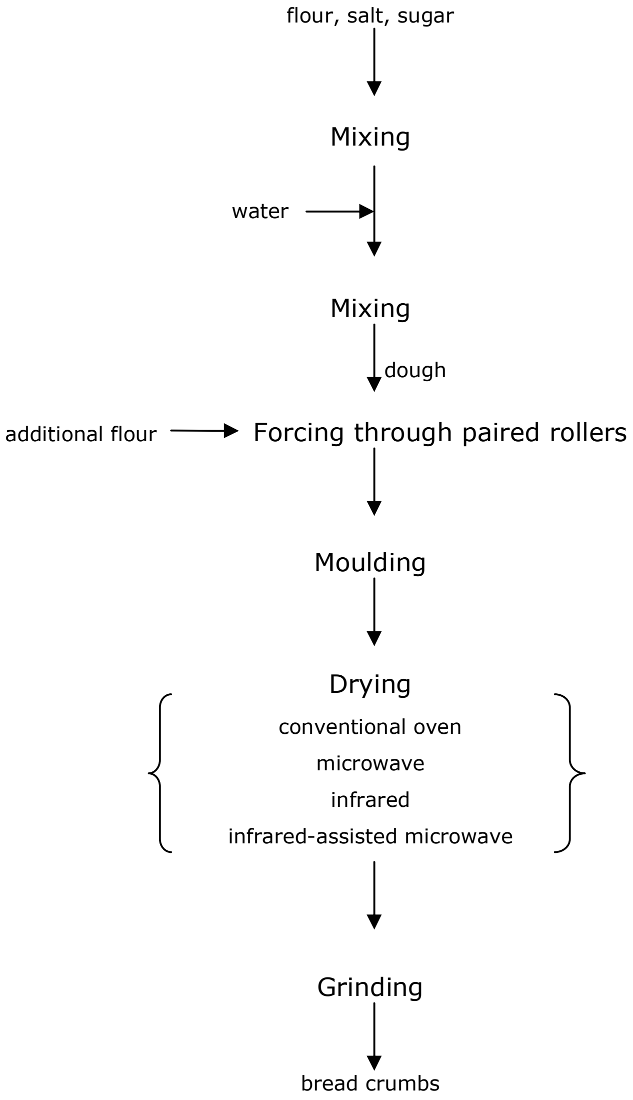

**Figure 2.1** Processing steps for bread crumb production

**Figure 2.2** Pasta machine

### 2.3 Determination of Power of Microwave Oven

IMPI 2-liter test was used for the determination of microwave oven power. The oven was operated at the highest power (100%) with a load of 2000±5 g of water placed in two 1 L Pyrex beakers. Initial temperature of water was adjusted to be $20\pm2^{\circ}$C. The beakers were placed in the center of the oven, side by side in the width dimensions of the cavity. The oven was turned on for 2 minutes and 2 seconds. The beakers were removed from the oven, and the final temperatures were measured and recorded. The power measurement was replicated three times. The power was calculated from the following formula:

$$P(W) = \frac{70(\Delta T_1 + \Delta T_2)}{2} \tag{2.1}$$

where, $\Delta T_1$ and $\Delta T_2$ are the temperature rises of the water in the two beakers, obtained by subtracting the initial water temperature from the final temperature (Buffler, 1993).

### 2.4 Drying

As mentioned earlier after the moulding step, crumb dough was dried to a moisture content of 8% by using four different drying methods. In each method, all weight measurements were done with the same electronic balance stated before. In all the drying treatments except for conventional oven drying, a different dough sample was dried for each time interval.

#### 2.4.1 Conventional Oven Drying

Conventional oven drying was conducted by using a commercial electrical oven (Arçelik ARMF 4 Plus, Turkey). The prepared dough samples were dried at 75°C. Weight of the dough samples were measured for every 120 seconds. The oven was preheated for 10 minutes at the same temperature before placing the dough samples into it. Conventionally dried crumbs were used as control.

#### 2.4.2 Microwave Drying

Halogen lamp-microwave combination oven (Advantium Oven™, General Electrics, USA) was used by operating only the mode of microwave heating for the purpose of microwave drying. Figure 2.3 shows the halogen lamp-microwave combination oven. The power of the oven was found as 706 W by the IMPI 2-liter Test (Buffler, 1993).

Microwave drying experiments were carried out at 30%, 50% and 70% microwave powers. During drying, weight of the crumb dough was recorded with 15 seconds of time intervals.

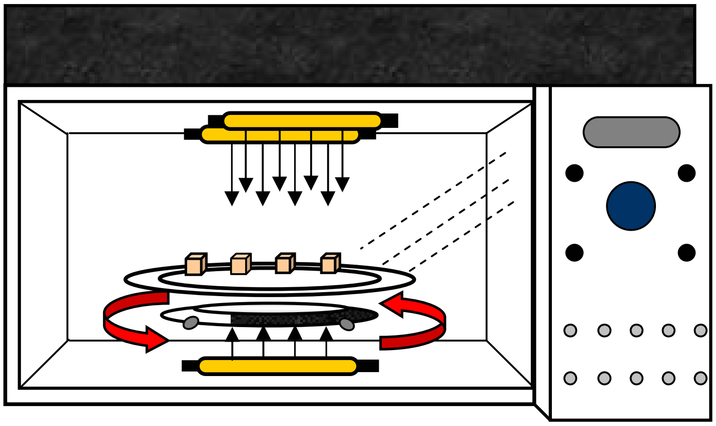

**Figure 2.3** Halogen lamp-microwave combination oven

### 2.4.3. Infrared Drying

Halogen lamp-microwave combination oven (Advantium Oven™, General Electrics, USA) was used by operating only the mode of halogen lamp heating (near-infrared heating). There are two 1500 W halogen lamps at the top of the oven and one 1500 W halogen lamp at the bottom of the oven. During halogen lamp drying, upper and lower halogen lamps were operated at the same power.

Drying experiments were performed at 30%, 50% and 70% halogen powers. Weight data were taken with a time interval of 60 seconds.

### 2.4.4 Infrared-assisted Microwave Drying

Halogen lamp-microwave combination oven (Advantium Oven™, General Electrics, USA) combines two different heating mechanisms, microwave and near-infrared heating.

Samples were dried at 30%, 50%, 70% halogen lamp powers and at 30%, 50% and 70% microwave powers in halogen lamp-microwave combination oven. Weight of the dough samples was measured for every 15 seconds.

### 2.5 Quality Measurements

Quality measurements were conducted for the purpose of determining the optimum drying method in the production of bread crumbs. The quality parameters were color and water binding capacity of crumbs.

### 2.5.1 Color

Color was evaluated by measuring CIE L*, a*, and b* parameters of bread crumbs by means of Minolta color reader (CR-10, Japan). L*, a* and b* indicates whiteness/darkness, redness/greenness, blueness/yellowness values, respectively. Three color data were taken from different locations for each sample. The changes in each color parameters were calculated from the following equations.

$$\Delta L^*=L^*-L_0^* \tag{2.2}$$

$$\Delta a^*=a^*-a_0^* \tag{2.3}$$

$$\Delta b^*=b^*-b_0^* \tag{2.4}$$

The subscript ‘0’ refers to the initial color parameter of dough at the beginning of the drying experiment. The total color difference ΔE was determined using Equation 2.5.

$$\Delta E=[\Delta L^{*2}+\Delta a^{*2}+\Delta b^{*2}]^{1/2} \tag{2.5}$$

### 2.5.2 Water Binding Capacity

The water binding capacity of bread crumbs were determined by using the method of Medcalf & Gilles (1965). 2.5 g of crumbs was added to 37.5 ml deionized water in a tared 50 ml centrifuge tube. The tube was then capped and agitated using an environmental shaker (Aeroton, Infors HT, Switzerland) for 1

hour. After that, it was centrifuged for 10 minutes at 2200*g. The water was decanted and the tube tipped up and allowed to drain for 10 minutes. The tube was then weighed and the amount of water held by the sample was calculated by subtracting the initial weight of the sample from the weight of ‘treated’ sample. The water binding capacity was obtained from Equation 2.6.

$$\mathbf{WBC(w/w)} = \frac{\textbf{Weight of treated sample - Initial weight of sample}}{\text{initial weight of sample}} \qquad \mathbf{(2.6)}$$

Three replications were done for determination of water binding capacity.

### 2.6 Data Analysis and Model Evaluation

Microsoft® Excel 2003 was used for modelling of conventional oven and microwave drying data.

Curve Expert Version 1.37 (Curve fitting system for Windows) was used for non-linear regression analysis of infrared and infrared-assisted microwave drying data and to determine the parameters of models. Several number of models were checked by using SPSS 10.0 for Windows and fitted models were plotted with Microsoft® Excel 2003.

The goodness of the fit of the models was assessed using coefficient of determination ($r^2$). $r^2$ measures how well a linear or a non-linear model fit the data and higher the $r^2$ value, the better is the adequacy of the model to describe the data (Neter et al., 1996).

### 2.7 Statistical Analysis

Analysis of variance (ANOVA) was performed in order to determine the significant differences between the independent variables ($p \leq 0.05$). Variable means were compared by Duncan's Multiple Range test. Three replications were used for all of the experimental conditions.

# CHAPTER 3

# RESULTS AND DISCUSSION

## 3.1 Drying Characteristics

Cut bread crumb dough sheets having an initial moisture content of 0.409 (wet basis) were dried by using conventional oven, microwave, infrared and infrared-assisted microwave drying methods to a final moisture content of 0.08 (wet basis).

According to Prabhanjan et al. (1995), under microwave drying conditions equilibrium moisture content can be expected to be different with respect to conventional drying methods since microwaves can induce compositional and structural alterations in the product. As opposed to convective and vacuum drying, when material is dried to equilibrium moisture content for a given process condition (pressure, temperature, relative humidity), during microwave drying overall moisture can be removed resulting into zero equilibrium moisture content (Sander et al., 2003). In this study in all the methods used, bread crumb doughs were dried to a final moisture content of 0.08 (wet basis) rather than equilibrium moisture content which is dependent on the drying method. Therefore, the effective diffusivities for different drying methods were not determined or reported due to the presence of microwave drying.

### 3.1.1 Conventional Oven Drying

Conventional oven drying was used as the control drying method. It was aimed to compare the effects of microwave, infrared, infrared-assisted microwave and conventional oven drying methods on the drying rates of bread crumb doughs.

The time versus weight data recorded in the conventional oven drying experiments and the calculated moisture content values on wet basis from these are given in Appendix A (Tables A.1.1 and A.2.1) by using the experimentally determined initial moisture content value of 0.409. The data in Table A.2.1 were used to plot the drying curve in Figure 3.1, where the mean of the three replicates were used. As can be seen from Figure 3.1, variation of the moisture content with drying time could be well represented by an exponential decay, which is consistent with Equation 1.3, with a coefficient of determination of 0.99. In fact, moisture content was described as mass ratio (dry basis) in Equation 1.3 whereas moisture content is described as mass fraction (wet basis) throughout this study. As the effective diffusivity was not determined, constants of the exponential model was not checked. However, it was sufficient to see the trend of moisture content with respect to time as an exponential decay, in order to check whether the model was similar to Equation 1.3.

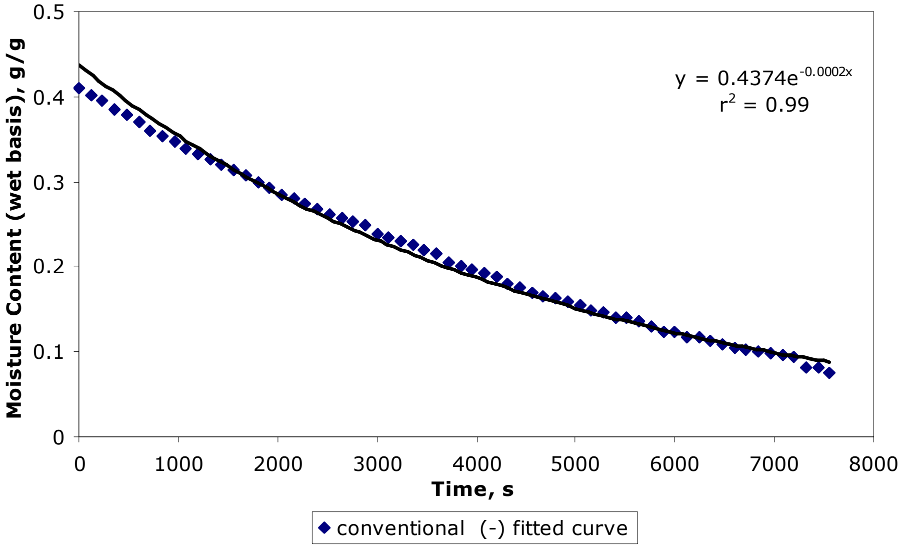

**Figure 3.1** Drying curve for conventional oven drying at 75°C.

In conventional oven drying, the time to dry bread dough from a moisture content of 0.409 to 0.08 (wet basis) was 7560 s at 75°C, which can be considered as a rather long drying time with respect to the weight and the dimensions of the dough. Temperature of the conventional oven was chosen as 75°C experimentally after trying 200°C, 175°C, 150°C and 100°C which caused non uniform drying due to crust formation on the surface of the dough as the thickness of the dough was small. Low thermal conductivity and case hardening of the material might be the main factors responsible for long drying times in conventional oven drying (Afzal et al., 1999).

### 3.1.2 Microwave Drying

The drying data obtained in microwave drying of bread crumb dough samples and the calculated moisture content on wet basis are given in Tables A.1.2 and A.2.2 by using the experimentally determined initial moisture content value 0.409. The data in Table A.2.2 were used in plotting the drying curves in Figure 3.2 where the effect of microwave power on microwave drying can be observed.

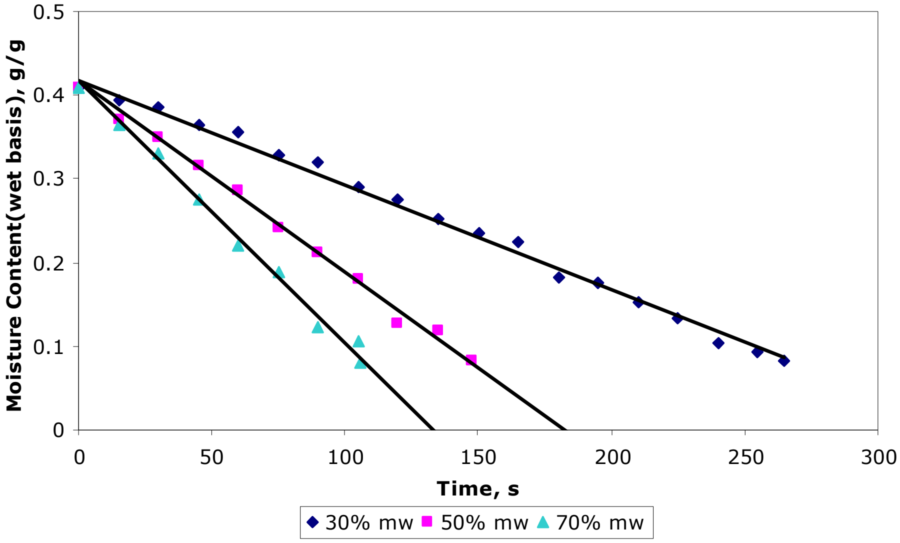

**Figure 3.2** Drying curves for microwave drying and the fitted lines for t>30 s.

As can be seen from 3.2, after about an initial period of 30 seconds moisture content decreased linearly with drying time in microwave drying, where this initial period may be considered as the adaptation period of the material to the drying conditions. The coefficient of determination value ($r^2$) of the fitted line was 0.99 for all of the microwave powers used (Table A.4.1). It was also reported that breads lost weight linearly with time in microwave oven which is in agreement with this study (Sahin et al., 2002; Keskin 2003).

The slopes of the drying curves correspond to the drying rates after the initial adaptation period. Hence, as shown in Table A.4.1 as microwave power increased, slope increased implying a proportional increase in the drying rate. This was expected since at higher microwave power more energy was supplied to the dough samples and higher internal temperatures were attained. This caused the vapor pressure to increase providing an increased driving force for mass transfer and hence the drying rate. Further, from Table A.4.1 it can be observed that the intercept values are same for all of the microwave powers studied and approximately equal to the initial moisture content (0.409).

Obtained slopes for the microwave drying conditions studied (Table A.4.1) were used to plot Figure 3.3 in order to see the effect of microwave power on the drying rate in microwave drying by taking the negative of the values. For the three points a linear regression was performed and with $r^2=1.0$ a relation for increase in the drying rate with microwave power between microwave powers of 30% and 70% was determined as,

$$-\frac{dX}{dt} = 0.00005(\%mw) - 0.00002 \tag{3.1}$$

where $X$ is the moisture content on wet basis (g/g), $t$ is the drying time (s) and $\%mw$ is the microwave power level.

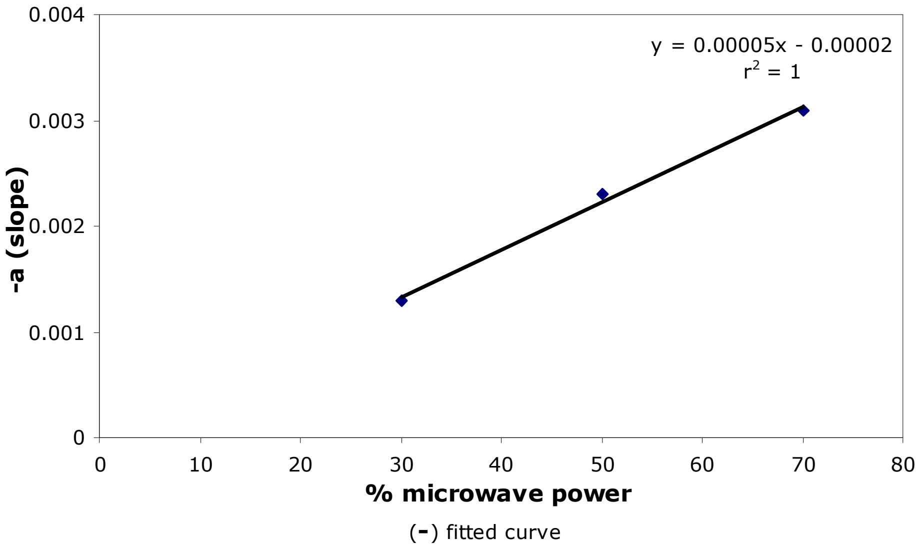

**Figure 3.3** Variation of the drying rate with microwave power.

It was also observed that microwave drying reduced the processing time drastically due to the high drying rates. It was possible to reduce the drying times by 96.5%, 98% and 98.6% at 30%, 50% and 70% microwave powers respectively compared to the conventional oven drying (Table 3.1). Shorter drying time in microwave oven can be explained by high internal pressure and concentration gradients created which increased the flow of liquid through the food to the boundary (Datta, 1990). Similar results were reported by different studies in which microwave drying was found to reduce convection drying time (Lin et al. 1998; Funeba and Ohlsson, 1998; Maskan 2000; Sumnu et al. 2005; Goksu et al. 2005).

### 3.1.3 Infrared (Halogen Lamp) Drying

The time versus weight data of infrared drying are tabulated in Table A.1.3 These data were converted into the moisture content on wet basis by using the initial moisture content value as 0.409 (Table A.2.3). The drying curves in Figure 3.4 were plotted by using the data in Table A.2.3. Figure 3.4 represents the influence of halogen lamp power on infrared drying.

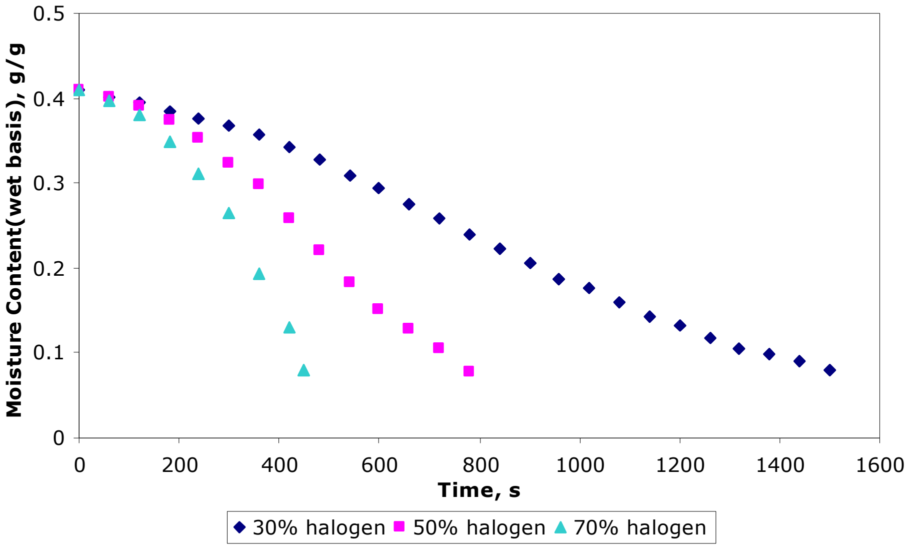

**Figure 3.4** Drying curves for infrared drying.

For all of the halogen lamp drying treatments, the drying time was found to decrease with increase in the halogen lamp power (Figure 3.4, Table A.3.1). Similar results have already been reported in the earlier studies on drying with infrared energy (Abe and Afzal, 1997; Afzal and Abe, 1999; Das et al., 2004). Again as expected with increasing halogen lamp powers, food was exposed to more radiative heat and the higher mass transfer driving force resulted in faster drying and consequently less drying time like the microwave case. Accordingly, 80.2%, 89.7% and 94% reduction in the drying time with respect to the conventional oven drying was observed at 30%, 50% and 70% halogen lamp powers, respectively (Table A.3.1). This shows that by infrared drying method it is possible to decrease drying time significantly. Similarly, Nowak et al. (2004) found that drying with application of infrared energy was much faster than convective drying.

From the trend of the curves and considering the theory model equation given as Equation 3.2 was used to express the moisture content on wet basis as a function of drying time. Used model equation was proposed with the inspiration from the infrared power flux which was modelled as an exponential decay (Ginzburg, 1969) and from the study of Datta and Ni (2002) in which infrared energy was assumed to decay exponentially.

$$y = 1 - \underset{\substack{\Downarrow \\ 1^{\text{st}}\text{part}}}{ae^{bx}} - \underset{\substack{\Downarrow \\ 2^{\text{nd}}\text{ part}}}{ce^{dx}} \tag{3.2}$$

where $y$ is the dependent variable (moisture content on wet basis, g/g), $x$ is the independent variable (drying time, min) and $a$, $b$, $c$ and $d$ are the model constants.

Model constants and the regression coefficients of the model were determined and are given in Table A.4.2. It was observed that measure of fit of data ($r^2$) was highly satisfactory for all of the halogen lamp powers studied. Model equations for infrared drying were also plotted and shown in Figure 3.5.

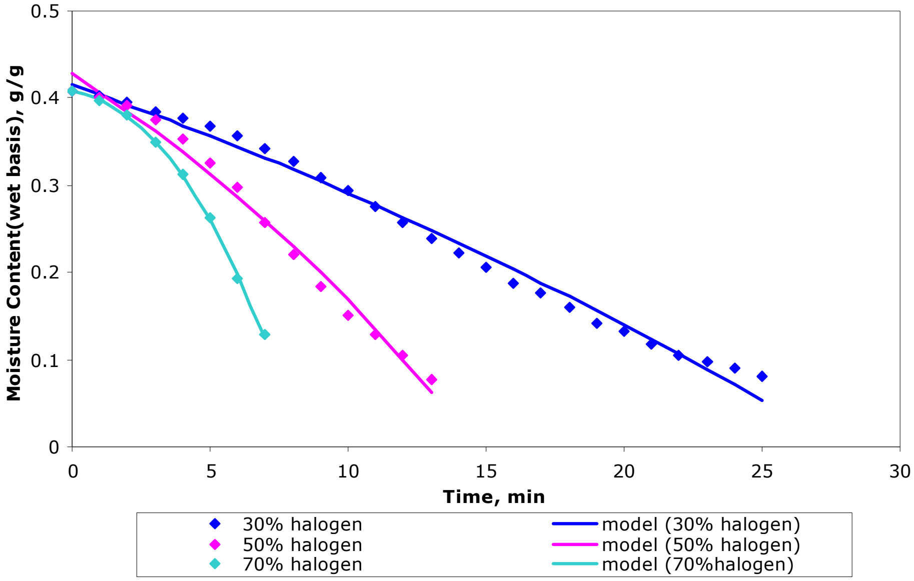

**Figure 3.5** Fitted models for infrared drying.

It was seen that at 30% halogen lamp power, contribution of both 1st and 2nd parts of Equation 3.2 were same as the model constants $a$ and $c$ were equal to each other and similarly the values of $b$ and $d$ were same. On the other hand, at 50% halogen lamp power, contribution of the 1st part was 1.19 to 1.97 greater than that of the 2nd part and at 70% halogen lamp power, contribution of the 1st part was 1.13 to 7.34 times greater than the contribution of the 2nd part (Table A.5.1). This shows that at high halogen lamp powers, 1st part of the model equation was more responsible for the moisture removal of the bread crumb dough samples. According to these observations, the 1st part may be related to the surface drying since more radiation is absorbed on the surface layers resulting into more surface moisture removal in infrared drying and the 2nd part may be related to the internal drying. In infrared heating, radiation is focused at the surface of the food which can help to remove moisture from the surface (Sumnu et al., 2005). Similarly, Datta and Ni (2002) showed surface removal advantages of infrared heating. In addition, 1 in the model can be thought as representing the maximum moisture content value on wet basis. It was also observed that contribution of the first part increased with respect to time at 50% and 70% halogen lamp powers (Table A.5.1). This was expected since as drying time increased, samples were subjected to more radiation resulting with more surface moisture removal. Furthermore, at low halogen lamp powers such as 30%, both the surface and the internal drying rates might have about the same amount of contribution to the overall moisture removal as the material being dried was rather thin enabling the internal moisture movement rate to supply the amount removed at the surface.

As only three halogen powers were studied in the complex mechanism of infrared drying, the effect of halogen power on the model constants could not be determined.

### 3.1.4 Infrared-assisted Microwave Drying

Weight data obtained in infrared-assisted microwave drying of bread crumb dough samples are given in Tables A.1.4, A.1.5 and A.1.6. These data were converted to moisture content on wet basis by using the initial moisture content value as tabulated in Tables A.2.4, A.2.5 and A.2.6. Drying curves were plotted by using Tables A.2.2-A.2.6 (Figures 3.6-3.14).

Figures 3.6-3.8 show the comparison of microwave and infrared-assisted microwave drying whereas Figures 3.9-3.11 show the comparison of infrared and infrared-assisted microwave drying. Figures 3.12-3.14 show the comparison of microwave, infrared and infrared-assisted microwave drying.

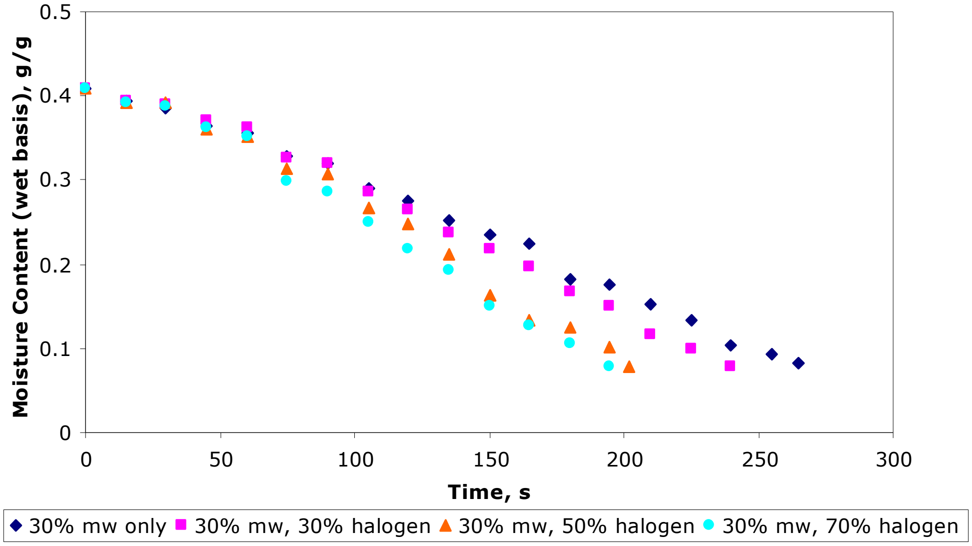

**Figure 3.6** Drying curves for microwave and infrared-assisted microwave drying at 30% microwave power.

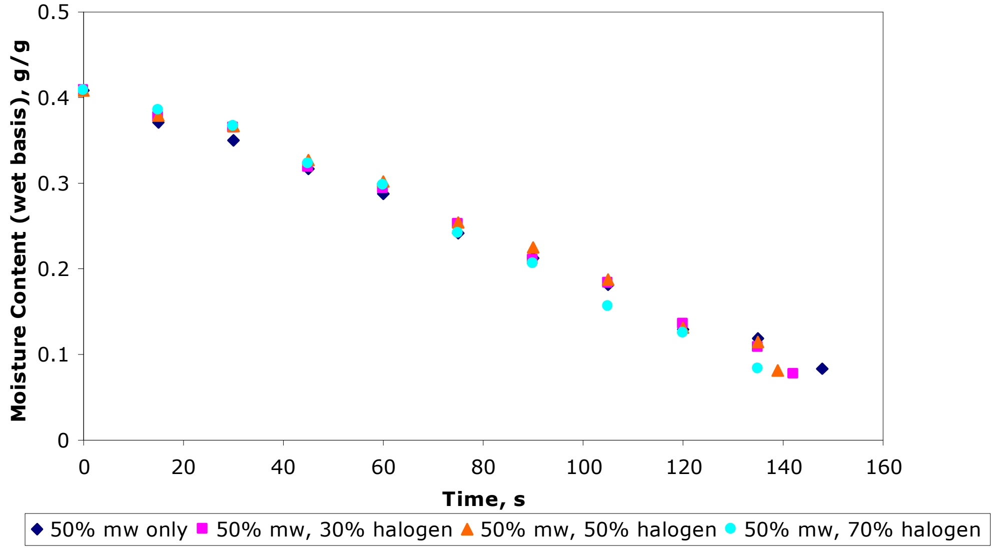

**Figure 3.7** Drying curves for microwave and infrared-assisted microwave drying at 50% microwave power.

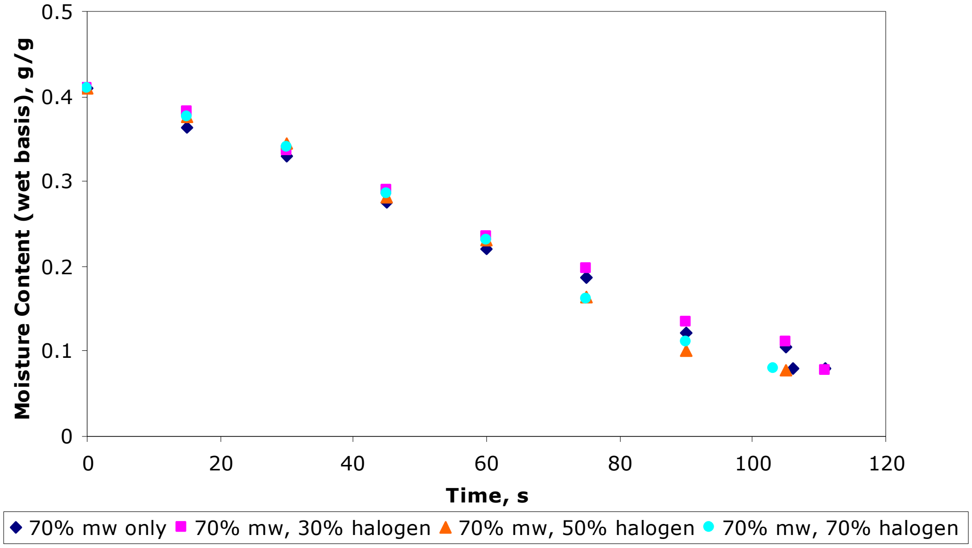

**Figure 3.8** Drying curves for microwave and infrared-assisted microwave drying at 70% microwave power.

Figures 3.6-3.8 indicate that microwave heating was the dominant mechanism affecting moisture loss in the infrared-assisted microwave drying at medium and high microwave powers. Since infrared-assisted microwave drying curves resembled the ones for microwave drying highly at 50% and 70% fixed microwave powers and the effect of halogen lamp power could not been observed as the data points coincided (Figures 3.7 and 3.8). Microwave heating being the dominant mechanism was also reported by Keskin et al. (2004) in infrared-assisted microwave baking of breads when weight loss was concerned. Similar behaviour at 30% fixed microwave power was seen at the first 60 s of drying. However, after 60 s the contribution of infrared power was seen clearly as the data points separated from each other showing that the increase in the halogen lamp power caused more moisture loss and hence faster drying (Figure 3.6).

Figures 3.9-3.11 show the role of microwave heating in the infrared-assisted microwave drying more clearly. Reduction in drying time due to the increase in microwave power was observed as quite similar to the microwave drying (Figures 3.2, 3.9, 3.10 and 3.11). This also shows that the contribution of microwave heating mechanism is more in the infrared-assisted microwave drying as was stated in discussion above.

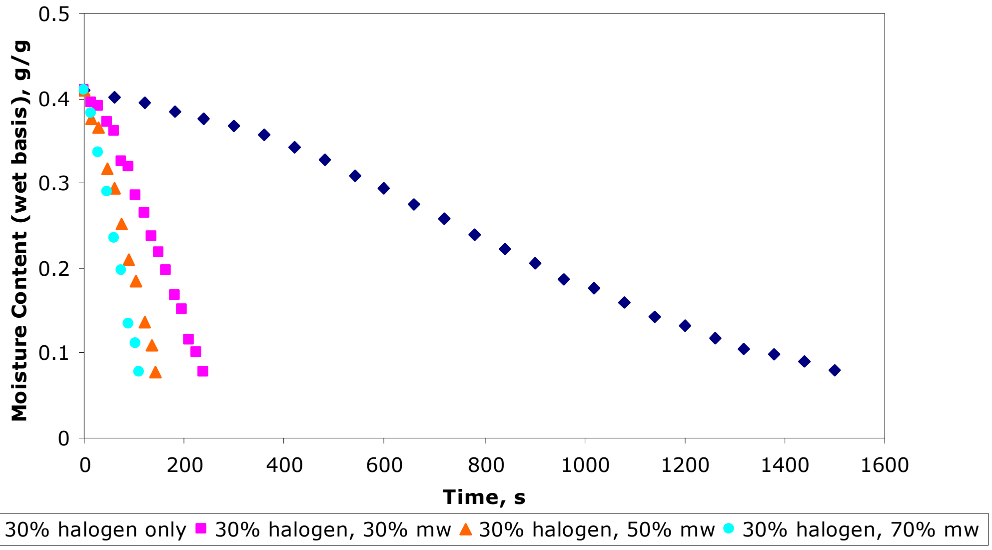

**Figure 3.9** Drying curves for infrared and infrared-assisted microwave drying at 30% halogen lamp power.

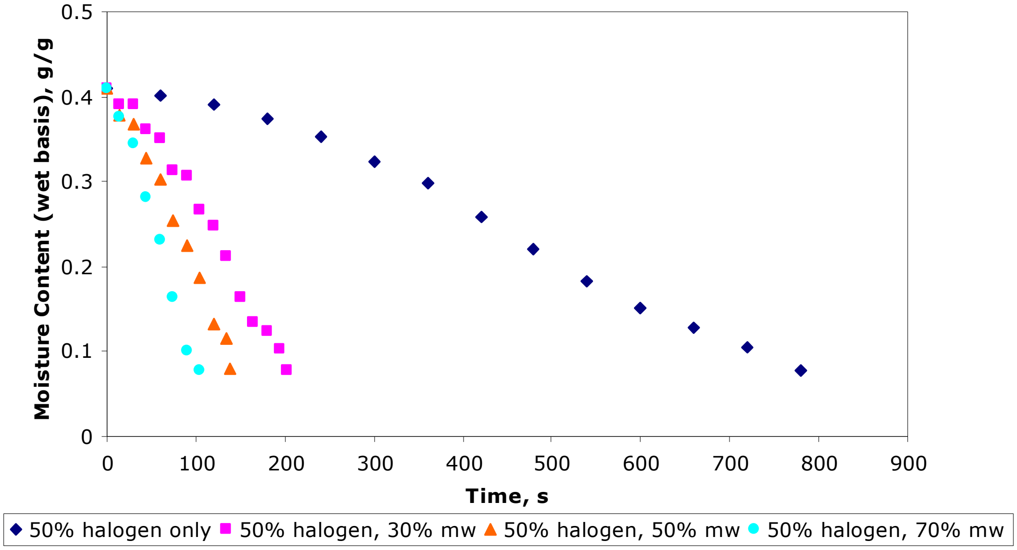

**Figure 3.10** Drying curves for infrared and infrared-assisted microwave drying at 50% halogen lamp power.

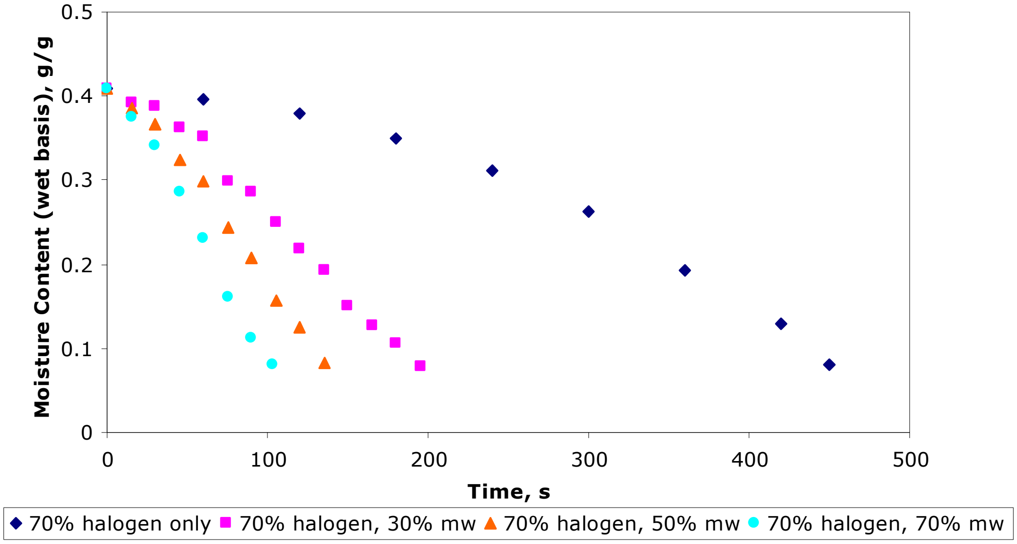

**Figure 3.11** Drying curves for infrared and infrared-assisted microwave drying at 70% halogen lamp power.

The results indicate that the drying behaviour under infrared-assisted microwave drying and microwave drying highly resemble each other. However, a difference for the drying behaviour under infrared drying from both when working at the same percent microwave power only and combined powers could be seen (Figures 3.12, 3.13 and 3.14). Hence, the fact that microwave heating dominated in the infrared-assisted microwave drying was encountered once more. Figures 3.12-3.14 also designated that microwave energy was more effective on the moisture removal resulting in reduction in drying time. This might be owing to the increased internal temperatures causing higher vapor pressure hence the driving force of the microwave energy with respect to the infrared drying.

As microwave heating was observed to be the dominant mechanism in the infrared-assisted microwave drying, further discussion of this part is on the infrared assisted drying at the studied microwave power contributions.

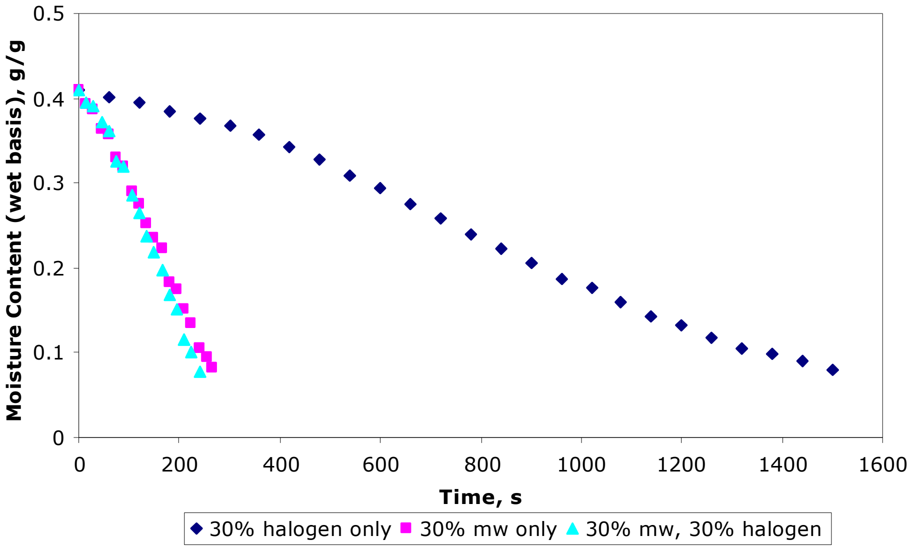

**Figure 3.12** Drying curves for microwave, infrared and infrared-assisted microwave drying at 30% values of each.

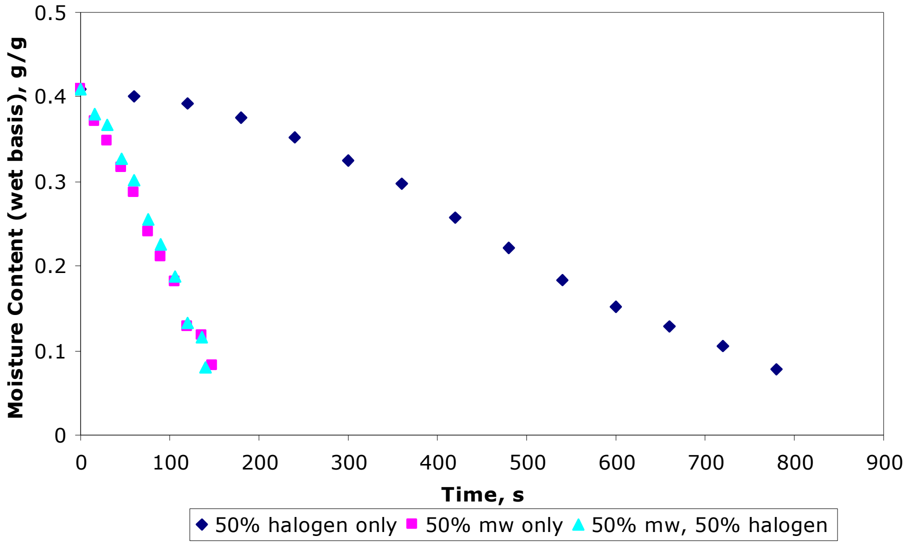

**Figure 3.13** Drying curves for microwave, infrared and infrared-assisted microwave drying at 50% values of each.

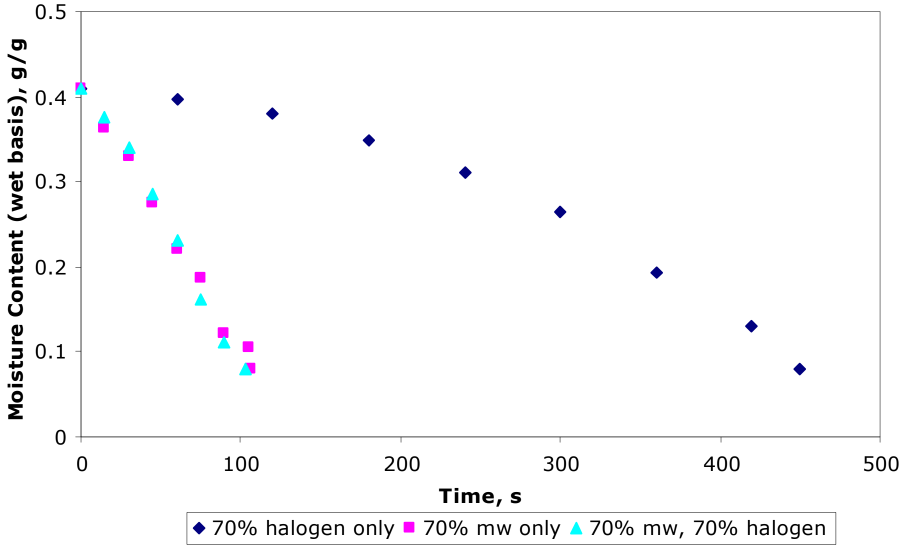

**Figure 3.14** Drying curves for microwave, infrared and infrared-assisted microwave drying at 70% values of each.

When infrared-assisted microwave drying was conducted at 30% and 50% fixed microwave powers, the dough samples dried faster as compared to using only infrared and microwave drying (Table A.3.1). This was an expected result since in the infrared-assisted microwave drying it was possible to reach higher internal temperatures due to microwave heating mechanism and higher surface temperatures due to infrared heating mechanism giving increased drying rate and therefore drying time decreased (Ni et al., 1999). Similar results were reported by Sumnu et al. (2005). In addition, infrared-assisted microwave drying reduced drying time significantly when compared with the conventional oven drying (Table A.3.1 and Table 3.1).

**Table 3.1** Percent reduction in the drying time with respect to the conventional oven drying for the studied infrared-microwave combinations.

| **mw**<br>**h** | 0% | 30% | 50% | 70% |
|---|---|---|---|---|
| 0% | - | 96.5 | 98.0 | 98.6 |
| 30% | 80.2 | 96.8 | 98.1 | 98.5 |
| 50% | 89.7 | 97.3 | 98.2 | 98.6 |
| 70% | 94.0 | 97.4 | 98.2 | 98.6 |

After modelling microwave drying and infrared drying individually, infrared-assisted microwave drying had been thought to show a behavior between linear and exponential. However, due to the high resemblence to infrared drying, proposed model equation (Equation 3.2), which describes the variation of moisture content with respect to time, was used as the model again for all of the power combinations in infrared-assisted microwave drying. Model constants and the regression coefficients were determined and are given in Table A.4.3 together with the $r^2$ values. Fitted models are illustrated by Figures 3.15-3.17 at which fixed microwave powers were used in order to see the effects of halogen lamp power and drying time.

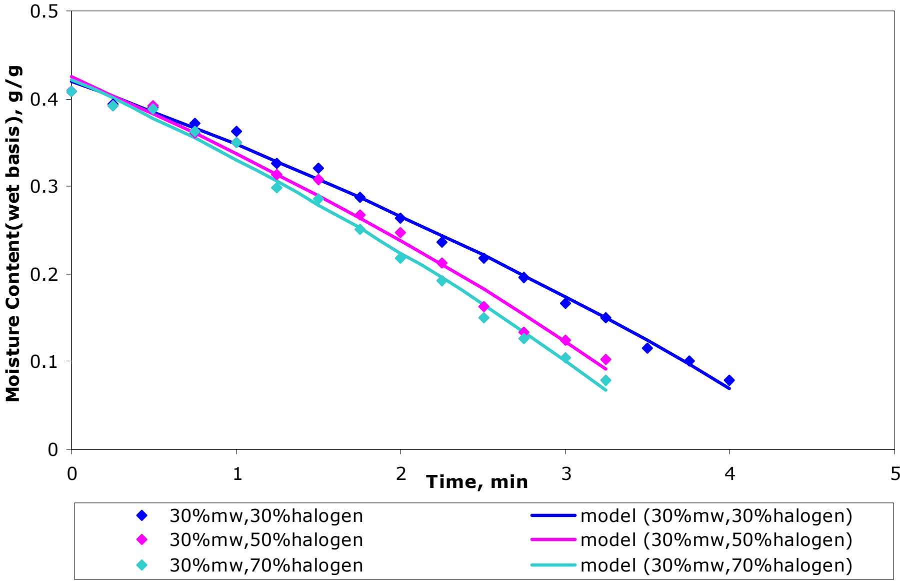

**Figure 3.15** Fitted models for infrared-assisted microwave drying at 30% fixed microwave power.

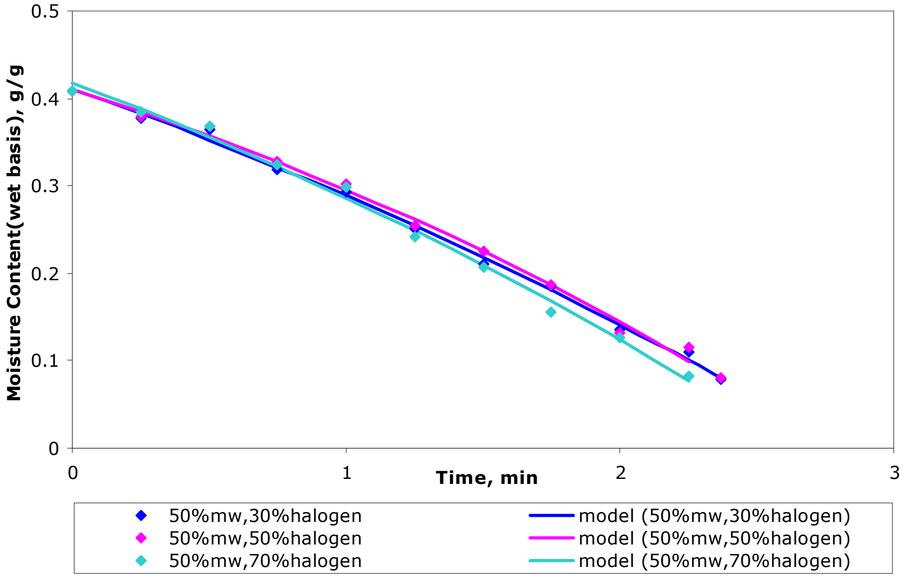

**Figure 3.16** Fitted models for infrared-assisted microwave drying at 50% fixed microwave power.

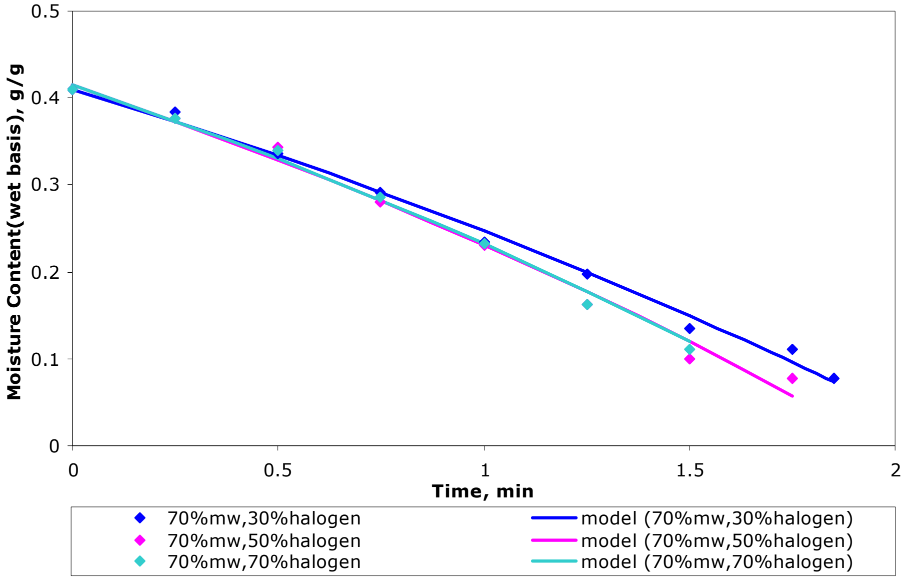

**Figure 3.17** Fitted models for infrared-assisted microwave drying at 70% fixed microwave power.

It was observed that except 50% microwave and 50% halogen lamp power, for all of the power combinations contribution of both the 1st and the 2nd part of the proposed model equation were about the same. According to the tabulated ratios, both parts of the model equation seem to be responsible for the moisture removal of the bread crumb dough samples equally (Tables A.5.2-A.5.4). Similar discussion for infrared drying is not valid for infrared-assisted microwave drying although the same model equation was used since combination of two complex heating mechanisms makes drying process more complex. Both parts might be responsible for both surface and internal drying and contribution of internal drying to both parts was thought to be higher than surface drying. Since microwave heating, which is responsible for internal drying, was found to be the dominant mechanism in infrared-assisted microwave drying. In addition, infrared heating mechanism might have provided additional internal moisture loss. It is quite impossible to determine the individual contribution of surface drying (infrared drying) and internal drying (microwave drying) to the proposed model equation.

At 50% microwave and 50% halogen lamp power, contribution of the 1st part was 1.30 to 2.35 times greater when compared with the contribution of the 2nd part and it was observed that ratio between two parts increased with respect to time (Table A.5.3). For this power combination, the 1st part was thought to reflect internal drying more. Furthermore, ratio increase with respect to time was an expected result due to more subjection of samples to more microwave and infrared heating.

### 3.1.5 Relative Drying Rate

Weitz et al. (1989) defined the relative rate of drying as:

$$\zeta = \frac{t_c}{t_s} \tag{3.3}$$

where, $\zeta$ is the relative drying rate, $t_c$ is the drying time of control sample (s), and $t_s$ is the drying time of treated sample (s) for the same initial and final moisture contents. In this study, conventional oven drying time was used as $t_c$. Drying times are defined as the time to reach a final moisture content of 0.08 g/g from 0.409 g/g (wet basis).

The relative drying rates (Table 3.2) varied from 5.04 to 73.40 (excluding 0% microwave and 0% halogen lamp power combination representing comventional oven drying), the highest being obtained with the infrared-assisted microwave drying at 70% microwave and 70% halogen lamp power combination. Infrared only drying gave smaller rates when compared with the other drying methods. This might be due to the fact that microwave heating is more effective and faster when compared to infrared heating for drying of the bread crumb doughs.

For all of the drying methods, an increase in microwave power and/or infrared power resulted with an increase in the relative drying rate. In addition, microwave power was found to be more effective on increasing the relative drying rate when compared with halogen lamp power (Table 3.2), which is another evidence of microwave heating being the dominant mechanism in the infrared-assisted microwave drying.

**Table 3.2** Relative drying rate of bread crumb dough (s/s) for different drying methods in reaching a moisture content of 0.08 g/g (wet basis) according to the Equation 3.3.

| **mw**<br>**hl** | 0% | 30% | 50% | 70% |
|---|---|---|---|---|
| 0% | 1 | 28.53 | 51.08 | 71.32 |
| 30% | 5.04 | 31.50 | 53.24 | 68.11 |
| 50% | 9.69 | 37.43 | 54.39 | 72.00 |
| 70% | 16.80 | 38.77 | 56.00 | 73.40 |

As a rough quantitative estimate for the fractional contributions, Table 3.2 can be inspected both column-wise and row-wise. It can be seen that for 20% increments in the powers the increase in the relative drying rate is about 16.81 s/s for the microwave and 1.88 s/s for the infrared power. Thus, contributions of the powers as microwave:infrared is about 9:1, which means that fractional contribution of microwave power is about 0.9 and that of infrared power is about 0.1.

So by having the relative drying rate results of microwave only and infrared only and the estimated fractional contributions, the change in the relative drying rate of infrared-assisted microwave drying for this study can be estimated from:

$$\Delta\zeta = (\Delta\zeta_i^{\,*} \times 0.1) + (\Delta\zeta_j^{\,*} \times 0.9) \tag{3.4}$$

where,

$$\Delta\zeta_i^{\,*} = \zeta_{i_2,1} - \zeta_{i_1,1} \tag{3.5.a}$$

$$\Delta\zeta_j^{\,*} = \zeta_{1,j_2} - \zeta_{1,j_1} \tag{3.5.b}$$

It should be noted that Table 3.2 is expressed in matrix notation, i.e. $\zeta_{i,j}$ indicates the relative drying rate for the $i^{th}$ row and the $j^{th}$ column combination of halogen lamp (infrared) and microwave powers in Equations 3.5.a and 3.5.b. i and j values represent power levels as 1=0%, 2=30%, 3=50% and 4=70%. Thus, $\Delta\zeta_i^*$ is the change in the relative drying rate between two halogen lamp powers in infrared drying only and similarly $\Delta\zeta_j^*$ is the change in the relative drying rate between two microwave powers in microwave drying only.

Equation 3.4 gives good estimates of the relative drying change for infrared-assisted microwave drying, i.e. $i_1$, $j_1>1$. Several examples comparing $\Delta\zeta$ according to experimental and calculated values are given in Table 3.3.

**Table 3.3** Several examples showing experimental and calculated values of $\Delta\zeta$ .

| **Powers** | $\Delta\zeta$ **(experimental)** | $\Delta\zeta$ **(calculated)** |
|---|---|---|
| $i_1=j_1=2$<br>$i_2=j_2=3$ | $\Delta\zeta=\zeta_{3,3}-\zeta_{2,2}$<br>=54.39-31.50=22.89 | $\Delta\zeta=(\Delta\zeta_i^*\times0.1)+(\Delta\zeta_j^*\times0.9)$<br>$\Delta\zeta_i^*=\zeta_{3,1}-\zeta_{2,1}$=9.69-5.04=4.65<br>$\Delta\zeta_j^*=\zeta_{1,3}-\zeta_{1,2}$=51.08-28.53=22.55<br>$\Delta\zeta=(4.65\times0.1)+(22.55\times0.9)$=20.76 |
| $i_1=3$, $j_1=2$<br>$i_2=4$, $j_2=3$ | $\Delta\zeta=\zeta_{4,3}-\zeta_{3,2}$<br>=56.00-37.43=18.57 | $\Delta\zeta=(\Delta\zeta_i^*\times0.1)+(\Delta\zeta_j^*\times0.9)$<br>$\Delta\zeta_i^*=\zeta_{4,1}-\zeta_{3,1}$=16.80-9.69=7.11<br>$\Delta\zeta_j^*=\zeta_{1,4}-\zeta_{1,3}$=51.08-28.53=22.55<br>$\Delta\zeta=(7.11\times0.1)+(22.55\times0.9)$=21.01 |
| $i_1=2$, $j_1=3$<br>$i_2=j_2=4$ | $\Delta\zeta=\zeta_{4,4}-\zeta_{2,3}$<br>=73.40-53.24=20.16 | $\Delta\zeta=(\Delta\zeta_i^*\times0.1)+(\Delta\zeta_j^*\times0.9)$<br>$\Delta\zeta_i^*=\zeta_{4,1}-\zeta_{2,1}$=16.80-5.04=11.76<br>$\Delta\zeta_j^*=\zeta_{1,4}-\zeta_{1,3}$=71.32-51.08=20.24<br>$\Delta\zeta=(11.76\times0.1)+(20.24\times0.9)$=19.39 |
| $i_1=3$, $j_1=2$<br>$i_2=4$, $j_2=2$ | $\Delta\zeta=\zeta_{4,2}-\zeta_{3,2}$<br>=38.77-37.43=1.34 | $\Delta\zeta=(\Delta\zeta_i^*\times0.1)+(\Delta\zeta_j^*\times0.9)$<br>$\Delta\zeta_i^*=\zeta_{4,1}-\zeta_{3,1}$=16.80-9.69=7.11<br>$\Delta\zeta_j^*=\zeta_{1,2}-\zeta_{1,2}$=28.53-28.53=0<br>$\Delta\zeta=(7.11\times0.1)+(0\times0.9)$=0.71 |
| $i_1=j_1=2$<br>$i_2=2$, $j_2=4$ | $\Delta\zeta=\zeta_{2,4}-\zeta_{2,2}$<br>=68.11-31.50=36.61 | $\Delta\zeta=(\Delta\zeta_i^*\times0.1)+(\Delta\zeta_j^*\times0.9)$<br>$\Delta\zeta_i^*=\zeta_{2,1}-\zeta_{2,1}$=5.04-5.04=0<br>$\Delta\zeta_j^*=\zeta_{1,4}-\zeta_{1,2}$=71.32-28.53=42.79<br>$\Delta\zeta=(0\times0.1)+(42.79\times0.9)$=38.51 |

## 3.2 Quality Evaluations

Microwave, infrared and infrared-assisted microwave dried bread crumbs were compared with the conventionally dried bread crumbs for the quality parameters color and water binding capacity.

### 3.2.1 Color Characteristics

Mean color values of bread crumbs, dried under different treatments, were compared to those of conventionally dried bread crumbs, which were used as control. The data obtained of L*, a*, and b* values, along with the calculated color difference (ΔE) are shown in Tables B.1-B.4 (Appendix B).

#### 3.2.1.1 Microwave Drying

The total color change (ΔE) values, which takes into account changes in lightness, redness and yellowness, were compared. No significant difference between bread crumbs dried at 30% microwave power and conventionally dried crumbs were found (Figure 3.18 and Table D.1). Similar trend between low power microwave drying and conventional drying was also reported by Sumnu et al. (2005) in L* and a* values which affect the total color change. It was further observed that samples dried at 50% and 70% microwave powers had significantly lower ΔE values than that of conventionally dried ones. This means that crumbs dried at 50% and 70% microwave powers were lighter in color when compared with conventionally dried crumbs (Figure 3.18 and Table D.1). This is in agreement with the previous studies of Feng and Tang (1998) and Maskan (2000) who reported lower ΔE values in microwave drying with respect conventional drying. Keskin et al. (2004) also observed lower ΔE values in microwave baked breads and explained this by short times and low temperatures common to microwave processing which did not promote browning reactions. However, Beaudry et al. (2004) observed no significant difference between microwave and conventionally dried cranberries. Different results with respect to Beaudry et al. (2004) are probably due to the type of the food material being dried, the dimensions and the weight of the samples. Three characteristic quantities determine the temperature profile: the sample size in relation to microwave penetration depth, the boundary conditions and the sample shape (Datta, 1990). Therefore, different temperature profiles with respect to the study of Beaudry et al. (2004) might have occurred and this might have influenced browning reactions in a way that gave different ΔE values. In addition, different results might be a consequence of using different drying conditions.

Bread crumbs dried at 30% and 50% microwave powers and crumbs dried at 50% and 70% microwave powers were observed to have significantly same ΔE values (Figure 3.18 and Table D.1). This is in agreement partially with the previous studies of Maskan (2000) and Demirekler et al. (2004). Demirekler (2004) reported that microwave power was not effective on total color change since distinct differences between different powers were not seen. Partial agreement might be due to the grinding process after drying as grinding provides mixing of inner and outer layers of the dried samples and hence might have caused the similarities in ΔE values. It was also observed that as the power of microwave increased, ΔE value of the crumbs decreased. This is similar to the studies of Sumnu et al. (2005) who reported lighter color in increased microwave powers. According to Sumnu et al. (2005), when high powers were used, drying was carried out in a shorter time resulting in smaller ΔE values meaning that color was much more preserved. In addition, Krokida and Maroulis (1999) also reported microwave drying and microwave-vacuum drying prevented color damages during drying.

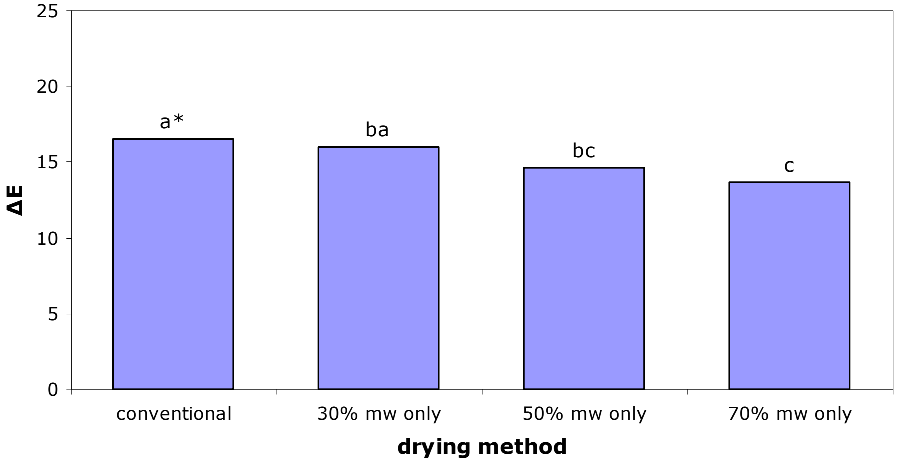

**Figure 3.18** Effect of microwave drying on ΔE values of bread crumbs.
* means bars containing different letters are significantly different ($p \leq 0.05$).

### 3.2.1.2 Infrared (Halogen Lamp) Drying

As can be seen from Figure 3.19 and Table D.2, ΔE values of infrared dried samples were found to be significantly higher than that of conventionally dried samples meaning that samples dried by infrared heating were darker in color. This was expected as infrared heating provided the achievement of browning, hence caused darkness in the color of dried samples (Keskin et al., 2004). Observed results are in agreement with the previous results reported by Tan et al. (2001) and Baysal et al. (2003). Variation of halogen lamp power did not affect the total color change of crumbs significantly (Figure 3.19, Table D.2).

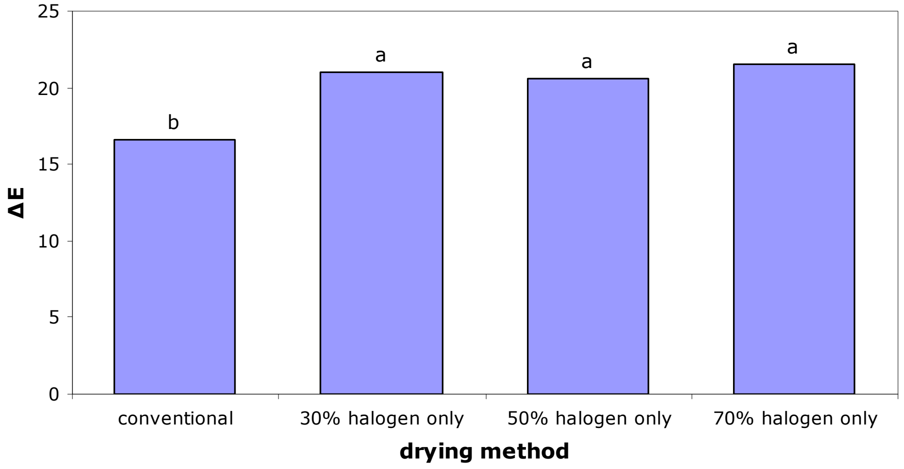

**Figure 3.19** Effect of infrared drying on ΔE values of bread crumbs.

### 3.2.1.3 Infrared-assisted Microwave Drying

According to Figure 3.20 and Table D.3, bread crumbs dried at 50% microwave and 70% halogen lamp power had significantly different total color change values from conventionally dried crumbs with higher ΔE value. This shows that samples dried at the stated power combination were darker than conventionally dried ones. This is probably due to the browning effect of infrared heating coming into play leading to darkness in color as the highest halogen power was used. Halogen lamp heating is known to provide low penetration depth and concentrate radiation at the surface resulting in higher surface temperatures and therefore browning (Demirekler et al. 2004; Keskin et al., 2004).

On the other hand, drying at 70% microwave and 30% halogen lamp power caused significant difference in ΔE value with respect to conventional oven drying with lower ΔE value (Figure 3.20 and Table D.3). This might be due to the fact that lowest halogen power was used resulting in less browning and hence darkness. In addition to this, short drying time might have had contribution to less browning.

Remaining power combinations provided ΔE values similar to conventionally dried samples (Figure 3.20 and Table D.3), which is in agreement with the previous studies in which halogen lamp-microwave combination oven provided color similar to conventionally baked breads at high halogen lamp powers (Keskin, 2003; Keskin et al. 2004; Demirekler et al. 2004).

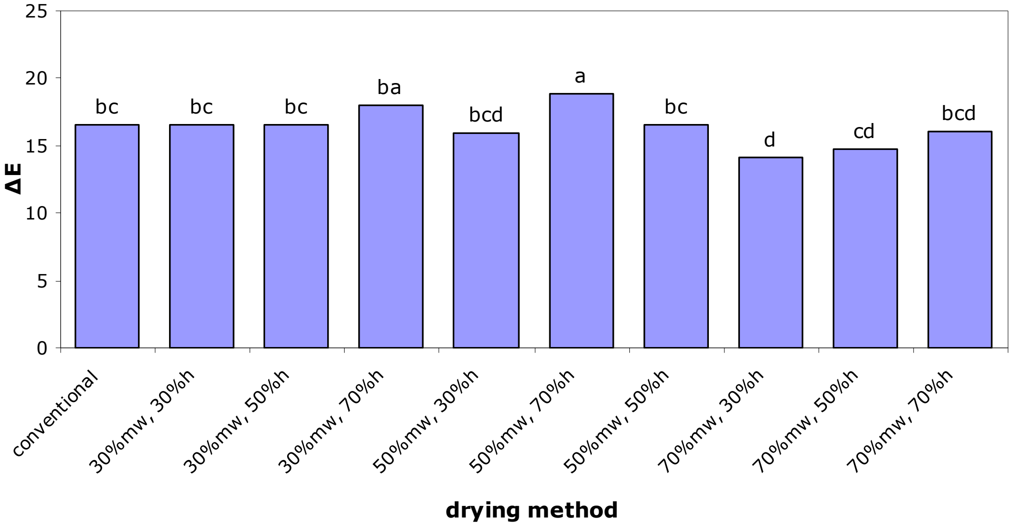

**Figure 3.20** Effect of infrared-assisted microwave drying on ΔE values of bread crumbs.

### 3.2.2 Water Binding Capacity

Water binding is the ability of an ingredient to contribute to the gel formation of firmness when water has been added (Pouttu and Puolanne, 2004). In foods, the term ‘water binding’ is often used to convey a general tendency for water to associate with hydrophilic substances, including cellular materials (Fennema, 1996).

Better taste, softer crumb, delayed staling, avoidance of water binding additives such as corn, gums in the coating and longer keepability are the advantages of increased water binding capacity. Impairment of the water binding capacity of foods has a profound effect on food quality (Fennema 1996). Viscosity of a coating is the key to control the amount of pickup and also the way the coating flows on coated-fried products before they enter the fryer. This produces the desired surface appearance (even or uneven) of the coating. Gelatinized starch provides the major framework of a coating. More gelatinization occurs with higher water binding capacity as the gelatinization of starches relies upon the water available to them in the system (Dyson, 1983).

Water binding capacities of bread crumbs were determined by using Equation 2.6 and given in Table C.1 in which the mean of three replicates were tabulated. Water binding capacities of bread crumbs, dried under different treatments, were compared to those of conventionally dried bread crumbs, which were used as control.

#### 3.2.2.1 Microwave Drying

Figure 3.21 shows the effect of microwave drying on water binding capacity of bread crumbs. Microwave dried samples were found to have significantly different water binding capacity values from conventionally dried samples. It was observed that microwave dried bread crumbs had higher water binding capacities with respect to conventionally dried ones (Figure 3.21, Table D.4).

According to Fennema (1996) the degree of water binding depends on a number of factors including the nature of the nonaqueous constituent, salt composition, pH and temperature. Water binding of wheat flour which is the main constituent of bread crumbs is to be attributed to protein, soluble pentosans and damaged starch. Increasing the amount of protein and soluble pentosans result in higher water binding capacities. Puolanne (1999) presented a hypothesis that the water-binding of an ingredient is related to the content of the ingredient in the formula and ingredient to ingredient interactions. In the area of batters and breadings, amount of gluten protein fraction and damaged starch are more pronounced when water binding capacity is concerned (Loewe, 1990).

Since it was aimed to determine the effects of different drying conditions in this study, recipe of the bread crumb dough was tried to be kept as simple as possible in order to avoid contribution from formulation influencing drying characteristics and quality parameters. Therefore, main reason for higher water binding capacities of microwave dried bread crumbs with respect to conventionally dried ones could be due to the two completely different heating mechanisms causing different temperature profiles. As stated by Fennema (1996) temperature is one of the factor affecting water binding capacity, this result was expectable. In addition, different heating mechanisms and hence different temperatures might have caused different ingredient interactions resulting in differences in water binding capacity values when the hypothesis of Puolanne (1999) was concerned.

As can be seen from Figure 3.21 and Table D.4, no significant differences between crumbs dried at 30% and 50% microwave power and dried at 50% and 70% microwave power in affecting water binding capacity were found. In addition, increase in microwave power resulted in higher water binding capacity values. Water binding capacity might have been increased due to the increase in porosity since microwave power was reported to be significant on influencing porosity (Demirekler, 2004). Porosity increase can be explained by the higher internal pressures produced by higher microwave powers which can cause structure of dough samples to expand and puff. Furthermore, effect of microwave power on water binding capacity may also be attributed to different temperatures attained at different microwave powers as discussed previously.

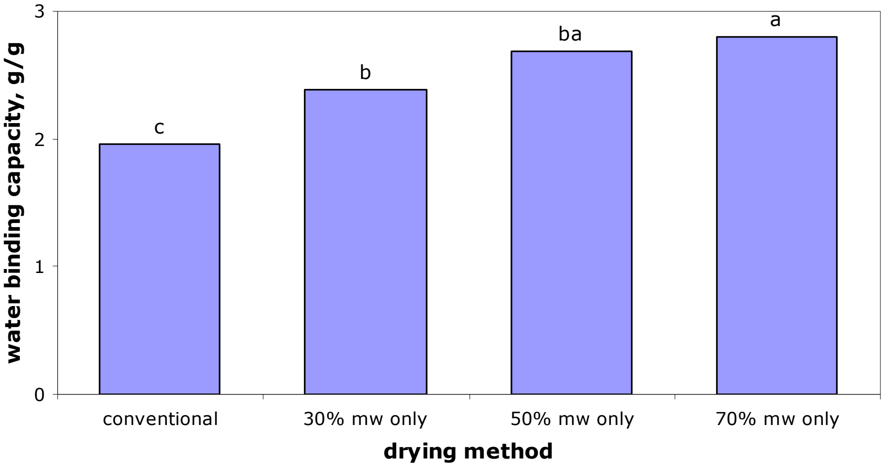

**Figure 3.21** Effect of microwave drying on water binding capacity of bread crumbs.

#### 3.2.2.2 Infrared Drying

The effect of infrared drying on water binding capacity is illustrated in Figure 3.22. Infrared dried crumbs were found to have significantly different water binding capacities from conventionally dried ones meaning that infrared dried crumbs bind more water than the conventionally dried ones. (Figure 3.22, Table D.5). Since infrared drying also has a different mechanism with respect to conventional drying, similar reasons discussed for the differences in water binding capacity values in microwave drying could be valid again.

In contrast to microwave drying, it was observed that there was no significant difference between different halogen lamp powers on affecting water binding capacity (Figure 3.22, Table D.5). This might be explained by the findings of the drying characteristics part of this study. It was seen that microwave drying was more effective with respect to infrared drying in terms of drying rates which might be a sign of different temperature profiles attained due to different heating mechanisms. Therefore, temperature might not have been altered significantly in infrared drying at 30%, 50% and 70% halogen lamp powers when compared with microwave drying performed at the same powers.

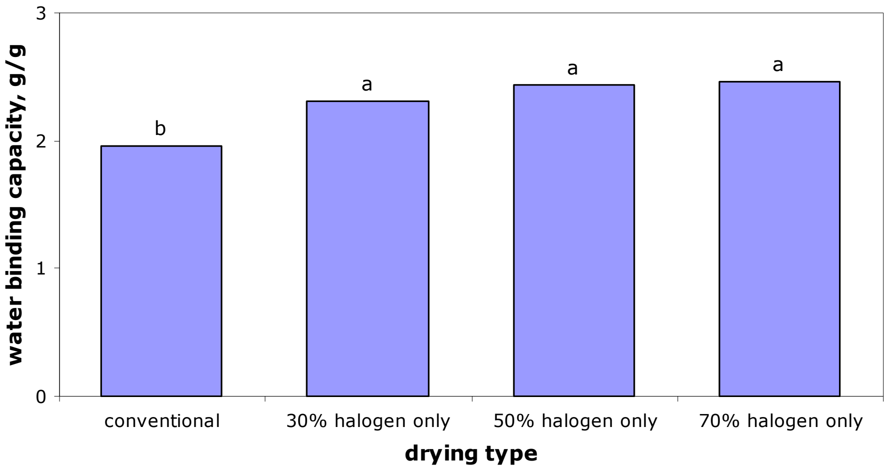

**Figure 3.22** Effect of infrared drying on water binding capacity of bread crumbs.

### 3.2.2.3 Infrared-assisted Microwave Drying

When water binding capacity of infrared-assisted microwave dried bread crumbs were compared with that of conventionally dried ones, infrared-assisted dried crumbs were found to have significantly different water binding capacity values from conventionally dried ones as similar to microwave and infrared dried samples (Figure 3.23, Table D.6). This may be attributed to the same reasons stated in the microwave and infrared drying sections since this section involves both drying mechanisms at the same time. Different temperature distributions with respect to conventional oven drying and higher porosity of crumbs might have caused different ingredient interactions and hence different water binding characteristics.

It was observed that at fixed microwave powers increase of halogen lamp power did not affect the water binding capacity and similarly microwave power was not effective on water binding capacity at fixed halogen lamp powers (Figure 3.23, Table D.6). However, it would be expected that samples subjected to infrared-assisted microwave drying would have similar trends like the ones subjected to microwave drying due to the fact that microwave mechanism was found to be the dominant mechanism previously. Therefore, it is difficult to explain the individual contributions of both microwave and infrared drying to water binding capacity when the two drying mechanisms were combined since rather than followable trends slight fluctuations were encountered in infrared-assisted microwave drying.

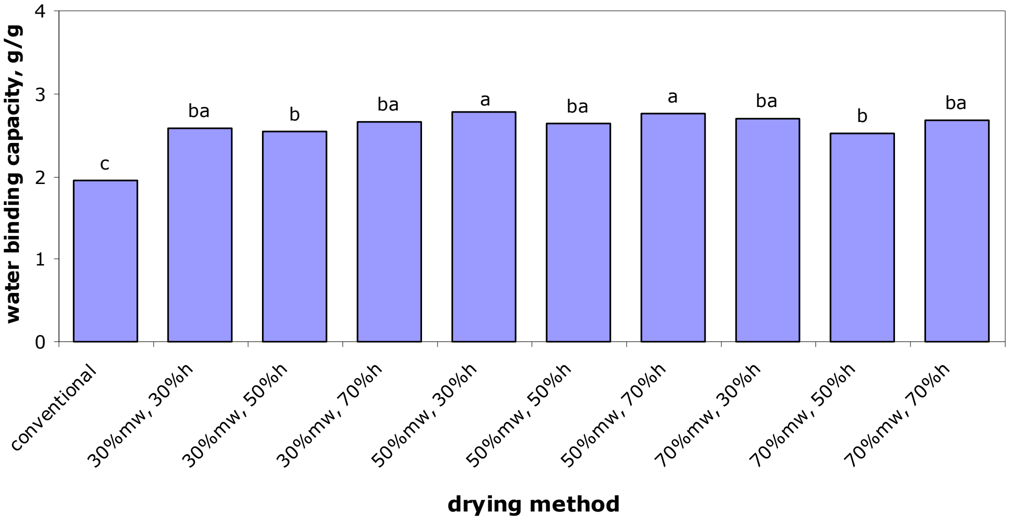

**Figure 3.23** Effect of infrared-assisted microwave drying on water binding capacity of bread crumbs.

## 3.3 Selection of the Optimum Method and Conditions for Bread Crumb Production

All of the different methods of drying (microwave, infrared, infrared-assisted) were effective to increase the water binding capacity of bread crumbs as compared to conventionally dried bread crumbs (Figures 3.21-3.23). However, as long as color was concerned microwave dried bread crumbs were lighter and infrared dried bread crumbs were darker than conventionally dried ones (Figure 3.18 and 3.19). On the other hand, ΔE values of most of the infrared-assisted microwave dried bread crumbs were not significantly different from conventionally dried ones (Figure 3.23). Therefore, infrared assisted microwave drying which reduced conventional drying time significantly can be selected as the best method for bread crumb production.

In order to determine the optimum processing condition in infrared assisted microwave drying ΔE values, water binding capacity of bread crumbs and reduction of conventional drying times were considered (Figure 3.20, Figure 3.23 and Table 3.1). Bread crumbs produced at 70% microwave and 70% halogen lamp, 50% microwave and 50% halogen lamp and 50% microwave and 30% halogen lamp power were the best conditions giving bread crumbs with the highest water binding capacity and acceptable color while reducing the processing time significantly. As long as energy saving is concerned 50% microwave and 30% halogen lamp power can be selected as the optimum condition for bread crumb production.

# CHAPTER 4

# CONCLUSION AND RECOMMENDATIONS

Microwave, infrared and infrared-assisted microwave drying shortened the drying time significantly with respect to conventional oven drying. The drying time was found to decrease with increase in power (microwave and/or halogen lamp) in all of the drying treatments. It was concluded that contribution of microwave drying was about nine fold of that of infrared drying showing that microwave heating was the dominant mechanism in the infrared-assisted microwave drying.

Modelling was done for each of the drying treatment to observe the effects of different drying conditions on the moisture content. In conventional oven drying moisture content decayed exponentionally with respect to drying time whereas in microwave drying moisture content showed a linear decrease. Both infrared and infrared-assisted microwave drying fitted the same non-linear model.

Microwave drying caused lower ΔE values and infrared drying resulted in higher ΔE values with respect to conventional oven drying. However, most of the infrared-assisted microwave dried bread crumbs had similar color value with the conventionally dried ones. Significant effects of both microwave and halogen lamp powers on color change were not observed.

All of the three drying methods, microwave, infrared and infrared-assisted microwave drying, caused significant differences in the water binding capacity of the bread crumbs when compared with the conventional oven drying. As microwave power increased, water binding capacity increased in microwave drying, however, effect of halogen lamp power was not significant on water binding capacity in infrared drying. At fixed microwave (halogen lamp) powers increase of halogen lamp (microwave) power did not effect the water binding capacity in infrared-assisted microwave drying.

As a result, infrared-assisted microwave drying can be recommended to be used for production of bread crumbs since bread crumbs obtained by this method were acceptable in terms of color and water binding capacity and conventional drying time was significantly reduced.

There is only one study on near infrared-assisted microwave drying in the scientific literature. For the future studies, it can be recommended to dry several types of food materials with different dimensions and sample sizes. The studies on these materials can be improved by modelling the process of drying via measuring temperature and/or pressure since there is a lack of understanding on the fundamentals of heat and moisture transport in foods when adding infrared to microwaves. In addition, different microwave and halogen lamp powers can be studied in order to support the modelling part and to check whether the relative drying rate change equation is applicable to all powers. In addition to these, formulation of the dough can be improved further and the effects of different drying methods on the coating and frying quality can be investigated. Effect of infrared-assisted microwave drying on shrinkage and rehydration ratio can also be studied.

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# APPENDIX A

# DRYING EXPERIMENTS

## A.1 Weight Data

**Table A.1.1** Weight data for conventional oven drying.

| time(s) | weight(g) | time(s) | weight(g) | time(s) | weight(g) |
|---|---|---|---|---|---|
| 0 | 20.80 | 2640 | 16.53 | 5280 | 14.40 |
| 120 | 20.53 | 2760 | 16.47 | 5400 | 14.30 |
| 240 | 20.30 | 2880 | 16.37 | 5520 | 14.30 |
| 360 | 20.00 | 3000 | 16.13 | 5640 | 14.23 |
| 480 | 19.80 | 3120 | 16.03 | 5760 | 14.13 |
| 600 | 19.50 | 3240 | 15.97 | 5880 | 14.03 |
| 720 | 19.23 | 3360 | 15.87 | 6000 | 14.03 |
| 840 | 19.00 | 3480 | 15.77 | 6120 | 13.93 |
| 960 | 18.83 | 3600 | 15.67 | 6240 | 13.93 |
| 1080 | 18.57 | 3720 | 15.47 | 6360 | 13.87 |
| 1200 | 18.43 | 3840 | 15.37 | 6480 | 13.80 |
| 1320 | 18.23 | 3960 | 15.30 | 6600 | 13.73 |
| 1440 | 18.07 | 4080 | 15.23 | 6720 | 13.70 |
| 1560 | 17.90 | 4200 | 15.13 | 6840 | 13.67 |
| 1680 | 17.73 | 4320 | 15.00 | 6960 | 13.63 |
| 1800 | 17.53 | 4440 | 14.90 | 7080 | 13.60 |
| 1920 | 17.37 | 4560 | 14.80 | 7200 | 13.57 |
| 2040 | 17.20 | 4680 | 14.73 | 7320 | 13.40 |
| 2160 | 17.07 | 4800 | 14.70 | 7440 | 13.40 |
| 2280 | 16.93 | 4920 | 14.63 | 7560 | 13.30 |
| 2400 | 16.80 | 5040 | 14.53 | | |
| 2520 | 16.63 | 5160 | 14.43 | | |

**Table A.1.2** Weight data for microwave drying.

| **time (s)** | **weight (g) 30% mw** | **time (s)** | **weight (g) 50% mw** | **time (s)** | **weight (g) 70% mw** |
|---|---|---|---|---|---|
| 0 | 20.80 | 0 | 20.80 | 0 | 20.80 |
| 15 | 20.27 | 15 | 19.57 | 15 | 19.33 |
| 30 | 20.03 | 30 | 18.90 | 30 | 18.37 |
| 45 | 19.33 | 45 | 17.97 | 45 | 16.97 |
| 60 | 19.10 | 60 | 17.23 | 60 | 15.77 |
| 75 | 18.33 | 75 | 16.20 | 75 | 15.13 |
| 90 | 18.07 | 90 | 15.60 | 90 | 14.00 |
| 105 | 17.33 | 105 | 15.00 | 105 | 13.73 |
| 120 | 16.97 | 120 | 14.10 | 106 | 13.37 |
| 135 | 16.43 | 135 | 13.93 | | |
| 150 | 16.10 | 148 | 13.40 | | |
| 165 | 15.83 | | | | |
| 180 | 15.03 | | | | |
| 195 | 14.90 | | | | |
| 210 | 14.50 | | | | |
| 225 | 14.20 | | | | |
| 240 | 13.73 | | | | |
| 255 | 13.57 | | | | |
| 265 | 13.40 | | | | |

mw: Microwave power

**Table A.1.3** Weight data for infrared (halogen lamp) drying.

| **time (s)** | **weight (g)** **30% h** | **time (s)** | **weight (g)** **50% h** | **time (s)** | **weight (g)** **70% h** |
|---|---|---|---|---|---|
| 0 | 20.80 | 0 | 20.80 | 0 | 20.80 |
| 60 | 20.57 | 60 | 20.50 | 60 | 20.37 |
| 120 | 20.30 | 120 | 20.20 | 120 | 19.83 |
| 180 | 19.97 | 180 | 19.67 | 180 | 18.90 |
| 240 | 19.73 | 240 | 19.00 | 240 | 17.87 |
| 300 | 19.47 | 300 | 18.20 | 300 | 16.70 |
| 360 | 19.10 | 360 | 17.53 | 360 | 15.23 |
| 420 | 18.70 | 420 | 16.57 | 420 | 14.13 |
| 480 | 18.27 | 480 | 15.80 | 450 | 13.37 |
| 540 | 17.80 | 540 | 15.07 | | |
| 600 | 17.43 | 600 | 14.50 | | |
| 660 | 16.97 | 660 | 14.10 | | |
| 720 | 16.57 | 720 | 13.73 | | |
| 780 | 16.17 | 780 | 13.33 | | |
| 840 | 15.80 | | | | |
| 900 | 15.50 | | | | |
| 960 | 15.13 | | | | |
| 1020 | 14.93 | | | | |
| 1080 | 14.63 | | | | |
| 1140 | 14.33 | | | | |
| 1200 | 14.17 | | | | |
| 1260 | 13.93 | | | | |
| 1320 | 13.73 | | | | |
| 1380 | 13.63 | | | | |
| 1440 | 13.50 | | | | |
| 1500 | 13.37 | | | | |

h: Halogen lamp power

**Table A.1.4** Weight data for infrared-assisted microwave drying at fixed 30% microwave power.

| **time (s)** | **weight (g) 30% mw & 30% h** | **time (s)** | **weight (g) 30% mw & 50% h** | **time (s)** | **weight (g) 30% mw & 70% h** |
|---|---|---|---|---|---|
| 0 | 20.80 | 0 | 20.80 | 0 | 20.80 |
| 15 | 20.30 | 15 | 20.20 | 15 | 20.20 |
| 30 | 20.17 | 30 | 20.20 | 30 | 20.07 |
| 45 | 19.57 | 45 | 19.23 | 45 | 19.30 |
| 60 | 19.27 | 60 | 18.93 | 60 | 18.93 |
| 75 | 18.23 | 75 | 17.90 | 75 | 17.53 |
| 90 | 18.07 | 90 | 17.73 | 90 | 17.20 |
| 105 | 17.23 | 105 | 16.77 | 105 | 16.40 |
| 120 | 16.70 | 120 | 16.33 | 120 | 15.73 |
| 135 | 16.10 | 135 | 15.60 | 135 | 15.23 |
| 150 | 15.73 | 150 | 14.70 | 150 | 14.47 |
| 165 | 15.30 | 165 | 14.20 | 165 | 14.07 |
| 180 | 14.77 | 180 | 14.03 | 180 | 13.73 |
| 195 | 14.47 | 195 | 13.70 | 195 | 13.33 |
| 210 | 13.90 | 202 | 13.33 |  |  |
| 225 | 13.67 |  |  |  |  |
| 240 | 13.33 |  |  |  |  |

mw: Microwave power

h: Halogen lamp power

**Table A.1.5** Weight data for infrared-assisted microwave drying at fixed 50% microwave power.

| time (s) | weight (g) 50% mw & 30% h | time (s) | weight (g) 50% mw & 50% h | time (s) | weight (g) 50% mw & 70% h |
|---|---|---|---|---|---|
| 0 | 20.80 | 0 | 20.80 | 0 | 20.80 |
| 15 | 19.73 | 15 | 19.80 | 15 | 20.00 |
| 30 | 19.37 | 30 | 19.43 | 30 | 19.43 |
| 45 | 18.03 | 45 | 18.27 | 45 | 18.17 |
| 60 | 17.40 | 60 | 17.60 | 60 | 17.53 |
| 75 | 16.43 | 75 | 16.50 | 75 | 16.23 |
| 90 | 15.57 | 90 | 15.87 | 90 | 15.50 |
| 105 | 15.07 | 105 | 15.13 | 105 | 14.57 |
| 120 | 14.23 | 120 | 14.17 | 120 | 14.07 |
| 135 | 13.80 | 135 | 13.90 | 135 | 13.40 |
| 142 | 13.33 | 139 | 13.37 | | |

mw: Microwave power

h: Halogen lamp power

**Table A.1.6** Weight data for infrared-assisted microwave drying at fixed 70% microwave power.

| time (s) | weight (g) 70% mw & 30% h | time (s) | weight (g) 70% mw & 50% h | time (s) | weight (g) 70% mw & 70% h |
|---|---|---|---|---|---|
| 0 | 20.80 | 0 | 20.80 | 0 | 20.80 |
| 15 | 19.93 | 15 | 19.73 | 15 | 19.70 |
| 30 | 18.53 | 30 | 18.73 | 30 | 18.63 |
| 45 | 17.33 | 45 | 17.10 | 45 | 17.20 |
| 60 | 16.07 | 60 | 16.00 | 60 | 16.00 |
| 75 | 15.30 | 75 | 14.70 | 75 | 14.67 |
| 90 | 14.20 | 90 | 13.67 | 90 | 13.83 |
| 105 | 13.83 | 105 | 13.33 | 103 | 13.37 |
| 111 | 13.33 | | | | |

mw: Microwave power

h: Halogen lamp power

### A.2 Moisture Content Data

**Table A.2.1** Moisture content (wet basis) data for conventional oven drying.

| time(s) | m.c. (g/g) | time(s) | m.c. (g/g) | time(s) | m.c. (g/g) |
|---|---|---|---|---|---|
| 0 | 0.4090 | 2640 | 0.2565 | 5280 | 0.1463 |
| 120 | 0.4013 | 2760 | 0.2535 | 5400 | 0.1404 |
| 240 | 0.3944 | 2880 | 0.2489 | 5520 | 0.1404 |
| 360 | 0.3854 | 3000 | 0.2380 | 5640 | 0.1363 |
| 480 | 0.3791 | 3120 | 0.2333 | 5760 | 0.1302 |
| 600 | 0.3696 | 3240 | 0.2301 | 5880 | 0.1240 |
| 720 | 0.3609 | 3360 | 0.2252 | 6000 | 0.1240 |
| 840 | 0.3530 | 3480 | 0.2203 | 6120 | 0.1177 |
| 960 | 0.3473 | 3600 | 0.2153 | 6240 | 0.1177 |
| 1080 | 0.3379 | 3720 | 0.2052 | 6360 | 0.1135 |
| 1200 | 0.3331 | 3840 | 0.2000 | 6480 | 0.1092 |
| 1320 | 0.3258 | 3960 | 0.1965 | 6600 | 0.1049 |
| 1440 | 0.3196 | 4080 | 0.1930 | 6720 | 0.1027 |
| 1560 | 0.3133 | 4200 | 0.1877 | 6840 | 0.1005 |
| 1680 | 0.3068 | 4320 | 0.1805 | 6960 | 0.0983 |
| 1800 | 0.2889 | 4440 | 0.1750 | 7080 | 0.0961 |
| 1920 | 0.2921 | 4560 | 0.1694 | 7200 | 0.0938 |
| 2040 | 0.2853 | 4680 | 0.1656 | 7320 | 0.0826 |
| 2160 | 0.2797 | 4800 | 0.1638 | 7440 | 0.0826 |
| 2280 | 0.2740 | 4920 | 0.1599 | 7560 | 0.0757 |
| 2400 | 0.2683 | 5040 | 0.1542 |  |  |
| 2520 | 0.2609 | 5160 | 0.1483 |  |  |

m.c.: Moisture content (wet basis)

**Table A.2.2** Moisture content (wet basis) data for microwave drying.

| time (s) | m.c. (g/g) 30% mw | time (s) | m.c. (g/g) 50% mw | time (s) | m.c. (g/g) 70% mw |
|---|---|---|---|---|---|
| 0 | 0.4090 | 0 | 0.4090 | 0 | 0.4090 |
| 15 | 0.3934 | 15 | 0.3717 | 15 | 0.3636 |
| 30 | 0.3864 | 30 | 0.3492 | 30 | 0.3307 |
| 45 | 0.3641 | 45 | 0.3158 | 45 | 0.2755 |
| 60 | 0.3564 | 60 | 0.2866 | 60 | 0.2202 |
| 75 | 0.3294 | 75 | 0.2411 | 75 | 0.1877 |
| 90 | 0.3196 | 90 | 0.2119 | 90 | 0.1219 |
| 105 | 0.2907 | 105 | 0.1804 | 105 | 0.1049 |
| 120 | 0.2754 | 120 | 0.1281 | 106 | 0.0803 |
| 135 | 0.2517 | 135 | 0.1177 | | |
| 150 | 0.2362 | 148 | 0.0826 | | |
| 165 | 0.2235 | | | | |
| 180 | 0.1823 | | | | |
| 195 | 0.1750 | | | | |
| 210 | 0.1522 | | | | |
| 225 | 0.1343 | | | | |
| 240 | 0.1048 | | | | |
| 255 | 0.0939 | | | | |
| 265 | 0.0826 | | | | |

m.c.: Moisture content (wet basis)
mw: Microwave power

**Table A.2.3** Moisture content (wet basis) data for infrared (halogen lamp) drying.

| time (s) | m.c. (g/g) 30% h | time (s) | m.c. (g/g) 50% h | time (s) | m.c. (g/g) 70% h |
|---|---|---|---|---|---|
| 0 | 0.4090 | 0 | 0.4090 | 0 | 0.4090 |
| 60 | 0.4023 | 60 | 0.4004 | 60 | 0.3964 |
| 120 | 0.3944 | 120 | 0.3914 | 120 | 0.3802 |
| 180 | 0.3843 | 180 | 0.3749 | 180 | 0.3496 |
| 240 | 0.3771 | 240 | 0.3530 | 240 | 0.3119 |
| 300 | 0.3685 | 300 | 0.3245 | 300 | 0.2637 |
| 360 | 0.3564 | 360 | 0.2984 | 360 | 0.1923 |
| 420 | 0.3426 | 420 | 0.2576 | 420 | 0.1295 |
| 480 | 0.3270 | 480 | 0.2213 | 450 | 0.0803 |
| 540 | 0.3094 | 540 | 0.1835 | | |
| 600 | 0.2948 | 600 | 0.1515 | | |
| 660 | 0.2754 | 660 | 0.1280 | | |
| 720 | 0.2579 | 720 | 0.1049 | | |
| 780 | 0.2395 | 780 | 0.0780 | | |
| 840 | 0.2218 | | | | |
| 900 | 0.2068 | | | | |
| 960 | 0.1876 | | | | |
| 1020 | 0.1767 | | | | |
| 1080 | 0.1599 | | | | |
| 1140 | 0.1423 | | | | |
| 1200 | 0.1322 | | | | |
| 1260 | 0.1177 | | | | |
| 1320 | 0.1049 | | | | |
| 1380 | 0.0983 | | | | |
| 1440 | 0.0894 | | | | |
| 1500 | 0.0803 | | | | |

m.c.: Moisture content (wet basis)

h: Halogen lamp power

**Table A.2.4** Moisture content (wet basis) data for infrared-assisted microwave drying at fixed 30% microwave power.

| time (s) | m.c. (g/g) 30% mw & 30% h | time (s) | m.c. (g/g) 30% mw & 50% h | time (s) | m.c. (g/g) 30% mw & 70% h |
|---|---|---|---|---|---|
| 0 | 0.4090 | 0 | 0.4090 | 0 | 0.4090 |
| 15 | 0.3944 | 15 | 0.3914 | 15 | 0.3914 |
| 30 | 0.3904 | 30 | 0.3914 | 30 | 0.3874 |
| 45 | 0.3717 | 45 | 0.3609 | 45 | 0.3631 |
| 60 | 0.3620 | 60 | 0.3507 | 60 | 0.3507 |
| 75 | 0.3258 | 75 | 0.3132 | 75 | 0.2989 |
| 90 | 0.3196 | 90 | 0.3068 | 90 | 0.2853 |
| 105 | 0.2867 | 105 | 0.2668 | 105 | 0.2504 |
| 120 | 0.2639 | 120 | 0.2474 | 120 | 0.2187 |
| 135 | 0.2365 | 135 | 0.2120 | 135 | 0.1930 |
| 150 | 0.2187 | 150 | 0.1637 | 150 | 0.1503 |
| 165 | 0.1965 | 165 | 0.1343 | 165 | 0.1261 |
| 180 | 0.1675 | 180 | 0.1240 | 180 | 0.1049 |
| 195 | 0.1503 | 195 | 0.1027 | 195 | 0.0780 |
| 210 | 0.1156 | 202 | 0.0780 |  |  |
| 225 | 0.1005 |  |  |  |  |
| 240 | 0.0780 |  |  |  |  |

m.c.: Moisture content (wet basis)
mw: Microwave power
h: Halogen lamp power

**Table A.2.5** Moisture content (wet basis) data for infrared-assisted microwave drying at fixed 50% microwave power.

| **time (s)** | **m.c. (g/g) 50% mw & 30% h** | **time (s)** | **m.c. (g/g) 50% mw & 50% h** | **time (s)** | **m.c. (g/g) 50% mw & 70% h** |
|---|---|---|---|---|---|
| 0 | 0.4090 | 0 | 0.4090 | 0 | 0.4090 |
| 15 | 0.3771 | 15 | 0.3791 | 15 | 0.3853 |
| 30 | 0.3652 | 30 | 0.3674 | 30 | 0.3674 |
| 45 | 0.3183 | 45 | 0.3270 | 45 | 0.3233 |
| 60 | 0.2934 | 60 | 0.3015 | 60 | 0.2988 |
| 75 | 0.2518 | 75 | 0.2549 | 75 | 0.2426 |
| 90 | 0.2100 | 90 | 0.2252 | 90 | 0.2068 |
| 105 | 0.1841 | 105 | 0.1874 | 105 | 0.1558 |
| 120 | 0.1362 | 120 | 0.1323 | 120 | 0.1259 |
| 135 | 0.1091 | 135 | 0.1156 | 135 | 0.0826 |
| 142 | 0.0780 | 139 | 0.0803 | | |

m.c.: Moisture content (wet basis)

mw: Microwave power

h: Halogen lamp power

**Table A.2.6** Moisture content (wet basis) data for infrared-assisted microwave drying at fixed 70% microwave power.

| **time (s)** | **m.c. (g/g) 70% mw & 30% h** | **time (s)** | **m.c. (g/g) 70% mw & 50% h** | **time (s)** | **m.c. (g/g) 70% mw & 70% h** |
|---|---|---|---|---|---|
| 0 | 0.4090 | 0 | 0.4090 | 0 | 0.4090 |
| 15 | 0.3833 | 15 | 0.3770 | 15 | 0.3760 |
| 30 | 0.3366 | 30 | 0.3438 | 30 | 0.3402 |
| 45 | 0.2907 | 45 | 0.2811 | 45 | 0.2852 |
| 60 | 0.2348 | 60 | 0.2315 | 60 | 0.2316 |
| 75 | 0.1965 | 75 | 0.1630 | 75 | 0.1618 |
| 90 | 0.1342 | 90 | 0.1005 | 90 | 0.1114 |
| 105 | 0.1114 | 105 | 0.0780 | 103 | 0.0803 |
| 111 | 0.0780 | | | | |

m.c.: Moisture content (wet basis)
mw: Microwave power
h: Halogen lamp power

## A.3 Drying time

**Table A.3.1** Drying times for different drying methods.

| Drying method | Drying time (s) |
|---|---|
| conventional | 7560 |
| 30% microwave power only | 265 |
| 50% microwave power only | 148 |
| 70% microwave power only | 106 |
| 30% halogen power only | 1500 |
| 50% halogen power only | 780 |
| 70% halogen power only | 450 |
| 30% microwave power & 30% halogen power | 240 |
| 30% microwave power & 50% halogen power | 202 |
| 30% microwave power & 70% halogen power | 195 |
| 50% microwave power & 30% halogen power | 142 |
| 50% microwave power & 50% halogen power | 139 |
| 50% microwave power & 70% halogen power | 135 |
| 70% microwave power & 30% halogen power | 111 |
| 70% microwave power & 50% halogen power | 105 |
| 70% microwave power & 70% halogen power | 103 |

## A.4 Model Constants

**Table A.4.1** Model constants for moisture content (wet basis) of bread crumb dough for microwave drying.

y=ax+b (a: slope; b: intercept)

| | **30% mw** | **50% mw** | **70% mw** |
|---|---|---|---|
| a (1/s) | -0.0013 | -0.0023 | -0.0031 |
| b (g/g) | 0.4178 | 0.4178 | 0.4178 |
| $r^2$ | 0.99 | 0.99 | 0.99 |

mw: Microwave power

**Table A.4.2** Model constants for moisture content (wet basis) of bread crumb dough for infrared (halogen lamp) drying.

Model : $y = 1 - ae^{bx} - ce^{dx}$

| | **30% h** | **50% h** | **70% h** |
|---|---|---|---|
| a (g/g) | 0.2923 | 0.3107 | 0.3142 |
| b (1/min) | 0.0193 | 0.0533 | 0.1259 |
| c (g/g) | 0.2923 | 0.2616 | 0.2776 |
| d (1/min) | 0.0193 | 0.0145 | -0.1233 |
| $r^2$ | 0.99 | 0.99 | 1 |

h: Halogen lamp power

**Table A.4.3** Model constants for moisture content (wet basis) of bread crumb dough for infrared-assisted microwave drying.

Model : $y = 1 - ae^{bx} - ce^{dx}$

| | **30% mw & 30% h** | **30% mw & 50% h** | **30% mw & 70% h** |
|---|---|---|---|
| a (g/g) | 0.2968 | 0.2880 | 0.2891 |
| b (1/min) | 0.1326 | 0.1453 | 0.1471 |
| c (g/g) | 0.2834 | 0.2880 | 0.2891 |
| d (1/min) | 0.1014 | 0.1347 | 0.1471 |
| $r^2$ | 1 | 0.99 | 0.99 |
| | **50% mw & 30% h** | **50% mw & 50% h** | **50% mw & 70% h** |
| a (g/g) | 0.2947 | 0.3325 | 0.2910 |
| b (1/min) | 0.1892 | -0.2830 | -0.1690 |
| c (g/g) | 0.2947 | 0.2564 | 0.2910 |
| d (1/min) | 0.1867 | -0.0262 | -0.2378 |
| $r^2$ | 1 | 0.99 | 1 |
| | **70% mw & 30% h** | **70% mw & 50% h** | **70% mw & 70% h** |
| a (g/g) | 0.2952 | 0.2928 | 0.2927 |
| b (1/min) | 0.2242 | 0.2699 | 0.2724 |
| c (g/g) | 0.2952 | 0.2928 | 0.2927 |
| d (1/min) | 0.2619 | 0.2742 | 0.2711 |
| $r^2$ | 0.99 | 0.99 | 0.99 |

mw: Microwave power

h: halogen lamp power

## A.5 Comparison of contribution of the 1st and the 2nd part of the model equation to the moisture loss

$$y = 1 - \underset{\substack{\Downarrow \\ 1^{st}\text{part}}}{ae^{bx}} - \underset{\substack{\Downarrow \\ 2^{nd}\text{ part}}}{ce^{dx}}$$

**Table A.5.1** Calculated ratios of the 1st part to the 2nd part for infrared drying.

| time (min) | 1st part/2nd part 30% h | time (min) | 1st part/2nd part 50% h | time (min) | 1st part/2nd part 70% h |
|---|---|---|---|---|---|
| 0 | 1.00 | 0 | 1.19 | 0 | 1.13 |
| 1 | 1.00 | 1 | 1.23 | 1 | 1.45 |
| 2 | 1.00 | 2 | 1.28 | 2 | 1.86 |
| 3 | 1.00 | 3 | 1.33 | 3 | 2.39 |
| 4 | 1.00 | 4 | 1.39 | 4 | 3.07 |
| 5 | 1.00 | 5 | 1.44 | 5 | 3.93 |
| 6 | 1.00 | 6 | 1.50 | 6 | 5.05 |
| 7 | 1.00 | 7 | 1.56 | 7 | 6.48 |
| 8 | 1.00 | 8 | 1.62 | 7.5 | 7.34 |
| 9 | 1.00 | 9 | 1.68 | | |
| 10 | 1.00 | 10 | 1.75 | | |
| 11 | 1.00 | 11 | 1.82 | | |
| 12 | 1.00 | 12 | 1.89 | | |
| 13 | 1.00 | 13 | 1.97 | | |
| 14 | 1.00 | | | | |
| 15 | 1.00 | | | | |
| 16 | 1.00 | | | | |
| 17 | 1.00 | | | | |
| 18 | 1.00 | | | | |
| 19 | 1.00 | | | | |
| 20 | 1.00 | | | | |
| 21 | 1.00 | | | | |
| 22 | 1.00 | | | | |
| 23 | 1.00 | | | | |
| 24 | 1.00 | | | | |
| 25 | 1.00 | | | | |

h: Halogen lamp power

**Table A.5.2** Calculated ratios of the 1st part to the 2nd part for infrared-assisted microwave drying (fixed 30 % microwave power).

| **time (min)** | **1st part/2nd part 30% mw & 30% h** | **time (min)** | **1st part/2nd part 30% mw & 50% h** | **time (min)** | **1st part/2nd part 30% mw & 70% h** |
|---|---|---|---|---|---|
| 0.00 | 1.05 | 0.00 | 1.00 | 0.00 | 1.00 |
| 0.25 | 1.06 | 0.25 | 1.00 | 0.25 | 1.00 |
| 0.50 | 1.06 | 0.50 | 1.01 | 0.50 | 1.00 |
| 0.75 | 1.07 | 0.75 | 1.01 | 0.75 | 1.00 |
| 1.00 | 1.08 | 1.00 | 1.01 | 1.00 | 1.00 |
| 1.25 | 1.09 | 1.25 | 1.01 | 1.25 | 1.00 |
| 1.50 | 1.10 | 1.50 | 1.02 | 1.50 | 1.00 |
| 1.75 | 1.11 | 1.75 | 1.02 | 1.75 | 1.00 |
| 2.00 | 1.11 | 2.00 | 1.02 | 2.00 | 1.00 |
| 2.25 | 1.12 | 2.25 | 1.02 | 2.25 | 1.00 |
| 2.50 | 1.13 | 2.50 | 1.03 | 2.50 | 1.00 |
| 2.75 | 1.14 | 2.75 | 1.03 | 2.75 | 1.00 |
| 3.00 | 1.15 | 3.00 | 1.03 | 3.00 | 1.00 |
| 3.25 | 1.16 | 3.25 | 1.04 | 3.25 | 1.00 |
| 3.50 | 1.17 | 3.37 | 1.04 |  |  |
| 3.75 | 1.18 |  |  |  |  |
| 4.00 | 1.19 |  |  |  |  |

mw: Microwave power
h: Halogen lamp power

**Table A.5.3** Calculated ratios of the 1st part to the 2nd part for infrared-assisted microwave drying (fixed 50 % microwave power).

| **time (min)** | **1st part/2nd part 50% mw & 30% h** | **time (min)** | **1st part/2nd part 50% mw & 50% h** | **time (min)** | **1st part/2nd part 50% mw & 70% h** |
|---|---|---|---|---|---|
| 0.00 | 1.00 | 0.00 | 1.30 | 0.00 | 1.00 |
| 0.25 | 1.00 | 0.25 | 1.38 | 0.25 | 0.98 |
| 0.50 | 1.00 | 0.50 | 1.47 | 0.50 | 0.97 |
| 0.75 | 1.00 | 0.75 | 1.57 | 0.75 | 0.95 |
| 1.00 | 1.00 | 1.00 | 1.68 | 1.00 | 0.93 |
| 1.25 | 1.00 | 1.25 | 1.79 | 1.25 | 0.92 |
| 1.50 | 1.00 | 1.50 | 1.91 | 1.50 | 0.90 |
| 1.75 | 1.00 | 1.75 | 2.03 | 1.75 | 0.89 |
| 2.00 | 1.01 | 2.00 | 2.17 | 2.00 | 0.87 |
| 2.25 | 1.01 | 2.25 | 2.31 | 2.25 | 0.86 |
| 2.37 | 1.01 | 2.32 | 2.35 | | |

mw: Microwave power

h: Halogen lamp power

**Table A.5.4** Calculated ratios of the 1st part to the 2nd part for infrared-assisted microwave drying (fixed 70 % microwave power).

| **time (min)** | **1st part/2nd part 70% mw & 30% h** | **time (min)** | **1st part/2nd part 70% mw & 50% h** | **time (min)** | **1st part/2nd part 70% mw & 70% h** |
|---|---|---|---|---|---|
| 0.00 | 1.00 | 0.00 | 1.00 | 0.00 | 1.00 |
| 0.25 | 0.99 | 0.25 | 1.00 | 0.25 | 1.00 |
| 0.50 | 0.98 | 0.50 | 1.00 | 0.50 | 1.00 |
| 0.75 | 0.97 | 0.75 | 1.00 | 0.75 | 1.00 |
| 1.00 | 0.96 | 1.00 | 1.00 | 1.00 | 1.00 |
| 1.25 | 0.95 | 1.25 | 0.99 | 1.25 | 1.00 |
| 1.50 | 0.95 | 1.50 | 0.99 | 1.50 | 1.00 |
| 1.75 | 0.94 | 1.75 | 0.99 | 1.72 | 1.00 |
| 1.85 | 0.93 | | | | |

mw: Microwave power

h: Halogen lamp power

# APPENDIX B

# COLOR DATA

**Table B.1** L* data for different drying methods.

| Drying method | L* value |
|---|---|
| conventional | $70.64^{m}$±$0.254^{se}$ |
| 30% microwave power only | 70.22±0.272 |
| 50% microwave power only | 71.35±0.988 |
| 70% microwave power only | 71.48±0.559 |
| 30% halogen power only | 67.53±0.796 |
| 50% halogen power only | 68.06±1.211 |
| 70% halogen power only | 65.48±0.697 |
| 30% microwave power & 30% halogen power | 70.02±0.234 |
| 30% microwave power & 50% halogen power | 70.30±0.390 |
| 30% microwave power & 70% halogen power | 69.12±0.669 |
| 50% microwave power & 30% halogen power | 69.51±0.734 |
| 50% microwave power & 50% halogen power | 68.83±0.531 |
| 50% microwave power & 70% halogen power | 66.75±0.819 |
| 70% microwave power & 30% halogen power | 72.53±0.754 |
| 70% microwave power & 50% halogen power | 71.26±1.063 |
| 70% microwave power & 70% halogen power | 70.02±1.307 |

m: arithmetic mean of triplicates

se: standard error

**Table B.2** a* data for different drying methods.

| **Drying method** | **a* value** |
|---|---|
| conventional | $3.75^{m}$±$0.128^{se}$ |
| 30% microwave power only | 2.40±0.077 |
| 50% microwave power only | 2.32±0.213 |
| 70% microwave power only | 1.75±0.194 |
| 30% halogen power only | 4.75±0.388 |
| 50% halogen power only | 3.73±0.100 |
| 70% halogen power only | 3.69±0.090 |
| 30% microwave power & 30% halogen power | 2.49±0.119 |
| 30% microwave power & 50% halogen power | 2.55±0.236 |
| 30% microwave power & 70% halogen power | 3.49±0.480 |
| 50% microwave power & 30% halogen power | 1.99±0.240 |
| 50% microwave power & 50% halogen power | 2.19±0.238 |
| 50% microwave power & 70% halogen power | 2.19±0.039 |
| 70% microwave power & 30% halogen power | 2.32±0.152 |
| 70% microwave power & 50% halogen power | 2.31±0.254 |
| 70% microwave power & 70% halogen power | 2.31±0.302 |

m: arithmetic mean of triplicates

se: standard error

**Table B.3** b* data for different drying methods.

| **Drying method** | **b* value** |
|---|---|
| conventional | 27.76$^{m}$±0.480$^{se}$ |
| 30% microwave power only | 26.04±0.552 |
| 50% microwave power only | 25.26±0.279 |
| 70% microwave power only | 23.04±0.291 |
| 30% halogen power only | 30.92±0.108 |
| 50% halogen power only | 31.12±0.656 |
| 70% halogen power only | 28.87±0.406 |
| 30% microwave power & 30% halogen power | 26.75±0.343 |
| 30% microwave power & 50% halogen power | 27.30±0.287 |
| 30% microwave power & 70% halogen power | 27.97±0.847 |
| 50% microwave power & 30% halogen power | 24.32±0.149 |
| 50% microwave power & 50% halogen power | 24.17±0.603 |
| 50% microwave power & 70% halogen power | 24.90±0.357 |
| 70% microwave power & 30% halogen power | 26.36±0.414 |
| 70% microwave power & 50% halogen power | 25.40±0.416 |
| 70% microwave power & 70% halogen power | 25.74±0.594 |

m: arithmetic mean of triplicates

se: standard error

**Table B.4** ΔE data for different drying methods. (reference: dough)

| Drying method | ΔE |
|---|---|
| conventional | $16.57^{m}$±$0.150^{se}$ |
| 30% microwave power only | 15.99±0.408 |
| 50% microwave power only | 14.65±0.813 |
| 70% microwave power only | 13.71±0.582 |
| 30% halogen power only | 20.99±0.562 |
| 50% halogen power only | 20.55±1.251 |
| 70% halogen power only | 21.56±0.672 |
| 30% microwave power & 30% halogen power | 16.49±0.105 |
| 30% microwave power & 50% halogen power | 16.50±0.458 |
| 30% microwave power & 70% halogen power | 17.99±0.416 |
| 50% microwave power & 30% halogen power | 15.98±0.654 |
| 50% microwave power & 50% halogen power | 16.58±0.660 |
| 50% microwave power & 70% halogen power | 18.78±0.764 |
| 70% microwave power & 30% halogen power | 14.13±0.523 |
| 70% microwave power & 50% halogen power | 14.77±1.114 |
| 70% microwave power & 70% halogen power | 16.08±1.172 |

m: arithmetic mean of triplicates

se: standard error

# APPENDIX C

# WATER BINDING CAPACITY DATA

**Table C.1** Water binding capacity data for different drying methods.

| Drying method | water binding capacity |
|---|---|
| conventional | $1.96^{m}$±$0.078^{se}$ |
| 30% microwave power only | 2.38±0.181 |
| 50% microwave power only | 2.68±0.087 |
| 70% microwave power only | 2.79±0.031 |
| 30% halogen power only | 2.31±0.065 |
| 50% halogen power only | 2.43±0.067 |
| 70% halogen power only | 2.46±0.138 |
| 30% microwave power & 30% halogen power | 2.59±0.039 |
| 30% microwave power & 50% halogen power | 2.54±0.061 |
| 30% microwave power & 70% halogen power | 2.67±0.017 |
| 50% microwave power & 30% halogen power | 2.79±0.058 |
| 50% microwave power & 50% halogen power | 2.63±0.045 |
| 50% microwave power & 70% halogen power | 2.76±0.045 |
| 70% microwave power & 30% halogen power | 2.69±0.131 |
| 70% microwave power & 50% halogen power | 2.52±0.031 |
| 70% microwave power & 70% halogen power | 2.68±0.058 |

m: arithmetic mean of triplicates

se: standard error

# APPENDIX D

# ANOVA AND DUNCAN TABLES

**Table D.1** ANOVA and Duncan's Multiple Range Test Table for ΔE value of bread crumbs dried by microwave and conventional oven drying.

| Class | Levels | Values |
|---|---|---|
| Drying method | 4 | conventional, 30% mw, 50% mw, 70% mw |
| Replications | 3 | 1, 2, 3 |

Number of observations in data set=12

| Source | DF | Sum of Squares | Mean Square | F value | $P_r$>F |
|---|---|---|---|---|---|
| Model | 3 | 15.04454095 | 5.01484698 | 5.63 | 0.0227 |
| Error | 8 | 7.13134619 | 0.89141827 | | |
| Total | 11 | 22.17588713 | | | |

| Source | DF | Type III SS | Mean Square | F value | $P_r$>F |
|---|---|---|---|---|---|
| Drying method | 3 | 15.04454095 | 5.01484698 | 5.63 | 0.0227 |

Alpha=0.05

Means with the same letter are not significantly different.

| **Duncan Grouping** | **Mean** | **N** | **Drying Method** |
|---|---|---|---|
| A | 16.5653 | 3 | conventional |
| BA | 15.9906 | 3 | 30% mw |
| BC | 14.6468 | 3 | 50% mw |
| C | 13.7091 | 3 | 70% mw |

**Table D.2** ANOVA and Duncan's Multiple Range Test Table for ΔE value of bread crumbs dried by infrared and conventional oven drying.

| Class | Levels | Values |
|---|---|---|
| Drying method | 4 | conventional, 30% h, 50% h, 70% h |
| Replications | 3 | 1, 2, 3 |

Number of observations in data set=12

| Source | DF | Sum of Squares | Mean Square | F value | $P_r$>F |
|---|---|---|---|---|---|
| Model | 3 | 46.47927177 | 15.49309059 | 8.77 | 0.0065 |
| Error | 8 | 14.12494346 | 1.76561793 | | |
| Total | 11 | 60.60421523 | | | |

| Source | DF | Type III SS | Mean Square | F value | $P_r$>F |
|---|---|---|---|---|---|
| Drying method | 3 | 46.47927177 | 15.49309059 | 8.77 | 0.0065 |

Alpha=0.05

Means with the same letter are not significantly different.

| **Duncan Grouping** | **Mean** | **N** | **Drying Method** |
|---|---|---|---|
| A | 21.5600 | 3 | 70% h |
| A | 20.9920 | 3 | 30% h |
| A | 20.5550 | 3 | 50% h |
| B | 16.5650 | 3 | conventional |

**Table D.3** ANOVA and Duncan's Multiple Range Test Table for ΔE value of bread crumbs dried by infrared-assisted microwave and conventional oven drying.

| Class | Levels | Values |
|---|---|---|
| Drying method | 10 | conventional,<br>30%mw-30%h, 30%mw-50%h, 30%mw-70%h,<br>50%mw-30%h, 50%mw-50%h, 50%mw-70%h,<br>70%mw-30%h, 70%mw-50%h, 70%mw-70%h |
| Replications | 3 | 1, 2, 3 |

Number of observations in data set=30

| Source | DF | Sum of Squares | Mean Square | F value | $P_r$>F |
|---|---|---|---|---|---|
| Model | 9 | 49.18884979 | 5.46542775 | 3.83 | 0.0059 |
| Error | 20 | 28.50880052 | 1.42544003 | | |
| Total | 29 | 77.69765031 | | | |

| Source | DF | Type III SS | Mean Square | F value | $P_r$>F |
|---|---|---|---|---|---|
| Drying method | 9 | 49.18884979 | 5.46542775 | 3.83 | 0.0059 |

Alpha=0.05

Means with the same letter are not significantly different.

| **Duncan Grouping** | **Mean** | **N** | **Drying Method** |
|---|---|---|---|
| A | 18.7842 | 3 | 50%mw-70%h |
| BA | 17.9936 | 3 | 30%mw-70%h |
| BC | 16.5815 | 3 | 50%mw-50%h |
| BC | 16.5653 | 3 | conventional |
| BC | 16.5033 | 3 | 30%mw-50%h |
| BC | 16.4917 | 3 | 30%mw-30%h |
| BCD | 16.0790 | 3 | 70%mw-70%h |
| BCD | 15.9762 | 3 | 50%mw-30%h |
| CD | 14.7702 | 3 | 70%mw-50%h |
| D | 14.1294 | 3 | 70%mw-30%h |

**Table D.4** ANOVA and Duncan's Multiple Range Test Table for water binding capacity of bread crumbs dried by microwave and conventional oven drying.

| Class | Levels | Values |
|---|---|---|
| Drying method | 4 | conventional, 30% mw, 50% mw, 70% mw |
| Replications | 3 | 1, 2, 3 |

Number of observations in data set=12

| Source | DF | Sum of Squares | Mean Square | F value | $P_r$>F |
|---|---|---|---|---|---|
| Model | 3 | 1.25709167 | 0.41903056 | 11.86 | 0.0026 |
| Error | 8 | 0.28253333 | 0.03531667 | | |
| Total | 11 | 1.53962500 | | | |

| Source | DF | Type III SS | Mean Square | F value | $P_r$>F |
|---|---|---|---|---|---|
| Drying method | 3 | 1.25709167 | 0.41903056 | 11.86 | 0.0026 |

Alpha=0.05

Means with the same letter are not significantly different.

| **Duncan Grouping** | **Mean** | **N** | **Drying Method** |
|---|---|---|---|
| A | 2.7933 | 3 | 70% mw |
| BA | 2.6800 | 3 | 50% mw |
| B | 2.3800 | 3 | 30% mw |
| C | 1.9567 | 3 | conventional |

**Table D.5** ANOVA and Duncan's Multiple Range Test Table for water binding capacity of bread crumbs dried by infrared and conventional oven drying.

| Class | Levels | Values |
|---|---|---|
| Drying method | 4 | conventional, 30% h, 50% h, 70% h |
| Replications | 3 | 1, 2, 3 |

Number of observations in data set=12

| Source | DF | Sum of Squares | Mean Square | F value | $P_r$>F |
|---|---|---|---|---|---|
| Model | 3 | 0.47910000 | 0.15970000 | 6.29 | 0.0169 |
| Error | 8 | 0.20326667 | 0.02540833 | | |
| Total | 11 | 0.68236667 | | | |

| Source | DF | Type III SS | Mean Square | F value | $P_r$>F |
|---|---|---|---|---|---|
| Drying method | 3 | 0.47910000 | 0.15970000 | 6.29 | 0.0169 |

Alpha=0.05

Means with the same letter are not significantly different.

| **Duncan Grouping** | **Mean** | **N** | **Drying Method** |
|---|---|---|---|
| A | 2.4567 | 3 | 70% h |
| A | 2.4333 | 3 | 30% h |
| A | 2.3067 | 3 | 50% h |
| B | 1.9567 | 3 | conventional |

**Table D.6** ANOVA and Duncan's Multiple Range Test Table for water binding capacity of bread crumbs dried by infrared-assisted microwave and conventional oven drying.

| Class | Levels | Values |
|---|---|---|
| Drying method | 10 | conventional,<br>30%mw-30%h, 30%mw-50%h, 30%mw-70%h,<br>50%mw-30%h, 50%mw-50%h, 50%mw-70%h,<br>70%mw-30%h, 70%mw-50%h, 70%mw-70%h |
| Replications | 3 | 1, 2, 3 |

Number of observations in data set=30

| Source | DF | Sum of Squares | Mean Square | F value | $P_r$>F |
|---|---|---|---|---|---|
| Model | 9 | 1.50081333 | 0.16675704 | 13.82 | 0.0001 |
| Error | 20 | 0.24126667 | 0.01206333 | | |
| Total | 29 | 1.74208000 | | | |

| Source | DF | Type III SS | Mean Square | F value | $P_r$>F |
|---|---|---|---|---|---|
| Drying method | 9 | 1.50081333 | 0.16675704 | 13.82 | 0.0001 |

Alpha=0.05
Means with the same letter are not significantly different.

| **Duncan Grouping** | **Mean** | **N** | **Drying Method** |
|---|---|---|---|
| A | 2.7867 | 3 | 50%mw-30%h |
| A | 2.7567 | 3 | 50%mw-70%h |
| BA | 2.6933 | 3 | 70%mw-30%h |
| BA | 2.6767 | 3 | 70%mw-70%h |
| BA | 2.6667 | 3 | 30%mw-70%h |
| BA | 2.6333 | 3 | 50%mw-50%h |
| BA | 2.5900 | 3 | 30%mw-30%h |
| B | 2.5400 | 3 | 30%mw-50%h |
| B | 2.5200 | 3 | 70%mw-50%h |
| C | 1.9567 | 3 | conventional |