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Microwave Baking in Food Industry: A Review

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Abstract: Microwave ovens are now increasingly being used by the masses. Microwave treatment has been gaining increasing recognitions in the food industry and household frameworks alike. Better energy and finishing efficiencies can be obtained by adding an additional transport mechanism, such as forced air convection heating. The advantages of microwave related include the following: shorter drying time, improved product quality and flexibility in producing a wide variety of dried products. The MW-related combination drying takes advantages of conventional drying methods and microwave heating, leading to better processes than microwave drying alone. This study presents a comprehensive review of recent progresses in microwave and microwave-combined baking and drying operations and recommendations for future research to bridge the gap between laboratory research and industrial applications.

Key words: Microwave baking, bread, cake, biscuit, pasta

INTRODUCTION

Apart from the nutritional aspect, the growing tendency to spend less time on food preparation has lead to a great demand for time-saving ready-to-heat frozen food products for microwave-heating. The change in eating trend can be seen from the growth in demand for bread and biscuits, which account for over 85% of the bakery product (Bhatt *et al*., 2008). Interest in microwave processing began shortly after World War II with the introduction of the first microwave oven by the Raytheon Co. (Waltham, Mass) a manufacturer of magnetrons for radar. The first US patent granted to Raytheon Co., which claimed the novelty of microwave cooking, was illustrated with a food product moving on a conveyor belt past a microwave source. Enersyst Development Center in Dallas developed and patented the impingement microwave oven, which was used in the space station and now serves as a food service oven. Microwave heating techniques have many unique advantages when compared to conventional heating methods because they are; convenient to operate and control, energy-efficient and clean. These advantages make microwave ovens common household appliances today. Thus, besides trying to adopt these techniques into food processing operations such as drying or pasteurization, the food industry has been developing microwavable products for families and foodservice industry with various degrees of success. As a unique thermal processing technology, microwave heating has been successfully used in food industry, including tempering or thawing of bulk frozen foods (meat, fish and others), cooking of bacon and sausage and drying of pasta and vegetables

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(Ohlsson and Bengtsson, 1975; Schiffmann, 1992). Research on microwave treatment of foods has also been reported for disinfesting of insects in agricultural commodities (Wang *et al*., 2003), blanching of vegetables, inactivating of enzyme, pasteurization of breads, cured hams and sausage emulsions, sterilization of food products (Venkatesh and Ragavan, 2004).

However, development of acceptable microwave-baked goods is still a problem because of the less desirable texture, color and aroma of the products (Shukla, 1993). These microwaved bakery products are often described by consumers as flat, with tough and leathery crumbs but without crust and sufficient browning. The short microwave baking time also influences flavour development, as the flavour compounds may not have the opportunity to develop as they would under conventional baking.

HOW MICROWAVE HEATING WORKS?

The driving forces for heat and mass transfer when a food is heated by microwave differ from conventional methods. In foods heated by microwave, time-temperature profiles within the product are caused by internal heat generation owing to the absorption of electrical energy from the microwave field and heat transfer by conduction, convection and evaporation (Mudgett, 1986). Microwaves are electromagnetic (EM) waves of very short wavelength. In the EM spectrum, microwaves lie between the television frequencies and infrared. In terms of wavelength, radio waves are measured in kilometers, television frequencies in meters, microwaves in centimeters and infrared in microns. The wavelength and frequency are related by the expression:

$$\text{Wavelength } (A_0) = \frac{\text{Speed of light (c)}}{\text{Frequency (f)}}$$

Microwave (MW) heating is a result of interaction between alternating electromagnetic field and dielectric material. Compared with conventional heating using water or steam as the heating media for package foods, MW energy has the potential to provide more uniform and rapid volumetric heating. The major mechanisms of microwave heating of foods involve orientation, polarization and interfacial distribution. Some dielectric materials contain permanent dipoles that tend to reorient under the influence of alternating fields, thus causing orientation polarization. Heat is generated because of the inability of rotating molecules to keep pace with the alternating field. Because of its dipolar nature, water, the major constituent of most food products, is the main source of microwave interactions with food materials (Alton, 1998). Interfacial distribution arises owing to the charge build up in the interfaces of components in heterogeneous systems (Metaxas and Meredith, 1983). In interfacial distribution any charged particles in foods will experience a force alternating at the rate of microwave frequency. The net force will accelerate the particle in one direction and then in the opposite. The accelerated particle collides with adjacent particles and heat is generated by this collision (Buffler, 1993; Sumnu, 2001).

For microwave heating the energy equation includes a heat generation term:

$$\frac{\partial T}{\partial t} = \alpha \nabla^2 T + \frac{Q}{\rho C_p}$$

where, T is temperature, t is time, α is thermal diffusivity, ρ is density, C_p is specific heat of the material and Q is the heat generated per unit volume of material.

The heat generated per volume of material per time (Q) represents the conversion of electromagnetic energy. Its relationship to the electric field intensity (E) at that location can be derived from Maxwell's equations of electromagnetic waves as shown by:

$$Q = 2\pi\, \varepsilon_0\, \varepsilon'' f E^2$$

where, the magnetic losses of the food material have been ignored. ε_0 is the dielectric constant of free space, ε'' is the dielectric loss factor of the food, f is the frequency of oven and E is the electric field intensity (Sumnu, 2001).

Two frequencies, 2450±50 and 915±13 MHz, are allocated by the US Federal Communications Commission for MW heating applications (Decareau, 1985; Metaxas and Meredith, 1983). Two thousand four hundred fifty megahertz is widely used in domestic MW ovens and some industrial applications but they have limitations of small penetration depth (~1 cm) and multi-mode cavities, causing non-uniform and unpredictable heating patterns in food packages. In general, 915 MHz microwaves can penetrate much deeper (~3 cm) in foods and therefore may provide more uniform heating and could be established with a single-mode cavity, which could provide predictable electromagnetic field, resulting in predictable and reproducible heating patterns in foods (Mudgett, 1986).

PROPERTIES OF FOOD AFFECTING MICROWAVE HEATING

Dielectric properties and penetration depth are the electrical properties which play an important role in improving the quality of microwave-baked products. The dielectric properties can be divided into the dielectric constant and the dielectric loss factor. These properties reflect the ability of a material to store and dissipate electrical energy, respectively (Mudgett, 1982). Beside dielectric properties and penetration depth, there are also several properties like geometry of the food, surface to volume ratio, specific heat, etc., are also discussed in detail:

Dielectric Loss Factor

As the field strength (E) and the frequency are essentially constant for the microwave oven being used, the loss factor (e") is the only variable. The term loss originated from the discovery that energy loss occurred when the electrical energy through a capacitor was cycled on and off. In the context being used, the loss factor represents a property of the material being processed and a lossy material is one that heats well, while a low loss material is one that heats poorly and is, therefore, more transparent to microwave energy (Bengtsson and Risman, 1971; Ohlsson and Bengtsson, 1975).

Penetration

The penetration depth is that depth in a material at which the energy level is 37% (or 1/e) of the surface value. The term half-power depth is also used and is that depth in a material at which the power level is one-half that at the surface as shown in the equation (Metaxas and Meredith, 1983).

$$Z = \frac{\lambda_0}{2\pi(2\varepsilon')^{0.5}}\left\{\left[1+\left(\frac{\varepsilon''}{\varepsilon'}\right)^2\right]^{0.5}-1\right\}^{-0.5}$$

where, Z is the penetration depth (cm), λ_0 is the wavelength in free space, ε' is the dielectric constant and ε'' is the dielectric loss factor.

Geometry

The shape of food items plays a critical part to obtain better microwave heating results. The sphere is the ideal shape as energy tends to be focused to give heating at the center of the sphere. Heating can be concentrated in the center of spheres with diameters that measure between 20 and 60 mm (Ohlsson and Risman, 1978). Such concentrated heating can be a disadvantage in that conduction heating may not be able to dissipate the temperature gradient and the mass would erupt, as in the heating of an egg in its shell. At lower microwave heating rates, more time is provided for conduction heating to take place. In the example of beef roasting the post microwave heating time could have been reduced if a lower heating rate were used, as the temperature gradients would not have been as great (Meisel, 1972).

Shielding and Shadowing

Shielding is the use of metal to reflect microwave energy and thereby reduce the heating rate in selected areas. Aluminum foil is usually used because of its availability, but also because it can be wrapped around the specific parts to be shielded. Shadowing is a shielding effect by a food product that results in a reduced heating rate where the products are in contact. Thus it is a mutual effect with products shadowing each other and so food masses should always be spaced apart for best cooking (Bengtsson and Risman, 1971; Ohlsson and Bengtsson, 1975; Ohlsson and Risman, 1978; Meisel, 1972).

Surface-to-Volume Ratio

As with conventional heating, the greater the surface area, the faster that cooking occurs. Thus potatoes and carrots can be cooked faster if they are diced. Vegetables such as corn and peas have a high surface-to-volume ratio and cook rapidly. This same condition also means that foods will cool more rapidly. This is an important consideration when developing new products and means to reduce the cooling rate should be provided where possible, for example, by using insulated containers or preheated serving dishes.

Specific Heat

The specific heat of a material is the ratio of its thermal capacity to that of water. It is a measure of the energy required to raise product temperature by a specific amount. The specific heat of a food is closely related to its moisture content. It is generally believed that oil samples heat faster than water samples of the same mass (Barringer *et al*., 1994).

Density

Usually, there is a clear relationship between density and moisture content. Thus bread, which has a low moisture content (about 35%) is not as dense as beef (65%); for example, 1 Ib of bread requires about two-thirds as much energy as 1 Ib of beef to heat to the same temperature. Thermal conductivity also comes into play in that the dimensions involved could mean substantial overheating of the surface of beef because of its density, while the more open structure of bread would not rely on thermal conductivity to the same extent.

Thermal Conductivity

Thermal conductivity is a measure of a material's ability to transfer heat in response to a temperature difference. Even in microwave cooking it plays an important role in spite of the penetrating nature of microwave energy. Without heat conduction unacceptable temperature differences would occur in most microwave heated or cooked foods. Such differences can be minimized by reducing the rate of microwave heating (Bengtsson and Risman, 1971; Ohlsson and Risman, 1978; Meisel, 1972).

Starting and Final Temperature

Heating time depends not only on the power level but also on the temperature range that must be bridged to accomplish the desired result. Thus, frozen foods take longer than refrigerated foods, which in turn take longer than shelf-stable food heated from room temperature assuming all were heated to the same final temperature.

Evaporative Cooling

This is a phenomenon that is much more evident when cooking with microwave energy. This effect is responsible for the lower surface temperature of some foods cooked in microwave ovens and, therefore, is responsible for the myth that microwaves cook from the inside out. It is not noticeable in a conventional oven because of heat radiation to the surface of foods.

ADVANTAGES AND DISADVANTAGES OF MICROWAVE PROCESSING

Microwave food processes offer a lot of advantages such as less start-up time, faster heating, energy efficiency, space savings, precise process control, selective heating and food with high nutritional quality (Marra *et al.*, 2010). Quality problems associated with microwave baking include reduced height of the product, dense or gummy texture, crumb hardness and an undesirable moisture gradient along a vertical axis in the final baked product (Sumnu and Sahin, 2005). One of the reasons for these problems is that physicochemical changes and interactions of major ingredients, which would normally occur over a lengthy baking period in a conventional system, cannot always be completed during the short baking period of a microwave system. During conventional baking, dough is heated from the outer surface inward by conductive, radiant heat and undergoes structural transformations, including starch gelatinization, protein denaturation, volume increase, liberation of carbon dioxide from leavening agents, water evaporation, crust formation and non-enzymatic browning (Therdthai and Zhou, 2003). In contrast, under ambient oven conditions, microwave radiation interacts with molecules that are coupled, such as water (including its dissolved solutes and ions), to produce heat that results in structural changes and water movement (Umbach *et al.*, 1990). Other reasons are the differences between microwave and other heating mechanisms and specific interactions of each component in the formulation with microwave energy.

The biggest difference between convection ovens and microwave ovens is the inability of the microwave ovens to induce browning. The cool ambient temperature inside a microwave oven causes surface cooling of microwave-baked products and low surface temperature prevents Maillard browning reactions from being formed, these are responsible for the production of many flavoured and coloured compounds. Brown surfaces, produced by the Maillard reaction and caramelization of sugars, are a result of high temperatures accompanied by dehydration. Direct heating of carbohydrates produces complex reactions namely as caramelisation reactions. Whereas minimum substrates requirements for Maillard browning are the presence of an aminic compound, usually a protein, a reducing sugar and some water. The Maillard reaction is influenced by temperature, pH, moisture content, presence or absence of metallic cations and inner sugar structure. Particularly, the reaction is accelerated at medium moisture level and high temperature (Fennema, 1996). The short microwave baking time may also influence flavour development, as the flavour compounds may not have the opportunity to develop as they would under conventional baking. Microwave energy causes different flavour components to become completely volatilized at different rates and in different proportions than occurs during conventional heating. It was also found that different chemical reactions take place during microwave cooking as opposed to conventional cooking; in this way different flavours are produced.

TYPES OF MICROWAVE OVENS USED IN FOOD INDUSTRY

The driving forces for heat and mass transfer when a food is heated by microwave differ from conventional methods. In foods heated by microwave, time-temperature profiles within the product are caused by internal heat generation owing to the absorption of electrical energy from the microwave field and heat transfer by conduction, convection and evaporation. A porous media was found to be hotter in the inside when heated by microwaves and hotter on the outside when heated by convection. Compared to conventional heating, moisture flows, owing to concentration and pressure gradients, are uniquely and significantly altered during microwave heating. Relatively large amounts of internal heating seem to result in increased moisture vapour generation inside a solid food material, which creates significant internal pressure and concentration gradients.

Jet Impingement Ovens

Jet impingement ovens have been used for many years in meat processing and have been the standard for pizza cooking. The advantages of jet impingement heating over more traditional convection heating include faster cooking, higher efficiency and better water retention. Research on combination baking showed that jet impingement required half the cooking time when compared to a convection oven. Impingement-heated product had higher final moisture content and maintained a higher level of compressibility. A review of the energy efficiency of ovens has shown that the jet impingement ovens are 65% efficient while gas fired ovens have only a 35% fuel efficiency (Wahlby *et al*., 2000; Anderson and Singh, 2006a, b; Nitin *et al*., 2006).

Previous Microwave Heating Models

The earliest microwave heating models were primarily analytical. However, with the availability of extensive computing facilities, solution of Maxwell's equations for electromagnetics coupled with heat transfer in the oven cavity can be obtained using different numerical methods such as Finite Difference Time Domain (FDTD) method and Finite Element Method (FEM). The FEM has the advantage over FDTD method in that FDTD is difficult to apply for complex geometry and can require long computational time. Other studies have modeled microwave heating by solving the heat and mass transfer equation and assuming a source term with exponential decay (Lambert's Law) for implementing microwave heating instead of solving the set of Maxwell's equations for the electromagnetic field (Zhang and Datta, 2000; Swain *et al*., 2004; Campanone and Zaritzky, 2005; Nott and Hall, 2005).

Combination of Microwave with Infrared, Convection and/or Jet Impingement

Combination heating involves heating foods with microwave in combination with infrared, convection and/or jet impingement and is one of the most significant methods used to achieve uniform temperatures in the food. Jet impingement systems were originally developed to supplement microwave heating in combination ovens. The soggy surface issue of microwave heating disappears as hot air impinging on the food removes the excessive moisture. A crispy brown surface is indeed possible with combination heating. The problem of edge over-heating in microwave can be partially reduced by using combination heating, as lower temperature difference between the surrounding hot air and the product edges leads to a lower contribution from jet impingement to the edges. Jet impingement combined with radiofrequency waves has also been reported, but has not been as popular as its combination with microwave. The pizza industry in particular has successfully commercialized the combination of air impingement with radiofrequency wave heating (Ovadia, 1994; Datta and Ni, 2002; Wappling-Raaholt *et al*., 2002).

COMPARISON OF MICROWAVE AND CONVENTIONAL BAKING

During conventional baking, dough is heated from the outer surface inward by conductive, radiant heat and undergoes structural transformations, including starch gelatinization, protein denaturation, volume increase, liberation of carbon dioxide from leavening agents, water evaporation, crust formation and non-enzymatic browning. In contrast, under ambient oven conditions, microwave radiation interacts with molecules that are coupled, such as water (including its dissolved solutes and ions), to produce heat that results in structural changes and water movement. Industrial baking oven conditions are usually generated using the three modes of heat transfer: radiation, convection and conduction. The proportion of each individual mode of heat transfer in the baking process depends on oven design, configuration and operation. Several authors have studied the contribution of individual modes of heat transfer in bread, biscuit and cake baking using electrically powered, forced convection or gas-fired ovens. Radiation was found to be the predominant mode of heat transfer, accounting for between 50 and 80% of total heat, while convection was the least important mode in conventional baking ovens. Heat supply is more difficult to control by radiation than by convection in industrial baking ovens. Forced air flow in baking chambers is one solution for controlling and accelerating the baking process, as the convective component of heat transfer is increased (Umbach *et al*., 1990; Therdthai and Zhou, 2003). In microwave heating, the heating mechanism differs from conventional methods. Absorption of energy from the microwave field results in internal heat generation and as a consequence internal vapor generation. The internal vapor generation leads to the development of a pressure gradient which increases the rate of moisture transfer significantly as compared to conventional heating methods (Baik *et al*., 2000; Mirade *et al*., 2004; Zareifard *et al*., 2009).

Undesirable qualities of breads baked in nonconventional ovens have been observed by most researchers. The altered heat and mass transfer patterns and much shorter baking times associated with microwave radiation resulted in a crustless product with tougher, coarser, but less firm texture. Insufficient starch gelatinization, microwave-induced gluten changes and rapidly generated gas and steam caused by the heating mode could be reasons for quality changes in the microwave-baked breads. Although, breads baked in an electrical resistance oven did not brown, their interior characteristics and shelf-life were superior to those of products baked in a conventional oven. Bread with a superior keeping quality was obtained using an air impingement convection oven. The determination and explanation of the physical and biochemical changes that occur in products during baking in conventional versus nonconventional ovens are fruitful areas for future research. During baking heat energy is mainly transferred to the product surface by radiation from oven walls and by convection from hot air flowing inside the oven and by conduction from the surface to the core of the product. For biscuit baking in band ovens, found that all three heat transfer modes, conduction, convection and radiation, were involved and of the total heat transfer, 43% was by radiation, 37% by convection and 20% by conduction from the band to the biscuit bottom. This predominance of radiative heat transfer to the product for bread baked in an electric oven, with a proportion of about 70% (Umbach *et al*., 1990; Therdthai and Zhou, 2003; Mirade *et al*., 2004; Zareifard *et al*., 2009).

MICROWAVE BAKING OF FOOD PRODUCTS

During the baking process of cereal products such as bread, cakes and cookies, many textural, physicochemical and organoleptic changes may occur. All these cooking-induced changes are important for digestibility and sensorial acceptance by the consumers (Sablani *et al*., 1998). The Maillard reaction, caramelisation and lipid peroxidation explain most of these changes, although if it is very difficult to characterize the complex mixture of the compounds formed. Direct heating of carbohydrates produces complex reactions namely as caramelisation reactions. Whereas minimum substrates requirements for Maillard browning are the presence of an aminic compound, usually a protein, a reducing sugar and some water. The Maillard reaction is influenced by temperature, pH, moisture content, presence or absence of metallic cations and inner sugar structure. Particularly, the reaction is accelerated at medium moisture level and high temperature. Microwave can be use for baking of biscuits, pound cakes, cakes, breads and other food products as discussed in the following section.

Biscuits and Cookies

The use of microwave heating for final baking of cookies results in a more uniform moisture distribution than does forced convection (Schiffmann, 1992). Bernussi *et al*. (1998) studied effects of microwave baking on the moisture gradient and overall quality of the cookies. After conventional (forced-convection heating) baking at 240°C for 4 min, biscuits (cookies) were baked further in a microwave oven at medium and high settings (617.3 and 745.5 W, respectively). Microwave baking significantly reduced the moisture gradient and total moisture content of the cookies and implementing high and medium microwave settings for 30 or 40 sec, respectively, avoided cracking but produced slight darker cookies. The expansion ratio of the control cookies sample (11.3) was significantly higher than the combined process sample (10.7), showing a shrinkage effect attributed to the microwave treatment.

Ahmad *et al*. (2001) observed the influence of high-frequency radiation on quality in terms of checking and mechanical strength of biscuits which were baked in a convection, reel oven and then immediately microwaved for 30 sec in a 700 W microwave oven. Microwave baking was found to significantly reduce checking to 5% compared to 61% in conventional biscuits. The structure of conventional biscuits was generally found to weaken at a faster rate than microwaved biscuits. Microwaved biscuits were also found to be less susceptible to checking upon exposure to high ambient humidity. The RF heating of foods is similar in effect to microwave heating and involves applying a high voltage signal to a set of parallel electrode. Food is located between the electrodes and current flows through the food and as a result, rotation of polar molecules take place and heating occurs in a similar way to microwave heating. RF units installed in sequence after the conventional oven were shown to increase the baking speed 30 to 50%. RF energy was used to remove excess moisture uniformly from crackers and cookies and no discolouration and flavour damage took place owing to the thermal build up (Zhao *et al*., 2000). Browning during baking of biscuits has also been studied. Colour development depends only on temperature and a first-order kinetic model, dependent on average temperature and moisture content, was developed to predict lightness variation of cracker surface during baking. More recently, it was observed that accumulation of 5-hydroxymethyl-2-furfural (HMF) follows first-order kinetics during baking and is highly dependent on the water activity, which must reach levels lower than 0.4 for allowing a significant formation of HMF (Ameur *et al*., 2006; Mundt and Wedzicha, 2007).

Pound Cakes

Imaging, light microscopy and scanning electron microscopy were used to compare the microstructure of crumbs from pound cakes baked in a microwave or conventional oven. The microwave baking conditions for pound cake (240 W, 5 min) were established in previous research, conventional baked pound cakes were obtained using a swing oven at 180°C for 40 min. Statistical differences in total cell, cell cm^{-2} and mean cell area were observed in the image analysis. Cells from microwaved pound cake crumbs were 20% larger. However, factor shape was 0.81 for both microwave and conventionally baked crumbs and crumbs from both oven types were similar in appearance. Light microscopy revealed birefringence in crumbs from both types of pound cakes. Scanning electron microscopy revealed that the conventionally baked product had a greater amount of protein matrix however; the matrix structure of the crumb was comparable between microwave-baked and conventionally baked pound cakes. Results suggested that the unique aspects of pound cake dough, including its high content of fat, sugar and moisture, make it well suited to microwave baking (Sanchez-Pardo *et al*., 2008; Seyhun *et al*., 2003; Sumnu *et al*., 2005).

Bread

The role of baking is to alter the sensory properties of bread, to improve palatability and to extend the range of taste, aromas and texture. Baking results in evaporation of water, volume expansion, formation of a porous structure, denaturation of protein, protein crosslinking, gelatinization of starch, crust formation, browning reaction, melting of fat crystals and their absorption onto the surface of air cells and rupture of gas cells (Sablani *et al*., 2002; Chavan *et al*., 2008a). Microwave heating is very popular for thawing frozen bread. Although, popular in recent years, bakery products heated or reheated in a microwave oven are often considered of low quality, because they may develop undesirable characteristics: low volume, lack of browning and flavor development, no homogeneous heating, tough, rubbery, coarse, difficult to tear crust, firm and difficult to chew crumb, rapid staling after heating mainly caused by recrystallisation of starch (Pan and CastellPerez, 1997; Sumnu, 2001).

Halogen lamp-microwave combination heating is a new technology that combines the time saving advantage of microwave heating with the browning and crisping advantages of halogen lamp heating. Many alternatives to conventional heating are reported such as infrared and hot air assisted microwave heating (Datta and Ni, 2002), microwave-hot air combination heating and microwave–impingement combination heating (Li and Walker, 1996). Conventional formulations of bread develop unacceptable textures when baked in microwave oven, the exterior parts of the bread are tough while inner parts are firm (Shukla, 1993). The reasons for firm texture in microwave-baked breads were high moisture loss, interactions of microwave with gluten and high amylose leaching during baking.

Keskin *et al*. (2004) compared the effects of halogen lamp–microwave combination baking on quality of breads with other baking methods (conventional, microwave and halogen lamp baking). Weight loss, specific volume, firmness and color of the breads were measured as quality parameters. Halogen lamp–microwave combination oven reduced the conventional baking time of breads by about 75%. Microwave heating was found to be the dominant mechanism in halogen lamp-microwave combination baking in terms of affecting weight loss and texture development. Breads baked in halogen lamp-microwave combination oven had specific volume and color values comparable with the conventionally baked breads but their weight loss and firmness values were still higher.

In recent years for improving the quality of microwave breads different recipe formulations have been tried, mainly focused on gluten effect (hydrolysis, addition of gliadin, low gluten flour use) (Miller *et al*., 2003), on emulsifiers use (Ozmutlu *et al*., 2001), or on combinations of different ingredients including emulsifiers and water-binding agents (Clarke and Farrell, 2000; Chavan and Prajapati, 2009). Improvers including gums retard staling after the full-baking of part-baked, frozen stored breads (Barcenas *et al*., 2003). Gums such as carboxymethylcellulose (CMC), carrageenan, gum arabic and Locust Bean Gum (LBG) may be used to alleviate the problem of freeze/thaw damage in frozen doughs since they trap free water and control moisture migration (Chavan *et al*., 2008a).

Cakes

Common complaints about microwave cakes are the low volumes and the tough textures achieved. Studies on microwave baked products in recent years were usually about improving the quality of these products (Sumnu, 2001). Microwave baked cakes had some quality defects such as lack of colour, high weight loss, very firm texture and low volume. Combining air impingement with microwaves reduced the baking time significantly and produced cakes with acceptable colour but the lowest volume and firmest texture (Li and Walker, 1996). Sumnu *et al*. (2005) suggested a cake formulation for preparing a white-layer cake formulation for cake mix was on a flour weight basis; 100% flour, 100% sugar, 50% margarine, 12% milk powder, 9% egg white, 5% baking powder, 3% salt and 90% water. In the cake preparation step, first the margarine was melted and cooled to room temperature. Sugar and egg white were mixed with a mixer then, melted margarine was added and mixed at the same speed for one minute. The pre-mixed dry ingredients were added alternatively with water, mixed at medium speed for 3 min, then the sides were scraped down and mixed at high speed for an additional one minute. The final mixing took place at medium speed for 2 min. One hundred gram of cake batter was weighed in a greased glass baking pan (8 cm in diameter) lined with wax paper. Conventional baking was performed in an electrical oven (Arçelik ARMF 4 Plus, Turkey) at 175°C for 24 min. An Infrared-microwave combination oven (Advantium oven™, General Electric Company, Louisville, KY, USA) was used with only the microwave operating mode. An IR-microwave combination oven (Advantium oven™, General Electric Company, Louisville, KY, USA) was used with only the halogen lamp operating mode to identify the characteristics of IR baking. An IR-microwave combination oven (Advantium oven™, General Electric Company, Louisville, KY, USA) combines microwave and IR heating in the oven. Cake batter was baked at 50% microwave power and 50 and 70% infrared power levels. By using Infrared-microwave combination baking, the time saving advantage of microwave baking was combined with the surface browning advantage of infrared heating.

Microwave baking characteristics (surface and internal temperature, normalized height, moisture content) of Madeira cake. Cake batter was baked in a bench-scale microwave oven (output power 100-900 W) while the control sample was baked in a convective oven at 200°C. The variation in sample centre temperature exhibited two distinct stages; a short warming-up period and a constant temperature (approximately 103°C) stage. A height profile across the sample cross-section revealed the maximum obtainable height was at the sample centre, with the maximum final sample height being achieved using 900 W. Cake baked in the microwave oven at 250 W showed improved textural properties (springiness, moisture content, firmness) as compared to cake baked in the convective oven.

When Microcrystalline Cellulose is used at levels from 2 to 4% it improves the sponginess, increases cake volume, better handling properties and improved product appearance. Chavan *et al*. (2008b) and Al-Muhtaseb *et al*. (2010a) observed the moisture absorption isotherms of microwave-baked Madeira cake, flour and sugar using a standard static gravimetric method within the temperature range 5-60°C and relative humidity range of 0.04-0.96. Microwave-baked Madeira cake and sugar samples exhibited type III isotherm behaviour, whereas flour exhibited type II characteristics, with the sorption capacity decreasing with increasing temperature for Madeira cake and flour. It showed a power law relationship with moisture content for microwave-baked Madeira cake and exponential relationship for flour. Al-Muhtaseb *et al.* (2010b) measured dielectric constant and loss factor of Madeira cake batter and its constituents (sugar, cake concentrate, margarine, flour, egg) at a range of moisture contents (0.429-1.000 kg kg^{-1}, dry basis), temperatures (20-80°C) and over a frequency range of 915-2450 MHz. Irrespective of frequency and sample moisture content, the dielectric constant of batter and flour was relatively independent of sample temperature, whereas that of the sugar samples increased with increasing temperature, particularly within the lower moisture range. At 2450 MHz the loss factor of batter and flour samples decreased by a limited amount as temperature was increased, whereas at 915 MHz they were relatively unaffected. The sugar samples showed a significant decrease in loss factor with increasing temperature, irrespective of frequency. During microwave baking the dielectric properties of Madeira cake batter initially increased sharply and then decreased steadily until the end of the baking process.

Other Microwave-Baked Products

Pasta is made by hydrating semolina, mixing, kneading, extruding through a die to obtain the desired shape and then drying it. Drying is the most difficult and critical step to control in the pasta production process (Zweifel *et al*., 2000). Pasta products are difficult to dry because moisture slowly migrates to the surface. Hot air is, by itself, relatively efficient at removing free water at or near the surface, whereas the internal moisture takes time to move to the surface. Microwave energy solves this problem by providing a positive moisture flow towards the surface. Therefore, it is possible to improve the efficiency and economics of the drying process by combining properly both unit operations (hot air+microwave drying) in a unique way. Goksu *et al*. (2005) studied microwave assisted fluidized bed drying of macaroni beads using a household microwave oven. They found that the increase in microwave power and air temperature significantly reduced the drying time of the macaroni beads. It was concluded that the fluidized bed drying time was reduced approximately by 50% with the addition of microwave energy into the system when the average drying times of fluidized bed and microwave assisted fluidized bed drying were compared. Berteli and Marsaioli (2005) evaluated the efficiency of air drying the type Penne short cut pasta with the assistance of microwave energy by using at first an adapted domestic microwave oven and later transferring the bench scale experimental parameters to test a continuous pilot scale microwave assisted hot air rotary dryer. They observed that average drying time was reduced by more than ten times when compared to the air conventional drying, without being harmful to the appearance of the final product (Altan and Maskan, 2005).

Microwave related combination drying is a rapid dehydration technique that can be applied to specific foods, particularly to fruits and vegetables. Increasing concerns over product quality and production costs have motivated the researchers to investigate and the industry to adopt combination drying technologies. The advantages of microwave-related combination drying include the following: shorter drying time, improved product quality and flexibility in producing a wide variety of dried products. But current applications are limited to small categories of fruits and vegetables due to high start-up costs and relatively complicated technology as compared to conventional convection drying (Zhang *et al.*, 2006). There are few studies about the usage of microwaves in deep-fat frying process (Barutcu *et al.*, 2009). In these studies, the effects of different frying conditions on product quality have been investigated. Microwaves frying was found to result in lower acrylamide formation in potato strips (Sahin *et al.*, 2007) and in coating part of chicken sample (Barutcu *et al.*, 2009) when compared to conventional deep-fat frying. In addition, microwaves frying provided lower oil uptake in potato strips (Oztop *et al.*, 2007).

Doughnut proofing by using microwave energy can be accomplished in 4 min compared with 40-60 min in conventional proofing. The cake-doughnuts (including chemical raising agents) were first fried in hot fat and subsequent microwave baking enabled the products to bake more rapidly. Browning of the dough was achieved by deep-frying on both sides. The interior of the doughnuts were light with a non-uniform structure of low density (Schiffmann, 1992; Sumnu *et al.*, 2005). Microwave heating could be successfully introduced in the final stages of cookie baking, producing products with excellent properties and no cracking (Schiffmann, 1992).

Radio Frequency (RF) energy was used to remove excess moisture uniformly from crackers and cookies and no discolouration and flavour damage took place owing to the thermal build up (Sumnu *et al.*, 2005).

CONCLUSIONS

Baking is a complex process that brings about a series of physical, chemical and biochemical changes in a product such as volume expansion, evaporation of water, formation of a porous structure, denaturation of protein, gelatinization of starch, crust formation and browning reaction. Microwave baking has limited applications in the food industry. However, investigating the interaction of different ingredients with microwave energy should provide insight that will help to improve the quality of microwave-baked products. In microwave heating, the heating mechanism differs from conventional methods. Absorption of energy from the microwave field results in internal heat generation and as a consequence internal vapor generation. The internal vapor generation leads to the development of a pressure gradient which increases the rate of moisture transfer significantly as compared to conventional heating methods. The most prominent advantages of microwave heating are the reachable acceleration, space, nutrient and time savings and the possible volume, instead of surface heating. Presently, industrial microwave dryers could be commercially viable for food industries that require short drying time and higher product throughput at the expense of higher energy input. Also, food industries dealing with products that are susceptible to case hardening may consider microwave drying to be a good alternative in quality enhancement. Thus there is a large market for microwave foods and one of the potentially important growth areas is microwave-baked products improving the quality of microwave-baked products will remain a major task for researchers.

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