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# Microwave Applications in Thermal Food Processing

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## 1. Introduction

In this chapter an overview of microwave heating as one method of thermal food processing is presented. Due to the limited space, this overview cannot be complete; instead some important theoretical information and also examples of practical uses at home and in industry are shown. This chapter provides a starting point, and the interested reader is directed to the references, where more information about the special themes discussed in this chapter can be found (Dehne, 1999). Additional to the references in the text the interested reader is also referred to two bibliographies that cover more or less all the published work on microwaves (W.H.O, 2012).

## 2. History

The development of dielectric heating applications in food industry started in the radio frequency range in the 1930s (Püschner, 1966). The desired energy transfer rate enhancement led to an increased frequency: the microwaves. The first patent, describing an industrial conveyor belt microwave system was issued in 1952 (Spencer, 1952), however its first application started 10 years later. This was caused by the need for high power microwave sources to be developed. The first major applications were finish drying of potato chips, pre-cooking of poultry and bacon, tempering of frozen food and drying of pasta (Decareau, 1985). Whereas the first applications were only temporarily successful, since the quality enhancement due to the microwave process could quickly be achieved by a more economic improvement of the conventional technique, the other techniques survived and are still successful in industrial application.

### **3. Uses, advantages and disadvantages of microwave heating applications**

Today's uses range from these well known applications over pasteurization and sterilization to combined processes like microwave vacuum drying. The rather slow spread of food industrial microwave applications has a number of reasons: there is the conservatism of the food industry (Decareau, 1985) and its relatively low research budget. Linked to this, there are difficulties in moderating the problems of microwave heating applications. One of the main problems is that, in order to get good results, they need a high input of engineering intelligence.

Different from conventional heating systems, where satisfactory results can be achieved easily by intuition, good microwave application results often do need a lot of knowledge or experience to understand and moderate effects like uneven heating or the thermal runaway. Another disadvantage of microwave heating as opposed to conventional heating is the need for electrical energy, which is its most expensive form. Nevertheless, microwave heating has a number of quantitative and qualitative advantages over conventional heating techniques that make its adoption a serious proposition. One main advantage is the place where the heat is generated, namely the product itself. Because of this, the effect of small heat conductivities or heat transfer coefficients does not play such an important role. Therefore, larger pieces can be heated in a shorter time and with a more even temperature distribution. These advantages often yield an increased production.

## **4. Microwave applications**

### **4.1. Application in food industries**

Due to the very large number of microwave ovens in households, the food related industry not only uses microwaves for processing but also develops products and product properties especially for microwave heating. This way of product enhancement is called product engineering or formulation.

#### *4.1.1. Baking and cooking*

Detailed references to the baking process of bread, cakes, pastry etc. by the help of microwaves on industrial scale can be found. An enhanced throughput is achieved by an acceleration of the baking where the additional space needs for microwave power generators are negligible. Microwaves in baking are used in combination with conventional or infrared surface baking; this avoids the problem of the lack of crust formation and surface browning. An advantage of the combined process is the possible use of European soft wheat with high alpha-amylase and low protein content.

In contrast to conventional baking microwave heating inactivates this enzyme fast enough (due to a fast and uniform temperature rise in the whole product) to prevent the starch from extensive breakdown, and develops sufficient CO<sub>2</sub> and steam to produce a highly porous (Decareau, 1986). One difficulty to be overcome was a microwavable baking pan, which is

sufficiently heat resistant and not too expensive for commercial use. By 1982 patents had been issued overcoming this problem by using metal baking pans in microwave ovens (Schiffmann et al., 1981 and Schiffmann, 1982).

The main use of microwaves in the baking industry today is the microwave finishing, when the low heat conductivity lead to considerable higher baking times in the conventional process. A different process that also can be accelerated by application of microwave heating is (pre-) cooking. It has been established for (pre)cooking of poultry (Helmar et al., 2007), meat patties and bacon. Microwaves are the main energy source, to render the fat and coagulate the proteins by an increased temperature. In the same time the surface water is removed by a convective air flow. Another advantage of this technique is the valuable by-product namely rendered fat of high quality, which is used as food flavoring (Schiffmann, 1986).

#### 4.1.2. *Thawing and tempering*

Thawing and tempering have received much less attention in the literature than most other food processing operations. In commercial practice there are relatively few controlled thawing systems. Frozen meat, fish, vegetables, fruit, butter and juice concentrate are common raw materials for many food-manufacturing operations. Frozen meat, as supplied to the industry, ranges in size and shape from complete hindquarters of beef to small breasts of lamb and poultry portions, although the majority of the material is 'boned-out' and packed in boxes approximately 15 cm thick weighing between 20 and 40 kg. Fish is normally in plate frozen slabs; fruit and vegetables in boxes, bags or tubs; and juice in large barrels. Few processes can handle the frozen material and it is usually either thawed or tempered before further processing.

Thawing is usually regarded as complete when all the material has reached 0 °C and no free ice is present. This is the minimum temperature at which the meat can be boned or other products cut or separated by hand. Lower temperatures (e.g. -5 to -2 °C) are acceptable for product that is destined for mechanical chopping, but such material is 'tempered' rather than thawed. The two processes should not be confused because tempering only constitutes the initial phase of a complete thawing process. Thawing is often considered as simply the reversal of the freezing process.

However, inherent in thawing is a major problem that does not occur in the freezing operation. The majority of the bacteria that cause spoilage or food poisoning are found on the surfaces of food. During the freezing operation, surface temperatures are reduced rapidly and bacterial multiplication is severely limited, with bacteria becoming completely dormant below -10 °C. In the thawing operation these same surface areas are the first to rise in temperature and bacterial multiplication can recommence. On large objects subjected to long uncontrolled thawing cycles, surface spoilage can occur before the centre regions have fully thawed.

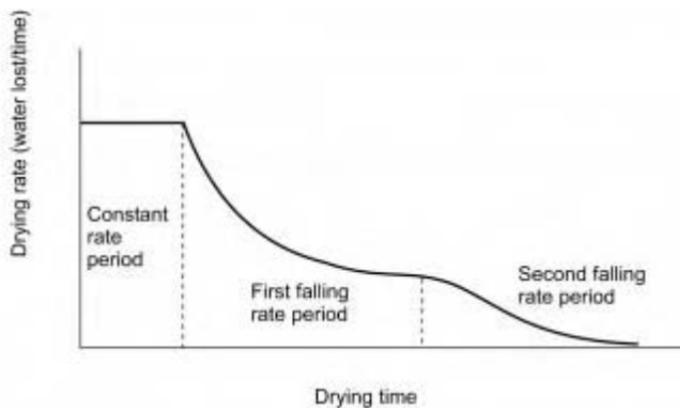
Conventional thawing and tempering systems supply heat to the surface and then rely on conduction to transfer that heat into the centre of the product. A few, including microwave,

use electromagnetic radiation to generate heat within the food. In selecting a thawing or tempering system for industrial use a balance must be struck between thawing time, appearance and bacteriological condition of the product, processing problems such as effluent disposal, and the capital and operating costs of the respective systems. Of these factors, thawing time is the principal criterion that often governs selection of the system. Appearance, bacteriological condition and weight loss are important if the material is to be sold in the thawed condition but are less so if it is for processing. The main detrimental effect of freezing and thawing meat is the large increase in the amount of proteinaceous fluid (drip) released on final cutting, yet the influence of thawing rate on drip production is not clear.

James and James (2002) reported that studies have shown that there was no significant effect of thawing rate on the volume of drip in beef or pork. Several authors concluded that fast thawing rates would produce increased drip, while others showed the opposite. Thawing times from -8 to 0 °C of less than 1 minute or greater than 2000 minutes led to increased drip loss (James et al., 2002). The results are therefore conflicting and provide no useful design data for optimizing a thawing system. With fish, fruit and vegetables ice formation during freezing breaks up cell structure and fluids are reduced during thawing. In microwave tempering processes the heating uniformity and the control of the end temperature are very important, since a localized melting would be coupled to a thermal runaway effect.

#### 4.1.3. Drying

The benefits of microwave drying we should first have a quick look at the much more conventional method of air drying. As shown in Fig.1, a typical drying curve of a foodstuff can be subdivided into three phases. The first period is one of constant drying rate per unit of surface area. During this period the surface is kept wet by the constant capillary-driven flow of water from within the particle. The factors that determine and limit the rate of drying in the so-called 'constant rate period' all describe the state of the air: temperature and relative humidity as well as air velocity (Erle, 2000).



**Figure 1.** Typical drying curve for air drying

In drying the main cause for the application of microwaves is the acceleration of the processes, which are (without using microwaves) limited by low thermal conductivities, especially in products of low moisture content. Correspondingly sensorial and nutritional damage caused by long drying times or high surface temperatures can be prevented. The possible avoidance of case hardening, due to more homogeneous drying without large moisture gradients is another advantage. Two cases of microwave drying are possible, drying at atmospheric pressure and that with applied vacuum conditions.

Combined microwave-air-dryers are more widespread in the food industry, and can be classified into a serial or a parallel combination of the both methods. Applied examples for a serial hot air and microwave dehydration are pasta drying and the production of dried onions (Metaxas et al., 1983) whereas only intermittently successful in the 1960s and 1970s was the finish drying of potato chips. The combination of microwave and vacuum drying also has a certain potential. Microwave assisted freeze drying is well studied, but no commercial industrial application can be found, due to high costs and a small market for freeze dried food products (Knutson et al., 1987). Microwave vacuum drying with pressures above the triple point of water has more commercial potential has microwave vacuum drying with pressures above the triple point of water.

Microwave energy overcomes the problem of very high heat transfer and conduction resistances, leading to higher drying rates. These high drying rates correspond also to lower shrinkage and to the retention of water insoluble as shown in Figure 4. In parsley, for example, most of essential oils are present as a separate phase with high boiling temperature. For fast drying conditions (high microwave energy input) only the small amount of volatile essential oils that is dissolved is lost, whereas there is not enough time to resolve the remaining oil in the separated phase (Erle, 2000).

In contrast the retention of water soluble aromas, as in apples, is not as advantageous, since the microwave energy generates many vapour bubbles, so that the volatile aromas have a large surface to evaporate. Nevertheless, the low pressures limit the product temperatures to lower values, as long as a certain amount of free water is present and this helps to retain temperature sensitive substances like vitamins, colours etc. So, in some cases the high quality of the products could make also this relative expensive process economical.

Microwave vacuum dehydration is used for the concentration or even powder production of fruit juices and drying of grains in short times without germination. Newly and successfully applied is the combination of pre-air-drying, intermittent microwave vacuum drying (called puffing) and post-air-drying. It is predominantly used to produce dried fruits and vegetables, with improved rehydration properties (Räuber, 2000). After the form is stabilized by case hardening due to conventional air-drying, the microwave vacuum process opens the cell structures (puffing) due to the fast vapourization of water and an open pore structure is generated. The subsequent post-drying reduces the water content to the required value.

#### 4.1.4. *Quality of microwave-dried food products*

In general, the quality is somewhere between air-dried and freeze-dried products. The reduction of drying times can be quite beneficial for the colour and the aroma. Venkatesh and Raghavan (2004) dried rosemary in a household microwave oven with good aroma retention. Krokida and Maroulis (1999) measured colour and porosity of microwave-dried apples, bananas, and carrots. Khraisheh et al. (2004) compared air-dried and microwave-dried potatoes and found a reduction of shrinkage and improved rehydration for the latter. Venkatesh et al (2004) reported on chicken products, seafood, and vegetables of good quality. He used air at  $10\pm 20$  °C to cool the product during microwave drying. Quality can often be improved further by the use of vacuum. This reduces thermal as well as oxidative stress during processing.

For instance, Yongsawatdigul and Gunasekaran (1996) showed that colour and texture of microwave-vacuum-dried cranberries were better than those of air-dried samples. If we look specifically at the retention of aroma, it becomes necessary to distinguish between two basic cases. In most foods the aroma molecules are present in very small amounts, so that they are likely to be dissolved in the water phase. In this situation, the volatility of the aroma molecule in water is essential.

Considering the fact that we perceive aroma -as opposed to taste - with our noses, it is quite clear that aroma molecules are normally volatile; otherwise they would stay in the food during eating and not contribute to the aroma. In other words, if there is an interface between a water phase (i.e. a food) and a gas phase, the aroma molecules tend to choose the gas phase. In air drying, the surface where the aroma molecules can escape is mainly the outer surface of the particles. This is also where the water molecules evaporate. So the surface of the food particle will be depleted of aroma, but the losses cannot be higher than those that come with the capillary water flow from within. As a result, the losses of water and aroma are coupled.

## 5. Microwave drying applied in the food industry

Microwave drying is not common in the food industry. There are many reasons for its limited use: the technical problems described above were not well- understood in the past. This has led to some failures, which have surely discouraged other potential users. Schiffmann (2001) has listed a number of formerly successful applications that have been discontinued. Among these are the finish drying of potato chips, pasta drying, snack drying, and the finish drying of biscuits and crackers. It is apparently not always the microwave process itself but rather changes in the circumstances of production that make competing technologies more successful.

In spite of these difficulties, there are some current applications. Schiffmann (2001) mentions cereal cooking and drying with a production rate of nearly 1 ton/h. Pasta drying with microwaves is carried out in Italy. Microwave- vacuum drying is being used for meat extract and, at least for a number of years, for the production of a powder made from orange juice concentrate.

The combination of air drying and microwave-vacuum puffing is being used in Germany and Poland for fruits and vegetables. As the food industry does not disclose all its production processes, we cannot expect this list to be complete. Hauri (1989) has provided values for the necessary investment and the specific energy requirements of five different drying methods (Table 1). Based on the same throughput, the investment needed for microwave-vacuum drying is rather high, while the energy figures are more favorable than for air drying.

Types of drying process	Specific energy demand kwh/kg	Specific investment costs for equal throughput
Air band drying	1.9	100%
Spry drying	1.6	120%
Vacuum contact drying	1.3	150%
Microwave Vacuum drying	1.5	190%
Freez drying	2.0	230%

**Table 1.** Comparison of five different drying method

## 6. Pasteurization and sterilization

Studies of microwave assisted pasteurization and sterilization have been motivated by the fast and effective microwave heating of many foods containing water or salts. A detailed review can be found in (Rosenberg et al., 1987). Although, physically non-thermal effects on molecules are very improbable, early works seemed to show just these effects. But in most cases the results claimed could not be reproduced, or they lacked an exact temperature distribution determination. The improbability of non-thermal effects becomes clear, when the quantum energy of photons of microwaves, of a thermal radiator and the energy of molecular bonds are compared. The quantum energy of a photon of  $f = 2.45$  GHz is defined by  $E = hf \approx 1 \cdot 10^{-5}$  eV, the typical energy of a photon radiated from a body of  $25^\circ\text{C} \approx 298$  K equals  $E = kT \approx 0.26$  eV and the energy of molecule bonds are in the eV-range.

Since the collection of energy with time for bound electrons are forbidden by quantum mechanics, only multi-photon processes, which are very unlikely, could yield chemical changes. Recently Lishchuk also showed that even a deviation of the energy distribution of water molecules from the conventional Boltzmann distribution cannot be proved (Lishchuk et al., 2001).

More thinkable is the induction of voltages and currents within living cell material, where eventual consequences are still in discussion (Sienkiewicz, 1998). Due to the unquestioned thermal effects of microwaves, they can be used for pasteurization and sterilization. Studied applications of microwave pasteurization or sterilization cover pre-packed food like yoghurt or pouch-packed meals as well as continuous pasteurization of fluids like milk (Helmar et al., 2007). Due to the corresponding product properties either conveyor belt systems or continuous resonator systems are invented.

The possibly high and nearly homogeneous heating rates, also in solid foods (heat generation within the food) and the corresponding short process times, which helps preserving a very high quality yield advantages of microwave compared to conventional techniques. The crucial point in both processes is the control and the knowledge of the lowest temperatures within the product, where the destruction of microorganisms has the slowest rate. Due to the difficult measurement or calculation of temperature profiles it is still very seldom industrially used.

## **7. Blanching using microwave processing**

Blanching is an important step in the industrial processing of fruits and vegetables. It consists of a thermal process that can be performed by immersing vegetables in hot water (88-99 °C, the most common method), hot and boiling solutions containing acids and/or salts, steam, or microwaves. Blanching is carried out before freezing, frying, drying and canning. The main purpose of this process is to inactivate the enzyme systems that may cause color, flavor and textural changes, such as peroxidase, polyphenol-oxidase, lipoxygenase and pectin enzymes. The efficiency of the blanching process is usually based on the inactivation of one of the heat resistant enzymes: peroxidase or polyphenoloxidase.

Blanching has additional benefits, such as the cleansing of the product, the decreasing of the initial microbial load, exhausting gas from the plant tissue, and the preheating before processing. A moderate heating process such as blanching may also release carotenoids and make them more extractable and bioavailable (Arroqui et al., 2002).

However, this operation has also some inconvenient effects such as losses in product quality (texture and turgor), environmental impact, and energy costs. Leaching and degradation of nutritive components, such as sugars, minerals and vitamins, may occur when blanching with water or steam. The blanching process should assure enzyme inactivation while minimizing the negative effects, taking into account the interdependence of every aspect (Arroqui et al., 2002).

The use of microwaves for food processing has increased through the last decades. Some of the advantages compared with conventional heating methods include speed of operation, energy savings, precise process controls and faster start-up and shut-down times (Kidmose and Martens, 1999). Microwave blanching of fruits and vegetables is still limited. Some of the advantages compared with conventional heating methods include speed of operation and no additional water required. Hence there is a lower leaching of vitamins and other soluble nutrients, and the generation of waste water is eliminated or greatly reduced.

## **8. Applications of microwave blanching foods**

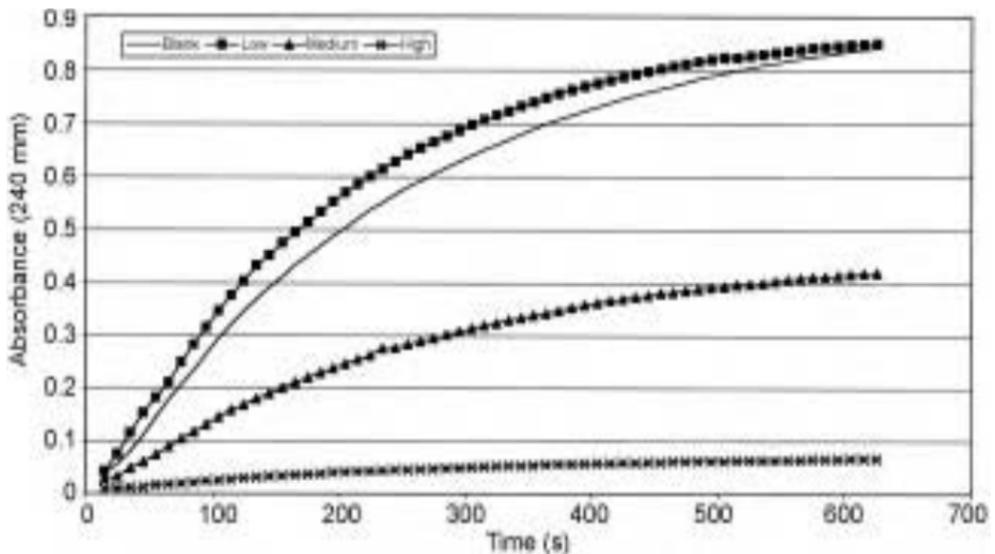
Blanching with hot water after the microwave treatment compensates for any lack of heating uniformity that may have taken place, and also prevents desiccation or shriveling of delicate vegetables. And while microwave blanching alone provides a fresh vegetable flavor, the combination with initial water or steam blanching provides an economic advantage. This is

because low-cost hot water or steam power is used to first partially raise the temperature, while microwave power, which costs more, does the more difficult task of internally blanching the food product.

A still further advantage is that microwave blanching enables a finish blanching of the center sections more quickly and without being affected by thick or non-uniform sections. Uniformity is also more rapidly accomplished in microwave ovens of the continuous tunnel types in contrast to the customary non-uniformity in institutional or domestic ovens (Smith and Williams, 1971).

The spraying of cold water at the end of the blanching process allows a better nutrient retention than the immersion of the food in cold water. Sub-atmospheric pressure, when applied to the steam blanching process, reduces the amount of oxygen and therefore results in a lower degradation of vegetable pigments and nutrients. Pressurized steam reduces blanching time. Optimal conditions of time, temperature, vapor pressure and microwave power depend on the particular vegetable that is being processed and must be empirically determined.

The knowledge of precise microwave power per weight of food that is needed to inactivate a particular enzyme should be sufficient to achieve a successful blanching and to avoid adverse effects. When the process temperature is not adequate, the enzymatic deteriorative action may prevail or even increase in some cases. Figure 2 shows the activity of mushroom polyphenol oxidase in a phosphate buffer 0.05M solution. The samples were previously treated in a microwave oven at specific times, using different potency levels: high, medium and low, which correspond to 770, 560 and 240 watts, respectively.



**Figure 2.** Mushroom tyrosinase as affected by microwaves.

## 9. Advantages of microwave blanching

Microwave heating involves conversion of electromagnetic energy into heat by selective absorption and dissipation. Microwave heating is attractive for heating of foods due to its origin within the material, fast temperature rise, controllable heat deposition, and easy clean-up. The very high frequencies used in microwave heating allow for rapid energy transfers and, thus, high rates of heating. These rates are a main advantage of this technique. Also, because microwaves penetrate the sample, heating is accomplished in the interior of the food. When heating rapidly, the quality of fruits and vegetables such as flavor, texture, color and vitamin content is better kept (Dorantes-Alvarez et al., 2000). However, rapid heating can also lead to problems of non-uniform heating when excessively high energy transfer rates are used (Ohlsson, 2000). It has been observed that microwave processing of chicken, beef, bacon, trout, and peanut oil does not change the fatty acid composition of these products, nor produces trans- isomers (Helmar et al., 2007).

## 10. Development of unique-single systems for microwave blanching

The most likely future for microwave food processing is in the continued development of unique single systems that overcome the limitations discussed previously. Compared to the development of traditional blanching systems, it is still a challenge to design appropriate equipment for microwave blanching.

This is due mainly to the following factors:

- Better control of the process is required due to the shorter heating times that microwave heating requires.
- The temperature distribution within the food product is affected by additional factors. A better distribution can be achieved by the use of standing and hold times at the end of the process. More research is needed in order to develop a method that would assure better repeatability of the process and equilibration of temperatures. The last objective can also be helped by a careful control of the food composition (Anantheswaran and Ramaswamy, 2001). Since the heating migration in microwave processing occurs from the initial and hottest locations in the interior of the food, it is difficult to locate and assess the cold point, as in traditional thermal methods. Therefore, the use of specific software to calculate the parameters of the process will help to achieve a higher efficiency (Rodr   guez et al., 2003).

In the near future, it is expected that researchers interested in this matter will discover more specific effects that may be advantageous in the processing of food by microwave blanching. This would give an additional value to food products and would overcome the cost of microwave energy for this particular application.

## 11. Waste treatment under microwave irradiation

Many industrial activities involve the creation and subsequent disposal of waste, which represents a noticeable cost in terms of money and pollution. Moreover, sometimes waste

materials are hazardous as well, i.e. materials containing asbestos or byproducts of nuclear plant. In this case, regulatory procedures are particularly restrictive, to guarantee the safety of the operators, and the choice of an inertization process becomes a compromise between safety issues, energetic evaluations and economical aspects. Thus, the waste treatment has to be evaluated nation of the final product.

The disposal of waste materials is now becoming a very serious problem, since in recent years the great increase of their production was not matched by a corresponding rise in the number of authorized dumps. Moreover, the existing regulation does not always allow all kind of waste material to be recycled, especially if harmful or hazardous materials are involved (Oda et al., 1992). But considering the present year production of wastes like ashes, or the wide spread presence on the territory of asbestos containing materials, it seems impossible to handle this environmental issue only by disposal in dumps. To face this situation, it is necessary to study and develop alternative ways to treat and re-use the components of waste materials, for instance converting them in secondary raw materials and, if possible, restoring them to accomplish the task they were initially meant for. Waste, even if originated by the same manufacturing process, and thus belonging to the same category (i.e. ashes, nuclear waste, asbestos containing materials, etc.), can be regarded as a multi-component material having a wide range of compositions, and usually it is the presence of only some of these components that makes all the mixture a product to be disposed of. Thus, a process allowing selective treatment of the "unwanted" portion of the waste, and to do this volumetrically, could represent an enormous advantage in terms of time and money, especially as far as materials presenting low thermal conductivity are concerned (Marucci et al., 2000). Microwaves can be an interesting candidate to fulfill the need for this kind of processes, and this is particularly true if the matrix of the waste materials exhibits dielectric properties significantly different from those of the unwanted components.

## **12. Safety of food processed in microwave for consumers**

The food processed by this novel technology is safe for consumption. "Because the microwave energy is changed to heat as soon as it is absorbed by the food, it cannot make the food radioactive or contaminated (O.S.H.A, 2012). When the microwave energy is turned off and the food is removed from the oven, there is no residual radiation remaining in the food. In this regard, a microwave oven is much like an electric light that stops glowing when it is turned off (Gallawa, 2005).

## **13. Summary and outlook**

Microwave ovens are commonplace in households and are established there as devices of everyday use. Their primary function is still the reheating of previously cooked or prepared meals. The relatively new combination of microwaves with other (e.g. conventional, infrared or air jet) heating systems should enhance their potential for a complete cooking device, that

could replace conventional ovens. Unfortunately, in industry the distribution of microwave processes is still far away from such high numbers. Only a relatively low number of microwave applications can be found in actual industrial production, compared with their indisputable high potential. These successful microwave applications range over a great spectrum of all thermal food processes. The most prominent advantages of microwave heating are the reachable acceleration and time savings and the possible volume instead of surface heating. Reasons mentioned for the failure of industrial microwave applications range from high energy costs, which have to be counterbalanced by higher product qualities, over the conservatism of the food industry and relatively low research budgets, to the lack of microwave engineering knowledge and of complete microwave heating models and their calculation facilities. The latter disadvantage has been partly overcome by the exponentially growing calculating power which makes it possible to compute more and more realistic models by numerical methods. Very important for the task of realistic calculations is the determination of dielectric properties of food substances by experiments and theoretical approaches. Nevertheless in order to estimate results of microwave heating applications and to check roughly the numerical results, knowledge of simple solutions of the one-dimensional wave propagation like the exponentially damped wave is of practical (and also educational) relevance. But still the best test for numerical calculations is experiments, which yield the real temperature distributions within the product, which is really important especially in pasteurization and sterilization applications. While more conventional temperature probe systems, like fibre optic probes, liquid crystal foils or infrared photographs only give a kind of incomplete information about the temperature distribution within the whole sample, probably magnetic resonance imaging has the potential to give very useful information about the heating patterns. Hopefully, this together with the enormous calculation and modeling power will give the microwave technique an additional boost to become more widespread in industrial food production.

The breakthrough of microwave technology in the food industry due to its high potential has been predicted many times before, but it has been delayed every time up to now. That is why we are cautious in predicting the future of microwaves in industrial use. However, we think that the potential of microwave technology in the food industry is far from being exhausted.

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