MICROWAVE ASSISTED DRYING OF SHORT-CUT (DITALINI) MACARONI

M.Sc. Thesis

in

Food Engineering

University of Gaziantep

By

Aylin ALTAN

June 2003

Approval of the Graduate School of Natural and Applied Sciences

Prof.Dr.Bülent GÖNÜL
Director

I certify that this thesis satisfies all the requirements as a thesis for the degree of Master of Science.

Prof.Dr.Sami EREN
Chairman of the Department

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

Assoc.Prof.Dr. Medeni MASKAN
Supervisor

Examining Committee Members

Assoc.Prof.Dr. Sevim KAYA

Assoc.Prof.Dr. Medeni MASKAN

Assist.Prof.Dr. Bülent BELİBAĞLI

ABSTRACT

MICROWAVE ASSISTED DRYING OF SHORT-CUT (DITALINI) MACARONI

ALTAN, Aylin
M.Sc. in Food Engineering
Supervisor: Assoc. Prof. Dr. Medeni MASKAN
June 2003, 84 Pages

Macaroni samples were dried by conventional hot air, microwave and hot air followed by microwave drying methods. The drying of macaroni samples took place in the falling rate period. Higher drying rates were observed with the higher microwave power levels. A model was employed to fit the experimental drying data and gave a good fit for all experimental runs except hot air-microwave (210 W) finish drying data. Drying only with microwave energy (70 W and 210 W) or hot air-microwave energy (70 W and 210 W) resulted in substantial shortening of the drying time (61.8%, 87.3%, 61% and 78%, respectively). The total drying time, the color, rehydration capacity and macaroni cooking quality, related to cooked weight, cooking loss and firmness were evaluated. The textural properties of uncooked and cooked macaroni samples were measured by using a TA-XT2i Texture Analyzer. Protein denaturation increased significantly as microwave power increased. Macaroni samples dried with combined hot air-microwave (210 W) was equal or better than hot air. Also, hot air-microwave combination drying exhibited superior cooking properties. Cooked weight and firmness increased while cooking loss decreased generally as microwave applied after hot air drying, i.e., hot air-microwave combination shortened the drying time and improved the physical, textural and cooking quality of macaroni samples.

Key words: drying, macaroni, microwave, color, rehydration, cooking quality, texture.

ÖZ

KISA KESME (DITALINI) MAKARNANIN MİKRODALGA YARDIMIYLA KURUTULMASI

ALTAN, Aylin
Yüksek Lisans Tezi, Gıda Mühendisliği Bölümü
Tez Yöneticisi: Doç. Dr. Medeni MASKAN

Haziran 2003, 84 Sayfa

Makarna örnekleri geleneksel sıcak hava, mikrodalga ve sıcak havayı takiben mikrodalga uygulaması metotlarıyla kurutuldu. Makarna örneklerinin kuruması azalan kuruma hızı döneminde gerçekleşti. Yüksek mikrodalga güç seviyelerinde yüksek kuruma hızı gözlendi. Deneysel verilere uyarlamak için bir model kullanıldı ve mikrodalga (210 W) ile sona eren kurutma verilerinin dışında bütün deneysel verilerde iyi sonuç verdi. Sadece mikrodalga (70 W ve 210 W) ve sıcak havayı takiben mikrodalga enerjisiyle (70 W ve 210 W) yapılan kurutma işlemleri, kuruma zamanını önemli ölçüde kısalttı (sırasıyla 61.8%, 87.3%, 61% ve 78%). Toplam kuruma zamanı, renk, rehidrasyon kapasitesi ve makarnanın piştikten sonraki ağırlığı, pişme kaybı ve sertliğiyle ilişkili olarak pişme kalitesi değerlendirildi. Pişmemiş ve pişmiş makarna örneklerinin texstürel özellikleri TA-XT2i Dokusal Analiz Cihazı kullanılarak ölçüldü. Mikrodalga gücü artıkça protein denatürasyonun da önemli ölçüde arttığı görüldü. Birleştirilmiş sıcak hava ve mikrodalga (210 W) ile kurutulmuş makarna yüksek kalitede pişme özellikleri gösterirken renk kalitesi ve rehidrasyon kapasitesi, hava ile kurutulmuş makarnadan daha iyi yada eşit olduğu tespit edildi. Sıcak hava ile kurutmadan sonra mikrodalganın uygulanmasıyla, genellikle pişmiş ağırlık ve sertliğin artmasıyla birlikte, pişme kaybı azaldı, başka bir deyişle, sıcak hava-mikrodalga kombinasyonu makarnanın kurutmanın kurutma zamanını azalttı ve fiziksel, tekstürel ve pişme kalitesini iyileştirdi.

Anahtar kelimeler: kurutma, makarna, mikrodalga, renk, rehidrasyon, pişme kalitesi, tekstür.

ACKNOWLEDGEMENTS

I wish to express my gratitude to my supervisor Assoc. Prof. Dr. Medeni MASKAN for his continuous encouragement and invaluable suggestions throughout this study.

I gratefully acknowledge Beslen Makarna Sanayi (Gaziantep, Turkey) for making their facilities available for this research.

I would like to thank Assoc. Prof. Dr. Ahmet KAYA for his interest and helps.

I would like to thank the entire staff of the Food Engineering Department.

I would also like to thank to my friends Sibel KUŞ, Ozan N. ÇİFTÇİ and Ko SANGHOON for their continuous help and support.

Special thanks go to my parents for always believing in me and supporting me throughout my education. Thanks them forever for standing by me.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

λ : Wavelength, cm
λo : Wavelength in Free Space, cm
ε' : Dielectric Constant
ε'' : Dielectric Loss Factor
ΔE : Total Color Difference
a* : Redness/Greenness
AAIP : Acetic Acid-Insoluble Protein
AOAC : Association of Official Analytical Chemists
b* : Yellowness/Blueness
d.b. : Dry Basis
D_{50} : Half-power Penetration Depth, cm
DSC : Differential Scanning Calorimetry
DSG : Durum Wheat Sulfur Rich Glutenin
HMWG : High Molecular Weight Glutenin
HT : High Temperature, °C
k : Rate Constant, 1/min
kg : Kilogram
L* : Whiteness/Darkness
LMWG : Low Molecular Weight Glutenin
LOX : Lipoxygenase
LT : Low Temperature
M : Moisture Content, kg water/kg dry solids
MHz : Megahertz
MR : Moisture Ratio
MW : Microwave
N : Force Applied in Newton
Pa : Pascal, N/m^2
R^2 : Coefficient of Determination

R : Drying Rate, kg water/kg dry solids.min

SE : Standard Error

t : Drying Time, min

$\tan\delta$: Loss Tangent

TPA : Texture Profile Analysis

VHT : Very High Temperature, °C

W : Watt

w.b. : Wet Basis

W_d : Weight of Dried Sample, g

W_t : Weight of Rehydrated Sample at any time, g

CHAPTER I

INTRODUCTION

Pasta is an ancient foodstuff. Evidence indicates that some types of wheat and water mixtures existed in prehistoric Mesopotamia (Giese, 1992a). Ancient sources said that it was the Chinese who invented pasta and gave the legendary Marco Polo the credit for having brought it to Italy. To be more realistic, however, the origins of "macaroni" in Italy go back as far as the time of the Ancient Romans, who gave the credit to the "gods" (Baroni, 1988).

Pasta is gradually losing its 'cheap and filling' image and this makes it an attractive food to more consumers. This change in image can possibly be attributed to the consumers' realization that pasta has the positive attributes of versality, convenience, economics, taste and nutrition. Pasta is versatile that it is available in numerous shapes and sizes and can be prepared and served with other foods as an appetizer, main dish, side dish, salad, soup or dessert, thus allowing good menu flexibility for the consumer (Dick and Matsuo, 1988). Nutritionists consider pasta to be highly digestible. It also provides significant quantities of complex carbohydrates, proteins, B-vitamins and iron and is low in sodium and total fat (Douglass and Matthews, 1982).

1.1. Pasta Manufacturing

1.1.1. Raw materials

Durum wheat (*Triticum durum*) is preferred over other classes of wheat for the production of pasta products because of the excellent rheological properties of durum wheat pasta dough and the superior color and cooking quality of durum wheat pasta (Dexter and Matsuo, 1978).

This wheat is generally very hard, having a tough, horny endosperm and for this reason lends itself readily to the production of semolina. Semolina has a number of advantages over flour in the manufacture of pasta products; perhaps the most important is that it requires less water to form dough. Any added water must later be removed in the drying process and the less water that must be removed, the simpler the drying operation. One characteristic of durum wheat which readily distinguishes itself from almost all varieties of common wheat is its high level of carotenoid pigments. The endosperm of durum wheat contains about twice the concentration of yellow carotenoid pigments present in the endosperm of the bread wheat, and the yellow color imparted by this high pigment concentration has long been a distinguishing feature of macaroni products made from durum, as opposed to those made from other wheat classes. The most important difference between durum wheat and common wheat is that macaroni products made from durum have a much greater stability when cooked; they tend not to disintegrate to the same extent when boiled and tend not to become as mushy if kept in water after cooking, or if canned. Pasta products contain milled wheat, water and occasionally eggs and/or optimal ingredients (Irvine, 1971).

1.1.2. Wheat milling

Durum milling involves three basic processes. These are cleaning, conditioning and milling.

Cleaning is very important and more difficult to achieve than in the case of other flour milling, because the larger semolina particle sizes lead to correspondingly larger impurity sizes, which are consequently easier to see in finished products.

Conditioning prepares durum wheat for milling by making the outer layers more friable, while maintaining the vitreous structure of the endosperm.

Milling is designed to obtain the highest possible yield of pure semolina from a given quantity of wheat. The semolina needs to satisfy certain physicochemical quality criteria imposed by pasta makers and consumers (granulation, color, etc.). Three unit operations are involved in the milling process:

1) Breaking and dissociation of grains by roller mills as break rolls or scratch rolls that produce crushing as well as shearing action.

2) Size classification of milling products by a Plansifter to grade the middlings and extract bran and flour as by-products.

3) Air classification of the product on a purifier, which is necessary to obtain clean semolina (the finished product of drum wheat milling) (Abecassis, 2001).

1.1.3. Mixing

In the mixing operation, water is added to the milled wheat in a mixing trough to produce dough with moisture content of approximately 32-34% for short cut pasta. The aim of the mixing operation is to distribute the water as evenly as possible throughout the semolina, thus promoting the hydration of particles. In pasta making, the right amount of water must be used to transform the semolina into dough that will stand up to the subsequent forming and drying operations. The amount of water added to the semolina normally ranges from 25 to 30 kg per 100 kg of semolina. Durum wheat semolina generally absorbs less water than wheat flour. Hard dough containing too little water (25-26%) will dry more easily and above all more rapidly. However if sufficient water is not uniformly distributed in the dough, the product will have a dull color with white spots.

It is the shape of the final product that determines the moisture content of the dough. Long shapes generally require dough with less moisture so that stretching during extruding and spreading is minimal and the predrying is made easier. For short goods that require more cutting, the dough should have higher water content (32-34%) so that mechanical action of the cutter blade does not tear the extruded product. Water is traditionally thought to have an important bearing on the quality of the end product. Besides being pure, clean and bacteriologically safe, the water should have a hardness of less than 30° French (1° French=1 mg $CaCO_3$/100ml H_2O) and a low content of sodium, magnesium and calcium ions, as these would give the pasta an unpleasant flavor and color (Dalbon *et al.*, 1996).

In order to obtain an even and homogeneous absorption of the liquids (water and/or egg emulsion) by the flour particles (semolina and/or flour), at least two basic conditions have to be guaranteed:

1-The particles must have the same size or average size ranging between not two distant minimum and maximum values;

2-The time needed for the liquid to be absorbed by the particles has to be evaluated while taking into account their average size and the temperature of both flour and liquid. The lower the flour temperature (semolina and flour), the higher has to be that of the liquid used in the dough (water and/or egg emulsion).

During the dough forming the contact with atmospheric oxygen would increase the enzymatic activities and may cause some changes, especially in the product color (grayish shade and lost of the yellow color due to oxidation of natural pigments in semolina). In order to avoid this, the kneading phases, and for some manufacturers, also the mixing, are carried out in vacuum. The vacuum applied throughout systems may differ from a manufacturer to another (Milatovic and Mondelli, 1991).

1.1.4. Extruding

The extrusion process allows continuous kneading and shaping of the dough to be carried out simultaneously and rapidly, in a matter of a few minutes. After the dough is mixed, it is transferred to the extruder. The extrusion auger not only forces the dough through the die, but it also kneads the dough into a homogeneous mass, controls the rate of production, and influences the overall quality of the finished product. The dough extrusion is complicated process that causes risk situations for both the product and the extrusion unit. Extrusion barrels are equipped with a water-cooling jacket to dissipate the heat generated during extrusion process. The cooling jacket also helps to maintain a constant extrusion temperature, which should be approximately 51°C (124°F). If the dough temperature exceeds 50-55°C, adverse changes can occur, such as denaturing of the gluten proteins and beginning of starch gelatinization. Since all the particles are in relative movement at this stage, the proteins coagulate to give rise to clusters instead of a continuous protein network. Pasta produced under these conditions has poor cooking quality (Dalbon *et al.*, 1996).

The most common physical approach is to remove molecular oxygen by applying a vacuum during extrusion. The vacuum inhibits or slows the chemical reactions that use atmospheric oxygen to form melanic compositions that are the main cause of the loss of the yellow color (Milatovic and Mondelli, 1991). Lipoxygenase activity has been shown to cause loss of pigment and thus decrease in the yellowness of the pasta. The homogeneity of the dough is also improved by the vacuum given that the lack of air favors the absorption of the water by the semolina particles, in proportion to their surface area, in addition to a more rapid formation of gluten. Because less air is present in the mixture, the characteristics of the end-product are improved considerably.

On visual inspection, the pasta has a more uniform appearance (air bubbles in the product cause light diffraction), and is smoother, more compact and therefore less subject to breakage. There is also an appreciable improvement in the cooking quality, probably because the product is more compact. The inside surface of the die also influences the product appearance. Until recently, most dies were made of bronze, which was relatively soft and required repairements or periodic replacements. Recently, dies have been improved by fitting the extruding surface of the die with teflon inserts to extend the life of dies and improve the quality of pasta. Some manufacturers still prefer bronze dies because they produce a product with a rougher surface which apparently helps the sauce to stick to the pasta once it is cooked . Presses fitted with teflon dies offer much greater efficiency than those with bronze dies since the dough has lower water content and is very soft, allowing optimal filling of the extrusion worms. This results in higher pressure, a higher extrusion speed and ultimately a higher output per hour. Bronze dies require dough with higher water content, and therefore lower extrusion pressures in order to avoid an unduly rough extruded product. Their average life is though considerably shorter than that of teflon inserts dies and are therefore used mainly for small special productions (Dalbon *et al.*, 1996).

1.1.5. Drying

Drying is the most difficult and critical step to control in the pasta production process (Zweifel *et al.*, 2000). The objective of drying is to lower the moisture content of the pasta from approximately 30-32% (w.b.) to 12-13% (w.b) so that the finished product will be hard, retain its shape, and store without shattering (Aktan and Khan, 1992). Most pasta drying operations use a preliminary drier immediately after extrusion to prevent the pasta from sticking together.

1.1.5.1. Shaker

The product undergoes an initial drying process, of just the right amount, so that it loses that surface stickiness that could make the individual pieces not to stick together and, in addition, it loses some of the moisture in its outermost layer. At the same time, this process must somehow stabilize the shape of pasta. As soon as it comes off the die the pasta is cut by a rotating blade and dropped onto an inclined surface that causes it to slide inside the shaker. Inside the unit there is at least one vibrating surface (or several surfaces placed one above the other, depending on the type and the capacity) composed of a support structure and grille with openings that are small enough to stop the pasta from falling through but large enough to allow the passage of air and ventilate the pasta where it rests on the grille itself. The air is forced through by a ventilation system and heated. The vibrating movement stops the individual pieces from sticking to each other when they touch. An efficient shaker must, however, ensure the optimum ventilation of the product, shake it energetically without damaging it mechanically and heat it as needed to stabilize its shape, modulate the internal velocity of the sliding of the pasta so as to adapt the treatment time to the needs of the shape (Milatovic and Mondelli, 1991).

1.1.5.2. Pre-Drying

The predrying stage is the most delicate phase in the drying process. The treatment has a longer or shorter duration according to the shape and, in practice, is an alteration of hot-humid ventilation stages and rest without ventilation (Baroni, 1988). In drying pasta, ventilation plays a fundamental role since, besides removing the water given off by the product due to evaporation; it is used as a vehicle to convey the heat. The heat energy conveyed by the ventilation air is used to heat the product and the water it contains, making it evaporate (Milatovic and Mondelli, 1991).

During the pre-drying the moisture content of the product falls from 30-32% (w.b.) to 18-17% (w.b.). The time of this phase obviously depends on the amount of energy (heat) and on the intensity of the ventilation. High temperatures and energetic ventilation reduce necessary time for the pre-drying phase to be completed. The evaporation of water contained in the pasta is a process based on complex phenomena of a physical, chemical and biochemical processes. So it needs to make some distinctions:

-As the evaporation takes place only on the surface of the water, it is necessary to keep the surface of the pasta constantly moist.

-If the evaporation is faster than the speed of migration of water from the internal layers of the pasta toward its surface, we will have to slow it down or block it for the necessary time so that the surface moisture is restored and evaporation can again take place with the required intensity.

-Since the migration of water from the internal to the external layers and so to the surface takes place capillarity, the pasta must maintain an appropriate structure (porosity) in relation to its current moisture.

-Since moisture (together with heat) helps reactions of both a chemical and enzymatic nature among the components of the dough, which may have undesirable effects on the end quality of the dried product, pre-drying should be completed in as short a time as possible, compatibly with the type of product and the technological characteristics of the systems used.

-The moisture of the dough helps the development of micro-organisms, especially bacteria and yeasts that can start fermenting and degenerating. In a correct pre-drying process, the hydrothermal conditions (temperature, moisture) should able to reduce or block this development.

In pre-drying period it is necessary to remove 50-55% (w.b.) of the water contained in the dough (from approximately 32 to 20% (w.b.), with final product moisture at 12.5% (w.b.). Temperature and ventilation must be adequate for fast removal of moisture. At the beginning of pre-drying the pasta has a high moisture level: the water contained in it and the water on the surface evaporates quickly. In the first place, the water found free on the surface, then the water called up from closest layers to the surface. It is above all the starch that gives up water in this first phase. It has a lower capacity for retention of water than that of gluten. Precisely as a consequence of this, the outer layer of the pasta tends to 'lose' its gluten, which is concentrated in the inner layers where there is high water. In the outermost layers of the product, therefore, we will have a greater concentration of starch, including the damaged starch, and broken chains of amylose. If this imbalance is not offset, the outside structure remains weak due to having less gluten there, and compromising the final quality of the pasta (surface stickiness, pasta feeling slimy to the palate, excessively cloudy cooking water). Up to when the average percentage of moisture of the pasta falls under 25%, the gluten keeps good mobility, therefore it is possible to redistribute it in the product before this limit is exceeded downwards. By temporarily stopping ventilation and adequately heating the pasta that will therefore soon be in an environment with very high humidity therefore also the surface evaporation will practically be interrupted.

The upshot of this is that the following results are obtained:

-Heat and very humid environment keeps the capillarity of the product active, helping migration towards the outside of the most internal water particles;

-Exploiting its greater capacity of water retention, the gluten 'follows' the migration of water particles, therefore redistributing its reticular structure as far as the surface of the product. The gluten can as a result also stop the outer most starch grains, to which it moreover yields part of the water absorbed during kneading phase, partially rehydrating them. In this way we again have the initial conditions of the phase and the surface evaporation of the pasta can be restarted, all the more effectively the higher the temperature of the product will have been kept in the meantime, even with the surface evaporation stopped.

It is not possible to implement proper pre-drying with an ambient temperature under 60-65°C, but much more effectiveness is obtained from this technological phase with higher temperatures, 75-85°C. Even higher values are specific for technologies proposed by some manufacturers and applied to highly progressive plants (Milatovic and Mondelli, 1991).

Shortly, the pre-drying technology makes it possible to accomplish:

1-Partial blockage of some enzyme activity and virtually total blockage of any product fermentation, helping to sanitize it, since there are relatively few micro-organisms that at 75°C are capable of surviving and also any insect eggs are easily destroyed.

2-Uniform gluten distribution making full use of capacity of gluten to hold back the starch particles (so better cooking capacity and less stickiness of the product).

3-A decrease in oxidation of yellow pigments contained in the semolina and therefore a brighter color of the dried product.

4-Better shape stability.

5-Maintenance of the product's capillarity, essential to redistribute the particles of water during the following phases of the process.

In the modern pasta making, the use of low temperatures (<40-45°C) in general in drying pasta, but particularly in the phase of pre-drying, not only has no sense at all, but is an absurdity from the productive point of view (Milatovic and Mondelli, 1991). In many cases, if not in all cases, this common practice is moreover a real technological mistake. It is necessary to take into account that during pre-drying the surface evaporation of the pasta cools the inside of the product, all the more the greater its current moisture level. Pre-drying of pasta at 45°C starting from the initial moisture level of 30% means keeping the product for between 30-38°C for a few hours, in conditions of high water activity that is determining an optimum situation for abnormal microbial proliferation, with the result of making the product leaven or ferment, to put its hygienic safety at risk due to the possible growth of pathogenic bacteria (Milatovic and Mondelli, 1991).

1.1.5.3. Final drying

Drying is the elimination of a liquid, normally water, from a substance or a solid body. The water to be eliminated may be just on the surface, or inside the solid body to be dried. If it is only on the surface, drying does not depend on properties of body at the issue. Whereas, if the water inside it, the methods of drying will depend on the body's physical and chemical properties. This is because the water particles need to move from the inside onto surface in order to be removed (normally by evaporation) (Milatovic and Mondelli, 1991).

On leaving the die, pasta normally has moisture content of approximately 31-32% (w.b.) (depending on the type of dough and the shapes made). It is considered dry when its internal moisture content is equal to or less than 12.5% (w.b.) and balanced with the surrounding environment. This means that, to keep well, besides being dry, pasta needs to be 'stable' in other words, within certain environmental climatic limits (air temperature and humidity) it must keep its remaining internal moisture content uniform. On leaving the die, with moisture content of approximately 31-32% (w. b.), pasta is in a 'plastic state'. This condition has specific physical properties: a body in a plastic state can deform under the action of external forces without any particular tension forming inside it and, moreover, it can permanently keep the shape acquired as a result of these forces. This property is perfectly clear in drawing the dough in its plastic state is deformed by the action of die and the shape obtained will not be altered at all after the pressure of the die has stopped. Pasta in plastic state can then undergo even powerful drying without causing any internal tension and the risk of damage; also the deformation (contraction) suffered due to extraction of water will be maintained. In the 'plastic state' the contraction of the pasta is generally in proportion to the amount of water subtracted from it.

When, proceeding with drying, the product's moisture content falls further (22-18%) (w.b.), the state of the pasta changes from plastic to elastic. In this new state the product's behavior is totally different: an elastic body subjected to stress deforms, but tends to recover its original shape as soon as the stress stops. Besides causing deformation, stresses can then bring about tension inside the product. If the tension comes within the product's specific limit of elasticity, it can be absorbed precisely by its own elasticity; whereas, if it exceeds this limit it will inevitably be damaged. This is exactly what happens when drying pasta when the moisture inside the product falls to approximately 20% (w.b.) its physical state passes from being 'plastic' to 'elastic'.

In practice, the change in the state of the pasta from 'plastic' to 'elastic', starting from 20-18% (w.b.) moisture has the following consequences:

1-From this point of the process onwards, drying generates tension inside the product.

2-The pasta tends to 'recover' the even minimal deformation caused by eliminating the water inside it.

3-The water extracted from the pasta produces a contraction that however can no longer be recovered from the product except by reabsorbing water, which is precisely what must not happen, since the goal is that of drying.

4-The water must therefore be extracted so that the tension generated does not exceed the product's limit of elasticity. If this occurs, the pasta will be damaged to a greater or lesser extent (cracks, splits, veining, etc.).

5-Since the water is extracted from the surface, during the drying process the internal part close to the surface will inevitably have lower moisture content than the central portion. This unbalance also generates tension that needs to be able to be reabsorbed to prevent damaging product (Milatovic and Mondelli, 1991).

During pasta drying, the gradients that are created are very strong as regards the moisture between the outside of the product and the zones closer to its center. The outermost zone is balanced with the temperature and the relative humidity of the air, while the most internal zones are completely affected by the spread of water, it follows that the volume reduction between zones does not take place linearly, but at different speeds. Therefore, the outside of the pasta, because of the greater decrease in moisture in unit time, tends to contract quickly; while the volume of the internal zones, due to slow diffusion of water, is reduced much less. The result is that the outside of the pasta cannot contract as much as its current moisture level would require, therefore stresses are created inside it, which correspond the compressions in the innermost zones of the product. As drying proceeds, the internal zones also tend to be submitted to tension, since the outside layer dries and solidifies more and more, blocking or anyhow reducing the spread of water toward the surface, basically preventing the internal part of the pasta from contracting. These stresses are unavoidable and must be managed adequately:

1-Checking the physical state of the product with a correct air temperature/moisture ratio and the right sequence and intensity of ventilation. It is clear that the given values (temperature and humidity of air, volume intensity and duration of ventilation flows) depend on a few variables which must be taken into consideration:

-temperature of the pasta and current level of moisture;

-kind and shape of the pasta, thickness, surface area/weight ratio (specific weight of the pasta);

-characteristics of the raw material, with particular reference to its protein content and the quality of the gluten;

-technical and construction characteristics of the drying plant.

2-Rationally alternating the drying phases with the rest phases and correctly setting their length.

3-Extending as much as possible the phase of the plastic state of the product, in which the tensions can easily relax (Milatovic and Mondelli, 1991).

Drying causes a series of physical phenomena that deeply modify the structure of the pasta. The critical aspect of this operation is that it must take place without minimally damaging the product either during or after. Because the physical state of the pasta changes during the drying process (plastic and elastic state), in order to proceed correctly it is important to respect at least two basic rules:

1-Between 30 and 18-20% (w.b.) moisture it is necessary to heat the product as much as possible in an environment with a sufficiently high relative humidity (in proportion to the temperature reached by the pasta). The pasta's surface must not dry out, but should stay porous and elastic. Only by respecting this criterion, the internal water rises to the surface and evaporate. This is the one and only method to use for pre-drying the pasta. To favor evaporation of the water the pasta must be ventilated with hot and humid air. The higher the temperature of the pasta, the higher the humidity should be.

2-Between 20-18 and 12-13% (w.b.) moisture the drying of the product must take place slowly, by alternating drying with brief 'recovery' pauses (stopping of surface evaporation and redistribution of the water micro-particles inside the product). If the temperature inside the dryer (and, therefore, of the pasta) stays constant for the entire duration of the process, the drying/recovery phases can be obtained as follows:

-(For the drying phase) by lightly ventilating the pasta with moderately humid air. This causes evaporation of the micro-particles of water that has migrated from inside the pasta to the surface.

-(For the recovery phase) by completely stopping ventilation, but at the same time making sure that the relative humidity inside the dryer stays as high as needed so that the pasta does not dry out any further. This way, when the recovery phase is over, the pasta can be ventilated again, causing the evaporation of the micro-particles of water that will have been reached the surface thanks to the capillarity of the semi-dry product. Then the drying phase is started up again. Until drying is finished (moisture of the pasta 12.5% (w.b.)) the capillarity of the pasta must remain functional so that the residual water particles can move from the center to the surface and then evaporate. If capillarity is compromised or stopped, the particles of water that are trapped 'inside' the product create strain and pressure that can crack or break the product.

There are three technologies being used in the production of dry pasta:

1-Low temperature (LT) technology based on drying at low temperatures (<60°C).

2-High temperature (HT) technology based on drying at high temperatures (<80°C). There are mainly two different approaches in utilizing HT technology. The first method uses a pre-drying stage at medium temperatures, very similar to those used in LT drying. A final drying at a very high temperature follows it. The second method utilizes very high temperatures from the first pre-drying stage, maintaining them only in a part of the final drying. In this case, the remaining processing time is used for the so-called 'warm' stabilization at fairly high temperatures, but not so high as to affect the product.

3-Very high temperature (VHT) technology based on drying at very high temperatures (>80°C). There are mainly two different approaches in utilizing VHT technology as in the case of HT drying.

1.2. Components of Pasta That Affect Its Drying

The drying of the pasta depends on the characteristics of the pasta itself. These characteristics are

-chemical characteristics (composition, percentage of components, etc.).

-physical characteristics (structure, dimensions, shape, etc.).

While the pasta is still moist, water is however a fundamental component, the other components which characterize pasta are starch, proteins, fat, cellulose, minerals, carotenoids, enzymes and vitamins. These chemical components are important because both during the formation of the dough and in the drying phase they interact in various ways with each other in a wide range of chemical reactions in which water always plays a decisive role (Milatovic and Mondelli, 1991).

1.2.1. Starch

Starch is the major component of semolina, and firmness is cooked spaghetti must, in part, be influenced by gelatinized starch properties (Dexter and Matsuo, 1979). Chemically it is a glucidic substance, composed of microscopic grains of diameter between 2 and 100 thousandths of a millimetre, comprising approximately 25 % amylose (a linear chain of glucose units) and 75% amylopectin (chain with branched structure of glucose units). These two components of starch are physically combined in a crystalline kind of reticular structure. In plain words, starch is a compound of sugars, grouped together in its two main functions, amylose and amylopectin. Starch is insoluble in cold water, while its two essential fractions have differentiated behaviours: amylose is soluble in hot water, amylopectin is not. Anyhow, in the presence of water and due to the aggression of the specific hydrolytic enzymes (amylase), some of the chemical bonds that in starch keep the sugars of the chains united break, freeing or forming products of demolition, in particular dextrins, maltose and glucose. We should note that they are mostly responsible for the surface stickiness of pasta. They are also the cause of its typical sweetish flavor. The attack on the starch by the amylase enzymes is aided by heat, but also by the damage of its grains that is inevitably caused by grinding the wheat (Milatovic and Mondelli, 1991).

Several physical and chemical changes have been reported, in the literature, due to change in starch structure. Some authors found that the first stage of Maillard reaction is favored during HT drying at low pasta moisture (<16%). High starch damage results in higher reducing sugar content in semolina. Elevated reducing sugar content, in combination with HT when pasta moisture is low, can result in advanced Maillard reaction. The pasta becomes undesirably red, which affects marketability (Resmini *et al.*, 1996).

Under high-temperature drying conditions with equilibrium relative humidity values ranging from 12 to 30%, the Maillard reaction can easily occur in pasta products during the thermal process. Some authors have observed the formation of ϵ-fructosyl-lysine from decomposition of Amadori compounds at the high temperatures applied, which results in the consumption of lysine by the reaction between reducing sugars and its ϵ-amino group (Anese *et al.*, 1999).

A water-soluble furanic compound was identified in dried pasta samples, arising from the advanced Maillard reaction between maltose and free amino acids, called 2-acetyl-3-D-glucopyranosylfuran (AGPF), and a ϵ-lysylpyrrolaldehyde (LPA), recognised as the main derivative of protein-bound lysylketoses degradation. It was found that the higher the drying temperature the higher the formation of these compounds, which, therefore, can be used as indices for evaluating the extent of the Maillard reaction in dried pasta. ϵ-N-(2-furoylmetyl)-L-lysine (furosine) and 2-acetyl-3-D-glucopyranosylfuran (AGPF) have been proposed as markers of the early and advanced Maillard reaction (Resmini *et al.*, 1993).

The nutritional availability of lysine may significantly decrease by the involvement of the ϵ-NH_2 group of lysine in intra and intermolecular crosslinkings in proteins as well as in reactios with various constituents. Therefore the lysine fate depends on pH, time, temperature and chemicals (copper salts, dimethyl sulfoxide). So, while lysine is transformed into lysinoalanine under heat treatment and/or alkaline conditions (Friedman *et al.*, 1984) in a biological system such as pasta, containing reducing sugars and free amino acids, the early Maillard reaction (first stage) mainly produces the stable α-N-formly-(ε-N-deoxyfructosyl)-lysine that, by acid hydrolysis, can be converted into furosine (Finot *et al.*, 1981).

Güler *et al.* (2002) observed that the majority of the starch granules (~80%) in HT and VHT dried pasta samples retained their birefringence and approximately half of the remaining 20% granules partially lost their birefringence. This was attributed to the moisture content of pasta. The pasta samples contained about 30% (w.b.) moisture at the beginning of drying. Most of this water is expected to be removed during the early stages of drying (i.e. during the predrying). Therefore, the amount of water remaining in the pasta sample during HT and VHT drying may not be sufficient to cause complete swelling and starch gelatinization. The gluten-starch interaction in raw pasta is mainly due to physical inclusion of starch in the gluten network (Delcour *et al.*, 2000). The physical constraints of this gluten matrix may also limit the swelling of starch granules. Thus, it can be deduced that the retention of birefringence during pasta drying might be due to an inadequate amount of remaining water (Güler *et al.*, 2002).

The first drying steps of an industrial pasta production render the starch granules in general and the small ones in particular less extractable, possibly due to increased physical inclusion or interaction between starch and gluten components. Other production steps had much less impact on the interaction behavior (Vansteelandt and Delcour, 1998). This concurs with the earlier findings that, during high-temperature drying, proteins coagulate and may envelop the starch granules within a continuous network (Resmini and Pagani, 1983; Pagani *et al.*, 1986) and that renders the starch granules less extractable (Vansteelandt and Delcour, 1998) and restricts their gelatinization and swelling during cooking.

Zweifel *et al.* (2000) also reported that the modifications in the starch fraction occurred during processing of pasta, in particular during the drying step. The changes in the thermal properties of starch during drying were dependent on the drying conditions. Low temperature drying (reference, 55°C) of pasta induces a decrease in the enthalpy of gelatinization due to partial melting of starch. In contrast, HT drying (100°C) increases the molecular order of starch, as concluded from increased gelatinization temperature and enthalpy. Moreover, an early or intermediate HT phase increases the melting enthalpy of amylose-lipid complexes that eventually contribute to a stabilization of starch granules. Analyses of the drying conditions based on the physical states of starch as a function of moisture content confirmed that HT drying favors an annealing of starch at limited moisture conditions. Based on DSC and X-ray diffraction, the molecular order of starch is increased at the double helical level whereas the crystallinity is not affected. It is reasonable to assume that an increased thermostability of starch has a positive influence on the cooking properties of pasta.

1.2.2. Proteins

The protein component of wheat changes according to the varieties, the areas of cultivation, hydroclimatic conditions of the farming years, techniques of cultivations, methods and duration of ensilage. The average percentage of protein content is approximately 13%, more or less, with concentrations that grow in the surface layers of the kernel and in the layers immediately adjacent to the germ. The proteins of wheat mostly comprise gliadin and glutenin (approximately 80%), the rest is composed of albumin, globulin and free amino acids. Gliadin and glutenin are commonly considered the 'star' proteins of pasta. When water is added to semolina (or to the flour) and the dough is mixed mechanically, glutenin and gliadin form gluten, forms a kind of mesh in the structure of the dough, trapping the starch grains and basically preventing the pasta during cooking from turning into polenta. Gluten is extremely hungry for water: it absorbs twice its own weight and moreover tends to hold it through complex chemical bonds. The percentage of gluten (gliadin and glutenin) and starches in the semolina (or the flour) in some way rebalance the quantities of water absorbed by these two antagonists: gluten absorbs 200% of its own weight, starch (not damaged) approximately 35-50%. Since starch is present in semolina in a quantity of approximately five times greater than that of gluten, the water of the dough is equally divided between them. The capacity of gluten to hold water depends on its quality: this is the main reason why durum wheat semolina pasta prevails over that of soft wheat flour pasta in tenacity, cooking capacity and less stickiness. The gluten of soft wheat flour, in fact, even if it is able to absorb more water than that of semolina, it is less able to hold it. The superior capacity of the gluten to hold water compared to starch obviously has to affect the drying of pasta (Milatovic and Mondelli, 1991).

Total protein content enhances cooking quality with high-temperature drying. However, the strong correlation between amount of acetic acid-insoluble proteins in semolina and cooking quality indicates that other factors such as gluten polypeptide composition and aggregative behavior of gluten proteins, i.e. the intrinsic quality of semolina, play an important role in determining pasta-making quality (De Stefanis and Sgrulletta, 1990).

At low temperature, protein content and gluten quality assumed the same importance in determining pasta cooking quality, whereas at high temperature, only protein content was essential. It is well known that protein content assumes a primary role in determining pasta quality in high temperature drying applications (Novaro *et al.*, 1993). The solubility of protein is considered an index of denaturation, with lower solubility indicating a higher degree of denaturation. It was reported that reduction in solubility as drying temperature increases may be a result of protein-starch interactions, as suggested by Resmini and Pagani (1983) from Scanning Electron Microscopy of spaghetti dried with high temperature and low moisture. It was concluded that the gliadin fraction was essentially not affected by high-temperature drying of spaghetti. The absence of major changes in gliadins attributable to drying temperature is indirect evidence that this fraction is not of primary importance to drying temperature-induced effects on pasta cooking quality. On the other hand, the stability of gliadin to temperature effects may be important in maintaining the cooking quality of pasta products (Aktan and Khan, 1992).

It has been reported that under HT conditions starch gelatinization properties could not be modified compared to LT conditions (Zweifel *et al.*, 2000). However, protein denaturation was much greater under HT conditions. There is the possibility that during HT drying the protein film on the surface of spaghetti is strengthened leading to increased resistance to strand disintegration (Dexter *et al.*, 1981). During high-temperature drying, the gluten is partially coagulated (Braibanti, 1980) and may envelop the starch granules within the continuous network (Resmini and Pagani, 1983). This gluten structure retaines the starch longer during cooking, leading to less starch loss (Braibanti, 1980).

1.2.3. Other components (fats, cellulose, minerals, enzymes, vitamins, carotenoids)

Fatty substances (lipids) are concentrated in the embryo of the wheat (germ), which is removed before grinding to prevent the fats turning rancid and the semolina or flour rapidly deteriorating. The presence of fats in the semolina brings about a decrease its preservation, but it also improves the technological characteristics of this raw material. It is clear that the formation of lipidic bonds, both during the formation of the dough and during drying reduces the stickiness of the pasta and its cooking losses during cooking, since they limit the sugars (dextrins and amylose) on its surface (Milatovic and Mondelli, 1991).

According to Olkku and Rha (1978), initial gelatinization temperature for wheat starch is 58°C, midpoint 61°C, and end-point 64°C. Although the low water activity of spaghetti dough will retard the onset of starch gelatinization at 70°C, the temperature at which HT samples are dried, some gelatinization may occur. With gelatinization, bound lipids, those inside starch granules, may be released or exposed to interact with amylose.

The presence of lipids lead to less exudation of amylose during gelatinization because of lipid-amylose complexing. It was implicated amylose on the surface of cooked spaghetti as a contributing factor to surface stickiness. Complexation of amylose with lipids, particularly monoglycerides, could lead to less amylose on the surface of cooked spaghetti resulting in reduced stickiness (Dexter *et al.*, 1985). To a lesser extent cooking loss is also influenced by lipids. Removal of nonpolar semolina lipids increases cooking loss, whereas addition of monoglycerides reduces cooking loss (Matsuo *et al.*, 1986).

Grant *et al.* (1993) observed that the addition of monoglycerides to semolina appeared to inhibit the loss of soluble carbohydrates, which may have a significant effect on stickiness of pasta. Drying temperature had a highly significant effect on amylose content. Cooked HT-dried spaghetti retained higher amounts of amylose than that of LT-dried spaghetti. The possibility of greater amylose-lipid complexing with HT drying might explain the higher amount of amylose in the samples, thus accounting for some of the reduction in cooking loss and stickiness.

The presence of lipids however includes the drawback of their oxidation, so much greater if the semolina was preserved too long, since in this case the dough tends to absorb more atmospheric oxygen if it is not preserved well. The oxidation of the lipids (and the yellow pigments) of the semolina during the kneading phase can be avoided only with techniques that make it possible to prepare the dough without the presence of oxygen (in a vacuum) (Milatovic and Mondelli, 1991).

Bright yellow color is an important factor in the use of pasta for food production, particularly to make good quality pasta products (Troccoli *et al.*, 2000). This color is the result of the natural carotenoid pigments present in the seeds of their residual contents after the storage of grain or semolina and after milling of their oxidative degredation by lipoxygenase (LOX) during pasta processing and of processing conditions (Borelli *et al.*, 1999). It was reported that LOX catalyzes the addition of molecular oxygen to polyunsaturated fatty acids containing cis, cis-1, 4 pentadiene systems to produce conjugated cis, trans-diene hydroperoxide. Fatty acid radicals produced during the intermediate steps of substrate peroxidation are responsible for oxidative degredation of pigments such as β-carotene, xantophylls, and chlorophylls (Troccoli *et al.*, 2000).

The most significant enzymes are the amylases that break the chains of starch, freeing dextrins (involved in stickiness of the pasta) and maltose (reducing sugar that increases the possibility of the Maillard reaction). However other enzymes affect the drying of pasta: for example, protease, that hydrolizes proteins and, therefore weakens the gluten. All these enzymes have different sensitivity to heat. The beta amylases (which free maltose from the amylopectin of starch) are easily deactivated at 50°C, while the alpha-amylases (which free from dextrins from the amylose of starch) and the lipoxidases are still active well beyond 65°C, becoming active precisely when the temperature of the pasta exceeds 50°C. The alpha-amylases, lipoxidases and lipoxigenases can be deactivated (at least partially) only with effective hydrothermal treatment of the pasta in the pre-drying phase and this is the only way of protecting the yellow pigments (carotenoids) of semolina and avoiding the grey coloring of the dried end product, due to the formation of brown melanin in the pasta. But the best results (no surface stickiness and brown yellow colour of the pasta) can only be obtained with an energetic hydrothermal treatment of the pasta during pre-drying phase (Milatovic and Mondelli, 1991).

Outside of the kernel and the germ have higher concentration of cellulose (lignin) and minerals. In terms of drying, these components have little importance, while they are important for the commercial value of the product, since too much of them has a negative effect on the appearence even if it increases their biological value. The presence of minerals in the semolina affects in particular the amber-colored appearence of the dried pasta.

1.3. Pasta Texture

The textural characteristics of pasta products play an essential role in determining the final accepance by consumers, although other factors (color, flavor and nutritional value) are also implicated (D'Egidio and Nardi, 1996). Texture refers to the human sensation of food derived from its rheological behavior during mastication and swallowing. Obtaining a quantitative description of texture using instrumental data is very complicated because no instrument can duplicate human capabilities. The mouth can be considered an intricate mechanical system and chemical reactor that can crush, wet, enzymatically degrade, pressurize, heat or cool, pump, chemically sample for taste, and sense force and temperature. Overall, there are two methods to evaluate food texture: sensory and instrumental (Steffe, 1992). Taste panels can be used to estimate pasta cooking quality, but they are time consuming and impractical when sample size is limited or large numbers of samples are to be evaluated (Edwards *et al.*, 1993). Instrumental methods, however, are much less costly and time consuming than sensory tests. Moreover, they often correlate to critical sensory attributes which allow some measure of consumer acceptability. Generating and interpretation texture profile information, with instrumental and sensory means, is called Texture Profile Analyses (TPA). TPA is a double compression test and is the most recognized instrumental means of characterizing the texture of solid and semi-solid foods (Steffe, 1992).

The test consists of compressing a bite-size piece of food two times in a reciprocating motion that imitates the action of the jaw (Bourne, 1978). The mechanical characteristics are of primary importance for pasta products; they are related to stress response and can be defined as follows (D'Egidio and Nardi, 1996):

Firmness (or hardness): Represents the degree of resistance to the first bite and sensorily defined as the force required to penetrate pasta with the teeth; the opposite term 'tenderness' is also used.

Cohesiveness (or consistency): It is defined as the force of internal bonds holding the pasta structure; the opposite term 'compressibility' is also utilized.

Elasticity (or springiness or recovery): Represents the capacity of a deformed pasta to go back to its initial condition when the deforming force is removed.

Stickiness (or adhesiveness): The force with which the cooked pasta surface adheres to other materials, e.g., tongue, teeth, palate, fingers.

The first three characteristics are related to attractive forces among particles opposing disintegration; stickiness, on the other hand, is linked to surface properties. Some secondary parameters can be useful to characterize cooked pasta texture:

Chewiness: It is defined as the time required to masticate a sample at the rate of one chew per second for reducing it to the consistency suitable for swallowing. It is related to firmness, cohesiveness and elasticity.

Resilience: It is measurement of how the sample recovers from deformation both in terms of speed and forces derived and developed from the elastic recovery of the sample.

1.4. Microwave Energy Generation and Microwave Applications in Food Processing

1.4.1. The basic structure of a microwave oven

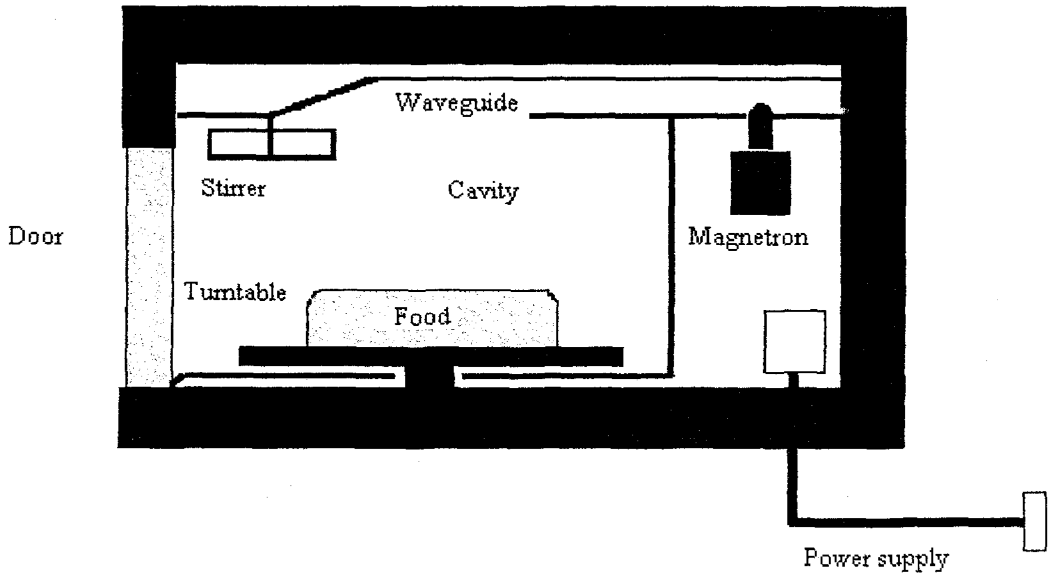

Figure 1.1 Basic structure of microwave oven

Figure 1.1 illustrates a typical microwave oven. It consists of a cavity surrounded by metal walls with a door at the front (Hill, 1998). The inside walls of this cavity are metallic surfaces that completely reflect the microwaves. A continuous train of reflected waves from the walls combines with the incoming waves from the magnetron to form standing waves inside the cavity, with nodes and antinodes that correspond to the zero and maximum amplitudes of the electric fields (Datta, 1990). The microwave, generated by a magnetron, enters the cavity via a metallic tube called a wave guide. To facilitate uniform heating of the food by the microwaves, it is necessary to establish as many 'modes' as possible inside the oven. A mode is a specific pattern of electromagnetic waves set up in the oven.

The two most common methods used to improve the uniformity of heating are moving the food and using mode stirrers. By moving the food (as is done by the rotating carousel in a domestic oven), all locations in the food material can be made to encounter both the nodes and antinodes of the standing microwave pattern. A mode stirrer is generally a multiblade rotating metallic reflector that continually changes the direction at which the microwaves are introduced into the cavity. This continuously perturbs the field distribution, which changes the locations of the nodes and antinodes and produces more uniform heating (Datta, 1990). In some models a mode stirrer also helps to distribute the electromagnetic energy, while in others a turntable is used to improve energy distribution in the food; many models have both. The multiplicity of modes and their interaction in such 'multimode' ovens ensures that the energy transferred from the source to the cavity is absorbed more efficiently by the food (Hill, 1998).

1.4.2. The heating process

Microwaves form part of the electromagnetic spectrum as do television and radio waves, infrared radiation, ultraviolet radiation and visible light. These electromagnetic waves are means of transmitting energy through space just as electricity is electrical energy transmitted through a wire. In order to minimise any interference with existing communications (Richardson, 1990) two frequencies have been set aside for use in microwave applications. These are 915 MHz and 2450 MHz. Domestic appliances operate on 2450 MHz, whilst industrial applications make use of both frequencies (Figure 1.2).

The magnetron in the oven converts electrical energy at low frequencies into an electromagnetic field that oscillates at a much higher frequency. Food is able to absorb microwave energy, later releasing the stored energy as heat. The main mechanism of heating occurs as a result of rotation of water molecules brought about by the microwaves. Water is a molecule which is unevenly charged along its structure, being more negatively charged in some parts of the molecule and more positively charged in others. Such molecules are called 'dipoles' (Hill, 1998).

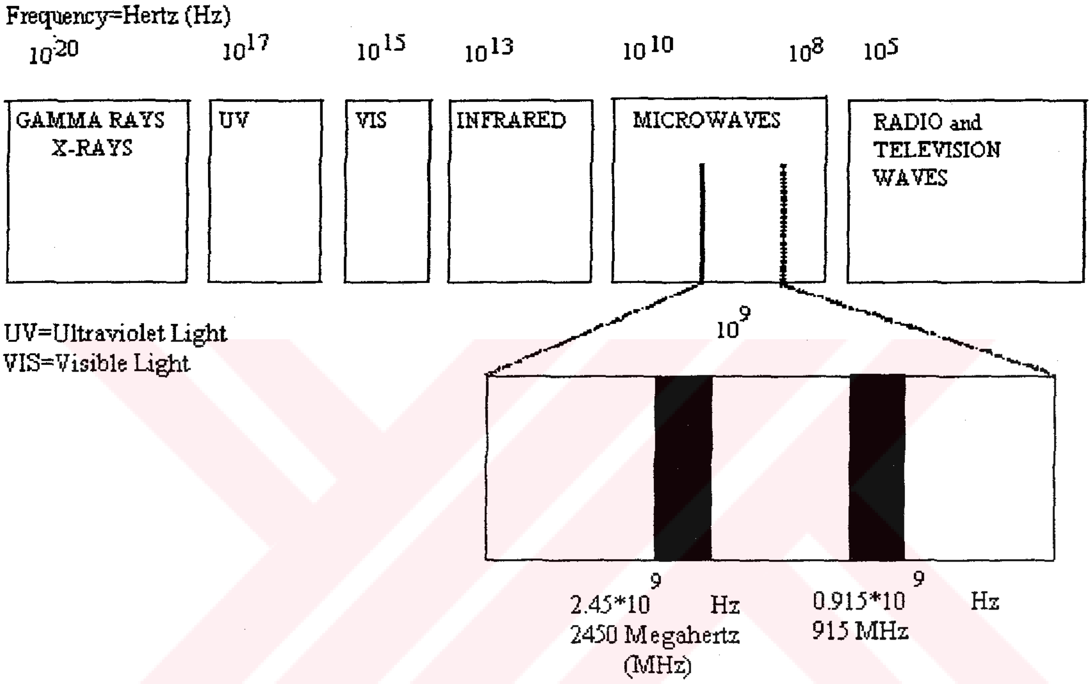

Figure 1.2 The electromagnetic spectrum

When food is subjected to microwave energy the dipoles in the water interact with the electrical component of the electromagnetic wave. The dipoles try to rotate in order to attempt to line up with alternating field (Richardson, 1990). The electromagnetic field generated in a microwave oven oscillates with a frequency of 2450 MHz (or 2450 million cycles per second), so these dipoles (or molecular magnets) have to move back and forth at a speed of over two thousand million times a second to follow the field shown in Figure 1.3. Energy is absorbed in this process affecting the molecules themselves and their interactions with neighbouring molecules. The energy of the microwaves is released in the form of heat, the amount produced being proportional to the energy absorbed by the food (Hill, 1998). The overall size of the food material influences its interior electric field. When the microwaves are randomly reflected from the metallic walls of the oven, they may be directed toward the food, but they also may reach another wall without encountering the food. Thus, a fraction of the microwave energy entering the oven either is dissipated by the walls or goes back to the magnetron (Datta, 1990).

Other dipole molecules are involved in the heating process, but for the food the most important dipole is water. Although some foods have water content of zero (for example, the sugar, sucrose), others have up to 96%. However, there is also a contribution to heating from ionic material in food. Ions are also accelerated by the microwave's electromagnetic field (Figure 1.3) and collide with other molecules to contribute to the heating process through the energy of the collision. This is important for foods with a high salt content. Molecular movement is also possible in fats, so these too can heat up in the presence of microwaves.

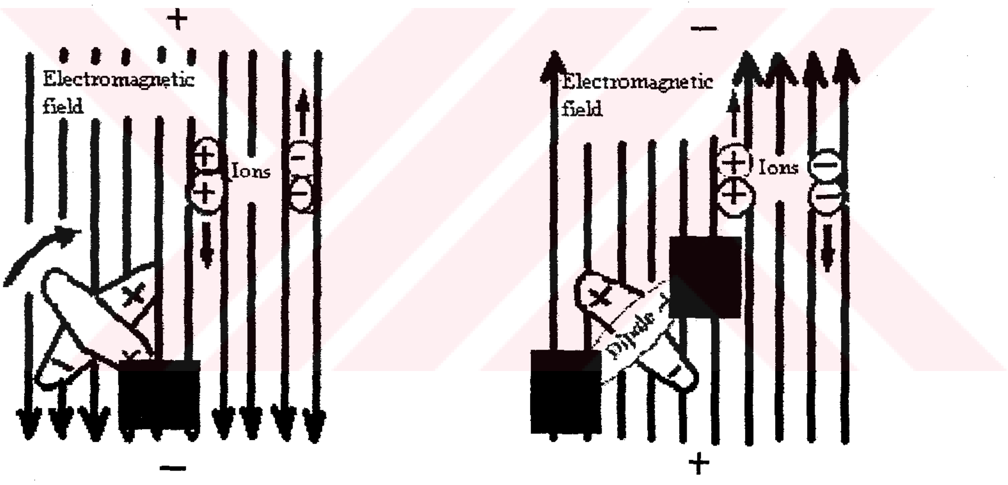

Figure 1.3 Movement of dipoles and ions due to oscillating electromagnetic field

The key difference between microwave heating and cooking in a conventional oven is the way in which the heat is generated and distributed. In a microwave oven food is heated directly by the microwaves, whereas in a conventional oven food is cooked by the heat from the surrounding environment. Food heated in a microwave oven is subjected to a heterogeneous temperature pattern with the potential for hot and cold spots. In a conventional oven the surface temperature of the food is very high (close to that of the oven atmosphere, which might range from 150 to 250°C) compared with that of interior, which generally peaks at about 90-94°C. In microwave-heated foods the inner food core may be either at a higher or at a lower temperature than the outer parts, depending on the size and shape of the product and on its water and salt contents (Hill, 1998).

Compared to conventional heating, moisture flows due to concentration and pressure gradients are uniquely and significantly altered during microwave heating. Relatively larger amounts of interior heating result in increased moisture vapor generation inside of a solid food material, which creates significant interior pressure and concentration gradients. Positive pressures generated inside of a food material increase the filtrational flow of the vapor and liquid through the food material to the boundary (Datta, 1990). Conventional heating processes generate a temperature gradient from the outside surface to the centre of the product during heating and vice versa during cooling (Richardson, 1990). This type of temperature gradient does not exist during microwave heating; in fact, temperatures at the surface are often lower, as a result of evaporative cooling, than those at the centre of the product. Conduction effects only come into play as a means of leveling out the temperature imbalances which result from microwave heating.

A gradient of water transfer is established which controls the internal transfer of material in hot air drying. The difference of temperature between the drying air and the product surface leads to heating up of the surface. So a temperature gradient is established between the product surface and the centre of the product which controls internal transfer. In the case of microwaves: the input of energy comes from the interior of the product and not exclusively from the surface, the density of energy brought into the product is greater; heating of a product is not linked to a temperature difference between its surface and the ambient air (Laguerre, 1999).

1.4.3. Penetration of microwaves into food

Penetration depth is defined as the depth into the material at which one third of the power at the surface is remaining. This is a practical measure for evaluating the ability of microwaves to heat uniformly foods of different composition and thickness (Ohlsson, 1991). The depth to which microwaves penetrate differs for each type of food. As the degree of absorbency in a food increases, the penetration depth decreases. Therefore, the greater the liquid water or salt content, the more limited is the depth where the influence of microwave heating is felt, and the greater the heating near the surface. Subsequent heat conduction and convection are responsible for the distribution of the heat throughout the food products (Hill, 1998).

The unique feature about microwave energy is its ability to penetrate a food product and its efficient conversion into heat, which is subsequently dissipated by conduction. This penetration mechanism offers a means of overcoming the slow surface-inward conduction mechanism encountered in conventional infrared and hot air systems. The degree of microwave penetration is attenuated exponentially as a function of depth and is inversely related to the dielectric constant and the frequency used (Ramaswamy and van de Voort, 1990). It is greater at 915 MHz than at 2450 MHz which is why the lower frequency is the favoured one for many industrial applications such as thawing large blocks of frozen material. Both frequencies have been used for other applications such as drying and bulk cooking (Hill, 1998). The high degree of energy penetration and rapid heat transfer has been the driving force for exploiting microwave technology (Ramaswamy and van de Voort, 1990).

Penetration depths are seen to increase as moisture content of the product and processing frequency are decreased. Generally, product thicknesses must be limited to their penetration depths to obtain uniform heating profiles. As thicknesses exceed penetration depths, more microwave energy is absorbed by surface layers and less by deeper layers, leading to nonuniform heating profiles and longer processing times. This may not be critical in drying operations, where surface evaporation of moisture is diffusion-limited and the moisture front continues to absorb energy as it recedes within the product (Mudgett, 1982).

The degree of reflection and penetration of microwaves depends on the dielectric properties of the material (Owusu-Ansah, 1991). The dielectric constant is one measure of microwave heating and penetration. The dielectric constant (ε') measures the distance between charges in a molecule and decreases with increasing temperature. It represents the ability of a food to store electrical energy. Another value that measures microwave heating properties of a food is the dielectric loss factor (ε''). When microwaves are absorbed into a food and causing heating, they lose electromagnetic energy. This loss of microwave energy is termed the loss factor and is related to the product of the dielectric constant and the loss tangent. Foods with large loss factors are heated more rapidly by microwaves. In addition, loss factors vary with the frequency and temperature (Giese, 1992b).

The dielectric constant predominantly provides indication on the reflection properties and wavelength in the material (Owusu-Ansah, 1991) and is related to the wavelength in the materials as follows:

$$\lambda = \frac{\lambda_o}{\sqrt{\varepsilon'}} \qquad [1]$$

where, λ is the wavelength in material and λ_o is the wavelength in free space. Another important dielectric terminology used in microwave heating is the loss tangent ($\tan\delta$) which is the ratio of the dielectric loss to the dielectric constant:

$$\tan\delta = \frac{\varepsilon''}{\varepsilon'} \qquad [2]$$

Loss tangent is related to the material's ability to be penetrated by an electrical field and dissipate (attenuate) electrical energy as heat (Mudgett, 1986). The dielectric properties of foods are dependent on various factors such as temperature, physical structure, frequency (Owusu-Ansah, 1991), and moisture and salt contents (Giese, 1992b).

1.4.4. Parameters affecting microwave heating

Power transfer is efficient for high-moisture products of having small volume, but less efficient for low-moisture products of small volume. Unreflected, i.e., transmitted, power is absorbed by interaction with active food constituents and decreases within the product with increasing penetration. The power level and, consequently, the heating rate needed for uniform heating very much on the product's composition, temperature, shape, structure, and size and on the microwave frequency. In terms of composition, moisture, solids, and salt contents determine microwave penetration depth and, therefore heating uniformity (IFT, 1989). The heating of materials by microwaves is affected by a number of properties of the equipment and the material being heated which are frequency, microwave power and speed of heating, mass, moisture content, density, shape, structure, temperature, physical geometry, conductivity, thermal conductivity and specific heat (Schiffmann, 1986). The impact of each of these must be considered in the design of a product/processing system.

1.4.4.1. Frequency

There are two available frequencies (915 and 2450 MHz) for microwave heating used in food processing. Their wavelengths in air are 33 and 12.2 cm, respectively.

The frequency affects the depth of penetration into material as follows:

$$D_{50} = \frac{0.189\lambda_o}{\sqrt{\varepsilon'}\sqrt{\sqrt{1+\tan^2\delta}-1}} \qquad [3]$$

where D_{50} is the half-power penetration depth, i.e., the depth at which half of the incident energy is absorbed; λ_o is the wavelength in free space; ε' is the dielectric constant of the material and $\tan\delta$ is the loss tangent of the material. For example, the half-power depth for water is approximately 2.3 cm at 2450 MHz and 20.0 cm at 915 MHz. Therefore, selection of the microwave frequency is important, as it relates to the size of object being heated.

1.4.4.2. Microwave power and speed of heating

The higher the power output, the faster the heating for a given mass. The speed of microwave heating is usually controlled by varying the power output. Speed is usually the most attractive feature of microwave heating. This is a double-edged sword, however, since it is possible to heat too rapidly. Cooking, baking, and other food processes are complex physicochemical systems requiring the input of heat to initiate and accelerate reactions. However, these reactions must occur in their proper order and be given the proper time to occur. It is possible with microwave heating to heat faster than the food can keep up with it.

In a drying process, this can cause generation of internal steam pressure faster than it can be relieved, resulting in overexpansion, rupture, or even explosion. Another problem which can arise from excess speed of heating is nonuniform temperature distribution. This occurs because the heating may be so fast as to prevent the effectiveness of thermal conductivity in transferring heat to the cooler portions. This is particularly a problem with unusually shaped pieces or pieces with sharp corners. A general rule to be followed in microwave processing is fast but as slow as possible.

1.4.4.3. Mass

There are two considerations here; the total mass being heated at one time, and the mass of an individual piece. The latter will be treated below under physical geometry and density. As for the total mass, there is a direct relationship between the mass and the amount of microwave power which must be applied to it to achieve the desired heating. When the total mass is small, this might best be done in a batch oven, whereas a larger throughput would often be better done in conveyorized system. Such conveyorized systems have the added advantage of providing greater heating uniformity by moving the product through the microwave field.

1.4.4.4. Moisture content

Water is usually the major influence in how well materials, particularly foods, absorb microwave energy. Usually, the more water present, the higher the dielectric loss factor and, hence, the better the heating. However, a lower moisture product may also heat well, since its specific heat decreases. At very low moisture level, the water is bound and not free to be affected by the rapidly alternating microwave field.

It was reported (Schiffmann, 1986) that in general:

a) the higher the moisture content, the higher the dielectric constant

b) dielectric loss usually increases with increasing moisture content, but it levels off at a value in the range of 20-30% and may decrease at still higher moisture contents

c) the dielectric constant of a mixture usually lies between those of its components

1.4.4.5. Density

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

1.4.4.6. Temperature

The dielectric loss may increase or decrease with temperature, depending upon the material. Since temperatures and moisture levels change during heating, they may have a profound effect upon the dielectric constant, dielectric loss factor and loss tangent and it is important to know what functional relationships exist between these parameters in any material. The starting temperature of food products being heated by microwaves should either be controlled or known, so the microwave power can be adjusted to obtain uniform final temperatures.

1.4.4.7. Physical geometry

The physical geometry of the product exerts its influence in several ways:

1.4.4.7.1. Size

If the size of each individual piece is very large in comparison to the wavelenght and, more importantly, to the depth of penetration, the heating will not be uniform. In other cases where the size is closer to the wavelength, the temperature may be highest in the center. Selection of frequency may be of assistance here, since, for example, the penetration depth at 915 MHz may compensate for large product size.

1.4.4.7.2. Shape

The more regular the shape, the more uniform the heating. Edge and corner overheating which is due to energy transfer at food surfaces from two to the three directions may be avoided by product shielding to limit energy transfer to one direction (IFT, 1989). Sharp edges and corners of foods are easily overheated by microwaves, leading to quality problems in the form of drying out and burn areas (Hill, 1998). A sharp edge will act as an antenna in the microwave field, absorbing high levels of microwave power (Ohlsson, 1991). Differential heating effects are seen in foods with regions of different dielectric activity one region of the food absorbs more or less energy than another and consequently heats at a different rate (IFT, 1989). The wave nature of microwaves is also important for understanding the centre overheating phenomena. When microwaves are transmitted to a surface of rounded item, such as a sphere or cylinder, the microwaves will be refracted or bent towards the centre or focal point of the sphere or cylinder. If the food item has a suitable geometrical size for creating a standing wave inside the food, a high concentration of energy to the centre will occur (Ohlsson, 1991). Round is better than square, and a torus is an ideal shape. If the shape is unusual, i.e., highly nonuniform, as in a chicken leg, there is a real danger of overheating the thinner portions near the ankle while the large muscle portion is still being cooked (Schiffmann, 1986).

1.4.4.8. Conductivity

This describes the ability of a material to conduct electric currents by the displacement of electrons and ions. Whereas dipolar rotation is the more frequently discussed means of generating heat in microwave systems, ionic conduction plays a major role in many cases, especially in food systems. The addition of salt can affect the microwave heating of a product, in some cases increasing its heating rate. This must be done judiciously, however, since it will also affect the depth of penetration, possibly causing more intensive heating near the surface and leaving the interior much cooler.

1.4.4.9. Thermal conductivity

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

1.4.4.10. Specific heat

The specific heat of a food is the ratio of the amount of energy required to raise the temperature by one degree to that required to raise the temperature of an equal mass of water by one degree. The specific heat can be used to calculate the amount of heat required to perform a given heating task. Since specific heat is closely related to the moisture content of food, it has considerable influence on microwave heating properties of foods.

1.4.5. Microwave heating applications

Microwave heating converts most of the purchased energy into heat and puts it right where heat is needed. It commences as soon as the unit is started. Heating is much faster and can be controlled precisely. Far less space is needed than for most conventional heating. Equipment installation and maintenance generally are much easier. Capital costs are in the conventional-heating ballpark. There are powerfull reasons for the growth of microwave systems in the food industry. They often result in large reductions in inventories, operating and maintenance labor, temperature degradation of product and surface damage, scrap, plant air conditioning, refrigeration, warehousing, product waste and downtime. In addition, they offer increases in usable plant space, immediate on-off product heat control, cleaner processing, leveling action, and selective heating (Svenson, 1987). Although a great number of applications have been studied over the years, actually relatively few have been reduced to practice. Table 1.1 contains a fairly comprehensive listing of microwave applications (Decareau, 1984).

Table 1.1 Applications of microwave power in the food field

Process	Products
Tempering	Meat, fish, poultry, berries
Cooking	Chicken, bacon, meat patties, fish, potatoes
Rendering	Lard, tallow
Blanching	Corn, potatoes, fruits
Pasteurization	Bread
Sterilization	Pouch pack foods
Drying	Pasta, onions
Freeze-drying	Meat, vegetables, fruits
Vacuum drying	Fruit juices, grains
Baking	Bread, doughnuts
Roasting	Peanuts, coffe, cocoa

The first commercial application of microwave energy in food processing was finish drying of potato chips. Among the former reasons were the low dielectric loss properties of the nearly dry chip, which made it increasingly difficult to attain the desired final moisture content, unexpected differences in drying rate among chips from supposedly similar potatoes and unexpected equipment problems such as fires caused by arcing that necessitated the installation of fire detection and control means (Decareau, 1985).

Microwave pasta drying is an excellent example of a process in which a relatively small amount of microwave energy is used to obtain maximum benefits. The main reason the pasta industry began using microwave processing was to save energy, to reduce both plant space and production time and improve product color, 'bite' and flavor. The microwave system will produce three to four times more product in the same space with less manpower. It would also be a better product made at lower cost. Furthermore, installation requires about 1000 manhours compare to 6000 to 8000 manhours for conventional system (Svenson, 1987).

1.4.6. The aim of the present study

The pasta drying process gives pasta its final characteristics of stability and preservability. It consists of removing moisture rapidly while maintaining the cooking qualities and flavor untouched. At the present time, the technology applied to pasta production varies greatly from country to country, mainly as concerns the higher or lower temperature of the air used for the final drying of the pasta. It is now commonly accepted that traditional or conventional drying refers to a drying cycle at a temperature of not higher than 58-60°C, and the high temperature drying means a drying cycle using temperatures that vary between 65 and 80°C. Drying time ranges almost from 6 to 14 hours depending on drying conditions, sample shape and size. Energy and labor expenses are therefore quite high.

In general, it is known that conventional air drying (especially high temperatures and longer drying times) can cause serious damages such as; flavor, color, nutrients losses, reduction in bulk density and rehydration capacity of dried food product. The desire to eliminate these problems, prevent significant quality loss and achieve fast and effective thermal processing has resulted in the increasing use of microwaves for food drying. In recent years, microwave drying has gained popularity as an alternative drying method for a wide variety of food products such as fruits, vegetables, snack foods, dairy products and noodles (Svenson, 1987; Bouraoui *et al.*, 1994; Prabhanjan *et al.*, 1995; Ren and Chen, 1998; Feng and Tang, 1998; Funebo and Ohlsson, 1998; Maskan, 2000; Maskan, 2001; Sharma and Prasad, 2001). Microwave drying is rapid and energy efficient (uses one-third less energy) compared to conventional hot air drying. In addition, it increases production rate, reduces labor and improves product quality.

Therefore, the aim of this study was to adopt microwave energy into pasta drying operation. In this study, the short-cut macaroni was dried by three different drying operations: 1) conventional hot air, 2) microwave energy alone using various microwave power intensities and 3) hot air followed by microwave energy. The drying time, drying rate and the quality parameters (color, rehydration capacity, cooking loss, protein solubility, cooked weight) and the textural properties of macaroni dried by these techniques were investigated. The textural analyses were performed on both cooked and uncooked macaroni samples.

CHAPTER II

MATERIALS AND METHODS

2.1. Materials

2.1.1. Sample

Short cut macaroni (ditalini) was used in this study. It was supplied from Beslen Makarna ve Gıda Sanayi A.Ş (Gaziantep, TURKEY).

2.1.2. Drying equipment

A programmable domestic microwave oven (Arçelik ARMD 580, TURKEY), with maximum output of 700 W at 2450 MHz. was used. The oven has adjustable power (wattage) and the time controllers and was fitted with a turntable. The hot air drying experiments were performed in an industrial dryer (Figure 2.1) established in Beslen Makarna ve Gıda Sanayi A.Ş. The dryer has three units which are shaker, pre-drying and drying units. The shaker is a five pass dryer with a product depth of approximately 1.5 cm and length of 4.0 m each pass. There are seven screens in the pre-dryer section with a screen width of 1.64 m. The length of upper screen is 5 m. The length of other six screens is 6.4 m. The dryer section also has seven screens. The length of upper screen is 10.0 m. The length of other six screens is 11.6 m (Table 2.1).

2.2. Methods

2.2.1. Drying procedure

2.2.1.1. Hot air drying

Short cut macaroni was dried with 650 kg/h capacity in an industrial plant. Drying macaroni means reducing its overall moisture from an initial 33% (w.b.) down to 12% (w.b.). The dough comes to the die made of bronze and teflon and macaroni is cut by a rotating blade and dropped onto an inclined surface that causes it to slide inside the shaker. The shaker works at 66°C (dry bulb) and 32% RH. The moisture content of the pasta falls from about 33% (w.b.) to 31% (w.b.). A bucket elevator collects the product coming out of the shaker and spreads the short goods on the upper screen of the pre-drying unit. The temperature of pre-drying unit is 62°C dry bulbs with 58% RH. The macaroni samples leave the pre-drying unit with a moisture content of 18.5% (w.b.). The product leaving the pre-drying unit is collected by a bucket elevator and spreads on the upper screen of the drying unit. The temperature of drying unit is 52°C dry bulb with 82% RH. The drying process is ended with cooling the product by ambient air. The macaroni samples were dried to a final moisture content of 12% (w.b.) in this study.

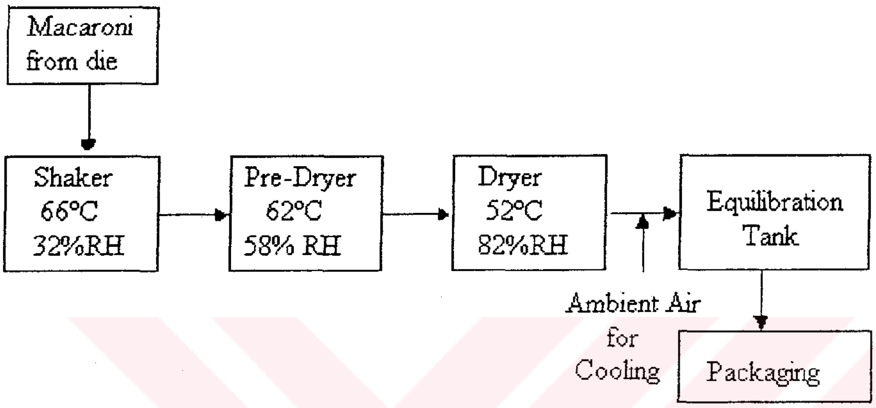

Figure 2.1 Illustration of an industrial macaroni drying unit

Table 2.1 Properties of industrial macaroni drying unit

Drying unit	Number of Screens	Retention time (min)	Product depth (cm)	Screen length (m)
Shaker 66°C 32% RH	1	1	1.5	4.0
	2	1	1.5	4.0
	3	1	1.5	4.0
	4	1	1.5	4.0
	5	1	1.5	4.0
Pre-Drying 62°C 58%RH	1	3	1.0	5.0
	2	6	1.5	6.4
	3	5	1.4	6.4
	4	7	1.6	6.4
	5	6	1.5	6.4
	6	9	2.0	6.4
	7	7	1.6	6.4
Final Drying 52°C 82%RH	1	15	2.5	10.0
	2	22	4.0	11.6
	3	29	6.0	11.6
	4	29	6.0	11.6
	5	56	8.0	11.6
	6	74	10.0	11.6
	7	80	10.0	11.6

2.2.1.2. Microwave drying

Different microwave power intensities (70, 210, 350 and 490 W) were investigated in microwave drying. It was observed that (our preliminary tests) charring occured at 350 and 490 W power. Therefore, only 70 W and 210 W power levels were choosen. The sample was put on a metal sieve, fitted to a tripod placed over a petri dish. In the dish there was definite amount of water to provide vapor (humidity) for the drying chamber. The vapor generated due to absorption of microwaves by the water present. Also, five beakers with 50 mL capacity were filled with water and placed on different locations of turntable to assist vapor generation. The drying was performed according to a pre-set power and time schedule as shown in Figure 2.2. The temperature and relative humidity of the drying chamber were measured by a hygrometer (Testo 605-H1 Model).

Moisture loss was measured by taking out and weighing the samples on the digital balance (CC062D10ABAAGA Model, Avery Berkel) at 15 min intervals during drying. Drying was stopped when the samples reached a moisture content of 12 % (w.b.). This value is the final moisture content of macaroni products in the market. The macaroni was then moved to the final stage of the process where it was remained for about one hour at a relative humidity of 80 % (Decareau, 1984) to cool to temperatures low enough to prevent thermal stress cracking.

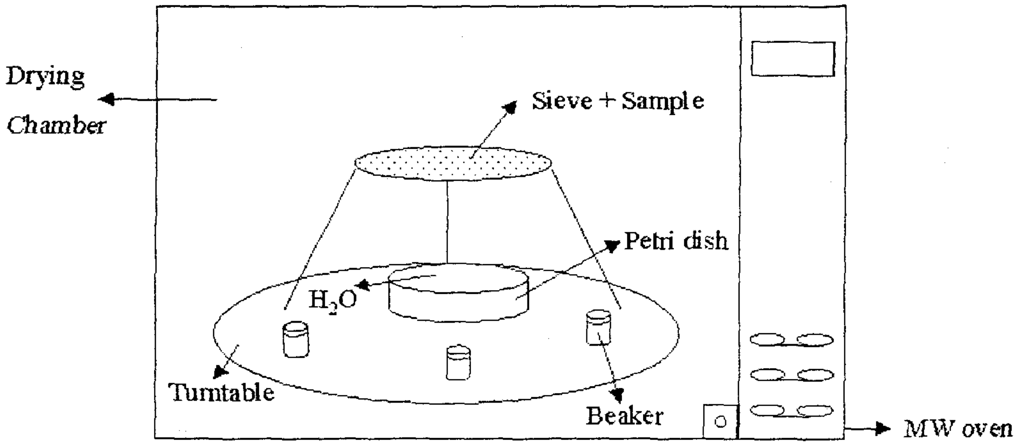

Figure 2.2 Illustration of experimental set up of microwave drying

2.2.1.3. Air followed by a microwave finish drying

The fresh macaroni was exposed to heated air at 66°C for 5 min in the shaker. The moisture content dropped from 33% (w.b.) to 31% (w.b.). The sample was dried at 62 °C dry bulb with 58 % RH in a pre-drying unit to reduce moisture to about 18.5% (w.b.). At this point, partially dried sample was transferred to the microwave oven and dried until 12% (w.b.) moisture content at 70 W and 210 W power levels. Moisture loss was recorded by a digital balance at 10 min intervals during drying. Finally, pasta products were cooled for about one hour at a relative humidity of 80 % to prevent cracking.

2.2.2. Moisture content determination

The moisture content of the samples leaving the shaker and each secreen of the industrial drying unit and microwave dryer was determined by oven method. Two g of ground sample was dried until constant weight at 130±3°C (AOAC, 1990).

2.2.3. Color measurement

The sample color was measured before hot air drying and microwave drying and also during drying by a HunterLab ColorFlex, A60-1010-615 model colormeter (Hunterlab, Reston, VA). Color values of macaroni were measured during hot air, microwave and combined hot air-microwave drying periodically. They were expressed as L* (whiteness/darkness), a* (redness/greenness) and b* (yellowness/blueness) at any time, respectively. The colorimeter was calibrated against a standard white plate (L*=93.01, a*=-1.11, b*=1.30). The results were expressed as total color difference (ΔE) between the reference (fresh) and samples to drying according to the equation [4].

$$\Delta E = \sqrt{(L_0^* - L^*)^2 + (a_0^* - a^*)^2 + (b_0^* - b^*)^2} \qquad [4]$$

The parameters L_o*, a_o* and b_o* refers to reference value, i.e., color parameters of fresh macaroni (wet sample) and L*, a* and b* refer to color values at various times during drying.

2.2.4. Rehydration

The dried samples, with the same initial moisture content, were ground and sieved to 1000-710 µm and immediately loaded (about 0.5 g each) into small aluminium sample dishes. 300 mL of distilled water in a dish was put into desiccator. The dishes were placed in the desiccator and then tightly closed and kept at 25°C for equilibration. The dishes were periodically weighed until equilibrium was reached. The rehydration ratio was calculated from equation [5]

$$Weight\ gain\ (\%) = \frac{(W_t - W_d)}{W_d} 100 \qquad [5]$$

Where W_d is the initial weight of dried sample (g) and W_t is the weight of rehydrated sample (g) at any time.

2.2.5. Cooking loss

Cooking loss (%) is the quantity of material lost to the water during cooking (Grzybowski and Donnelly, 1979). After cooking, the samples of the same initial moisture content, macaroni was rinsed with water in order to wash out the surface residues. The combined cooking and rinse waters were collected in a tared beaker, placed into an oven at 110°C and evaporated to dryness. The residue was weighed and reported as percentage of the starting material on a dry basis(Grant *et al.*, 1993).

2.2.6. Protein solubility

Two g of ground macaroni samples, dried with different drying methods, were weighed in duplicates and extracted in 40 mL of 0.05 M acetic acid on a stirrer for 3 h with constant stirring. The samples were centrifuged at 2000×g for 2.5 h, the supernatant was discarded and the pellets were combined and freeze-dried by a freeze dryer (FD-1, Eyela, Tokyo) at 10 Pa for 2 h. The protein (N×5.7) present in the pellets was determined by the Kjeldahl method and expressed as the acetic acid-insoluble protein (AAIP) in the original sample on a dry basis (Dexter *et al.*, 1981).

2.2.7. Protein determination

Protein content was determined by the standard Kjeldahl method. One g of ground sample was put in a digestion tube with 10 g of K_2SO_4 and little amount of $CuSO_4$ as catalyst. 25 mL of concentrated H_2SO_4 was added and the mixture was digested for 40 min at 420°C until a clear green solution was obtained and cooled down to room temperature. The digested solution was distilled with an automatic steam distilling unit (UDK 130 A, Velp Scientifica Milano, Italy) and collected in an erlenmeyer flask containing 25 mL of 4 % boric acid solution and titrated with 0.096 M of HCl solution until pink color was obtained.

2.2.8. Cooked weight

Ten g of dry macaroni samples of the same moisture content was cooked for 10 min in 250 mL of distilled water. The cooked macaroni was drained and rinsed with distilled water in a sieve. Excess water on the surface of sample was removed by paper towel, then immediately weighed. Results were expressed in grams (Fang and Khan, 1996).

2.2.9. Texture analysis of macaroni

Samples were used directly for texture analysis using a TA-XT2i Texture Analyzer (Texture Technologies Corp, Scarsdale, NY/Stable Micro Systems, Godalming, Survey, UK) equipped with a Texture Expert software program (Version 2.03). Texture analyses were performed for hot air, microwave and combined hot air-microwave dried pasta. Firmness testing method was applied to uncooked samples while Texture Profile Analysis (TPA) testing method was used for cooked samples.

2.2.9.1. Firmness test of uncooked macaroni

Macaroni firmness or hardness was measured by Texture Analyzer using a compression probe. The setting conditions of TA-XT2i were as follows:

Mode :Measure force in compression
Option :Return to start
Pre-test speed :2 mm/s
Test speed :0.1 mm/s
Post-test speed :2 mm/s
Test distance :2 mm
Trigger force :Auto-5g
Data acqusition rate :250 pps

The way that this test performs is to approach the sample at pre-test speed until a trigger force is detected. The probe then begins to compress the sample. This force is maintained for one second to allow a good contact between the probe and sample to be attained. After this time the probe then withdraws to a distance away from the sample at a post test speed during which time the force to separate the probe from the sample surface. Maximum peak force obtained from the analyzer gives the hardness (firmness) value of sample.

2.2.9.2. Texture profile analysis of cooked macaroni

Texture Profile Analysis of cooked macaroni samples dried by various drying techniques was measured by using pasta stickiness rig HDP/PFS. The test consists of compressing a bite size of macaroni sample two times in a reciprocating motion that imitates the action of jaw and extracting from the resulting force-time curve a number of textural parameters.

These include primary parameters of hardness, cohesiveness, springiness (elasticity) and adhesiveness and secondary or derived parameters of fracturability (brittleness), chewiness, gumminess and resilience. A typical TPA curve and calculations of some parameters are given in Figure 2.3.

TA-XT2i Texture Analyzer setting conditions for cooked macaroni were as follows:

Mode :Measure force in compression
Option :Return to start
Pre-test speed :2 mm/s
Test speed :0.5 mm/s
Post-test speed :2 mm/s
Test distance :1 mm
Trigger force :Auto-3g
Data acqusition rate :250 pps

2.3. Statistical Analysis

Analysis of variance (ANOVA) was conducted to determine the effect of drying methods on the physical and textural properties of macaroni samplesusing SPSS 8.0 (SPSS Inc, Chicago, IL, USA) for Windows software. Duncan's multiple range test was performed to differentiate the significant effect of drying methods on drying rate. The parameter of non-linear model [Eqs. 6 and 7] was calculated by the NLIN procedure of the Sigma Plot (Scientific Graph System, version 8.00, SPSS). A Pearson's correlation matrix on TPA parameters, cooking loss and acetic acid-insoluble protein values were carried out using SPSS in order to determine any correlation between parameters.

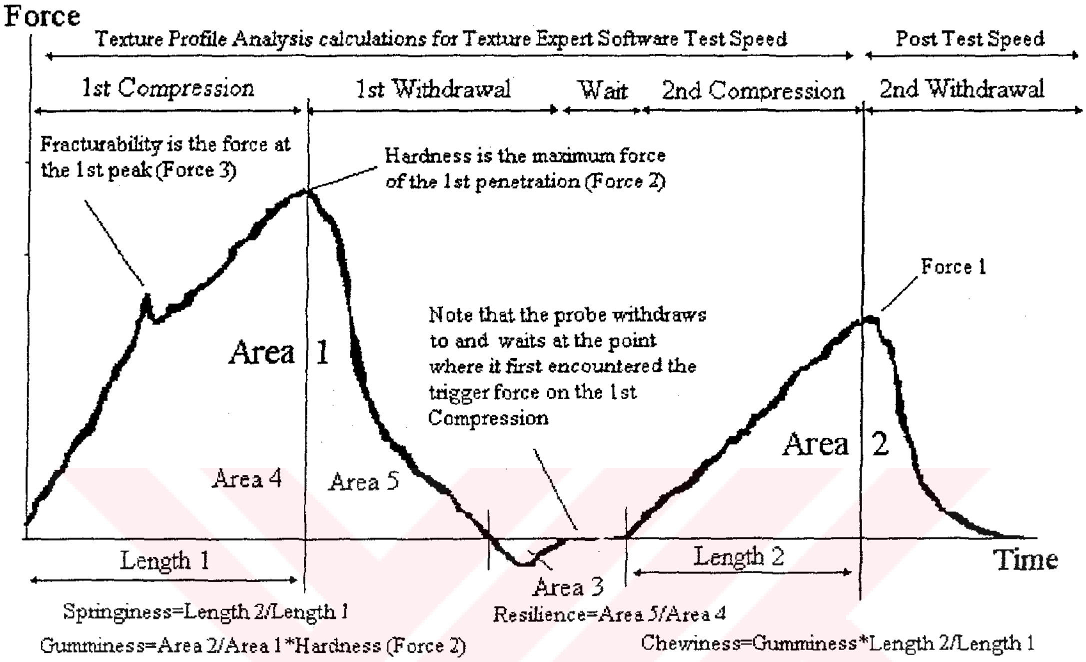

Figure 2.3 A typical Texture Profile Analysis curve

CHAPTER III

RESULTS AND DISCUSSION

3.1. Drying of Macaroni Samples

It is necessary to compare drying time and quality parameters such as color, rehydration, cooking loss, cooked weight, protein solubility, and texture of cooked and uncooked macaroni samples in order to decide which drying process produces the best quality final product.

Typical drying curves, shown in Figures 3.1 and 3.2, exhibited the change in the moisture content of macaroni samples with time dried by hot air, microwave at two power levels and hot air followed by microwave finish drying. The moisture content versus time data were fitted to the following equation [Eqn. 6]. Then, the drying rates were calculated from the first derivative of this equation.

$$M = M_0 + \frac{a.b}{b+t} \qquad [6]$$

where, M is the moisture content at time t=t, kg water/kg dry solids, t is the time, min, a and b are constants. The fresh extruded macaroni was introduced to the shaker at about 0.497 kg water/kg dry solids, where it was exposed to heated air at 66°C for 5 min. This provides better shape stability and maintenance of the product's capillarity, essential to redistribute the particles of water during the following phases of the process. The moisture content of macaroni samples reduced from 0.497 kg water/kg dry solids to 0.452 kg water/kg dry solids in this section. The drying time required to reduce moisture from 0.452 kg water/kg dry solids to 0.228 kg water/kg dry solids in the predrying phase was 43 min at air temperature of 62°C and 58% relative humidity. The predrying technology makes it possible to accomplish partial blockage of any product fermentation. It also enhances uniform gluten distribution making full use of the capacity of gluten to hold back the starch particles so better cooking capacity and less stickiness of the product are obtained (Milatovic and Mondelli, 1991). The predried macaroni samples were put into final drying section where the air temperature was 52°C and 82% RH. The moisture content was reduced to the desired moisture level the final product, approximately 0.136 kg water/kg dry solids, in 305 min.

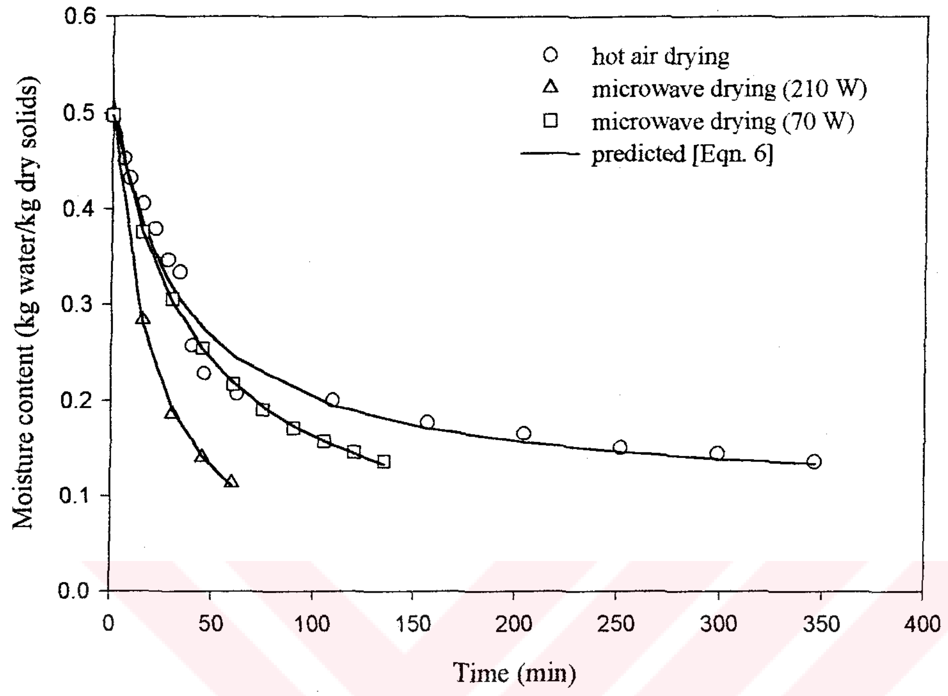

Figure 3.1 Drying curves of macaroni samples dried by hot air and microwave energy with different microwave power levels

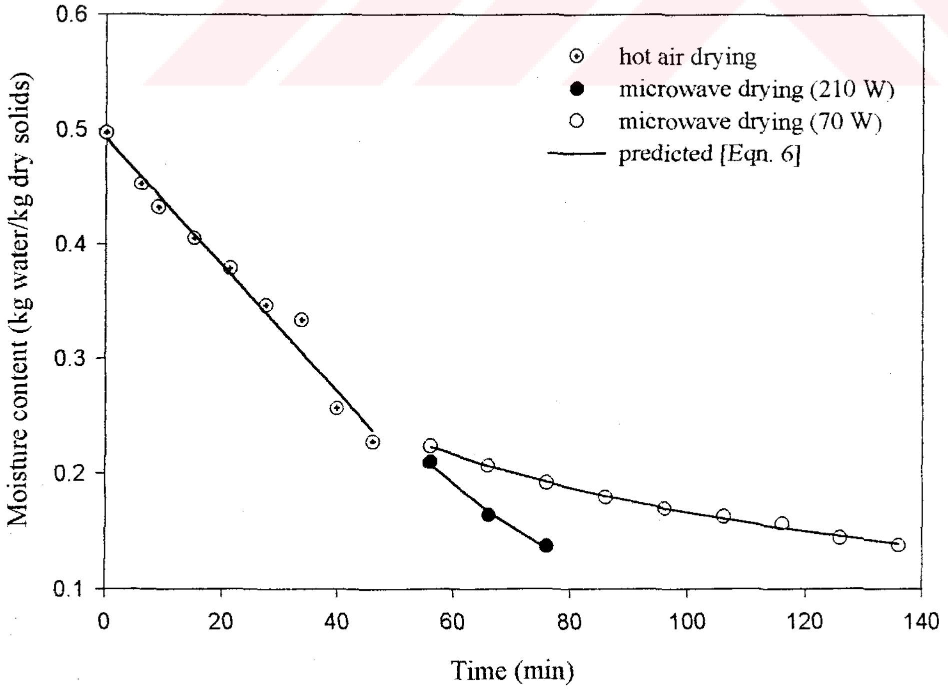

Figure 3.2 Drying curves of macaroni samples dried by combined hot air-microwave operation with different microwave power levels

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. The unique pumping action of microwave energy provides an efficient way of removing internal free water (Decareau, 1985).

Combining properly both unit operations (hot air+microwave drying) in a unique way, that it is possible to improve the efficiency and economics of the drying process. The drying of macaroni samples by microwave was much faster than drying by hot air or hot air-microwave combination as shown in Figures 3.1 and 3.2, respectively. The drying time required to reduce the moisture from initial moisture content of about 0.497 kg water/kg dry solids to desired moisture in the final product, approximately 0.136 kg water/kg dry solids was 353, 135 and 138 min for hot air, microwave at 70 W power level and combined hot air-microwave (70 W) drying, respectively. On the other hand, as the additional microwave power was applied, the drying time significantly diminished. The time required to reach the same final moisture content was 45 and 78 min, respectively for macaroni samples dried with only microwave at 210 W power level and hot air-microwave (210 W) combination. These results revealed that, compared to hot air drying, the drying time reduced about 61.8% and 87.3% by applying microwave energy at 70 W and 210 W power levels, respectively. On the other hand, the reduction was about 61% with the hot air-microwave (70 W) and 78% with the combined hot air-microwave (210 W) drying methods. The results showed that the drying time requirement was significantly reduced as microwave was integrated to the conventional drying unit.

These findings are in good agreement with the previous studies. Sharma and Parasad (2001) found that combined microwave-hot air drying resulted in a reduction in the drying time to an extent of 80-90% in comparison to conventional hot air drying and a superior quality final product. Similar results were obtained by various studies on drying of fruits and vegetables by different drying techniques (Garcia *et al.*, 1988; Bouraoui *et al.*, 1994; Funebo and Ohlsson, 1998; Maskan, 2000; Maskan, 2001). These authors reported that the shorter drying time under microwave heating conditions could be due to the additional energy input, rapid heat penetration by microwave and forced expulsion of gases. In conventional systems, heat which is applied at the surface has to be carried inwards through a moisture-resistant dry layer for the evaporation of water at the receding water front. In a microwave drying system, the microwaves can easily penetrate into the inert dry layers to be absorbed directly by the moisture at the front. The quick energy absorption causes rapid evaporation of water and resulted in shorter drying time.

Drying rate is defined as amount of water removed per unit time per dry solids (kg water removed/kg dry solids.min). The drying rate data were estimated by taking the first derivation of Equation 6 with respect to time. Then, the drying rates (dM/dt) were plotted against moisture contents. The drying rates of macaroni samples dried by hot air and microwave at different power levels were shown in Figure 3.3. The drying occurred mainly in the falling rate period, regardless of drying conditions. This indicated a diffusion-controlled type mechanism of drying (Feng and Tang, 1998). As microwave power level increased from 70 W to 210 W, drying rate increased almost 2 times higher compared to that with hot air and microwave (70 W) drying at the start of drying process. The Duncan's multiple range test showed a significant difference ($P<0.05$) in drying rates between microwave at 210 W and other two drying techniques, microwave at 70 W and hot air drying. Although microwave has many advantages, the drying of foods or food ingredients at high moisture content over 20% moisture with microwave only is not comparatively economical (Owusu-Ansah, 1991). It has been reported that at high moisture contents conventional heating methods more effectively remove water than microwaves. This is because although water has high dielectric constant and would absorb microwaves easily, it also has a very high specific heat. Considerable amount of microwave energy would be needed to significantly raise the temperature for dehydration if the bulk of water is high. So, microwave drying has been used as a combined process with hot air drying rather than a single unit operation (Rosenberg and Bögl, 1987).

Drying rate curves for macaroni samples dried by combined hot air-microwave drying process at different power levels were illustrated in Figure 3.4. It is evident from examination of these curves that the drying of macaroni samples by hot air was much slow before introducing microwave energy. The linear regression analysis results confirm our results. The slopes of drying rate lines of the hot air, microwave 70 W and microwave 210 W were $1.3613*10^{-5}$ ($R=0.989$), 0.0131 ($R=0.995$) and 0.0264 ($R=0.999$), respectively. The steeper drying rate line (microwave 70 and 210

W) with greater slopes indicate faster removal of moisture as shown in Figure 3.4., i.e., the higher the microwave power setting, the higher the temperature in microwave drying chamber. For example, the drying chamber temperature and humidity, measured by a hygrometer, reached to 40 to 43°C during drying of samples with microwave at 70 and 210 W microwave power levels, respectively from initial temperature of 30°C. The sample internal temperature is expected to be very higher than the chamber temperature. Nevertheless, it is understood that increasing power level to 210 W resulted in faster heating and faster drying of macaroni samples. The faster drying is due to the microwave energy that can drive the moisture to the surface in minutes where in the conventional dryer that moisture migration to the surface takes hours.

Excess speed of heating causes nonuniform temperature distribution. This occurs because the heating may be so fast as to prevent the effectiveness of thermal conductivity in transferring heat to the cooler portions (Schiffmann, 1986). So, during drying process, non-uniform heating may cause partial scorching. In our preliminary studies surface cracks were observed in the macaroni samples dried by microwave 210 W and combined hot air-microwave at 210 W drying operations. This is due to thermal stresses occurred because of high internal sample temperature. In order to prevent surface cracking, macaroni samples were put in an environment equilibriated with 80% relative humidity at 50°C for 1 h immediately after drying. This treatment prevented surface cracks of macaroni samples dried by microwave at 210 W power level, combined hot air-microwave at 210 W drying operations. This cooling and equalization stage is vital for prevention of surface cracking. Because the product comes off the microwave at extremely high internal temperature and is drying so fast, this process must then be applied and the product cooled as well as the wall temperature equalized so that the temperature difference between the product and the ambient air to which it finally will be exposed, must be close enough that it will not cause the product to check or crack.

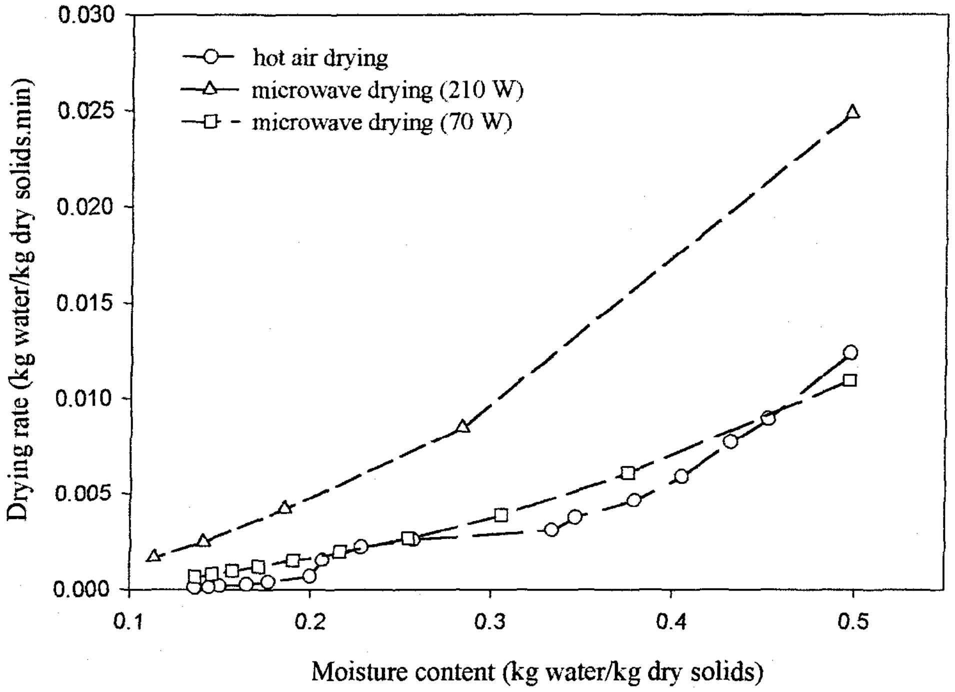

Figure 3.3 Drying rate curves of macaroni samples dried by hot air and microwave with different microwave power levels

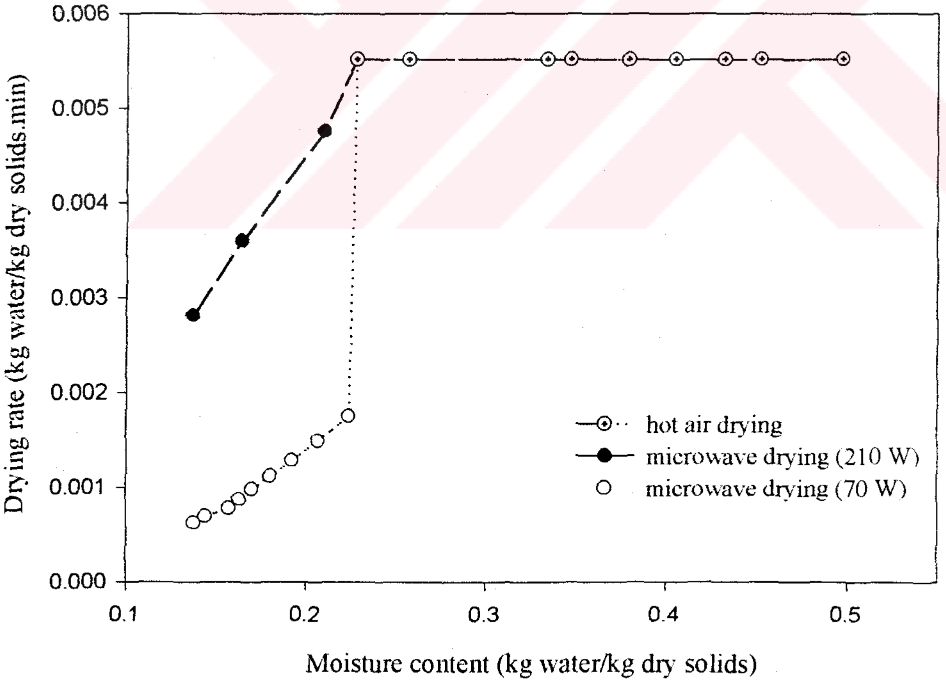

Figure 3.4 Drying rate curves of macaroni samples dried by combined hot air-microwave drying with different microwave power levels

3.2. Modelling Drying Data

Drying data obtained from moisture loss against time for each test run were fitted to the diffusion model, Eqn. [7] in order to characterize the drying curves (Maskan, 2000; Maskan, 2001).

$$MR = \exp(-kt) \qquad [7]$$

where, MR is the moisture ratio, $(M_t\text{-}M_e)/(M_o\text{-}M_e)$ is dimensionless, M_t is the moisture content at time t=t, kg water/kg dry solids, M_o is the moisture content at time t=0, kg water/kg dry solids, M_e is the equilibrium moisture content, kg water/kg dry solids, k is the rate constant, min^{-1} and t is the time, min. The drying data of macaroni samples obtained from hot air, microwave (70 W and 210 W) and combined hot air-microwave (70 W and 210 W) processes were used to test the applicability of Eqn. 7. The equilibrium moisture content was assumed to be the final moisture content of each run (Prabhanjan *et al.*, 1995; Ren and Chen, 1998; Sharma and Parasad, 2001).

The rate constant k was evaluated through non-linear regression analysis and the results were tabulated in Table 3.1. The results of nonlinear regression analysis showed high values of R^2 except for combined hot air-microwave (210 W). High R^2 values implies a good fit of model to the experimental data.

Table 3.1 Nonlinear regression analysis results of one parameter diffusion model [Eqn. 7] for drying of macaroni samples

	Drying method				
	Hot air drying	Microwave drying		Hot air-microwave drying	
Parameter		70 W	210 W	70 W	210 W
k	0.0220^a	0.0258^b	0.0563^c	0.0237^{ab}	0.0253^b
SE (±)	0.0014	0.0005	0.0020	0.0010	0.0029
R^2	0.972	0.997	0.997	0.979	0.919

^{a,b,c}Within each column, means without a common superscript differ ($P<0.05$)

As expected, the value of drying rate constant k was higher for microwave drying at 210 W power level compare to the other drying techniques. It has been reported that the higher the power output, the faster the heating for a given mass (Schiffmann, 1986). So, the shorter the drying duration, the highest the drying rate resulted in the higher the rate constant. The drying rate constant increased as it is compared to hot air drying for microwave drying combined with hot air drying. This difference was significant ($P<0.05$) for microwave with a power level of 210 W while not significant ($P>0.05$) for microwave at 70 W power level. This means that drying macaroni samples with hot air gives almost the same rate constant as combined hot air-microwave drying at 70 W power level. There was no significant difference ($P>0.05$) in rate constant between the macaroni samples dried with microwave (70 W) and combined hot air-microwave (70 W and 210 W) but there was a significant difference ($P<0.05$) between these three samples and microwave (210 W) dried samples. The fitness of the diffusion model for different drying methods was illustrated in Figures 3.5, 3.6 and 3.7.

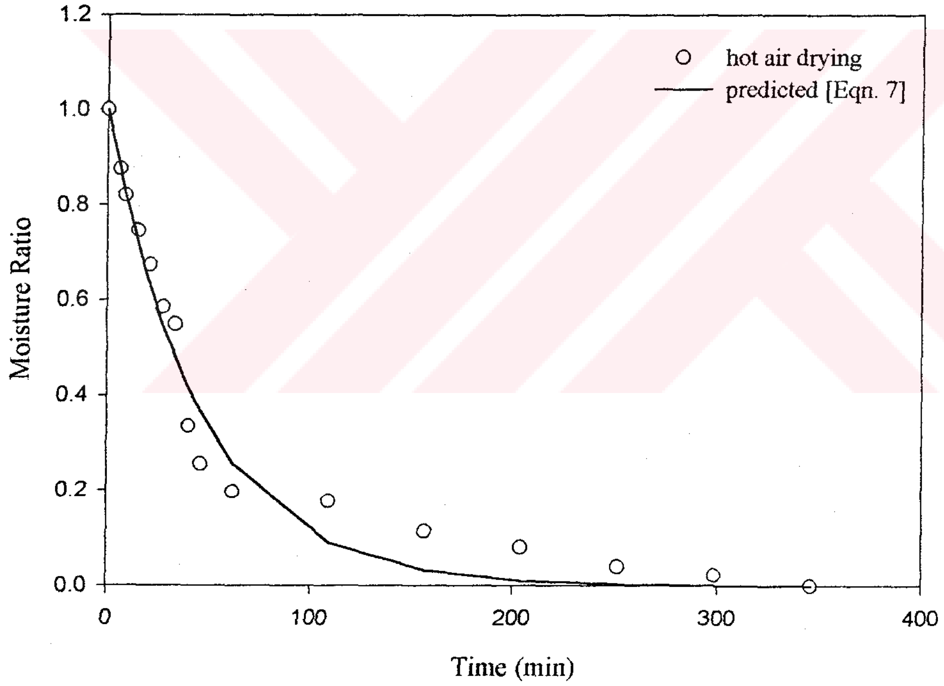

Figure 3.5 Moisture ratio vs time comparing experimental curve with the predicted one through diffusion model for hot air drying

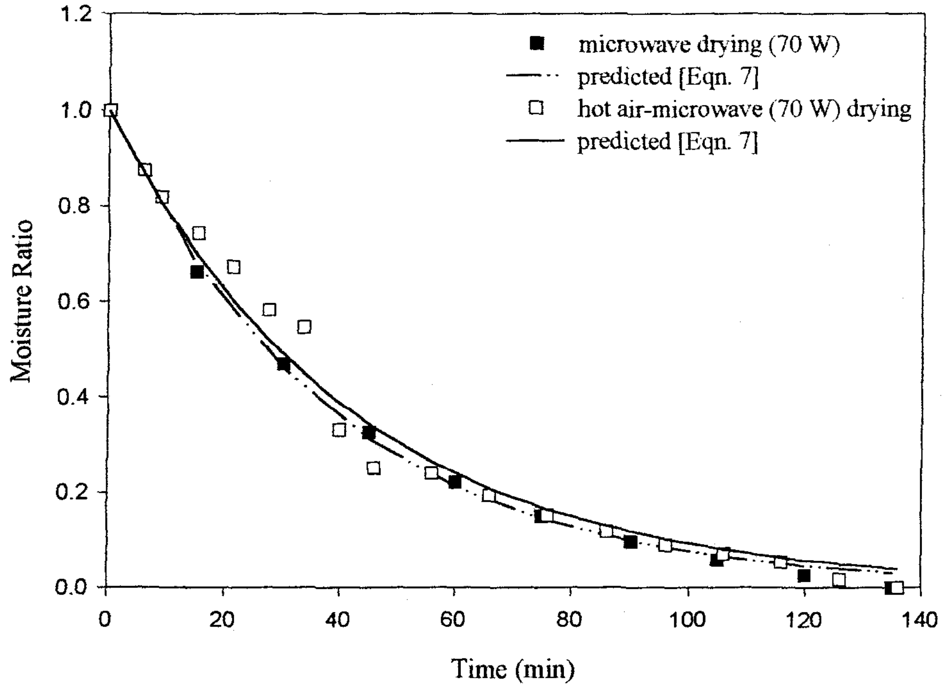

Figure 3.6 Moisture ratio vs time comparing experimental curve with the predicted one through diffusion model for microwave and combined hot air-microwave drying at 70 W

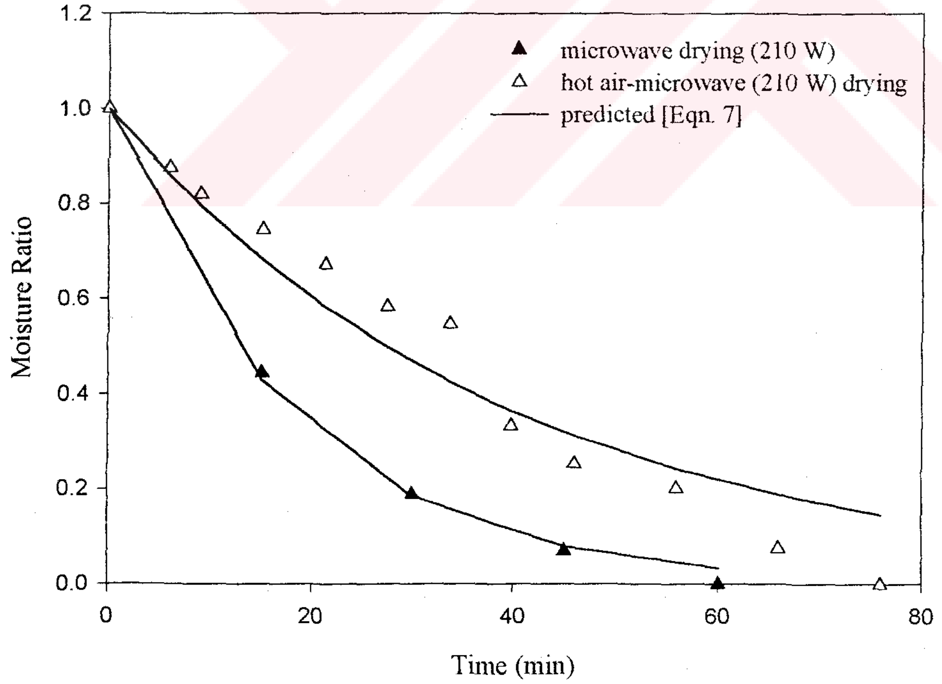

Figure 3.7 Moisture ratio vs time comparing experimental curve with the predicted one through diffusion model for microwave and combined hot air-microwave drying at 210 W

3.3. Color Change of Macaroni Samples during Drying

Factors that influence the apperance of the macaroni other than its size and shape are its color, uniformity and surface texture. It is well known that yellow and brown indices are correlated both to pigment amount and to enzymatic reactions, while the red index is strictly related to the development of Maillard reaction (Oliver *et al.*, 1993). The change in Hunter color parameters L*, a* and b* of macaroni during drying were shown in Figures 3.8, 3.9 and 3.10, respectively. Regardless of drying method, there was change in color parameters. This is inevitable because of heat involved in the drying process.

The brightness index (L*) decreased (Figure 3.8) while the consequent increase in the brown index (100-L*) was observed in all drying techniques. Average brightness index (L*) over drying periods for hot air, microwave at 70 and 210 W and combined hot air-microwave at 70 and 210 W power levels was 54.01±2.50, 53.28±2.25, 53.86±3.06, 54.16±2.22 and 54.89±2.32, respectively. Statistical analysis of the data exhibited significant difference ($P<0.05$) in brightness index between microwave drying at a power level of 70 W and combined hot air-microwave drying at 210 W. On the other hand the L* values of hot air, combined hot air-microwave at 70 W and microwave at 210 W were not significantly differrent ($P>0.05$) (Table 3.2).

Table 3.2 Average color parameters of macaroni samples

Drying method	L*	a*	b*	ΔE
Air	54.01 ± 2.50^{ab}	5.09 ± 0.55^{a}	36.63 ± 0.58^{bc}	5.34 ± 2.52^{a}
MW (70 W)	53.28 ± 2.25^{a}	4.99 ± 0.43^{a}	36.26 ± 0.40^{ab}	6.02 ± 2.31^{a}
Air-MW (70 W)	54.16 ± 2.22^{ab}	4.96 ± 0.40^{a}	36.95 ± 0.56^{c}	5.16 ± 2.22^{a}
MW (210 W)	53.86 ± 3.06^{ab}	4.98 ± 0.65^{a}	36.22 ± 0.65^{a}	5.52 ± 3.15^{a}
Air-MW (210 W)	54.89 ± 2.32^{b}	4.94 ± 0.51^{a}	36.58 ± 0.72^{abc}	4.40 ± 2.30^{a}

^{a,b,c}Within each column, means without a common superscript differ ($P<0.05$)

The brownness of macaroni samples has been attributed to a brown colored molecule in the endosperm, enzymatic reactions and Maillard reactions (Feillet, 2000). If the polyphenol oxidase is not inactivated, this enzyme exhibits negative effects. It has been reported that (Milatovic and Mondelli, 1991) at temperatures lower than 60°C, it causes enzymatic browning in food material through an initial oxidation of phenoles into quinones. Quinones readily undergo self-polymerisation or condensation with amino acids or proteins via their amino groups to form complex brown polymers, consequently, resulting in decrease in L* value.

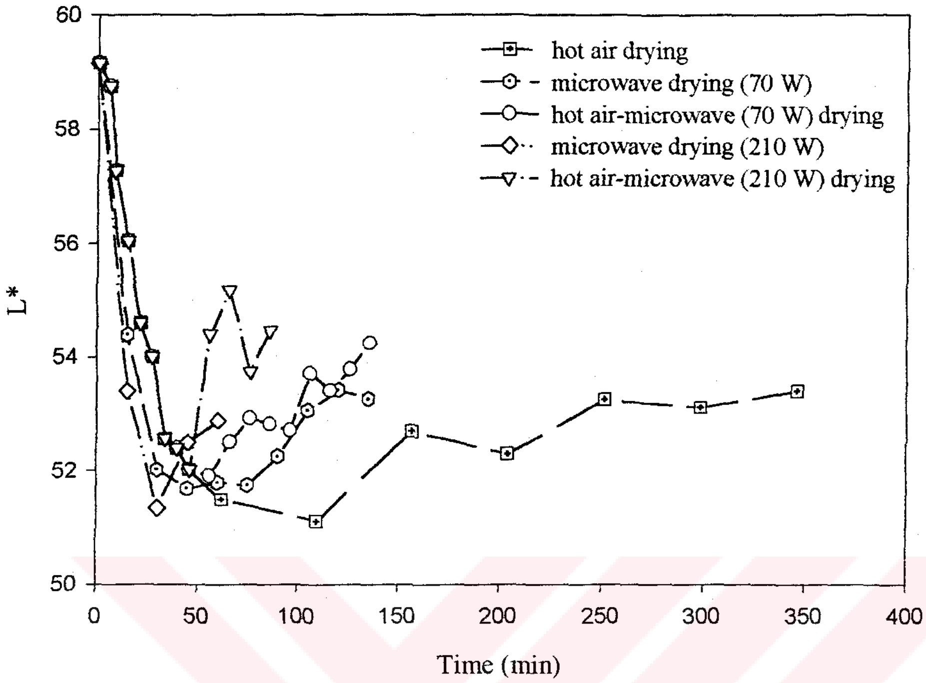

Figure 3.8 The changes of brightness index of macaroni samples during drying with different methods

The redness index (a*) increased in all drying techniques as shown in Figure 3.9. As mentioned earlier, redness index (a*) is related to Maillard reactions. In pasta products, nonenzymatic browning related to the Maillard reaction occurs when carbonyl groups, usually reducing sugars, condense with free amino groups from amino acids, peptides and proteins (Sensidoni, 1999). The redness index of macaroni samples dried with different methods increased sharply in the same trend for initial 45 min period. Then, it showed some fluctuations and increased slightly in all drying techniques. Average redness index over drying periods for hot air, microwave at 70 and 210 W and combined hot air-microwave at 70 and 210 W power levels was 5.09±0.55, 4.99±0.43, 4.98±0.65, 4.96±0.40 and 4.94±0.51, respectively. The redness index of hot air, microwave (70 W and 210 W) and combined hot air-microwave (70 W and 210 W) dried macaroni samples was not significantly different (P>0.05) (Table 3.2).

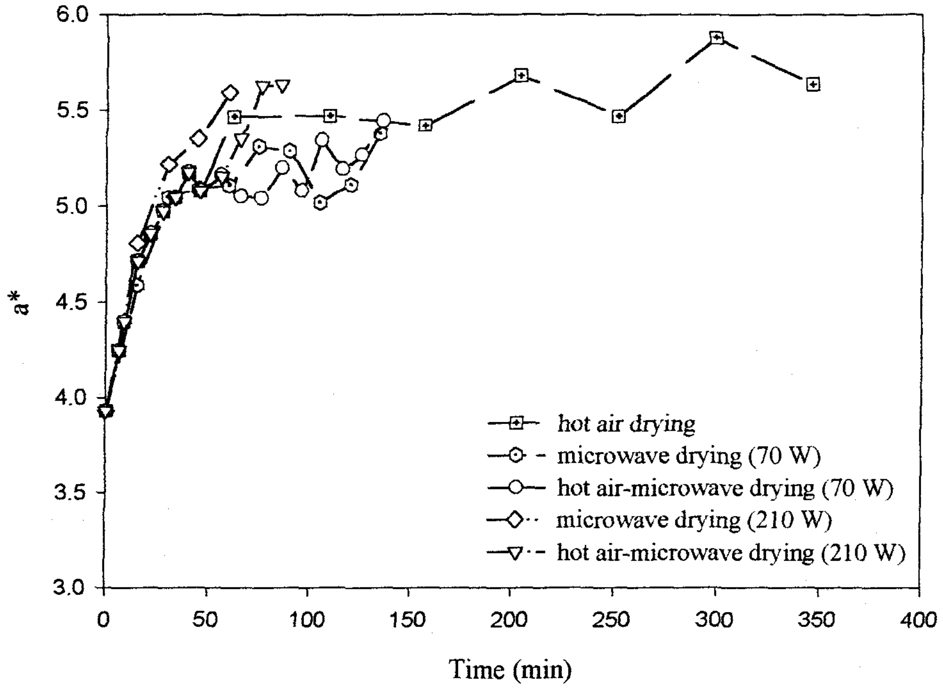

Figure 3.9 The changes of redness index of macaroni samples during drying with different methods

Figure 3.10 shows the variation of the yellowness index (b*) during drying with different drying techniques. The yellowness index demonstrates retention of pigment depending on enzyme inactivation (Acquistucci, 2000). Pasta yellowness is affected by different factors, the most important of which are intrinsic to the quality of semolina (natural carotenoid pigments, protein, ash and lipoxygenase activity) and processing conditions (Debbouz, 1994; Borelli *et al.*, 1999). In this study, the yellowness index of macaroni samples increased in initial 15 min during hot air drying, but after this time sharp decrease was observed. The reason for this might be partial inactivation of lipoxygenase activity. Because fresh macaroni samples were exposed to 66°C for 5 min and to 62°C of temperature for 43 min. However, this temperature might not be enough for inactivation. It was reported that a drying temperature of 65°C for spaghetti is not enough to inactivate lipoxygenase; only a temperature of 80°C is enough to keep the yellow color of pasta (Milatovic and Mondelli, 1991). Similar results were observed for combined hot air-microwave (at 70 and 210 W) drying. On the contrary of hot air drying, there was a sharp decrease in initial 15 min for microwave drying at 210 W power levels. During drying with microwave at 70 W of power level, slight decrease in yellowness index was observed and then increased as time progressed. Average yellowness index over drying periods for hot air, microwave at 70 and 210 W and combined hot air-microwave at 70 and 210 W power levels was 36.63±0.58, 36.26±0.40, 36.22±0.65, 36.95±0.56 and 36.58±0.72, respectively. The Duncan's multiple range test showed that there was a significant difference ($P<0.05$) in yellowness index between microwave (210 W) and the other two samples dried with hot air and combined hot air-microwave (210 W) drying (Table 3.2). Good retention of yellow pigment in macaroni samples was observed with drying of combined hot air-microwave at 70 W power level compare to the other drying techniques. This difference was not significant ($P>0.05$) for hot air and combined hot air-microwave (210 W) drying but significant for microwave (70 W and 210 W) drying (Table 3.2).

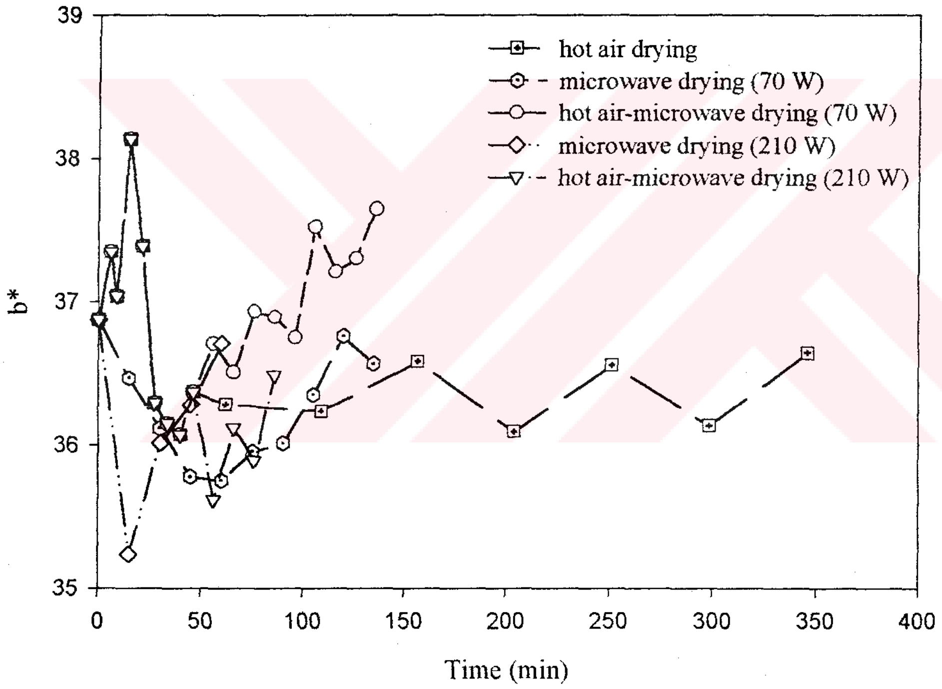

Figure 3.10 The changes of yellowness index of macaroni samples during drying with different methods

The total color change (ΔE) of macaroni samples dried with different methods was shown in Figure 3.11. Besides drying temperature and time, enzyme inactivation is important parameter for color change during drying of macaroni samples. The total color change of macaroni samples depends on changes in brightness, yellowness and redness. The total color change of macaroni samples increased for 45 min related with the three colorimetric indices and after this time, it decreased as shown in

Figure 3.11. Average and standard deviations of total color change of macaroni samples for hot air, microwave at 70 W and 210 W and combined hot air-microwave at 70 and 210 W power levels was 5.34±2.52, 6.02±2.31, 5.52±3.15, 5.16±2.22 and 4.40±2.30, respectively. It is clear that microwave finish drying at these two power levels maintained the color quality of macaroni samples compared to the hot air and microwave drying methods alone. However, statistical analysis showed no significant difference ($P>0.05$) in total color change value of macaroni samples dried with any method. Moreover, it can be said that color enhancement was achieved with the fact that less oxidation of the pigments occurred with the combined hot air-microwave drying processes. It is evident from low ΔE values (5.16 and 4.40).

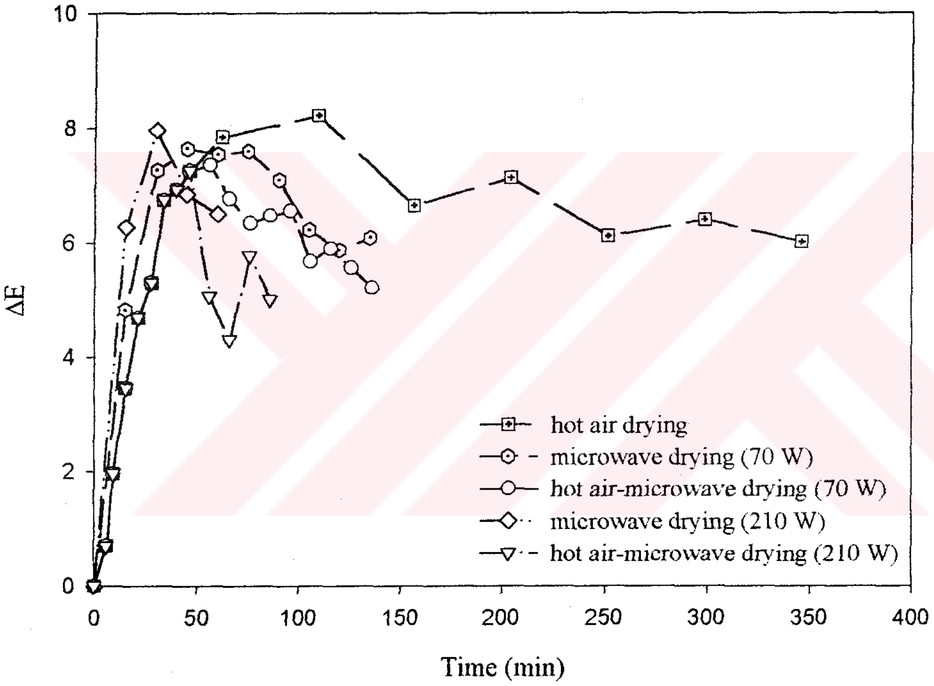

Figure 3.11 The total color change (ΔE) of macaroni samples during drying with different methods

3.4. Rehydration Capacity of Macaroni Samples

The rehydration characteristics of a dried product are widely used as a quality index. Rehydration is a complex process and indicates the physical and chemical changes caused by the drying (Lewicki, 1998; Feng and Tang, 1998).The rehydration curves of macaroni samples dried with different methods at 25°C were shown in Figure 3.12. The samples used for rehydration experiment had the same initial moisture content.The rehydration capacities of macaroni samples were calculated from Eqn.

[5] which is used to characterize the ability of foods to absorb water (Maskan, 2000; Maskan, 2001). The rehydration capacity of macaroni samples dried with combined hot air-microwave (210 W) showed the highest value among macaroni samples. In general, higher water absorption capacity is expected for microwave dried sample (Lewicki, 1998; Feng and Tang, 1998) because of short drying duration. However, the Duncan's multiple range test showed that the drying conditions did not influence (P>0.05) the rehydration behavior of macaroni samples dried with different methods. Similar results were reported by Funebo and Ohlsson (1998) and Maskan (2000) for microwave assisted air drying of apple and mushroom and banana. Although the water absorption capacity of all samples was similar, there was a tendency of macaroni sample dried by hot air-microwave at 210 W power level to absorb more water (Figure 3.12). This may be due to the short drying time that causes less damage on the water binding sites of macaroni. It also can be attributed to the denaturation of proteins that provides more water holding sites upon unfolding.

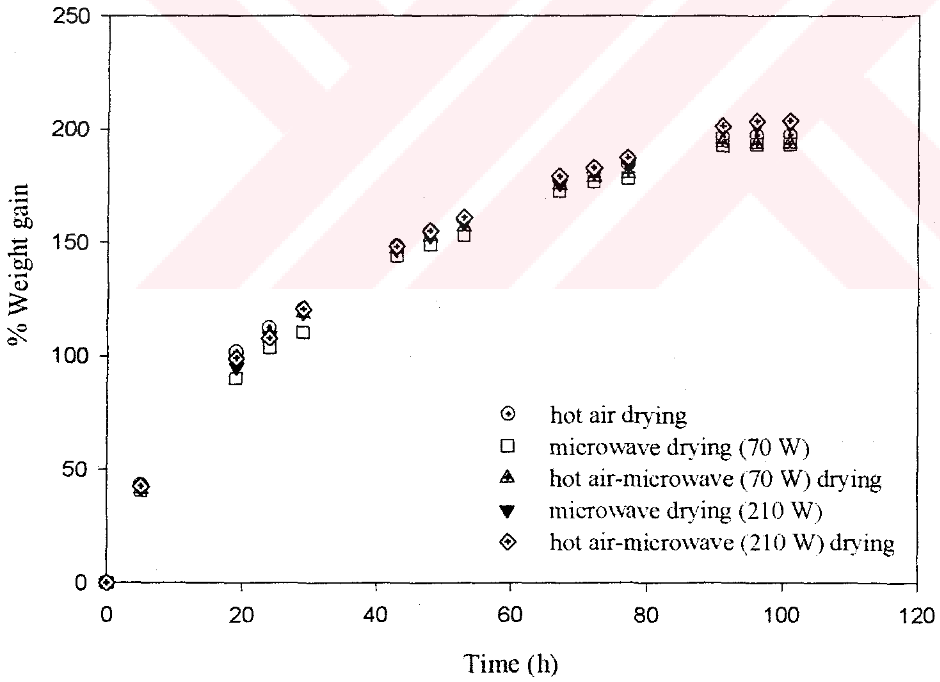

Figure 3.12 Effect of drying methods on rehydration capacity of macaroni samples measured at 25°C

3.5. Cooking Loss of Macaroni Samples

Cooking loss is defined as the amount of material leached out of the pasta strand during cooking (Grzybowski and Donnelly, 1979). Figure 3.13 shows cooking loss of macaroni samples dried with hot air, combined hot air-microwave (70 W and 210 W) and microwave (70 W and 210 W) drying techniques. Macaroni samples were cooked to previously determined optimal cooking time in deionized water. Optimal cooking time was defined as the time required for the white core in the center of the macaroni sample to disappear (Dexter *et al.*, 1981). It was found as 10 min for macaroni samples dried with different methods. The percent of cooking loss was determined as 6.40, 6.34, 6.62, 6.22 and 5.77%, respectively for macaroni samples dried with hot air, microwave at 70 and 210 W and combined hot air-microwave at 70 and 210 W drying. The combined hot air-microwave at 210 W and 70 W dried macaroni samples exhibited the least cooking loss, 5.77 and 6.22% respectively. The Duncan's multiple range test showed a significant difference ($P<0.05$) in cooking loss between combined hot air-microwave at 210 W dried samples and the other samples dried with hot air, combined hot air-microwave at 70 W and only microwave at 70 and 210 W drying, i.e., combined hot air-microwave at 210 W drying process gave the lowest cooking loss value (5.77%).

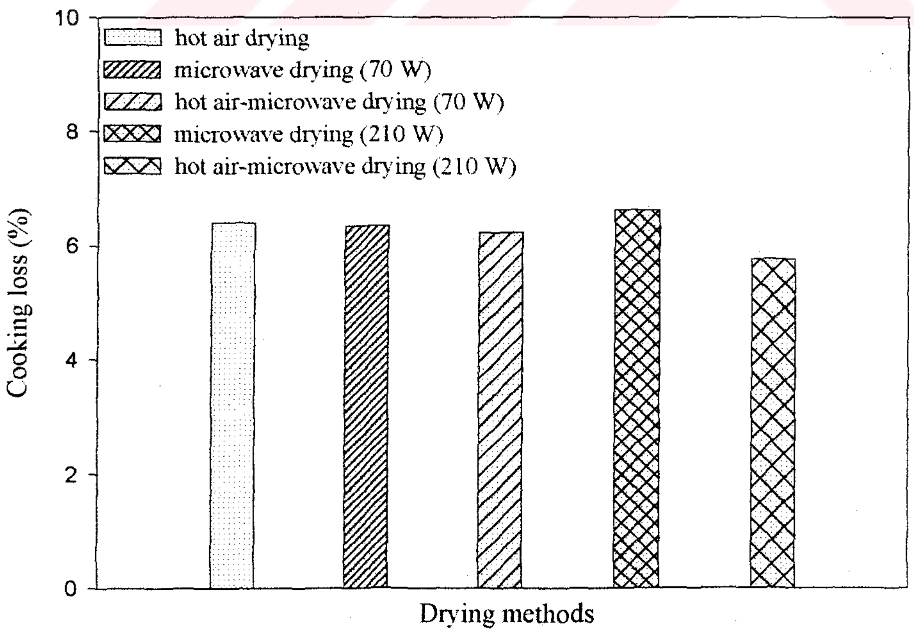

Figure 3.13 Cooking loss of macaroni samples dried with different methods

Vansteelandth and Delcour (1998) reported that the first drying steps of an industrial pasta production render the starch granules in general and the small ones in particular less extractable, possibly due to increased physical inclusion or interaction between starch and gluten components. This result explains why combined hot air-microwave drying techniques have lower cooking loss compared to the microwave drying only. The higher cooking loss of macaroni samples (6.34 and 6.62%) dried with microwave drying techniques might be due to the inadequate interaction between starch and protein components because of short drying time. The highest value of cooking loss was observed in macaroni samples dried with microwave alone at 210 W power level. There are various reasons for this phenomenon; protein affects the gelatinization of starch by forming complexes with starch molecules on the granule surface and preventing the escape of exudates from the granules thereby increasing the gelatinization temperature of starch (Olkku and Rha, 1978). Also Resmini and Pagani (1983) stated that extensive protein denaturation may occur during processing when a temperature higher than 60°C is attained in drying. During drying, proteins coagulate and may envelop the starch granules within a continuous network (Pagani *et al.*, 1986) and that renders the starch granules less extractable (Vansteelandth and Delcour, 1998) and restricts their gelatinization and swelling during cooking (Delcour *et al.*, 2000). There was no significant difference ($P>0.05$) in cooking loss between microwave (210 W) dried and hot air dried macaroni samples. However, microwave (70 W) dried and combined hot air-microwave (70 W and 210 W) dried macaroni samples were significantly different ($P<0.05$) from microwave (210 W) dried macaroni samples (Table 3.3).

Another possible reason for the higher cooking loss may be explained by the interaction of microwaves with gluten adversely. Walde *et al.* (2002) concluded that the functionality of gluten was altered during drying of wheat with microwave which was observed by the absence of elasticity and stretchability of the dough. They also concluded that there was no cohesiveness among the particles to each other (Campana *et al.*, 1993). Hence, the higher cooking loss is inevitable under such drying conditions.

On the contrary of protein, microwaved starch shows similar behaviour with starch of pasta dried with high temperature found by different authors. Lewandowicz *et al.* (2000) found that microwave irradiation reduced the crystalinity, solubility and swelling characteristics of wheat starches as well as increased the gelatinization temperature. They also concluded that a higher gelatinization temperature of microwave irradiated starch indicated an association and more stable configuration in a granular structure. Similarly, Zweifel *et al.* (2000) reported that starch isolated from HT-dried pasta showed higher gelatinization temperature and viscosity and lower swelling power and solubility. These observations confirm the results found in this study.

3.6. Protein Solubility of Macaroni Samples Dried by Different Methods

The solubility of protein is considered an index of denaturation with lower solubility indicating a higher degree of denaturation (Aktan and Khan, 1992). The percent insoluble protein quantity of macaroni samples dried by different methods was given in Table 3.3. Duncan's multiple range test showed that introducing the microwave energy caused a significant increase in acetic acid-insoluble protein of macaroni samples (Table 3.3).

Table 3.3 Acetic acid-insoluble protein content, cooked weight and cooking loss of macaroni samples dried by different methods

Drying method	Protein (%) (d.b.)	Cooking loss (%)	AAIP (%) (d.b.)	Cooked weight (g)
Air	12.40	6.40^{ab}	4.99^{b}	24.49^{ab}
MW (70 W)	12.40	6.34^{a}	5.51^{a}	24.53^{ab}
Air-MW (70 W)	12.40	6.22^{a}	5.49^{a}	24.14^{a}
MW (210 W)	12.40	6.62^{b}	6.08^{c}	24.65^{b}
Air-MW (210 W)	12.40	5.77^{c}	7.46^{d}	24.67^{b}

^{a,b,c,d}Within each column, means without a common superscript differ ($P<0.05$)

Acetic acid-insoluble proteins of macaroni samples dried with combined hot air-microwave (70 W) and microwave (70 W) drying were not significantly different ($P>0.05$). However, there was a significant difference ($P<0.05$) between the other three samples dried by hot air, microwave (210 W) and combined hot air-microwave (210 W). This result indicates the highest degree of protein denaturation (7.46%) with hot air-microwave at 210 W and the lowest (4.99%) with only hot air drying methods. These results are in agreement with those of Aktan and Khan (1992). They reported that a greater degree of protein denaturation occured at very high-temperature drying. Thus, very high-temperature drying changes the properties of proteins and this may partly explain the improved cooking quality such as higher cooked weight and lower cooking loss that supports the results of this study.

3.7. Cooked Weight of Macaroni Samples Dried by Different Methods

Cooked weight is a measure of the water absorbing capacity of the spaghetti (Grzybowski and Donnelly, 1979). Cooked weights of macaroni samples dried with different methods were shown in Table 3.3. Cooked weight of hot air-microwave (210 W) dried sample was the highest (24.67 g) among the others. As indicated in Table 3.3, there was a significant difference ($P<0.05$) in cooked weight of combined hot air-microwave (70 W) dried macaroni samples and microwave (210 W) and combined hot air-microwave (210 W) dried macaroni samples. On the other hand, the difference was not significant ($P>0.05$) from the other macaroni samples dried with hot air and microwave (70 W) drying. Also both microwave (210 W) and combined hot air-microwave (210 W) dried macaroni samples were not significantly different from hot air and microwave (70 W) dried samples.

Several investigators reported that the cooked weight increased as drying temperature increased (Aktan and Khan, 1992; Fang and Khan, 1996). In agreement with these findings, the current study showed that increased microwave power increased cooked weight. Feillet *et al.* (1989) postulated that a durum wheat sulfur rich glutenin (DSG) proteins contribute to aggregation of LMWG (and possibly of HMWG) through hydrophobic and disulfide bonds. This type of denaturation increases the water absorption capacity (Saldamlı, 1998). One of the possible way for increased water absorption may be ensuing dissociation and unfolding after heating may bring to the surface previously buried peptide bonds and polar side chains with a resulting improvement in water binding (Fennema, 1985).

3.8. Textural Analysis of Macaroni

3.8.1. Firmness test of uncooked dry macaroni

The gluten strength/quality of the semolina determines the dry strength of the pasta (Smewing, 1997). The firmness test determines how well the product tolerates shipping and impact damage and may also indicate which drying method produce firm macaroni. It is also defined as maximum cutting force.

Figure 3.14 shows firmness of uncooked dry macaroni samples dried with different techniques. The highest firmness values were obtained for macaroni samples dried with combined hot air-microwave drying. The macaroni samples dried with hot air and combined hot air-microwave (70 W and 210 W) drying were significantly different ($P<0.05$) from microwave (70 W and 210 W) dried macaroni samples and there was no significant difference ($P>0.05$) in firmness of macaroni samples when dried with only microwave energy at 70 W and 210 W.

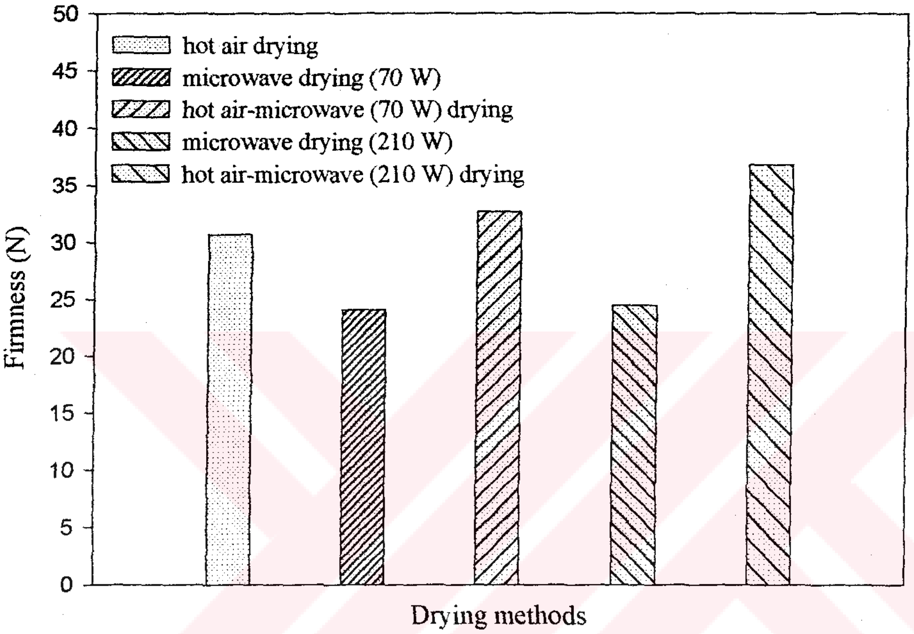

Figure 3.14 Firmness values of macaroni samples dried with different methods

Microwave dried macaroni samples at two power levels had lower firmness values compared to the other methods. This decrease was due to checking in the macaroni samples dried with microwave drying. As microwave power was increased from 70 W to 210 W checking slightly increased. This is because microwaves interact directly with water molecules. The tempearature can eventually rise to high values and macaroni samples dry too quickly. Microwave dried macaroni samples at 210 W had the highest amount of checking resulted from the inability of environment with 80 % relative humidity after drying during equilibration.

3.8.2. Texture profile analysis (TPA) of cooked macaroni

As earlier mentioned the properties of cooked pasta components are affected by semolina protein quality and quantity (Matsuo *et al.*, 1972), drying conditions (De Stefanis and Sgrulletta, 1990) and the composition of cooking water (Malcolmson and Matsuo, 1993). It is generally accepted that the main criterion for assessing overall quality of cooked pasta is based on evaluation of texture (Smewing, 1997). Cooked pasta must be firm, resilient and nonsticky for maximum consumer acceptance (Dexter *et al.*, 1983). To measure macaroni texture, TPA (hardness, cohesiveness, adhesiveness, chewiness, resilience) test was carried on the TA-XT2i Model Texture Analyzer. From the force time curve of TPA (Figure 2.3), seven textural parameters were determined. Among these textural parameters, hardness, cohesiveness, adhesiveness, springiness and resilience were measured and chewiness and gumminess were calculated from the measured parameters.

When cooking durum wheat pasta, starch gelatinization and protein coagulation cause major structural changes and hence influence final texture (Smewing, 1997). During the cooking of good quality pasta, the protein absorbs water and swells more rapidly than the starch. This process results from fibrous fibrillar network of coagulated protein surrounding gelatinized starch granules (Resmini and Pagani, 1983). In poor quality pasta, the proteins aggregate in discrete masses rather than in a continuous matrix. Hydration of protein fraction of pasta before the beginning of starch gelatinization appears to be important to produce a firm, good quality cooked pasta (Hahn, 1990).

Parameters derived from the TPA tests of cooked macaroni samples are given in Table 3.4. The macaroni samples dried with combined hot air-microwave at 210 W power levels had higher values for hardness and lower values for adhesiveness than those samples dried with hot air and microwave only at different power levels (70 W and 210 W). This can be considered as improvement in cooking quality while combining hot air with microwave energy. The Duncan's multiple range test showed a significant difference in hardness value between microwave (210 W) finish dried macaroni samples and the other samples (Table 3.4). Hardness (firmness) value was negatively correlated with cooking loss as shown in Table 3.5, i.e., as firmness of cooked pasta increased cooking loss (Table 3.3) and adhesiveness values decreased.

The results revealed that combination of microwave energy with hot air increased the firmness and decreased the adhesiveness of macaroni samples. This can be explained by the fact that during pasta cooking, proteins coagulate forming a continuous network and starch particles are trapped in the network completely due to microwave addition promoting firmness of cooked pasta. In opposite case, the pasta will be soft and usually sticky (Resmini and Pagani, 1983).

Table 3.4 TPA parameters of cooked macaroni samples dried with different drying methods

Drying method	Hardness (N)	Adhesivenes (N.s)	Springiness	Cohesiveness	Chewiness (N)	Resilience
Air	3.41±0.25^{a}	0.034±0.003^{a}	0.85±0.03^{a}	0.57±0.01^{a}	2.05±0.07^{a}	0.46±0.02^{a}
MW (70 W)	3.58±0.16^{a}	0.035±0.003^{a}	0.89±0.03^{ab}	0.55±0.01^{b}	1.60±0.08^{c}	0.45±0.02^{a}
Air-MW (70 W)	3.63±0.14^{a}	0.027±0.003^{b}	0.92±0.04^{b}	0.57±0.01^{a}	1.82±0.07^{b}	0.47±0.03^{a}
MW (210 W)	3.46±0.32^{a}	0.043±0.002^{c}	0.91±0.03^{b}	0.55±0.01^{b}	1.53±0.15^{c}	0.45±0.02^{a}
Air-MW (210W)	4.42±0.35^{b}	0.023±0.003^{b}	0.91±0.05^{b}	0.57±0.01^{a}	2.18±0.17^{a}	0.47±0.02^{a}

^{a,b,c}Within each column, means without a common superscript differ ($P<0.05$)

Fang and Khan (1996) also reported that the higher firmness values for the high temperature dried and ultra-high temperature dried spaghetti and elbow macaroni were attributed to the higher degree of protein denaturation. This is in good agreement with our results. The highest value of acetic acid-insoluble protein was observed in combined hot air-microwave (210 W) dried macaroni samples (Table 3.3). As indicated in Table 3.4, the highest value of hardness or firmness was observed for combined hot air-microwave (210 W) dried macaroni samples. Statistical analysis showed that there was a significant correlation (R=0.905) between hardness of cooked macaroni and acetic acid insoluble protein content of macaroni (Table 3.5).

Adhesiveness is known as the negative force area to pull the compressing plunger away from the sample (Area 3 in Fig. 2.3). As indicated in Table 3.4, the higher adhesiveness value, which is undesirable, was found for macaroni samples dried with microwave drying at 210 W among the samples. The significant decrease in firmness for microwave (210 W) dried macaroni samples was most likely due to partial checking problems that resulted from fast heating. This decrease resulted in higher adhesiveness degree and cooking loss of macaroni samples. The lower adhesiveness values were obtained with both combined hot air-microwave at 70 W and 210 W dried macaroni samples. Statistical analysis revealed that adhesiveness was significantly positively correlated with cooking loss (R=0.930) as shown in Table 3.5.

Cohesiveness is the ratio of the positive force area during the second compression to that during first compression (Area 2/Area 1 in Fig. 2.3). TPA indicated that macaroni samples dried with hot air and combined hot air-microwave (70 W and 210 W) drying were more cohesive than those from only microwave (70 W and 210 W) dried macaroni samples. This difference was significant ($p<0.05$). It may be due to the reduction of protein matrix cohesion appeared as a retracted protein network, unprotected starch granules, fissures and crevices (Grzybowski and Donnelly, 1979). Loss of cohesion caused reduction of mechanical breaking strength (firmness, Figure 3.14) and water absorption (Figure 3.12), decrease in hardness and cohesiveness (Table 3.4) and increased cooking loss (Table 3.3).

Table 3.5 Correlation coefficients between cooking loss, acetic acid-insoluble protein (AAIP) and TPA parameters of macaroni samples

	Hardness	Adhesiveness	Springiness	Cohesiveness	Chewiness	Resilience	Cooking loss
Adhesiveness	-0.762						
Springiness	0.415	-0.234					
Cohesiveness	0.399	-0.779	-0.131				
Chewiness	0.625	-0.769	-0.265	0.883*			
Resilience	0.613	-0.905*	0.269	0.913*	0.777		
Cooking loss	-0.937*	0.930*	-0.267	-0.607	-0.759	-0.766	
AAIP	0.905*	-0.441	0.552	0.106	0.362	0.357	-0.700

* Correlation is significant at the 0.05 level

Another TPA parameter is chewiness. Chewiness was measured as the energy required to masticate macaroni samples. The chewiness values of macaroni samples dried with microwave (70 W and 210 W) drying were lower than microwave finish and hot air dried macaroni samples. These results confirm the results of firmness (hardness) of macaroni dried by hot air-microwave drying process. The lower chewiness values for microwave drying at 70 (1.60 N) and 210 W (1.53 N) are an indication of a weak macaroni structure, i.e., less firm, more adhesive with higher cooking losses. As shown in Table 3.4, there was a significant difference ($P<0.05$) in chewiness values of microwave (70 W and 210 W) dried macaroni samples and the other samples. The chewiness values of macaroni samples dried with different methods were correlated with the cohesiveness values (R=0.883) as shown in Table 3.5.

Springiness (elasticity) (Figure 2.3) is related to the height that the food recovers during the time that elapses between the end of the first bite and the start of the second bite. Combined hot air-microwave (70 W and 210 W) and microwave (210 W) dried macaroni samples were not significantly different (P>0.05). However, there was a significant difference between the other three samples and hot air dried macaroni samples. As shown in Table 3.5, resilience was negatively correlated with adhesiveness while positively correlated with cohesiveness. No significant difference (P>0.05) was detected between the resilience values of the macaroni samples dried by different methods (Table 3.4).

CHAPTER IV

CONCLUSIONS

The study of microwave assisted drying of macaroni revealed the following conclusions:

1. It is possible to dry macaroni by combined hot air-microwave (70 W and 210 W) drying technique.
2. Combined hot air-microwave (70 W and 210 W) drying technique was more efficient than hot air drying for macaroni samples and resulted in time saving to an extent of about 61% and 78%, respectively.
3. The drying rate increased remarkably increasing with power output of the microwave oven.
4. Combined hot air-microwave (210 W) drying increased the drying rate compared to hot air drying alone.
5. The one-parameter diffusion model adequately described all drying data except microwave (210 W) finish drying data.
6. The average brightness index (L*) of macaroni samples dried with combined hot air-microwave (210 W) drying technique had highest value compared to the other drying techniques. On the other hand there was no difference in the average redness index (a*) of samples. The highest value of average yellowness index (b*) was observed in combined hot air-microwave (70 W) drying.
7. Combined hot air-microwave drying had little effect on the rehydration capacity of finished products as compared to the hot air and microwave drying techniques.
8. Cooking loss decreased and cooked weight increased as microwave applied after hot air drying especially at 210 W power level and cooking loss and hardness of cooked macaroni was negatively correlated.
9. Acetic acid-insoluble protein also increased as microwave power increased, i.e., degree of protein denaturation was high as microwave power increased.

10. Firmness of uncooked macaroni samples dried by combined hot air-microwave (70 W and 210 W) was equal or better than that those of dried by hot air method.
11. Significant correlation was observed between acetic acid-insoluble protein and hardness of cooked macaroni.
12. Better firmness was observed in cooked macaroni samples dried by combined hot air-microwave (210 W) method.
13. Finally, hot air-microwave combined drying method gave superior cooking quality. It is a result of an enhancement of the gluten quality along with a molding of starches to create more cohessive and firm product that resists the break down of starches during the boiling process.

REFERENCES

Abecassis, J. (2001). Durum wheat milling: principles and effects on pasta quality. *Cereals Foods World*, **46**, 357-359.

Acquistucci, R. (2000). Influence of Maillard reaction on protein modification and colour development in pasta. Comparison of different drying conditions. *Lebensmittel-Wissenschaft Untersuchung-Technoology*, **33**, 48-52.

Aktan, B. and Khan, K. (1992). Effect of high-temperature drying of pasta on quality parameters and on solubility, gel electrophoresis and reversed-phase high performance liquid chromatography of protein components. *Cereal Chemistry*, **69**, 288-295.

Anese, M., Cristina Nicoli, M., Massini, R. and Lerici, C.R. (1999). Effects of drying processing on the maillard reaction in pasta. *Food Research International*, **32**, 193-199.

Association of Official Analytical Chemists (AOAC), (1990). *Official methods of Analysis of the Association of Official Analytical Chemists* (15th ed.) Washington, DC.

Baroni, D. (1988). Drum wheat: chemistry and technology. In G. Fabriani & C. Lintas (Eds.), *Manufacture of Pasta Products*.

Borelli, G.M., Troccoli, A., Di Fonzo, N. and Fares, C. (1999). Durum wheat lipoxygenase activity and other quality parameters that affect pasta color. *Cereal chemistry*, **76**, 335-340.

Bouraoui, M., Richard, P and Durance, T. (1994). Microwave and convective drying of potato slices. *Journal of Food Process Engineering*, **17**, 353-363.

Bourne, M.C. (1978, July 32). Texture profile analysis. *Food Technology*, pp. 62-66,72.

Braibanti and C.S.P.A. (1980). New developments in pasta drying technology. *Macaroni Journal*, **61**, 48.

Campana, L.E., Sempe, M.N. and Filgueira, R.R. (1993). Physical, chemical and baking properties of wheat dried with microwave energy. *Cereal Chemistry*, **70**, 762-762

D'Egidio, M.G. and Nardi, S. (1996). Pasta and noodle technology. In J.E. Kruger, R.B. Matsuo & J.W. Dick (Eds.), *Textural measurement of cooked spaghetti.*

Dalbon, G., Grivon, D. and Pagani, M.A. (1996). Pasta and noodle technology. In J.E. Kruger, R.B. Matsuo & J.W. Dick (Eds.), *Pasta.*

Datta, A.K. (1990). Heat and mass transfer in the microwave processing of food. *Chemical Engineering Progress*, **86**, 47-53.

De Stefanis, E. and Sgrulletta, D. (1990). Effects of high temperature drying on technological properties of pasta. *Journal of Cereal Science*, **12**, 97-104.

Debbouz, A. (1994).What's new in pasta color. *Pasta Journal*, November/December, 31-32.

Decareau, R.V. (1984). Microwave in food processing. *Food Technology in Australia*, **36**, 81-86.

Decareau, R.V. (1985). *Microwaves in the food processing industry.* New York: Academic Press.

Delcour, J.A., Vansteelandt, J., Hythier, M.C., Abecassis, J., Sindic, M. and Deroanne, C. (2000). Fractionation and reconstitution experiments provide insight into the role of gluten and starch interactions in pasta quality. *Journal of Agriculture and Food Chemistry*, **48**, 3767-3773.

Dexter, J. E., Kilborn, R.H., Morgan, B.C. and Matsuo, R.R. (1983). Grain research laboratory compression tester: instrumental measurement of cooked spaghetti stickiness. *Cereal Chemistry*, **60**, 139-142.

Dexter, J.E. and Matsuo R.R. (1979). The effect of starch on pasta dough rheology and spaghetti cooking quality. *Cereal Chemistry*, **56**, 190-195.

Dexter, J.E. and Matsuo, R.R. (1978). The effect of gluten protein fractions on pasta dough rheology and spaghetti-making quality. *Cereal Chemistry*, **55**, 44-57.

Dexter, J.E., Matsuo, R.R. and Macgregor, A.W. (1985). Relatioship of instrumental assesment of spaghetti cooking quality to the type and the amount of material rinsed from cooked spaghetti. *Journal of Cereal Science*, **3**, 39.

Dexter, J.E., Matsuo, R.R. and Morgan, B.C. (1981). High temperature drying: Effect on spaghetti properties. *Journal of Food Science*, **40**, 1741-1747.

Dick, J.W. and Matsuo, R.R. (1988). Wheat: chemistry and technology. (3rd ed.). In Y. Pomeranz (Eds.), *Durum Wheat and Pasta Products.*

Douglass, J.S. and Matthews, R.H. (1982). Nutrient content of pasta products. *Cereals Foods World*, **27**, 558-561.

Edwards, N.M., Izydorczyk, M.S., Dexter, J.E. and Biliaderis, C.G. (1993). Cooked pasta texture: comparison of dynamic viscoelastic properties to instrumental assesement of firmness. *Cereal Chemistry*, **70**, 122-126.

Fang, K. and Khan, K. (1996). Pasta containing regrinds:Effect of high temperature drying on product quality. *Cereal Chemistry*, **73**, 317-322.

Feillet, P., Ait-Mout, O., Kobrehel, K. and Autran, J.C. (1989). The role of low molecular weight glutenin proteins in the determination of cooking quality of pasta products. A overview. *Cereal Chemistry*, **66**, 26-30.

Feillet, P., Autran, J.C. and Icard-Verniere, C. (2000). Pasta brownness: an assessment. *Journal of Cereal Science*, **32**, 215-233.

Feng, H. and Tang, J. (1998). Microwave finish drying of diced apples in a spouted bed. *Journal of Food Science*, **63**, 679-683.

Fennema, R.O. (1976). *Principles of Food Science*. New York: Marcel Dekker Inc.

Finot, P.A., Deutsch, R. and Bujiard, E. (1981). The extent of the Maillard reaction during the processing of milk. *Progress in Food and Nutrition Science*, **5**, 345-355.

Friedman, M., Levin, C.E. and Noma, A.T. (1984). Factors governing lysinoalanine formation in soy proteins. *Journal of Food Science*, **49**, 1282-1288.

Funebo, T. and Ohlsson, T. (1998). Microwave-assisted air dehydration of apple and mushroom. *Journal of Food Engineering*, **38**, 353-367.

Garcia, R., Leal, F. And Rolz, C. (1988). Drying of bananas using microwave and air ovens. *International Journal of Food Science and Technology*, **23**, 73-80.

Giese, J. (1992a, February 46). Pasta: new twists on an old product. *Food Technology*, pp. 118-126.

Giese, J. (1992b, September 46). Advances in microwave food processing. *Food Technology*, pp. 118-123.

Grant, L.A., Dick, W.J. and Shelton, D.D. (1993). Effects of drying temperature, starch damage, sprouting and additives on spaghetti quality characteristics. *Cereal Chemistry*,**70**, 676-684.

Grzybowski, R.A. and Donnelly, B.J. (1979). Cooking properties of spaghetti. Factors affecting cooking quality. *Journal of Agriculture and Food Chemistry*, **27**, 380-384.

Güler, S., Köksel, H. and Ng, P.K.W. (2002). Effects of industrial pasta drying temperatures on starch properties and pasta quality. *Food Research International*, **35**, 421-427.

Hahn, D.H. (1990). Dough rheology and baked product texture. In H. Faridi & J.M. Faubion (Eds.), *Application of Rheology in the Pasta Industry*.

Hill, A. (1998). The ILSI Europe microwave oven task force. In ILSI Europe, *Microwave Ovens*.

IFT. (1989, January 43). Microwave food processing. A Scientific Status Summary by the IFT Expert Panel on Food Safety & Nutrition. *Food Technology*, pp. 117-124.

Irvine, G.N. (1971). Wheat: chemistry and technology. (2nd). In Y. Pomeranz (Eds.), *Durum Wheat and Pasta Products*.

Laguerre, J.C., Tauzin, V. and Grenier, E. (1999). Hot air and microwave drying of onions: a comparative study. *Drying Technology*, **17**, 1471-1480.

Lewandowicz, G., Jankowski, T. and Fornal, J. (2000). Effect of microwave radiation on physico-chemical properties and structure of cereal starches. *Carbohydrate Polymers*, **42**, 193-199.

Lewicki, P.P. (1998). Some remarks on rehydration of dried foods. *Journal of Food Engineering*, **36**, 81-87.

Malcolmson, L.J. and matsuo, R.R. (1993). Effects of cooking water composition on stickiness and cooking loss of spaghetti. *Cereal Chemistry*, **70**, 272-275.

Maskan, M. (2000). Microwave/air and microwave finish drying of banana. *Journal of Food Engineering*, **44**, 71-78.

Maskan, M. (2001). Drying, shrinkage and rehydration characteristics of kiwifruits during hot air and microwave drying. *Journal of Food Engineering*, **48**, 177-182.

Matsuo, R.R., Bradley, J.W. and Irvine, G.N. (1972). Effect of protein content on the cooking quality of spaghetti. *Cereal Chemistry*, **49**, 707-711.

Matsuo, R.R., Dexter, J.K., Boudreau, A. And Daun, J.K. (1986). The role of lipids in determining spaghetti cooking quality. *Cereal Chemistry*, **63**, 484-489.

Milatovic, Lj. and Mondelli, G. (1991). *Pasta technology today*. Pinerolo, Italy: Chiriotti Publishing.

Mudgett, R.E. (1982, February 36). Electrical properties of foods in microwave processing. *Food Technology*, pp. 109-115.

Mudgett, R.E. (1986, June 40). Microwave properties and heating characteristics of foods. *Food Technology*, pp. 84-93.

Novaro, P., D'Egidio, M.G., Mariani, B.M. and Nardi, S. (1993). Combined effect of protein content and high-temperature drying systems on pasta cooking quality. *Cereal Chemistry*, **70**, 716-719.

Ohlsson, T. (1991).More uniformity in heat from microwave ovens. *Food Technology International*, Europe 1991. Sterling publications, London, 77-81.

Oliver, J.R., Blakeney, A.B. and Allen, H.M. (1993). The colour of flour streams as related to ash and pigment contents. *Journal of Cereal Science*, **17**, 169-182.

Olkku, J. and Rha, C.K. (1978). Gelatinization of starch and wheat flour starch. A review. *Food Chemistry*, **3**, 293-317.

Owusu-Ansah, Y.J. (1991). Advances in microwave drying of foods and food ingredients. *Canadian Institute of Food Science and Technology Journal*, **24**, AT/102-AT/107.

Pagani, M.A., Gallant, D.J., Bouchet, B. and Resmini, P. (1986). Ultrastructure of cooked spaghetti. *Food Microstructure*, **5**, 111-129.

Prabhanjan, D. G., Ramaswamy, H.S. and Raghavan, G.S.V. (1995). Microwave-assisted convective air drying of thin layer carrots. *Journal of Food Engineering*, **25**, 283-293.

Ramaswamy, H. and van de Voort, F.R. (1990). Microwave applications in food processing. *Canadian Institute of Food Science and Technology Journal*, **23**, AT/17-AT/21.

Ren, G. and Chen, F. (1998). Drying of American Ginseng (*Panax quinquefolium*) roots by microwave-hot air combination. *Journal of Food Engineering*, **35**, 433-443.

Resmini, P. and Pagani, M.A. (1983). Ultrastructure studies of pasta. A review. *Food Microstructure*, **2**, 1-12, 98.

Resmini, P., Pagani, M.A. and Pellegrino, L. (1996, August 48). Effect of semolina quality and processing conditions on nonenzymatic browning in dried pasta. *Food Australia*, pp. 362-367.

Resmini, P., Pellegrino, L., Pagani, M.A. and De Noni, I. (1993). Formation of 2-acetyl-3-D-glucopranolylfuran (glucosylisomaltol) from nonenzymatic browning in pasta drying. *Italian Journal of Food Science*, **5**, 341-353.

Richardson, P.S. (1990). Microwave heating: the food technologist's toolkit. Food Technology International Europe London: Sterling Publications, 65-68.

Rosenburg, U. And Bögl. W. (1987, June 41). Microwave thawing, drying and baking in the food industry. *Food Technology*, pp. 85-89.

Saldamlı, İ. (1998). *Gıda Kimyası*. Hacettepe Üniversitesi Yayınları.

Schiffmann, R.F. (1986, June 40). Food product development for microwave processing. *Food Technology*, pp. 94-98.

Sensidoni, A., Peressini, D. and Pollini, C.M. (1999). Study of the Maillard reaction in model systems under conditions related to the industrial process of pasta thermal VHT treatment. *Journal of the Science of Food and Agriculture*, **79**, 317-322.

Sharma, G.P. and Parasad, S. (2001). Drying of garlic (*Allium sativum*) cloves by microwave-hot air combination. *Journal of Food Engineering*, 50, 99-105.

Smewing, J. (1997). Analyzing the texture of pasta for quality control. *Cereal Foods World*, **42**, 8-12.

Steffe, J. F. (1992). *Rheological Methods in Food Process Engineering*. (2nd ed.). USA: Freeman Press.

Svenson, G. (1987, October 156). Microwave systems save time, energy. *Prepared Foods*, pp. 86-90.

Troccoli, A., Borelli, G.M., De Vita, P., Fares, C. and Di Fonzo, N. (2000). Durum wheat quality: a multidisciplinary concept. *Journal of Cereal Science*, **32**, 99-113.

Vansteelandt, J. and Delcour, J.A. (1998). Physical behavior of Durum Wheat Starch (*Triticum durum*) during industrial pasta processing. *Journal of Agriculture and Food Chemistry*, **46**, 2499-2503.

Walde, S.G., Balaswamy, V.V. and Rao, D.G. (2002). Microwave drying and grinding characteristics of wheat (*Triticum aestivum*). *Journal of Food Engineering*, **55**, 271-276.

Zweifel, C., Conde-Petit, B. and Escher, F. (2000). Thermal modifications of starch during high-temperature drying of pasta. *Cereal Chemistry*, 77, 645-651.

APPENDICES

Table A1 Drying curves data of macaroni samples dried by different drying methods

Time[a]	Exp. M[a]	Pred. M[a]	Time[b]	Exp. M[b]	Pred. M[b]	Time[c]	Exp. M[c]	Pred. M[c]	Time[d]	Exp. M[d]	Pred. M[d]	Time[e]	Exp. M[e]	Pred.M[e]
0.00	0.497	0.515	0.00	0.497	0.498	0.00	0.497	0.509	0.00	0.497	0.497	0.00	0.497	0.498
6.00	0.452	0.452	15.00	0.375	0.375	6.00	0.452	0.455	15.00	0.283	0.280	6.00	0.452	0.458
9.00	0.432	0.427	30.00	0.306	0.302	9.00	0.432	0.432	30.00	0.186	0.190	9.00	0.432	0.439
15.16	0.405	0.385	45.00	0.254	0.254	15.16	0.405	0.392	45.00	0.140	0.141	15.16	0.405	0.402
21.32	0.379	0.353	60.00	0.216	0.219	21.32	0.379	0.358				21.32	0.379	0.368
27.48	0.347	0.327	75.00	0.190	0.193	27.48	0.347	0.329				27.48	0.347	0.336
33.64	0.334	0.306	90.00	0.171	0.173	33.64	0.334	0.304				33.64	0.334	0.305
39.80	0.257	0.288	105.00	0.157	0.157	39.80	0.257	0.283				39.80	0.257	0.277
45.96	0.228	0.274	120.00	0.146	0.144	45.96	0.228	0.264				45.96	0.228	0.250
61.96	0.207	0.244	135.00	0.136	0.133	55.96	0.224	0.238				55.96	0.210	0.210
109.29	0.200	0.195				65.96	0.207	0.217				65.96	0.164	0.173
156.62	0.177	0.171				75.96	0.192	0.199				75.96	0.137	0.139
203.95	0.165	0.156				85.96	0.180	0.183						
251.28	0.150	0.146				95.96	0.170	0.170						
298.61	0.144	0.139				105.96	0.163	0.158						
345.94	0.136	0.134				115.96	0.157	0.147						
						125.96	0.144	0.138						
						135.96	0.138	0.130						

[a] hot air drying; [b] microwave drying at 70 W; [c] combined hot air-microwave at 70 W; [d] microwave drying at 210 W; [e] combined hot air-microwave at 210 W

Experimental, Exp; Predicted, Pred.

Table A2 Drying rate curves data of macaroni samples dried by different drying methods

M[a]	R[a]	M[b]	R[b]	M[c]	R[c]	M[d]	R[d]	M[e]	R[e]
0.497	0.012	0.497	0.011	0.497	5.525e-3	0.497	0.025	0.497	5.525e-3
0.452	8.928e-3	0.375	6.100e-3	0.452	5.524e-3	0.283	8.460e-3	0.452	5.524e-3
0.432	7.719e-3	0.306	3.881e-3	0.432	5.524e-3	0.186	4.215e-3	0.432	5.524e-3
0.405	5.897e-3	0.254	2.685e-3	0.405	5.523e-3	0.140	2.517e-3	0.405	5.523e-3
0.379	4.652e-3	0.216	1.967e-3	0.379	5.523e-3			0.379	5.523e-3
0.347	3.763e-3	0.190	1.503e-3	0.347	5.523e-3			0.347	5.523e-3
0.334	3.106e-3	0.171	1.186e-3	0.334	5.522e-3			0.334	5.522e-3
0.257	2.608e-3	0.157	9.591e-4	0.257	5.522e-3			0.257	5.522e-3
0.228	2.220e-3	0.146	7.918e-4	0.228	5.521e-3			0.228	5.521e-3
0.207	1.540e-3	0.136	6.647e-4	0.224	1.753e-3			0.210	4.766e-3
0.200	6.895e-4			0.207	1.494e-3			0.164	3.604e-3
0.177	3.893e-4			0.192	1.289e-3			0.137	2.821e-3
0.165	2.497e-4			0.180	1.123e-3				
0.150	1.736e-4			0.170	9.873e-4				
0.144	1.277e-4			0.163	8.748e-4				
0.136	9.786e-5			0.157	7.804e-4				
				0.144	7.006e-4				
				0.138	6.324e-4				

[a]hot air drying; [b]microwave drying at 70 W; [c]combined hot air-microwave at 70 W; [d]microwave drying at 210 W; [e]combined hot air-microwave at 210 W

Table A3 Moisture ratio vs time data with the predicted data through diffusion model for different drying techniques

Time[a]	Exp.MR[a]	Pred.MR[a]	Time[b]	Exp.MR[b]	Pred.MR[b]	Time[c]	Exp.MR[c]	Pred.MR[c]	Time[d]	Exp.MR[d]	Pred.MR[d]	Time[e]	Exp.MR[e]	Pred.MR[e]
0.00	1.000	1.000	0.00	1.000	1.000	0.00	1.000	1.000	0.00	1.000	1.000	0.00	1.000	1.000
6.00	0.875	0.876	15.00	0.663	0.679	6.00	0.875	0.867	15.00	0.443	0.430	6.00	0.875	0.859
9.00	0.820	0.820	30.00	0.470	0.462	9.00	0.819	0.808	30.00	0.188	0.185	9.00	0.819	0.796
15.16	0.745	0.716	45.00	0.327	0.314	15.16	0.744	0.698	45.00	0.069	0.079	15.16	0.744	0.681
21.32	0.673	0.626	60.00	0.222	0.213	21.32	0.672	0.603				21.32	0.672	0.583
27.48	0.584	0.546	75.00	0.150	0.145	27.48	0.583	0.521				27.48	0.583	0.499
33.64	0.548	0.477	90.00	0.097	0.098	33.64	0.546	0.451				33.64	0.547	0.427
39.80	0.335	0.417	105.00	0.057	0.067	39.80	0.332	0.389				39.80	0.333	0.365
45.96	0.255	0.364	120.00	0.026	0.045	45.96	0.252	0.336				45.96	0.253	0.313
61.96	0.197	0.256	135.00	0.000	0.031	55.96	0.240	0.265				55.96	0.202	0.243
109.29	0.177	0.090				65.96	0.193	0.209				65.96	0.075	0.188
156.62	0.114	0.032				75.96	0.151	0.165				75.96	0.000	0.146
203.95	0.080	0.011				85.96	0.118	0.130						
251.28	0.039	3.982e-3				95.96	0.090	0.103						
298.61	0.022	1.406e-3				105.96	0.071	0.081						
345.94	0.000	4.966e-4				115.96	0.054	0.064						
						125.96	0.018	0.051						
						135.96	0.000	0.040						

[a]hot air drying; [b]microwave drying at 70 W; [c]combined hot air-microwave at 70 W; [d]microwave drying at 210 W; [e]combined hot air-microwave at 210 W

Experimental, Exp; Predicted, Pred

Table A 4 Brightness index data with time of macaroni samples during drying with different methods

Time^a	L*^{a}	Time^b	L*^{b}	Time^c	L*^{c}	Time^d	L*^{d}	Time^e	L*^{e}
0.00	59.163	0.00	59.163	0.00	59.163	0.00	59.163	0.00	59.163
6.00	58.760	15.00	54.400	6.00	58.760	15.00	53.403	6.00	58.760
9.00	57.273	30.00	52.020	9.00	57.273	30.00	52.347	9.00	57.273
15.16	56.047	45.00	51.683	15.16	56.047	45.00	52.493	15.16	56.047
21.32	54.597	60.00	51.793	21.32	54.597			21.32	54.597
27.48	54.000	75.00	51.747	27.48	54.000			27.48	54.000
33.64	52.557	90.00	52.250	33.64	52.557			33.64	52.557
39.80	52.393	105.00	53.060	39.80	52.393			39.80	52.393
45.96	52.017	120.00	53.420	45.96	52.017			45.96	52.017
61.96	51.493	135.00	53.263	55.96	51.907			55.96	54.413
109.29	51.113			65.96	52.503			65.96	55.170
156.62	52.693			75.96	52.920			75.96	53.740
203.95	52.297			85.96	52.820				
251.28	53.260			95.96	52.710				
298.61	53.117			105.96	53.710				
345.94	53.407			115.96	53.413				
				125.96	53.790				
				135.96	54.243				

[a]hot air drying; [b]microwave drying at 70 W; [c]combined hot air-microwave at 70 W; [d]microwave drying at 210 W; [e]combined hot air-microwave at 210 W

Table A 5 Redness index data with time of macaroni samples during drying with different methods

Time[a]	a*[a]	Time[b]	a*[b]	Time[c]	a*[c]	Time[d]	a*[d]	Time[e]	a*[e]
0.00	3.930	0.00	3.930	0.00	3.930	0.00	3.930	0.00	3.930
6.00	4.247	15.00	4.587	6.00	4.247	15.00	4.810	6.00	4.247
9.00	4.397	30.00	5.047	9.00	4.397	30.00	5.220	9.00	4.397
15.16	4.713	45.00	5.093	15.16	4.713	45.00	35.353	15.16	4.713
21.32	4.857	60.00	5.110	21.32	4.857			21.32	4.857
27.48	4.973	75.00	5.313	27.48	4.973			27.48	4.973
33.64	5.047	90.00	5.290	33.64	5.047			33.64	5.047
39.80	5.177	105.00	5.020	39.80	5.177			39.80	5.177
45.96	5.080	120.00	5.113	45.96	5.080			45.96	5.080
61.96	5.470	135.00	5.380	55.96	5.163			55.96	5.157
109.29	5.473			65.96	5.053			65.96	5.353
156.62	5.420			75.96	5.043			75.96	5.630
203.95	5.680			85.96	5.200				
251.28	5.470			95.96	5.080				
298.61	5.880			105.96	5.347				
345.94	5.637			115.96	5.193				
				125.96	5.270				
				135.96	5.447				

[a]hot air drying; [b]microwave drying at 70 W; [c]combined hot air-microwave at 70 W; [d]microwave drying at 210 W; [e]combined hot air-microwave at 210 W

Table A 6 Yellowness index data with time of macaroni samples during drying with different methods

Time^a	b*^{a}	Time^b	b*^{b}	Time^c	b*^{c}	Time^d	b*^{d}	Time^e	b*^{e}
0.00	36.873	0.00	36.873	0.00	36.873	0.00	36.873	0.00	36.873
6.00	37.347	15.00	36.467	6.00	37.347	15.00	35.237	6.00	37.347
9.00	37.037	30.00	36.113	9.00	37.037	30.00	36.013	9.00	37.037
15.16	38.133	45.00	35.777	15.16	38.133	45.00	36.280	15.16	38.133
21.32	37.387	60.00	35.750	21.32	37.387			21.32	37.387
27.48	36.290	75.00	35.953	27.48	36.290			27.48	36.290
33.64	36.147	90.00	36.010	33.64	36.147			33.64	36.147
39.80	36.070	105.00	36.350	39.80	36.070			39.80	36.070
45.96	36.370	120.00	36.760	45.96	36.370			45.96	35.620
61.96	36.280	135.00	36.567	55.96	36.707			55.96	36.117
109.29	36.233			65.96	36.507			65.96	35.890
156.62	36.583			75.96	36.930			75.96	36.487
203.95	36.093			85.96	36.893				
251.28	36.557			95.96	36.750				
298.61	36.133			105.96	37.523				
345.94	36.640			115.96	37.210				
				125.96	37.303				
				135.96	37.650				

[a]hot air drying; [b]microwave drying at 70 W; [c]combined hot air-microwave at 70 W; [d]microwave drying at 210 W; [e]combined hot air-microwave at 210 W

Table A 7 Total color change data with time of macaroni samples during drying with different methods

Time[a]	ΔE[a]	Time[b]	ΔE[b]	Time[c]	ΔE[c]	Time[d]	ΔE[d]	Time[e]	ΔE[e]
0.00	0.00	0.00	0.000	0.00	0.000	0.00	0.000	0.00	0.000
6.00	0.698	15.00	4.826	6.00	0.698	15.00	6.273	6.00	0.698
9.00	1.954	30.00	7.270	9.00	1.954	30.00	7.969	9.00	1.954
15.16	3.452	45.00	7.649	15.16	3.452	45.00	6.846	15.16	3.452
21.32	4.688	60.00	7.548	21.32	4.688			21.32	4.688
27.48	5.300	75.00	7.600	27.48	5.300			27.48	5.300
33.64	6.740	90.00	7.099	33.64	6.740			33.64	6.740
39.80	6.931	105.00	6.222	39.80	6.931			39.80	6.931
45.96	7.256	120.00	5.865	45.96	7.256			45.96	7.256
61.96	7.846	135.00	6.083	55.96	7.363			55.96	5.063
109.29	8.222			65.96	6.764			65.96	4.306
156.62	6.646			75.96	6.342			75.96	5.768
203.95	7.129			85.96	6.469				
251.28	6.109			95.96	6.556				
298.61	6.396			105.96	5.672				
345.94	6.009			115.96	5.897				
				125.96	5.555				
				135.96	5.207				

[a] hot air drying; [b] microwave drying at 70 W; [c] combined hot air-microwave at 70 W; [d] microwave drying at 210 W; [e] combined hot air-microwave at 210 W

Table A 8 Rehydration capacity data with time of macaroni samples dried by different methods

Time(h)	Weight gain[a] (%)	Weight gain[b] (%)	Weight gain[c] (%)	Weight gain[d] (%)	Weight gain[e] (%)
0.00	0.000	0.000	0.000	0.000	0.000
5.00	43.050	40.766	41.086	41.517	42.689
19.00	101.788	90.166	98.398	95.155	99.108
24.00	112.377	103.630	109.150	118.871	107.850
29.00	120.673	110.224	118.560	118.908	120.701
43.00	148.746	143.917	147.172	146.827	148.227
48.00	155.235	149.123	152.641	153.179	155.120
53.00	160.423	153.246	156.862	158.628	161.206
67.00	177.911	172.800	175.490	176.225	179.422
72.00	181.507	176.924	178.945	181.586	183.070
77.00	184.698	178.496	180.287	184.575	187.435
91.00	196.894	192.728	193.829	200.277	201.521
96.00	197.490	193.338	193.538	201.909	203.771
101.00	197.490	193.338	193.538	202.457	203.841

[a] hot air drying; [b] microwave drying at 70 W; [c] combined hot air-microwave at 70 W; [d] microwave drying at 210 W; [e] combined hot air-microwave at 210 W

Table A 9 Firmness values of macaroni samples dried by different methods

Drying method	Firmness (N)
Hot air drying	30.67
Microwave drying at 70 W	24.86
Hot air-microwave drying at 70 W	32.65
Microwave drying at 210 W	24.46
Hot air-microwave drying at 210 W	36.79