DESIGN AND OPERATION OF A MICROWAVE OVEN WITH ROTATING DRUMS

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DESIGN AND OPERATION OF A MICROWAVE OVEN WITH ROTATING DRUMS

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ABSTRACT

DESIGN AND OPERATION OF A MICROWAVE OVEN WITH ROTATING DRUMS

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In this study it was aimed to design and operate a new system with sufficient number of rotating drums since rotation of turntable is incapable of providing uniformity. Effect of new design on final color values and moisture content were also investigated.

Macaroni beads were colored with $CoCl_2$ solution and processed in a domestic microwave oven starting from 11.3±0.10% moisture content and L*= 41.1±0.31 , a*= 8.5±0.27 , b*= 5.3±0.22 color value with turntable and the proposed design. In experiments 40%, 60%, 80% and 100% power levels and 1, 2 and 3 min processing times and 2 different locations were used.

The average color values measured were not affected significantly by the locations studied inside the cavity for both operation types. The changes in color values were found to be significant with altering power level for both operation types. Time also changed average color values for samples processed on turntable and in rotating drums.

The new design lowered the average L* values of the final product and kept the sample from burning. Average a* and b* values were not significantly affected by the operation type.

The uniformity of final product in terms of color distribution was affected significantly by the operation type and the improvement in uniformity calculated quantitatively by means of variances and found out that the new design improved the color uniformity of the final product by 94.7%.

The non-uniformity of the products processed on turntable was significantly changed with power level. Time or location did not affect uniformity significantly for both operation types.

The final average moisture contents of samples processed on turntable were lower than the ones processed with the new design. That is, the rotating drums lowered the moisture removal compared to the turntable.

Keywords: Uniformity, Microwave, $CoCl_2$, Design, Rotating Drums

ÖZ

DÖNER TAMBURLU MİKRODALGA FIRIN
TASARIMI VE ÇALIŞTIRILMASI

Cilvez, Eda
Yüksek Lisans , Gıda Mühendisliği
Tez Yöneticisi: Prof. Dr. Ali Esin

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Bu çalışmada aynı özelliklere sahip/tekdüze son ürün elde edilmesinde dönertablanın yetersiz kalması göz önünde bulundurularak yeterli sayıda döner tamburdan oluşan yeni bir sistemin tasarlanıp çalıştırılması amaçlanmıştır. Yeni tasarımın son renk değerleri ve son nem miktarı üzerine etkisi de incelenmiştir.

Kuskus (Boncuk) makarnaları %0,5 (g/mL) lik $CoCl_2$ çözeltisi ile boyandıktan sonra %11,3±0,10 nem miktarından ve L*= 41,1±0,31 , a*= 8,5±0,27 , b*= 5,3±0,22 renk değerinden başlayarak ev tipi mikrodalga fırında dönertabla üzerinde ve yeni tasarımla ayrı ayrı işlem görmüştür. Deneylerde %40, %60, %80 and %100 mikrodalga güç seviyeleri, 1, 2 and 3 dakika işlem süreleri ve 2 farklı işlem bölgesi kullanılmıştır.

Ortalama renk değerleri işlem bölgesinden önemli ölçüde etkilenmemiştir. Her iki işlem tipinde de mikrodalga güç seviyesi ortalama renk değerlerini istatistiksel olarak değiştirmiştir. İşlem zamanı da her iki işlem tipinde elde edilen renk sonuçları üzerinde etkili bulunmuştur.

Tasarım, işlem gören ürünün yanmasına engel olduğu için L* değerlerini değiştirmiştir. Ortalama a* ve b* değerleri değişen işlem tipinden etkilenmemiştir.

Son ürünün renk bakımından tekdüzeliği işlem tipinden önemli ölçüde etkilenmiş, yeni tasarımın sağlamış olduğu gelişme varyanslar göz önünde bulundurularak sayısal olarak hesaplanmış ve döner tamburların son ürünün tekdüzeliğini %94,7 oranında arttırdığı sonucuna ulaşılmıştır.

Dönertabla üzerinde işlem gören ürünlerin tekdüzeliği değişken güç seviyelerinden istatistiksel olarak etkilenmiştir. İşlem süresi veya işlem bölgesinin tekdüzelik üzerinde etkisi saptanmamıştır.

Ortalama nem miktarının son üründeki değeri, dönertabla üzerinde işlem görmüş ürünlerde, yeni tararımla işlem görenlere göre daha düşük bulunmuştur. Döner tamburlar nem çıkışını kısıtlamışlardır.

Anahtar kelimeler:Tekdüzelik, Mikrodalga, $CoCl_2$, Tasarım, Döner Tamburlar

To my family…

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CHAPTER 1

INRODUCTION

1.1 MICROWAVE HEATING

1.1.1 Microwaves

Microwaves are electromagnetic waves between radio waves and infrared waves on the electromagnetic spectrum with a frequency range of 300 MHz to 300 GHz, having wavelengths 1 mm to 1 m (Khraisheh et al., 1997). Since microwave frequencies are close to radio frequencies and can overlap radar range, the allowed values for public use are 2450 and 915 MHz (Giese, 1992).

The microwaves are created by magnetron which converts electrical energy at low frequencies into an electromagnetic field with centers of positive and negative charge that change direction billions of times each second.

Microwaves can be absorbed, transmitted and reflected. Microwaves can be transmitted through glass, ceramics, plastics, and paper, whereas metals such as aluminum foil and steel reflect microwaves. Metal containers should not be placed in the microwave oven since arcing may occur. (Giese, 1992).

Advantages of microwave oven usage can be listed as less start up time, faster heating, energy efficiency, space savings, precise process control, selective heating and food with high nutritional quality (Decareau & Peterson, 1986). Since microwaves penetrate within a food and do not retain just at the surface, heating occurs more rapidly and efficiently. Microwave processing can also be helpful to control energy costs, since heating takes place only in the food material being processed but not in the surrounding medium (Giese, 1992).

1.1.2 Mechanism of Microwave Heating

There are two mechanisms causing microwave heating of foods; dipolar rotation and ionic interaction (Owusu-Ansah, 1991).

Dipolar rotation mechanism is the basic phenomenon for heating of foods at the microwave frequencies (Schiffmann, 1987). Water molecule, being composed of two positively charged hydrogen atoms and one negatively charged oxygen atom, is the main polar molecule present in food products. When water molecules are exposed to an alternating electrical field, they experience a torque or rotational force attempting to orient them in the direction of the field because of their dipolar nature (Buffler, 1993). Due to the changing electrical field and orientation movements, water molecules start to collide with their neighbors randomly. In doing so, a considerable kinetic energy is extracted from microwave field and heating occurs (Buffler, 1993; Decareau & Peterson, 1986).

Distribution of water inside the food as well as shape of the food has the major effect on the amount of heating and causes differences in the rate of heating (Ohlsson and Bengtsson, 2002). Moreover the state of water in the food product, whether it is free or bound, also affects the microwave absorption and heating. Bound water exhibits much lower microwave absorptivities (Decareau, 1992; Ramaswamy & Van de Voort, 1990).

In ionic interaction mechanism, the dissolved salts present in the food yield charged particles or ions which are accelerated as a result of the force alternating at the rate of microwave frequency. When an accelerating particle collides with an adjacent particle, the temperature of the particle starts to increase due to the effect of impact. As the particle interacts with its neighbors, it transfers agitation and heat to them and when all neighboring particles have had their temperature increased, heat is started to be transferred to the other parts of food material. Since microwave heating of a food material with this mechanism depends on the amount of ions that the microwave can interact with, heating capacity of such a material increases with its conductivity (Buffler, 1993).

1.1.3 Parameters Affecting Microwave Heating

The parameters affecting microwave heating can be divided into two categories as the properties of the oven and the properties of the material being heated in the oven.

- Properties of the oven

The most important properties of microwave oven affecting heating are frequency and power. The frequency affects the penetration depth at which the magnitude of the field has been decreased to 1/e (36.8 %) of its value at the surface of the material. The penetration depth increases with decreasing frequency (Metaxas & Meredith, 1983). Power has effects on heating time, i.e. the higher the power, the faster the heating. According to the process, optimum power levels should be selected. Although faster heating is one of the most attractive features of microwave ovens, high power levels can cause product failures in some processes as in the case of drying (Secmeler, 2003).

The power and cycling were reported to affect the results showed that the microwave flux at the surface and its decay (Chamchong & Datta, 1999a).

- Properties of the material

The most important properties of the material subjected to MW radiation is its dielectric properties, i.e. its dielectric constant and dielectric loss factor. Dielectric constant (ε') is a measure of the ability of a food material to store electrical energy in an electromagnetic field (Mudgett, 1986; Giese, 1992). Dielectric loss factor (ε'') is the ability of a food material to dissipate electrical energy into heat (Mudgett, 1982). Generally, the dielectric properties of a food change with temperature, frequency, bulk density, moisture content and chemical composition of the food (Calay *et al*., 1995).

Moisture content of materials has a great influence on microwave heating since usually the more water present; the higher is the dielectric loss factor. When the dielectric loss factor is high, better microwave heating occurs. In drying operations, the effect of moisture content on dielectric loss factor becomes an advantage since a moisture-leveling effect is observed, i.e. wetter areas absorb more microwave energy than the drier parts. As the moisture level exceeds the critical moisture content, the loss factor increases and the product become more receptive to microwave heating. (Schiffmann, 1986)

Dielectric properties of foods affect the heating uniformity since they affect the microwave penetration. In a microwave thawing study it was found that a ‘shield’ develops from surface thawing and leads to reduced microwave penetration and this ‘shield' develops more readily at higher dielectric loss values. (Chamchong & Datta, 1999b),

The bulk density of a product has an effect on its dielectric properties. As material’s bulk density increases, its dielectric constant and loss factor also increase, often in a linear fashion (Schiffmann, 1986).

The physical geometry, namely the size and shape of the food, is another important parameter affecting microwave heating. The size of the food should be chosen with respect to the penetration depth in order to obtain uniform heating. If the sample size is smaller than the penetration depth, there will be little variation in the rate of heat transfer from the surface to the interior of food and the resulting heating will be uniform (Datta, 1990). Otherwise non-uniform heating and more surface heating take place, and runaway heating can be seen (Schiffmann, 1993).

When the shape of the material is considered, sphere is the ideal shape not only of symmetry but also because energy tends to be focused to give heating at or toward the center of the sphere. Sharp edges and corners should be avoided since they will tend to overheat (Schiffmann, 1986, Datta, 1990). Literature review showed that cylindrical shaped products exhibited pronounced center heating due to the focusing effect, and brick-shaped products showed significant heating along the edges and corners due to the scattering effect. (Vilayannur, Puri, & Anantheswaran, 1998). The more regular is the shape, the more uniform is the heating. Location of the sample in the oven also affects the heating uniformity. (Wappling-Raaholt & Ohlsson, 2000)

Thermal conductivity is a measure of a material's ability to transfer heat in response to a temperature difference. During microwave heating, thermal conductivity has less effect when compared to conventional heating due to the very short heating times (Schiffmann, 1993). However when large particles are taken into consideration, it may have an important role since this time the depth of penetration is not great enough to heat uniformly to the center. Moreover thermal conductivity has a considerable effect when long heating operations are practiced (Schiffmann, 1986).

Specific heat becomes an important parameter when materials having low loss factor, such as fats and oils, are heated by microwaves since it can cause a food material with a low loss factor to heat well in the microwave field. It was shown that for sufficiently large and thick samples, oil with a specific heat 1.67 kJ/kg. K heated up faster than water of the same mass, concluding that the trend is not true in smaller samples (Barringer *et al*., 1994). Controlling specific heat can be effective in formulating microwavable foods (Schiffmann, 1986).

1.1.4 Microwave Drying

Microwave drying differs from conventional drying in terms of mechanism since the internal heat generated by the microwave field creates an internal pressure gradient which pumps water to the surface. This can lead to a much higher rate of moisture loss. (Ni,1997)

One of the food products dried by microwave energy is pasta (Anonymous, 1972a; b; 1974; Fredrickson, 1975; Al-Duri and McIntyre, 1991). Microwave drying takes shorter time when compared to conventional drying. Moreover microwave drying prevents case hardening and cracks due to its mechanism. (Decareau, 1986; Schiffmann, 1986). Microwave energy is generally introduced in the falling rate period of the drying process since its usage is not economical and effective for the food materials having higher moisture content. This depends on the fact that although dielectric constant of water is high and it absorbs microwaves easily, its high heat capacity makes it difficult to raise the temperature for dehydration if the bulk of water is high. (Owusu-Ansah, 1991) Therefore, microwave drying of materials having moisture content about 20% and less is more reasonable and effective.

Microwave drying is generally combined with conventional drying. In combined systems, microwaves have the role of internal heating while the conventional heat source removes surface moisture and produce the desired surface browning or crispness. Pasta dehydration can be named as one of the highly developed commercial application of this technology. (Mugett, 1989)

Non-uniformity during drying was also observed and several methods were investigated. Fluidized bed drying combines both the conventional energy and microwaves and provides mixing by fluidization (Goksu, 2003). In fact, to achieve the uniform treatment of the particulate materials in microwave oven, agitation of material by some means, pneumatic or mechanical, has to be practiced. (Chen et al., 2001)

1.2 NON-UNIFORMITY PROBLEMS in MICROWAVE OVENS

1.2.1 Uneven Heating in Microwave Oven

Microwave ovens heat food volumetrically by electromagnetic radiation and microwave energy was studied by researchers for processes like heating (Dahl, Matthews, & Lund, 1981), drying (Drouzas, Tsami, & Saravacos, 1999; Wang & Xi, 2005), freeze drying (Wang & Shi, 1999), thawing (Taher & Farid, 2001) and looking at final food quality and changes in chemical (Welt & Tong, 1993) and other properties (Kentish, Davidson, Hassan, & Bloore, 2005) of the products due to microwave application. Besides, different methods to measure temperatures during microwave heating altering from the use of thermal cameras (Bengtsson & Lycke, 1969) in the past to magnetic resonance imaging (MRI) (Knoerzer et al., 2006; Nott & Hall, 2005) more recently have been explored.

During the studies performed on microwave applications, non-uniformities in temperature distribution and hot – cold spots developments were observed inside foods (Ohlsson & Risman, 1978; Watanabe, Suzuki, & Sugimoto, 1971, Secmeler). Heating uniformity is affected by different factors such as shape, size, location and dielectric properties of food, microwave power and cycling. (Geedipalli, Rakesh & Datta, 2007)

1.2.2 Methods to Overcome Uneven Heating

• <u>Combination heating :</u>

Combination heating involves heating food with microwaves in combination with another technology such as infrared or hot air. This method is one of the most significant alternatives to achieve uniform temperature distributions in food. The combination of microwaves with other modes of heating was found to be a solution to improve the uniformity of microwave heating and provide better control on moisture transport while increasing the speed of heating (Datta, Geedipalli, & Almeida, 2005).

Combination heating was studied for dehydration processes (drying operations) (Datta, Geedipalli, & Almeida, 2005) and baking (Sumnu, Sahin, & Sevimli, 2005; Keskin, Sumnu & Sahin, 2004).

- Using Variable Frequencies:

With the emergence of variable frequency microwave ovens, it is possible to exploit the frequency dependence of a food's permittivity and/or choice of heating frequency, as a new route to achieve targeted heating. Variable frequency heating procedures were developed to overcome the geometry of a roughly spherical foodstuff dominating the heating pattern when heated in fixed frequency applicators. (Bows, 1999)

- Using Mode Stirrers:

Static microwave applicator designs usually lead to non-uniform electric field patterns with undesirable hot temperature spots, with the heating process being more critical for low thermal conductivity materials. In order to achieve the desired uniformity, mode stirrers have been extensively used since multimode applicators were designed. Mode stirrers are mobile metallic elements that modify the electromagnetic (EM) boundary conditions within the microwave applicator, resulting in a temporal non-stationary electric field pattern over the material, which consequently improves heating uniformity (Chow-Ting-Chan & Reader., 2000; Kashyap & Wyslouzil, 1977; Plaza-Gonzalez, Monzo-Cabrera, Catala-Civera & Sanchez-Hernandez, 2004)

• Moving the Food (Turntable):

The carousel is one such rare addition to a microwave oven which works universally to increase temperature uniformity. As the food rotates, different locations on the food go through different field strengths. Though developed from intuitive reasoning and not from a basic scientific understanding of the process, the carousel still remains the most popular method to increase uniformity of food heating.(Geedipalli, Rakesh and Datta, 2007)

Geedipalli, Rakesh and Datta, 2007 investigated the contribution of turntable to the uniformity and found that the carousel helped in increasing the temperature uniformity of the food by about 40 %. However, they indicated that the carousel did not improve the temperature uniformity across different layers of the food.

1.2.3 Previous Designs for Microwave Ovens

• JP 63184285 A – A Removable Drum For Microwave Ovens

The removable drum design was patented in 1988 in Japan. In this project a single drum with flights inside was placed in the oven cavity instead of a turntable. The drum (the glass container) was fixed/immobile but the shaft where the flights were attached was rotating inside that drum. The rotation of that shaft was maintained by a different mechanism from the one that rotated the turntable. The location of the drum & shaft combination was fixed inside the oven. The effectiveness of this design has not been investigated yet. Figure 1 displays the original drawings of this design.

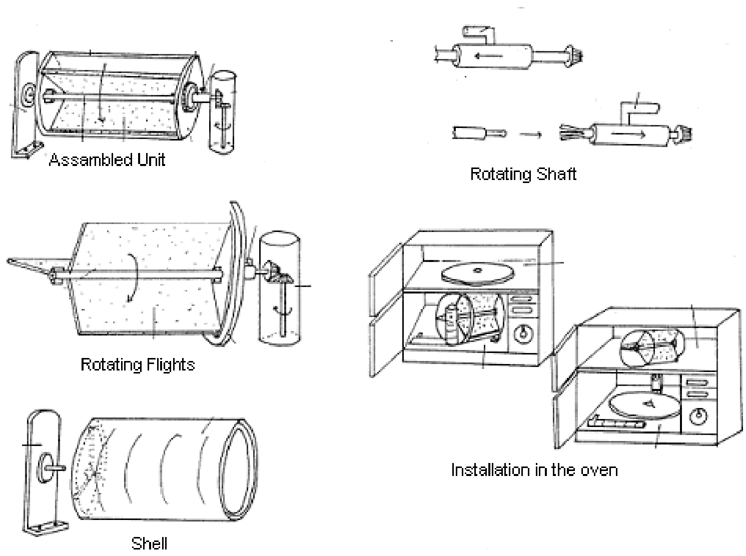

Figure 1 A removable rotary drum for microwave ovens

• <u>CN 201087969 Y</u> – Rotary Microwave Heating Mechanism For Solid Materials

This rotary mechanism was patented in 2007 in China. In this project a large well-insulated rotary drum which had a magnetron in its body was considered. The design was identical to a rotary dryer working with microwaves. The contribution of this design in uniformity has not been investigated. However, microwave assisted rotary dryer was compared with conventional one and it was reported that drying time was shortened significantly (Bertelli & Marsailoi, 2005). The original drawing of the design is given in Fig. 2.

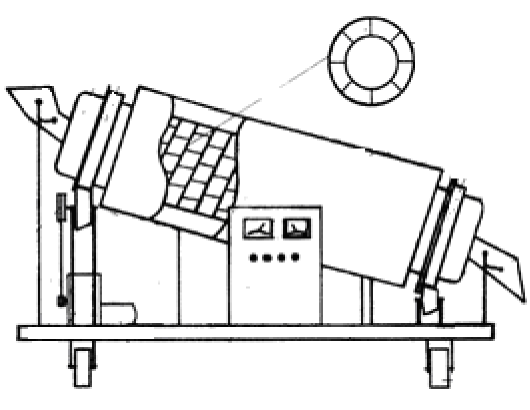

Figure 2 A rotary microwave heating mechanism for solid materials

• DE 10 2005 016179 A1 – A Vertical Stirrer Fixed on a Rotating Shaft For Microwave Ovens

The fixed vertical stirrer was patented in 2006 in Germany. In this project a stirrer similar to a spoon was placed on a shaft and provided mixing during the heating operation in the oven. The original drawing of the design can be seen in Fig. 3.

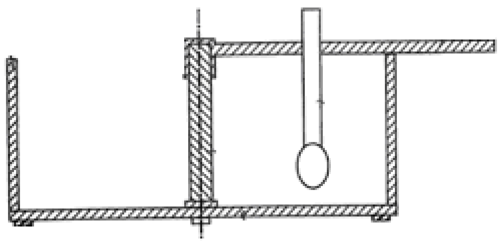

Figure 3 A vertical stirrer fixed on a rotating shaft for microwave ovens

• GB 2 230 409 A – Food Stirrer for Microwave Ovens

The stirrer was patented in 1990 in United Kingdom. In this project impellers/blades were placed on a shaft and mixing in food was maintained by the rotation of that shaft. The drawing of the design is given in Fig. 4.

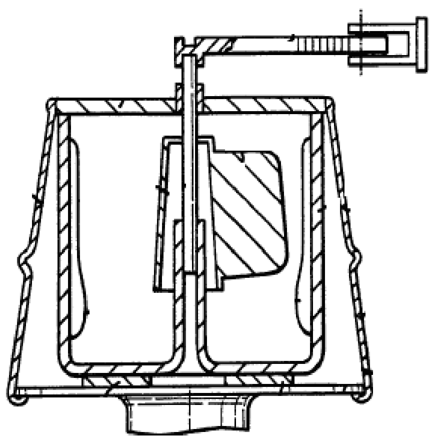

Figure 4 Food stirrer for microwave ovens

• GB 2 322 271 A- Food Stirrer for Microwave Ovens

The food stirrer design was patented in 1998 in United Kingdom. In this project the mixing pedals were placed at the bottom of the shaft as they would be parallel to the floor of the oven. The drawing of the design is given in Fig. 5.

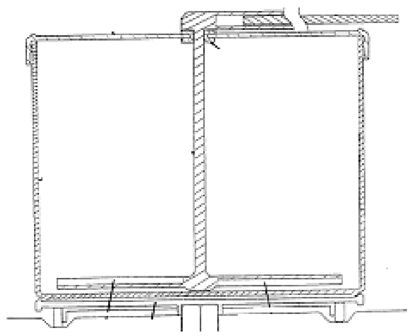

Figure 5 Food stirrer for microwave ovens

• GB 2 434 328 A- Microwave Stirrer

The microwave stirrer was patented in 2007 in United Kingdom. In this project, different from the previous ones, the stirring spoon was not placed on a shaft but on an arm attached to the wall of the oven. The stirring spoon did not rotate itself but the mixing was provided as the food container rotating in the oven cavity. The drawing of the design can be seen in Fig. 6.

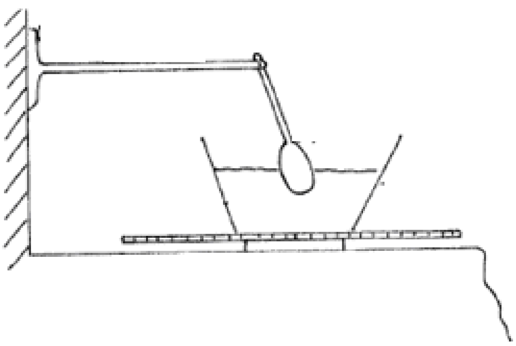

Figure 6 Microwave stirrer

• WO 93/10648- Microwave Strirring Device

The stirring device was patented in 1992. In this project, a stirrer with stirring blades was attached to the oven wall and mixing was provided as the food container rotated over the turntable. The design is given in Fig. 7.

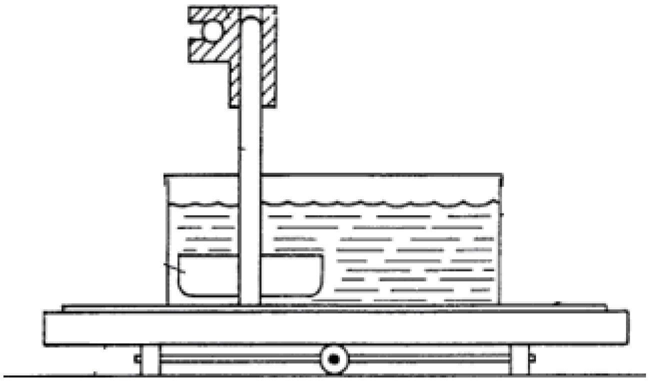

Figure 7 Microwave stirring device

Other designs can be listed as;

• US005902510A- Rotary Microwave Oven For Continuous Heating of Materials

• RU2109232C1- Drum-Type Microwave Drier

• US004087921- Microwave Drying Apparatus

• US20090218337A1- Microwave Oven with Rotary Cooking Apparatus

• WO2008/113338A3- Microwave Vacuum Drying Systems and Method For Drying Lumpy, Powdery, or Granulated Products by Means of Microwaves

1.3 MATHEMATICAL INTERPRETATION OF THE DESIGN

Mass, energy and momentum must be conserved in all systems. The conservation equations can be expressed in a mathematical form as; (Brodkey & Hershey, 1989)

$$\frac{\partial \psi}{\partial t} + (U \bullet \nabla)\psi = \dot{\psi} + (\nabla \bullet \delta \nabla \psi) - \psi(\nabla \bullet U) \tag{1.3.1}$$

During heating operation the property of a sample such as temperature or moisture content is a function of time and dimension, and expressed as;

$$\psi = f(t, 3D) \tag{1.3.2}$$

where t indicates time and D dimension.

When the distribution of a property inside a sample subjected to microwaves in a domestic oven is considered, the parameters affecting the distribution become t, r, Θ and z.

$$\psi = f(t, r, \theta, z) \tag{1.3.3}$$

The turntable (or carousel) in the microwave oven provides a motion in Θ-direction so the property becomes a function of t, r and z, and is shown as;

$$\psi = f(t, r, z) \tag{1.3.4}$$

However, when the sample inside the oven is provided to move in three directions during the operation as in the case of present study, then the property will only be a function of time.

$$\psi = f(t) \tag{1.3.5}$$

1.4 OBJECTIVES OF THE STUDY

As discussed above, non-uniform energy distribution and hence uneven treatment problems of microwave oven restrict its usage to limited processes. Further, absence of mixing of the materials during the treatment results in undesired final products with local burns, hot and cold spots inside the material.

To overcome these problems, in this study, we aimed to design a new system with sufficient number of rotating drums as rotation of turntable is incapable of providing uniformity.

Rotary drums were designed to maintain mixing inside the processed material while the drums were moving inside the cavity with the same mechanism which already rotated the turntable.

In this work the contribution of the rotary drums in uniformity at different power levels and for different operation times was investigated. Drying of macaroni beads using $CoCl_2$ as thermal marker visualized the uniformity achieved. The changing color of the dried macaroni beads were measured and analyzed statistically to detect the differences in distribution. The effect of new design on the amount of moisture vaporized during operation was also examined.

CHAPTER 2

MATERIALS AND METHODS

2.1 MATERIALS

2.1.1 Macaroni Beads

Macaroni beads (Selva, Turkey) having an average diameter of 3.54±0.03 mm, an average thickness of 2.23±0.07 mm, an average moisture content of 11% on wet basis and an average weight of 0.02g/bead were obtained from a local market. Macaroni beads were similar to short cylinder.

2.1.2 Cobalt Chloride Solution

A cobalt chloride solution was prepared by dissolving 50 g of cobalt chloride crystals in 1 liter of distilled water. The solution was stirred until a uniform red color is observed. Cobalt chloride has a red color when hydrated and it turns blue as it dries.

2.1.3 Microwave Oven

A home type microwave oven (Vestel MD-GDX23A) operating at 2450 MHz with a 310mm turntable (5 rev/min) was used in experiments. The oven has 5 power levels; 20%, 40%, 60% 80% and 100%. The value of power levels were determined by IMPI 2-L test (Buffer,1993). The procedure for the IMPI 2-L test is given in Appendix A.

2.1.4 Balance

A portable digital scale (KERN (EW) EW-1500-2M) was used for weight measurement in experiments.

2.1.5 Oven

An oven (ST-055, Şimşek Laborateknik) having a temperature range of 0-300 °C was used for moisture and dry weight determinations.

2.1.6 Thermometer

An infrared thermometer (Testo 845,Lenzkirch) having an operating range of -35-+950 °C was used in experiments. The thermometer was also capable of measuring the surface humidity in an operating temperature range of -20-+50 °C with a measuring range of 0-100% RH.

2.1.6 Color Reader

A color reader (Konica Minolta CR-10, Japan) operating in CIE – L* a* b* system was used in color measurements.

2.2 MECHANICAL DESIGN

2.2.1 The Scope of the Design

The mechanical design was based on the use of rotational motion coming from the rotator motor of the microwave oven. By the help of this idea, rotational motion was converted to both rotational and translation motion. In order to achieve this conversion, a transmission mechanism having 4 different parts was designed. The assembly of the parts and sectional views were given in Figures 8 and 9, respectively. These parts were the shaft, arm, drum and stopper numbered as 1, 2, 3, and 4 respectively (Figure 10).

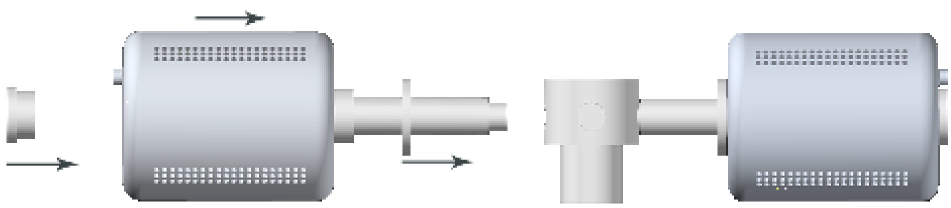

Figure 8 The Assembly

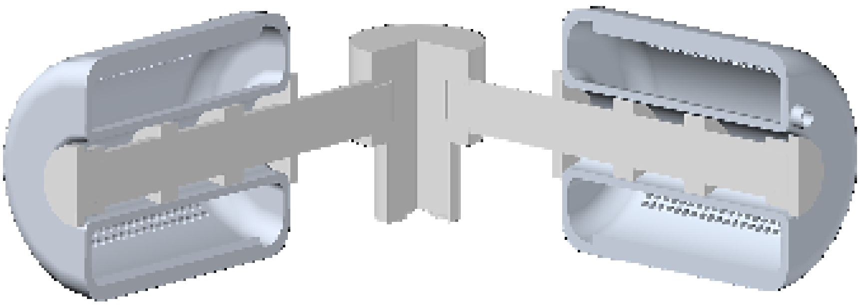

Figure 9 The Section view

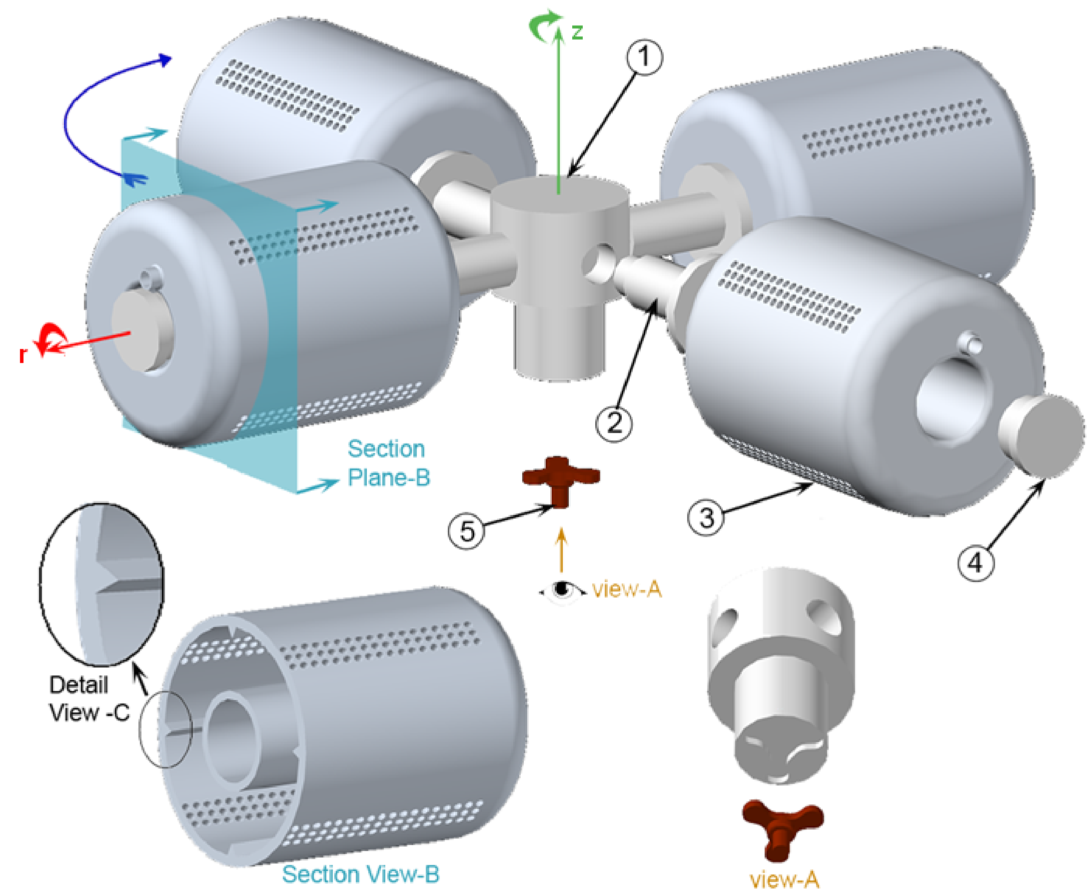

Figure 10 The Mechanical Design

2.2.2 The Working Principles of the Design

The shaft was connected to the oven's motor with the connector piece, which is item No.5 in Figure 10. This connector already exists in the oven in order to rotate the turntable. Coupling the shaft and the connector was done by having the bottom side of the shaft machined to fit onto the spur gears on the connector. View-A in Figure 10 shows the connection interface.

As the motor rotates the shaft around z axis, the drums roll on the circular path indicated with the blue arrow and as a result, the rotation about r axis occurs. This rotation together with the flights in the drums generates mixing action.

2.2.3 The Design of the Parts

The Shaft:

The Shaft (1 in Figure 10) was produced from PTFE (Polytetraflouroethylene), which is non-reactive to microwaves due to its molecular stability. PTFE has a high melting point and excellent dielectric properties, which make it an appropriate material for insulation of cables and manufacturing goods for microwave systems.

The shaft was designed to transmit rotation from horizontal to vertical direction. The bottom surface of the shaft was designed to fit the connector (number 5 in Figure 10) which was already present in the oven in order to provide the rotation of turntable. On the lateral surface of the shaft close to the top, four holes for the assembly of the four arms were drilled. The distance between the base of the oven and the center of the holes had to be equal to the outer radius of the rotating drums for them to roll. The shaft has two sections in terms of diameters. In the lower section, the diameter was specified according to the dimensions of the connector such that it could totally fit the shaft. In the above section the diameter was selected according to the depth of the holes for the arms which fits inside these holes. A 3-D view and dimensions (in mm) of the shaft are given in Figure 11.

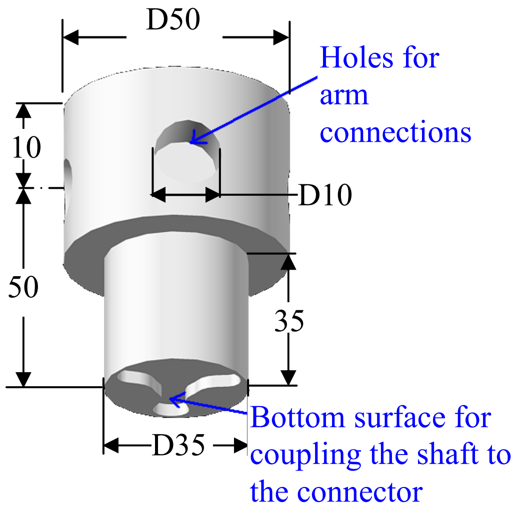

Figure 11 The Shaft

The Arm:

The Arms (2 in Figure 9) were also produced from PTFE. These were designed to carry the rotating drums along the desired path during operation in the microwave oven. They were connected to the shaft with shrink-fit joining method from one end as shown in Figures 8 and 10.

On the arm, the rotating drums were held in place by the barrier discs and the stopper fitted to the outer end of the arms. Besides, in order to gain smooth rotation of drums on the arms, bearings were added. The bearings were designed according to the inner diameter of drums such that there would be a small clearance which prevented the drums from vibratory motion through the rotation path. A 3-D view and dimensions (in mm) of the arm are given in Figure 12.

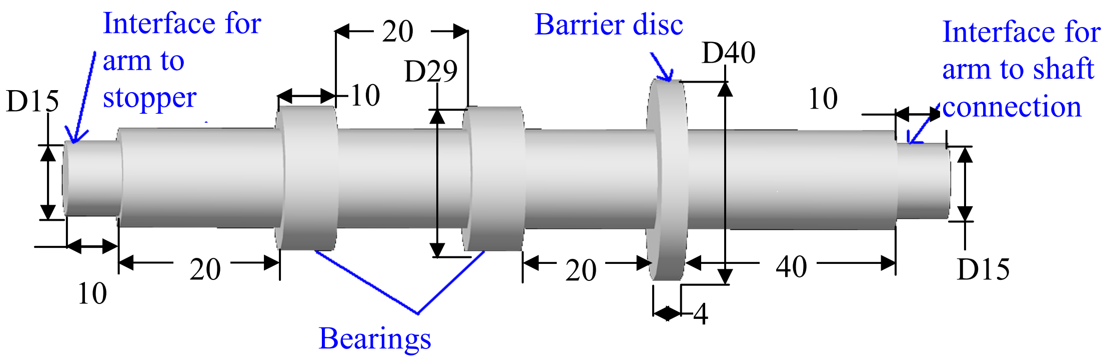

Figure 12 The Arm

The Rotating Drums:

Drums were manufactured from borosilicate glass through which microwave rays can pass. In the drums there were four flights (See Detail View-C) extending along the inner lateral surface to lift up the material, solid or liquid, and drop back and hence stir the food while process is being executed. As a result of this mixing operation, uniformity within the product is enhanced. The lateral surfaces of the drums were perforated in order to maintain the exit of the vapor. The dimensions of the drums were determined according to the base area of the oven such that the four drums could rotate without touching each other. A 3-D view and dimensions (in mm) of the drums are given in Figure 13.

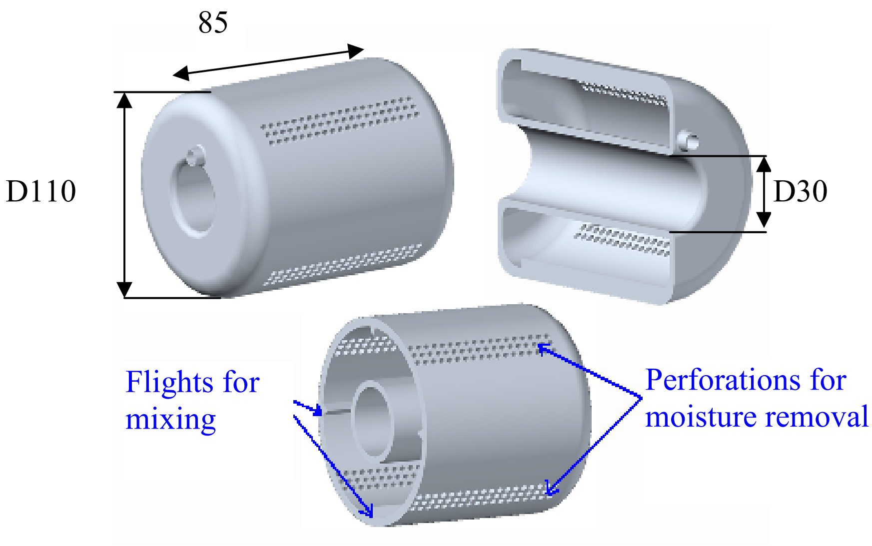

Figure 13 The Rotating Drums

The Stopper:

Stoppers were produced from PTFE to keep the rotating drums in place on the arms, and hence to cope with the effect of centrifugal force acting on the drums during rotation. A 3-D view and dimensions (in mm) of the stopper are given in Figure 14.

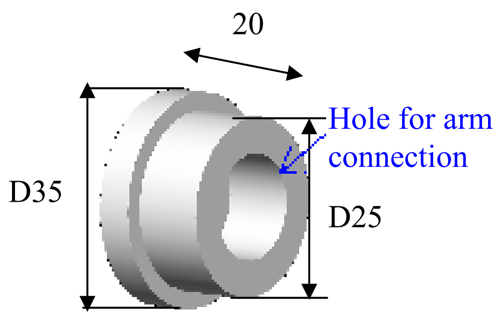

Figure 14 The Stopper

2.3 METHODS

2.3.1 Determination of Moisture Content of Macaroni Beads

For moisture measurement, standard gravimetric method was used. For this purpose 15 g of macaroni beads were weighed and placed in a dried petri dish as a single layer. The petri dish was placed in an oven at 100 °C ± 2°C and held there until constant weight was attained. Moisture content of macaroni beads were calculated from the dry weight.

2.3.2 Coloring of Macaroni Beads

80 g of macaroni beads were weighed and placed in a dried pyrex container as a single layer. The beads were soaked (wetted) in 40 mL of cobalt chloride solution and left in 27 ± 1.0% RH environment at 22°C ±1.0°C for 48 hrs in order to attain the desired color (L*= 41.1±0.31 , a*= 8.5±0.27 , b*= 5.3±0.22) and moisture content (11.3 ±0.10 %).

2.3.3 Experiments Performed on Turntable

Two petri dishes, 120mm diameters, were used in experiments and 15 g of colored macaroni beads were placed in each petri dish as a single layer. The petri dishes (A & B) were located on the turntable as shown in Figure 15.

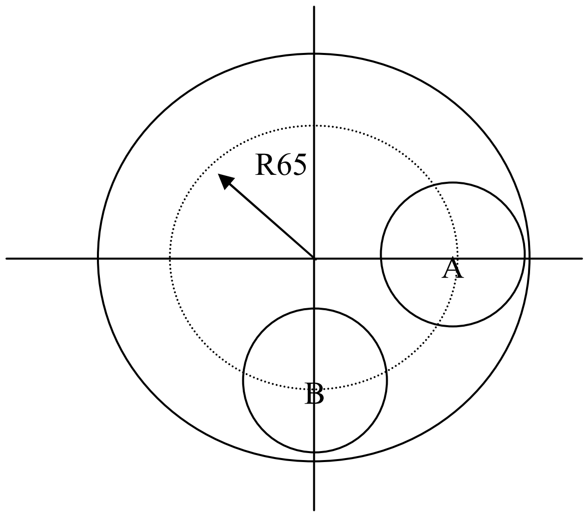

Figure 15 Location of the petri dishes in experiments with the turntable

The colored macaroni beads were processed in the microwave oven at 40, 60, 80, and 100 % power levels for 1, 2, and 3 minutes at two locations (A and B) with two replicates. The processed macaroni beads were immediately taken out from the oven and weighed. The color values of the samples were measured at 5 different locations (C, U, Lo, Le, and R) on the petri dish (Fig. 16).

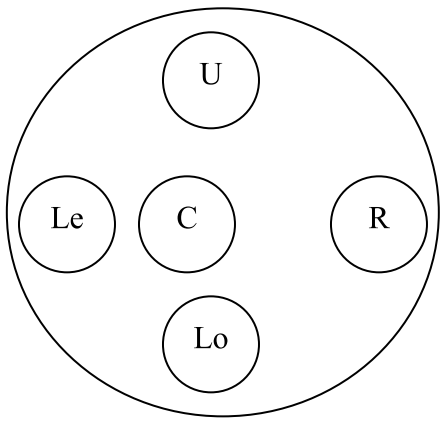

Figure 16 Location of color data points on the petri dish

2.3.3 Experiments Performed with Rotating Drums

Two drums were filled with 15 g of colored macaroni beads separately and placed on the two arms which were on the same positions with the petri dishes. The macaroni beads were then processed in the microwave oven at 40, 60, 80, and 100 % power levels for 1, 2, and 3 minutes. The processed macaroni beads were immediately discharged from the drums to petri dishes and weighed. Color values of the samples were measured at 5 different locations (C, U, Lo, Le, and R) on the petri dish.

2.3.4 Statistical Analysis

Minitab 13 (Minitab 13.20) was used for statistical analysis. Analysis of Variance (ANOVA) was used for the analysis of measured color and average moisture content values (α=0.05). The effects of design, power, time and location on the color distribution (uniformity) were determined by comparing and analyzing variances calculated statistically.

CHAPTER 3

RESULTS AND DISCUSSION

To assess the uniformity and effectiveness of treatments, color values of the product and the achieved drying were analyzed.

3.1 COLOR ANALYSIS

Color values were measured in CIE system. The L* value changes between 0 (black) and 100 (white) and indicates a lightness, positive a* value indicates red-purple whereas negative a* value shows bluish-green color. Yellow and blue colors are indicated by positive and negative b* values, respectively.

The color values of each sample were measured at 5 different data points (C, U, Lo, Le, and R) with two replications. The arithmetical mean of L*, a*, and b* values obtained at 5 different data points were calculated and an average color value was obtained for each sample as given in Tables 1 and 2.

The $CoCl_2$ solution has red color at room temperature however it becomes blue when heated (The Merck Index, 1960). This is mainly due to moisture loss. Therefore macaroni beads wetted with 0.05% $CoCl_2$ solution and containing less than 20% moisture changed color from red-pink to blue when processed in the microwave oven owing to drying.

Table 1 Average color L*, a* and b* values for samples processed on turntable at different conditions

	L* value Time(min)			a* value Time(min)			b* value Time(min)		
	1	2	3	1	2	3	1	2	3
Location A									
40% power	42.1±2.55	40.7±2.50	39.3±2.77	2.2±3.46	-2.4±3.55	-3.2±3.30	-0.6±4.00	-6.3±4.08	-6.6±3.98
60% power	40.9±2.24	38.9±2.98	39.1±1.93	-1.9±3.75	-4.4±4.59	-5.8±3.80	-5.5±5.85	-8.3±4.80	-8.8±2.98
80% power	41.2±3.30	40.7±2.88	39.7±2.39	-3.6±4.58	-7.5±3.95	-7.4±3.43	-8.0±6.33	-9.1±3.97	-6.0±4.59
100% power	40.7±3.15	40.5±1.42	34.2±4.93	-4.0±3.63	-8.7±2.95	-7.6±3.26	-7.7±4.36	-5.4±5.89	-1.9±8.21
Location B									
40% power	41.5±2.24	39.7±2.10	38.4±2.94	1.2±2.52	-1.9±2.64	-2.6±2.89	-2.0±3.43	-5.5±3.27	-6.5±3.26
60% power	40.2±2.65	39.7±3.13	40.9±2.98	-1.4±3.53	-4.7±4.02	-6.7±4.03	-5.1±4.48	-8.9±4.78	-7.0±4.26
80% power	41.2±4.05	42.0±1.08	38.7±1.58	-3.9±4.40	-7.4±4.08	-6.9±4.37	-8.0±5.88	-9.5±3.40	-7.8±4.64
100% power	39.6±4.14	41.3±2.32	34.2±4.69	-3.6±3.72	-8.1±3.12	-7.8±3.36	-7.0±4.83	-5.0±6.70	-1.7±8.01

Table 2 Average color L*, a* and b* values for samples processed in rotating drums at different conditions

	L* value Time (min)			a* value Time (min)			b* value Time (min)		
	1	2	3	1	2	3	1	2	3
Location A									
40% power	40.2±1.19	38.3±0.95	37.2±0.40	2.4±0.37	-0.4±0.41	-1.9±0.18	-0.7±0.43	-3.9±0.51	-6.9±0.16
60% power	37.8±0.63	36.0±1.73	36.6±1.65	0.3±0.25	-3.5±0.08	-4.5±0.39	-3.6±0.20	-8.1±0.66	-8.7±0.78
80% power	36.9±0.96	37.5±1.09	38.5±1.06	-2.2±0.50	-6.0±0.38	6.1±0.54	-6.7±0.97	-9.4±0.74	-9.1±0.67
100% power	37.3±1.17	37.0±0.50	37.5±1.35	-3.9±0.27	-6.5±0.24	-9.6±0.35	-9.0±0.42	-9.2±0.67	-9.6±0.81
Location B									
40% power	42.2±1.33	40.1±0.77	38.3±0.34	3.3±0.42	0.1±0.42	-1.4±0.22	0.5±0.19	-2.9±0.33	-5.6±0.14
60% power	37.7±0.84	37.0±1.02	35.9±0.96	0.0±0.18	-3.3±0.41	-4.8±0.45	-3.9±0.24	-7.2±0.88	-8.4±0.91
80% power	36.4±0.77	37.4±0.81	38.9±0.52	-2.3±0.42	6.4±0.41	-7.4±0.57	-6.2±0.66	-9.2±0.67	-9.8±0.48
100% power	36.4±1.31	37.8±0.29	37.5±1.11	-3.7±0.32	-6.7±0.33	-9.4±0.58	-8.9±0.40	-9.1±0.62	-10.0±1.20

3.1.1 Effect of Power Level on Average Color Values

The effect of power on average color values were statistically analyzed for the samples processed in petri dishes on turntable and rotating drums in the new design separately.

A. Analysis of the Experiments Performed on the Turntable

The petri dishes located in A and B positions on turntable processed at 40, 60, 80 and 100% power levels for 1, 2 and 3 minutes. Five measurements from 5 data points were performed for each sample and average of two replications for L*, a* and b* values were given in Table 1.

The color measurements indicated statistically significant changes of L* value with altering power ($p \leq 0.05$). The change of L* value can be attributed to burning occurred at higher power levels. In Fig. 18 the power dependency of L* value of colored macaroni beads is shown.

As long as the macaroni beads dried well without burning, it took a light blue color which resulted in a higher L* value. The increase in L* value measured at 80% power level compared to 60% power level can be associated with this fact. Further increase in power level (100%) decreased L* value due to local burning taking place in the petri dish (Fig. 17 & 18).

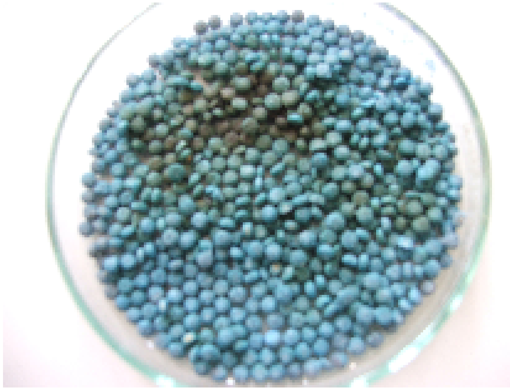

Figure 17 Sample processed at 100% power level and 3 min

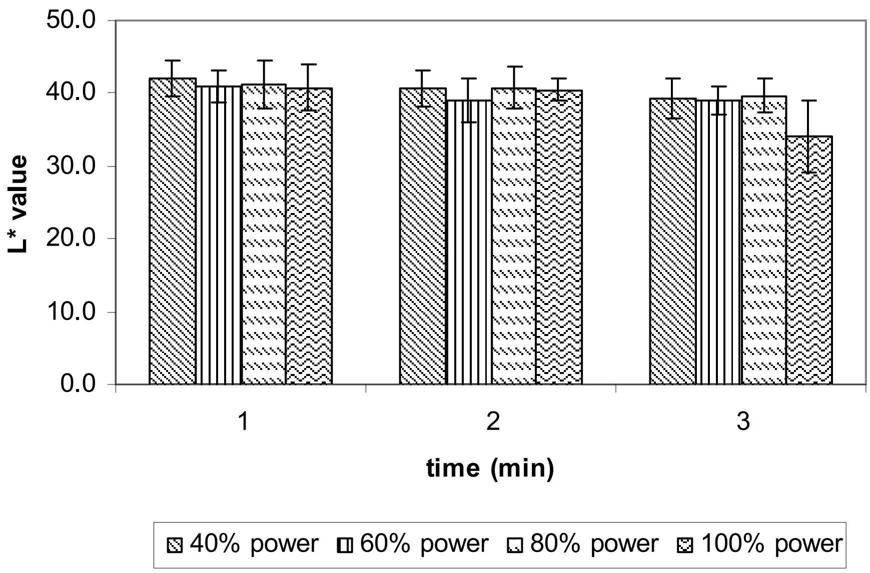

Figure 18 Average L* values of the samples processed at different power levels at location A on the turntable

Significant color differences were observed ($p \leq 0.05$) for a* values with altering power levels. Secmeler (2003) has reported that high power levels resulted in higher moisture loss in microwave operations causing a decrease in a* value. Experimental results showed that the change in the color of the beads from red to blue with decreasing moisture content was represented by a* value. In Figure 19, the variation of the average a* values is summarized. Average a* value decreased with increasing power level for all the time periods.

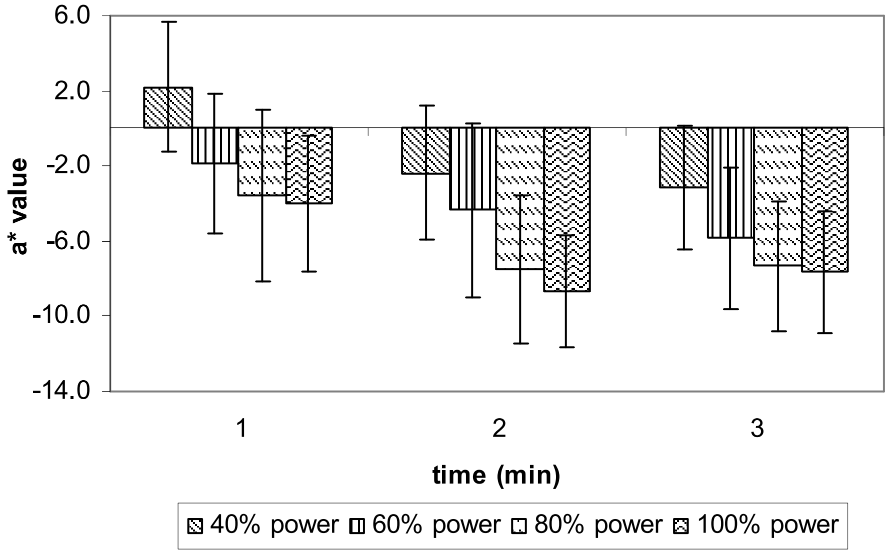

Figure 19 Average a* values of the samples processed at different power levels on location B on the turntable

As the macaroni sample loses moisture it turns blue due to the properties of $CoCl_2$ as mentioned before. Blue color is represented by negative b* value in CIE system.

The power level was found to affect the b* value significantly ($p \leq 0.05$). Increasing power level caused a decrease in the b* value similar to the case in the a* value. A decrease in the b* values was observed at the 40% power level for all of the time periods, whereas further increase in power level resulted in different trends of b* values (Fig.20). Increase in the b* values with increasing power levels can be attributed to burning sections occurred during microwave operation.

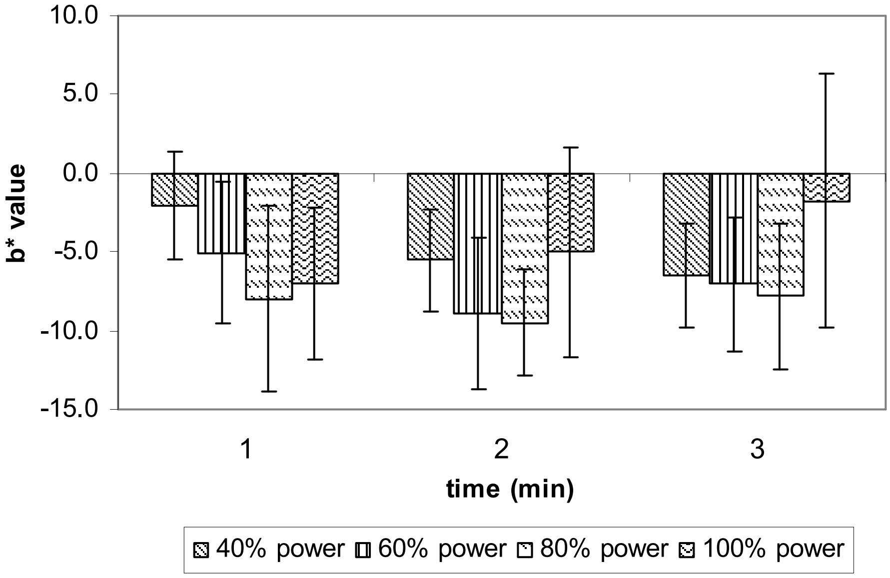

Figure 20 Average b* values of the samples processed at different power levels on location B on the turntable

B. Analysis of the Experiments Performed with the Rotating Drums

After the samples were processed, the macaroni beads were discharged from rotating drums to petri dishes and color measurements were performed. The average color values are given in Table 2. The samples placed in the rotating drums mixed during the process by flights inside the drums. The mixing operation avoided the sample from burning at higher power levels compared to the case in the experiments performed on the turntable.

L* values changed significantly with power levels ($p \leq 0.05$). However it is not possible to comment on the existence of a general trend for the variations in L* values as the trend observed with the turntable experiments. When the power level shifted from 40% to 60%, a slight decrease in the average L* value was observed as can be seen from Figure 21. For higher power levels L* values showed different trends at different processing times. The trend of L* values at higher power levels compared to 40 and 60% was attributed to the humidity increased in the drums at these power levels. The lateral surfaces of the drums were designed with perforations to remove the moisture inside them. However at higher power levels, moisture loss of drying material is fast and, the perforations on the surface of the drum were incapable of removing the vapor at the same rate which might have affected the variations in the L* values.

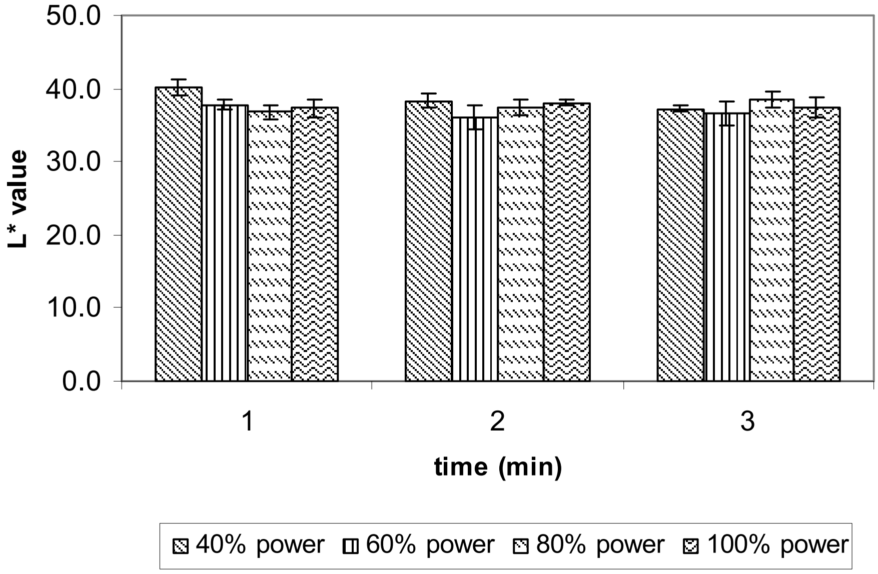

Figure 21 Average L* values of the samples processed at different power levels on location A with the rotating drums

The results of statistical analysis showed that the average a* value changed significantly with power level ($p \leq 0.05$). As the power increased a* value decreased due to the increasing moisture loss.

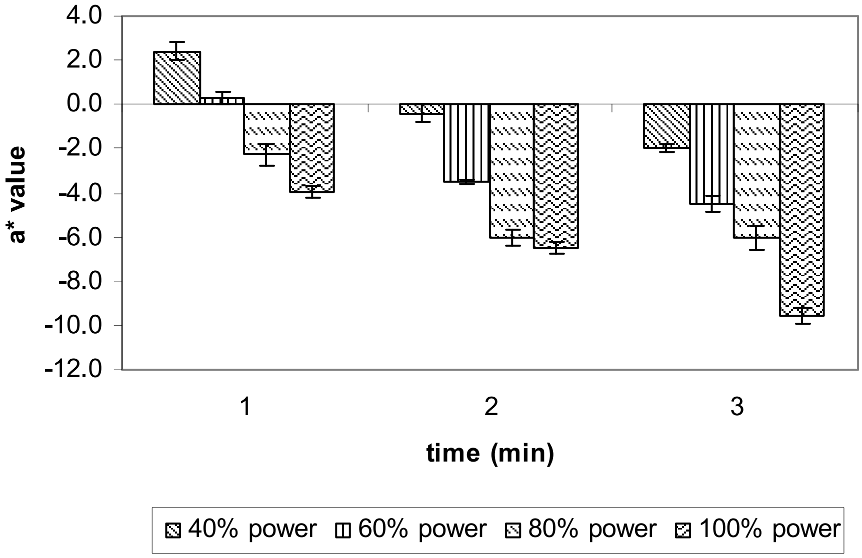

Figure 22 Average a* values of the samples processed at different power levels on location A with the rotating drums

There was a significant difference between the average b* values obtained at different power levels ($p \leq 0.05$). For power levels 40, 60 and 80% the average b* value decreased with increasing power level whereas at 100% power level, different behavior was observed which might have been a result of water vapor retained inside the drums.

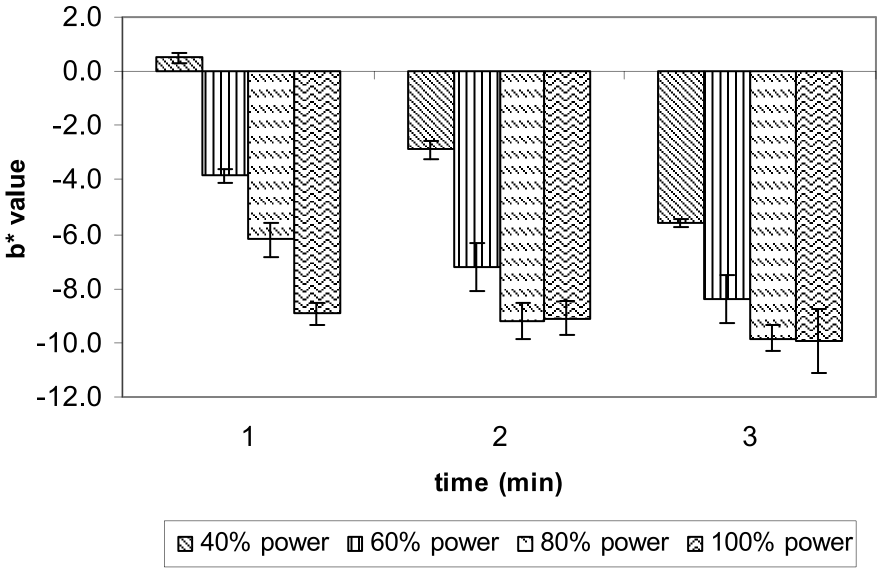

Figure 23 Average b* values of the samples processed at different power levels on location A with the rotating drums

3.1.2 Effect of Time on Average Color Values

<u>A. Analysis of the Experiments Performed on the Turntable</u>

Average color values were summarized in Table 1. The change in average L* values with time was found to be statistically significant ($p \leq 0.05$)

As can be observed, the average L* value decreases with increasing processing time (Fig. 24). The reason for this fact may be that as the time increases moisture loss increases, which also mentioned in pervious studies (Bertelli, 2005; Goksu, 2005), and the possibility of burning in the over-dried regions increased. Burnt regions have darker color which gives lower L* values.

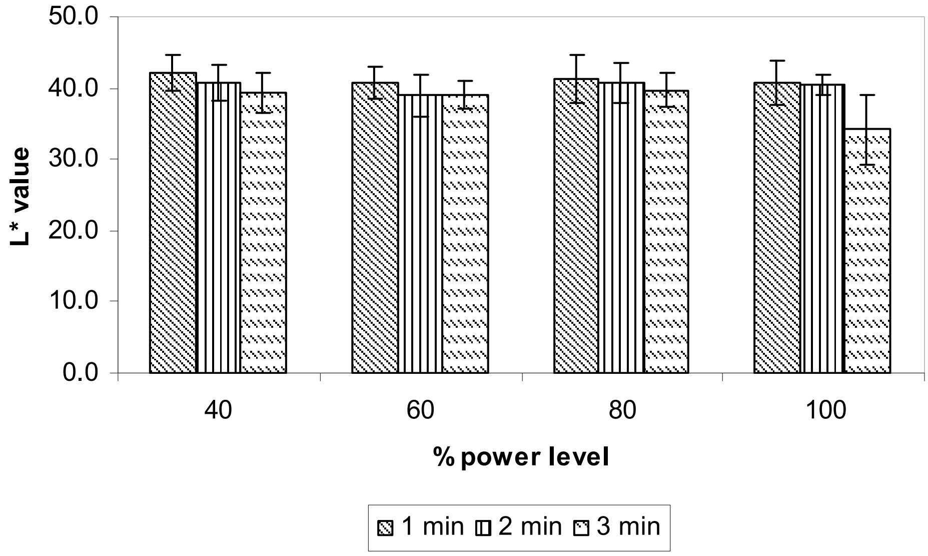

Figure 24 Average L* values of the samples processed for different time periods at location B on the turntable

There are significant differences ($p \leq 0.05$) between the average a* values measured at different time periods of turntable experiments (Fig. 25). Average a* value decreased with increasing time at 40% and 60% power levels. This may be due to the moisture loss dependency of coloring agent, which varied its color with the change of moisture content of material. When power levels of 80 and 100% were employed to carry out experiments, the measured a* values were lowered with shifting time period from 1 min to 2 min. However, 3 min treatment caused an increase in the average a* values. Burning at some locations of drying material in long time period may be the reason of that increase.

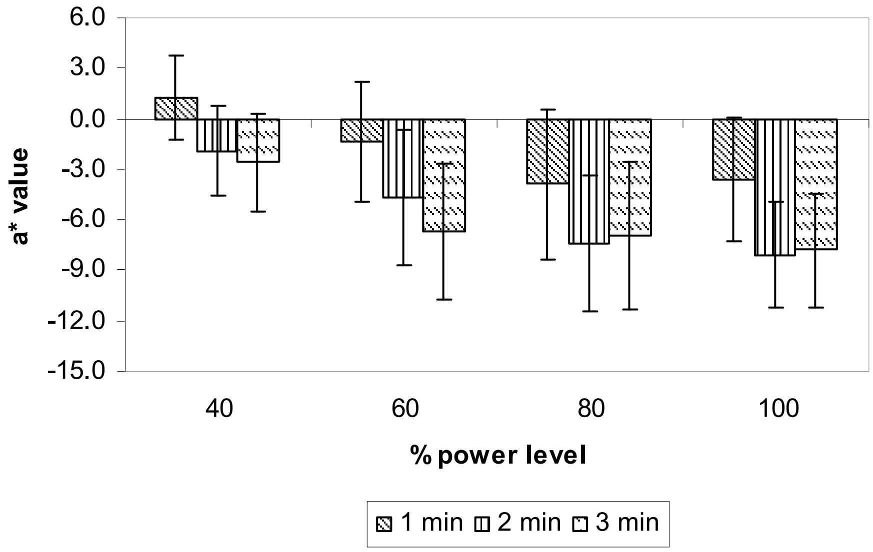

Figure 25 Average a* values of the samples processed for different time periods at location B on the turntable

The effect of time on b* values of drying material with turntable system was analyzed statistically and found that b* values significantly changed with time ($p \leq 0.05$)

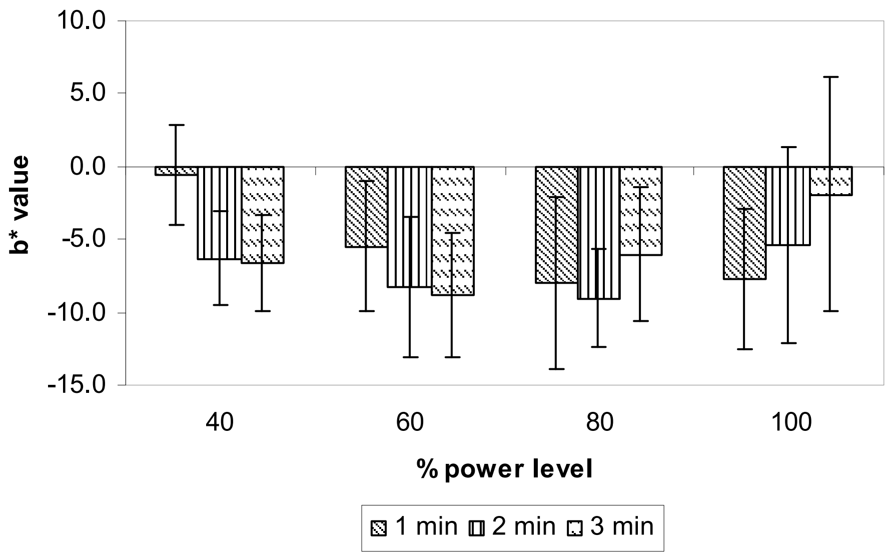

Figure 26 Average b* values of the samples processed for different time periods at location B on the turntable

The average b* value decreased with time at the 40% and 60% power levels since more moisture was removed and more blue color was obtained with increasing time. However at higher power levels, increasing time showed different behaviors in the average b* value. Increasing processing time caused decrease in the average b* values measured at power levels of 40 and 60%. Increase in processing time resulted first with a decrease than an increase in measured b* values at 80% power level. At the highest power level of processing, the average b* values decreased with increasing processing time (Fig. 26). This variation may be attributed to the effect of burning sections on color.

B. Analysis of the Experiments Performed with the Rotating Drums

Average color values of the dried material with rotating drums were given in Table 2 and Figure 27. When the average L* values were analyzed it was observed that no significant difference was present between the data obtained at the different power levels. The lightness was mostly affected by presence of burning sections. Since mixing provided by flights in the drums avoided the product from burning, average L* values did not change significantly.

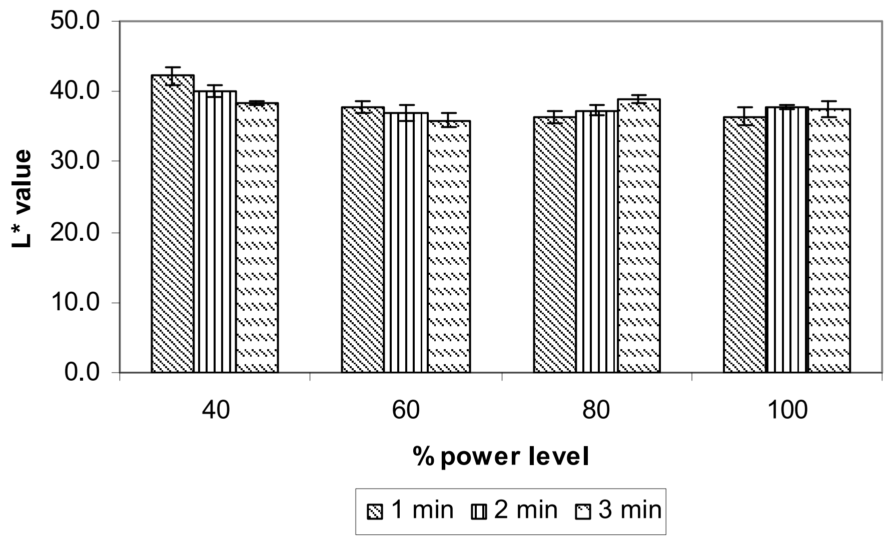

Figure 27 Average L* values of the samples processed for different time periods at location B with the rotating drums.

For the average a* values at the different processing times, there were significant differences. ($p \leq 0.05$) The average a* value decreased with time since red color was disappearing and blue color developing owing to the effect of heating (Fig 28). Longer processing resulted in temperature increase which was probably the reason for the decrease in the a* value of the processed material owing to moisture loss.

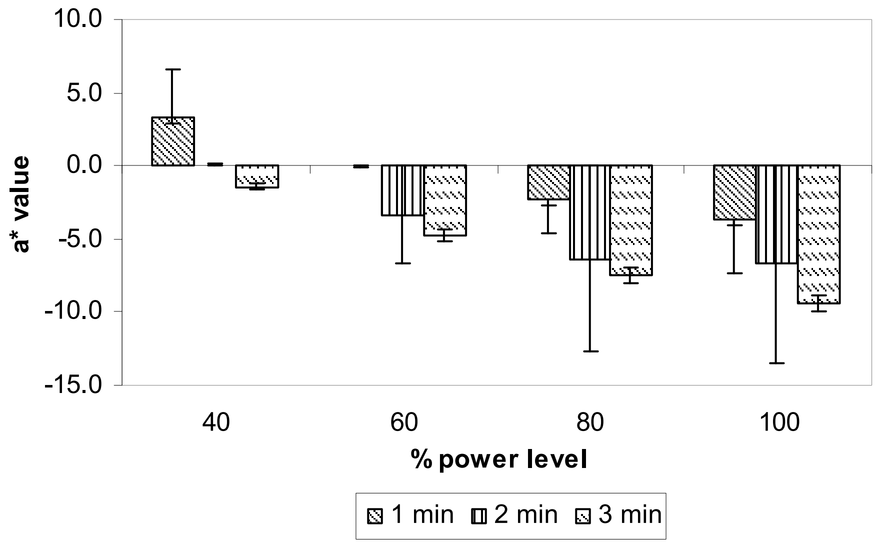

Figure 28 Average a* values of the samples processed for different time periods at location B with the rotating drums

The average b* values at different processing times were significantly different from each other ($p \leq 0.05$). The general trend was a decrease of average b* values with increasing time based on the fact that the influence of microwaves on the sample was increased as processing time extended; as a result amount of moisture removed during the process increased. As a property of coloring agent, blue becomes the abundant color of the sample as a consequence of the decrease in b* value.

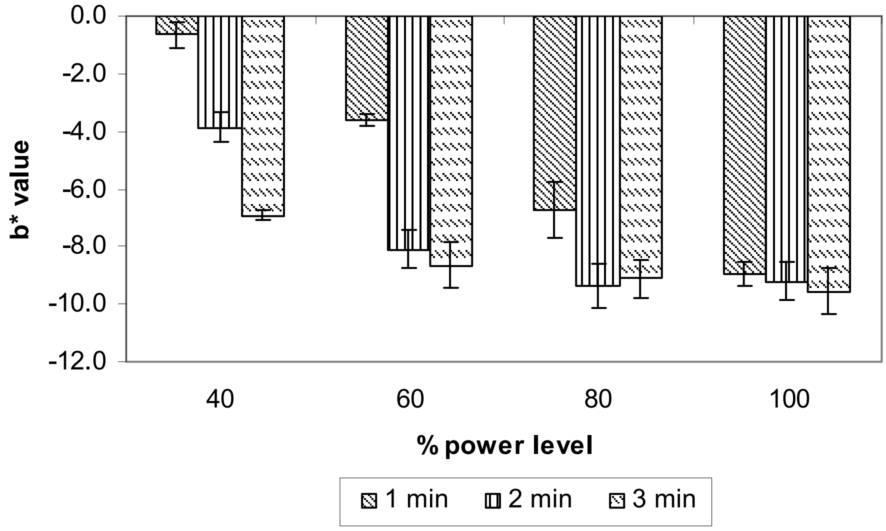

Figure 29 Average b* values of the samples processed for different time periods at location A with the rotating drums

3.1.3 Effect of Location on Average Color Values

A. Analysis of the Experiments Performed on the Turntable

The results of ANOVA showed that location did not significantly affect the color values ($p>0.05$). Figures 30, 31and 32 compares the effect of location on average L*, a* and b* values, respectively. Any trend representing change of color parameters depending on location was not observed.

Previous studies (Secmeler, 2003) showed that electrical field inside the oven was not uniform. Turntable aims to overcome this by rotating the food along ϴ-direction. This motion helps to obtain a uniform distribution in ϴ-direction. However in r-direction, distribution changes and the final appearance looks like a dartboard as given in Figure 30. The center is the location where the highest temperature is achieved and burning is observed.

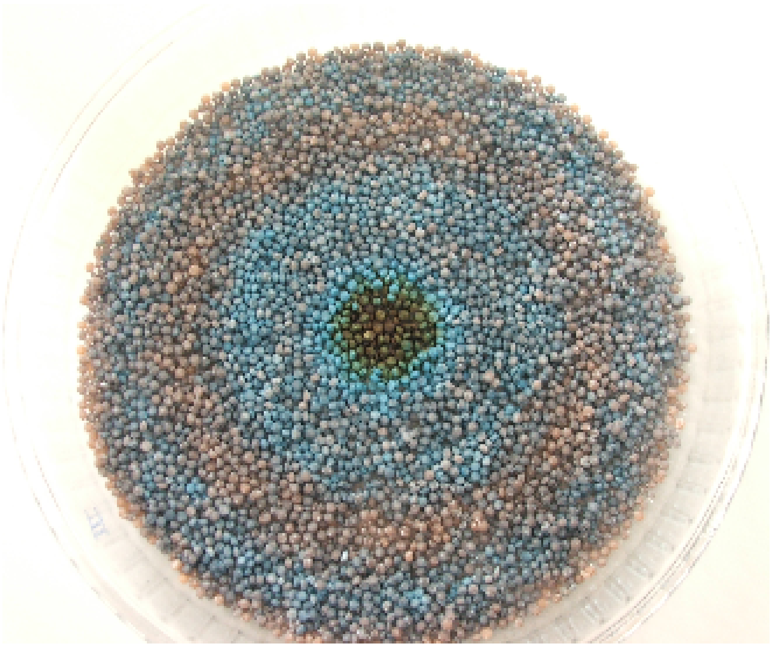

Figure 30 Electromagnetic field distribution over the turntable

Locations used in the present study were on a circular path near the edge of the turntable and away from the center. As can be seen from Figure 30, samples present in the same circular path have close color values. This may explain the result being similar color values in two different locations studied.

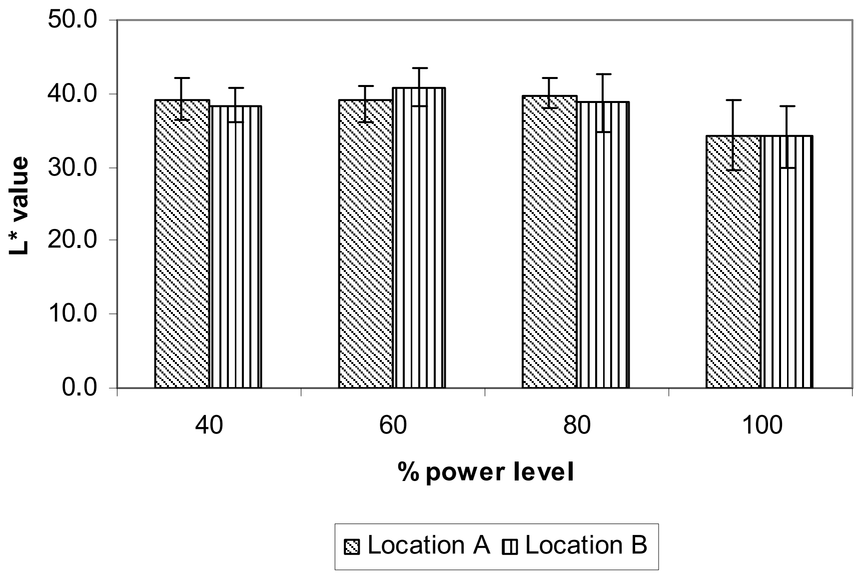

Figure 31 Average L* values of the samples processed at different locations for 3 min on the turntable

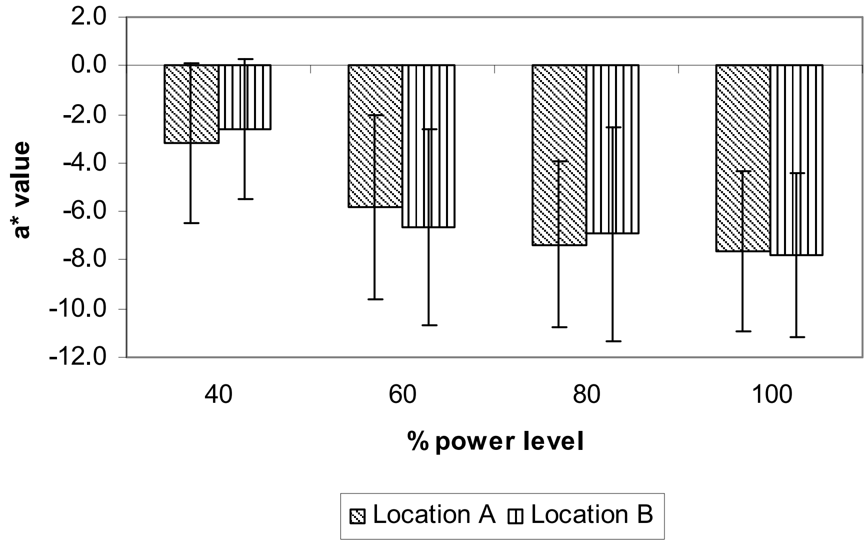

Figure 32 Average a* values of the samples processed at different locations for 3 min on the turntable

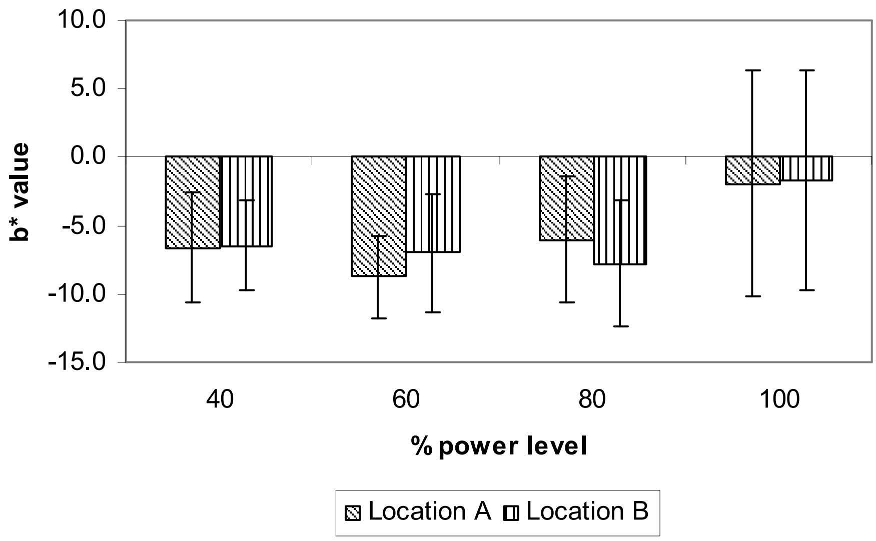

Figure 33 Average b* values of the samples processed at different locations for 3 min on the turntable

B. Analysis of the Experiments Performed with the Rotating Drums

Color parameters (L*, a* and *b) were found not to be significantly affected by locations studied. Detailed results are given in Appendix B. Figures 33, 34 and 35 represented the variation of color with location at different power levels. Similar changes of color parameters of the samples located at A and B were observed which is coincident with the statistical analysis.

The rotating drums also followed a circular path similar to the turntable. This circular path provided a motion in Θ-direction and this resulted in similar final products in terms of average color values since electromagnetic field mainly changes in r and z directions as given in Figure 30.

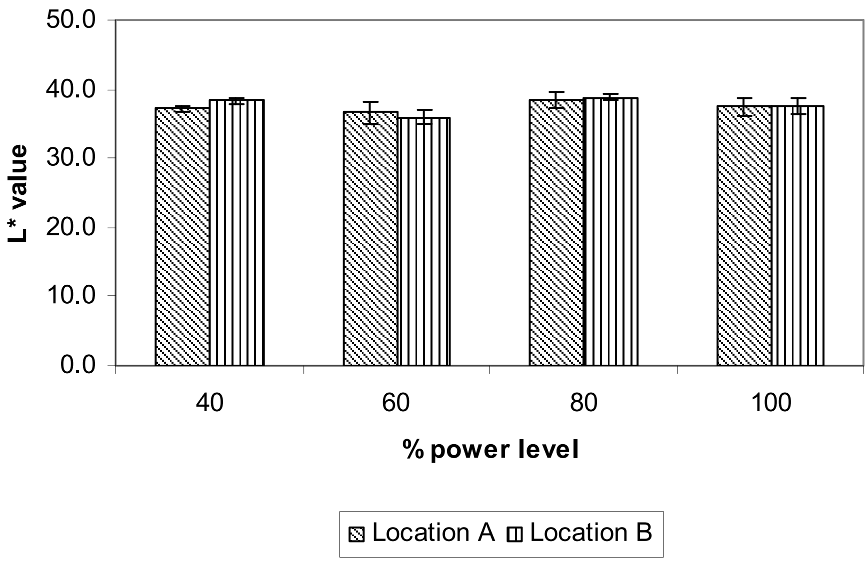

Figure 34 Average L* values of the samples processed at different locations for 3 min with the rotating drums

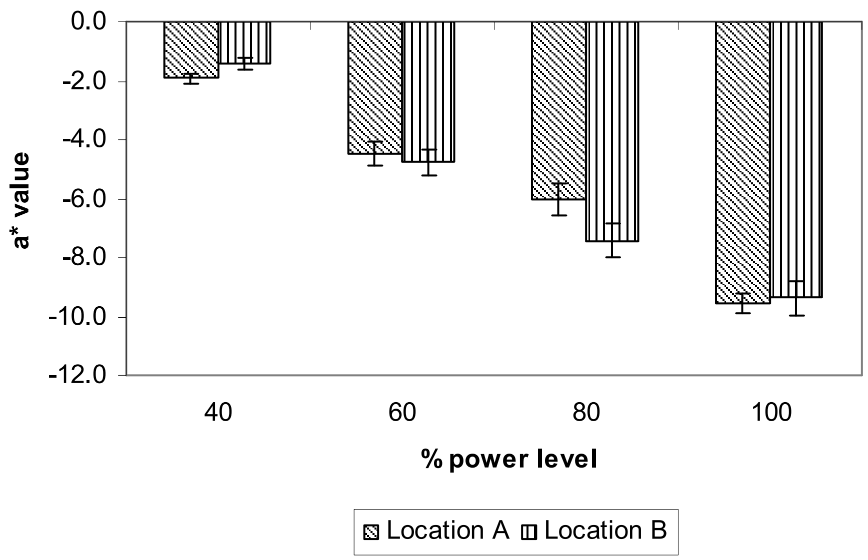

Figure 35 Average a* values of the samples processed at different locations for 3 min with the rotating drums

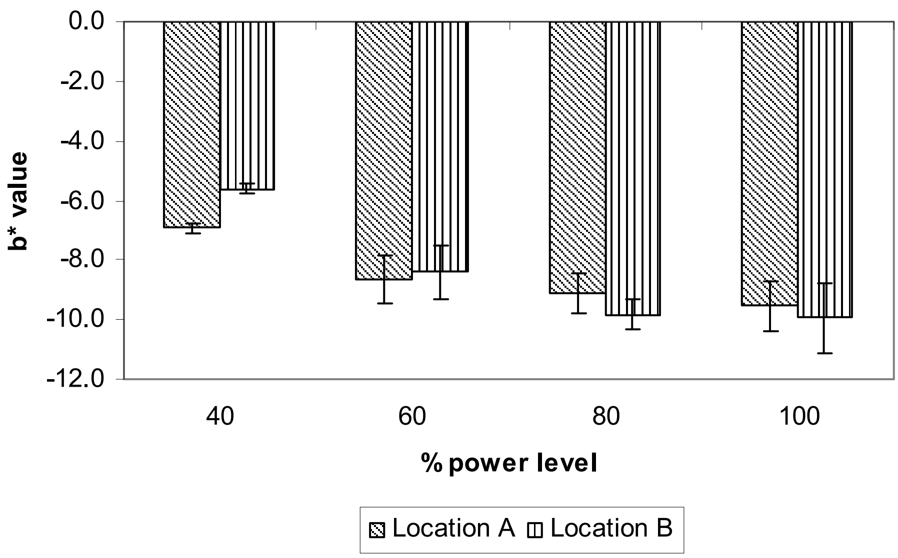

Figure 36 Average b* values of the samples processed at different locations for 3 min with the rotating drums

3.1.4 Effect of Operation Type on Average Color Values

Average L* values changed significantly with operation type ($p \leq 0.05$). .

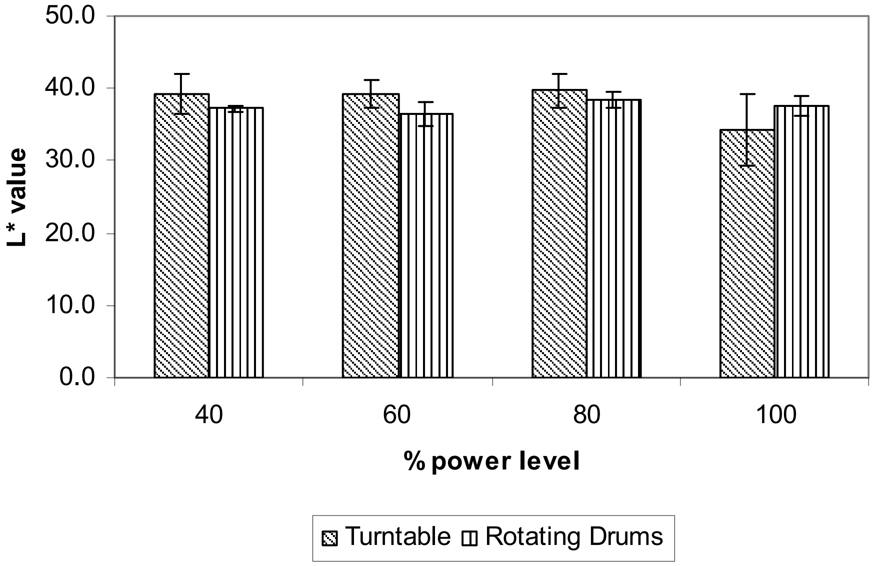

Figure 37 Average L* values of the samples processed for 3 min with the different operation types.

For power levels of 40, 60 and 80% the average L* value was higher for the samples processed on the turntable than the ones processed with the rotating drums. This was a result of the property of coloring agent which was related with the amount of moisture removed from the sample. Since more moisture was removed from the samples processed with the turntable, they had lighter color values. However, at 100% power level, significant amount of burning was observed in the sample which caused a decrease in the L* value.(Fig 37)

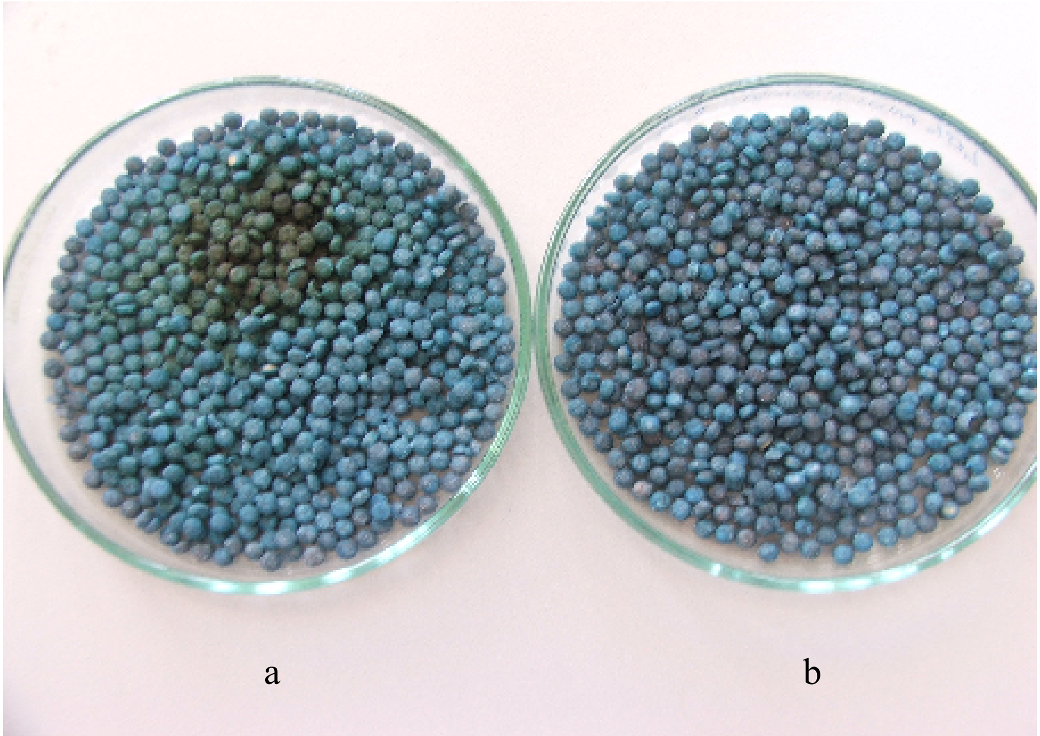

Figure 38 Comparison of the samples processed at 100% power level for 3 min by a) the turntable and b) the rotating drums

The operation type generally did not affect the average a* values and the average b* values significantly ($p>0.05$) except %100 power level and 3 min. In Figures 37 and 38 the change of the a* and the b* values with respect to operation type are compared. The difference in average b* value at 100% power level between operation types was due to the burnt regions in samples performed on the turntable. (Fig. 38)

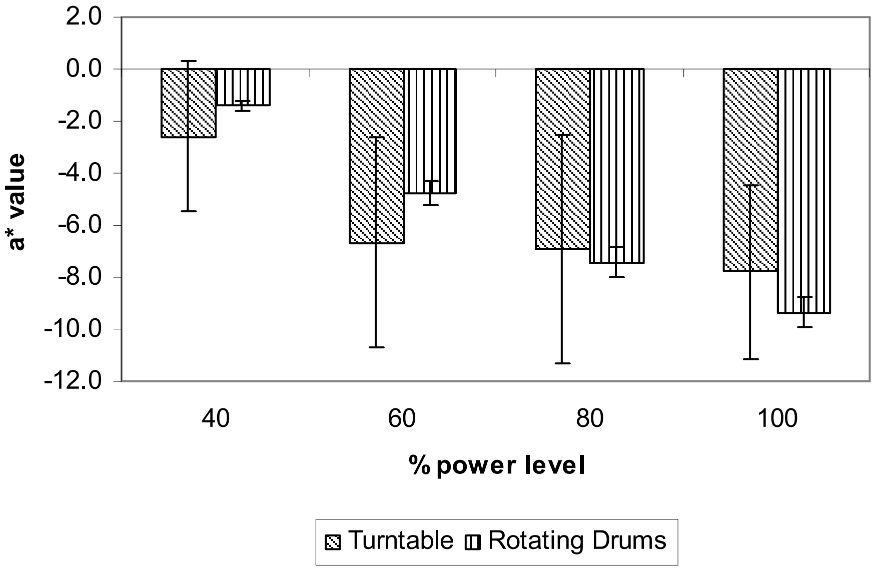

Figure 39 Average a* values of the samples processed for 3 min with the different operation types.

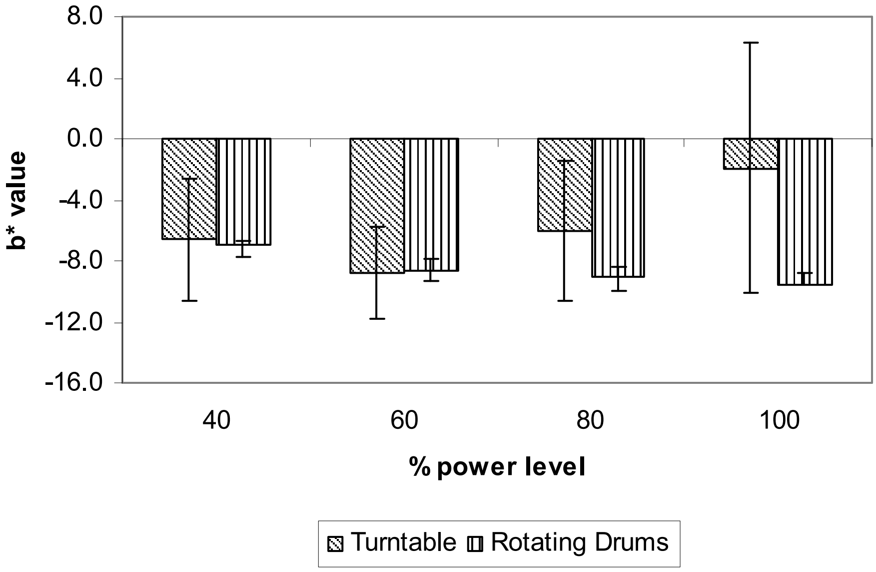

Figure 40 Average b* values of the samples processed for 3 min with the different operation types.

3.2 UNIFORMITY ANALYSIS

The color measurements performed at 5 locations (C, U, Lo, Le, and R) were used in order to analyze the uniformity of the final product. Significance of the differences between the values measured at these data points were investigated using ANOVA. Results have shown that non-uniformity exists in all experiments performed with turntable in terms of color whereas; rotating drums generally increased the uniformity in the final product (Figs 40 & 41). ANOVA tables were given in Appendix B. Figures 40 and 41 are shown below as examples for the change in color values in terms of the data points.

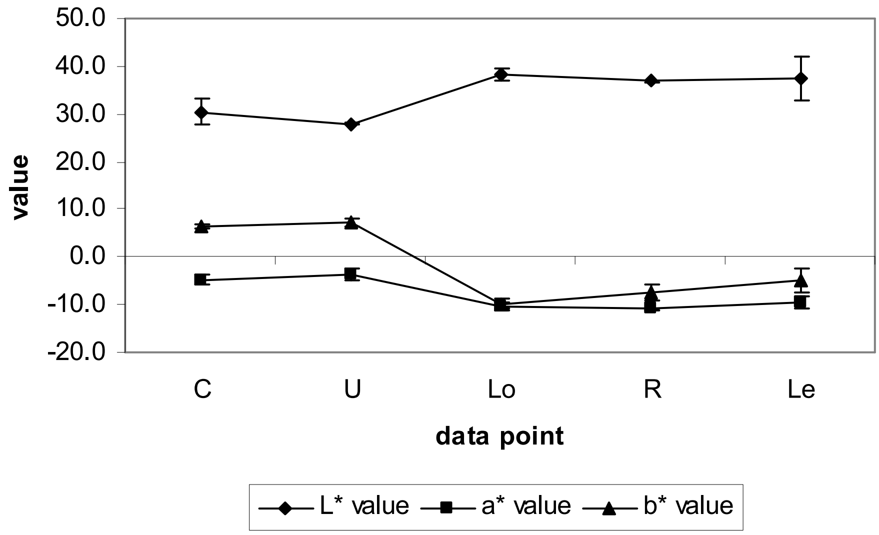

Figure 41 The change in color values of the samples according to the data points processed on the turntable at 100% power level and for 3 min

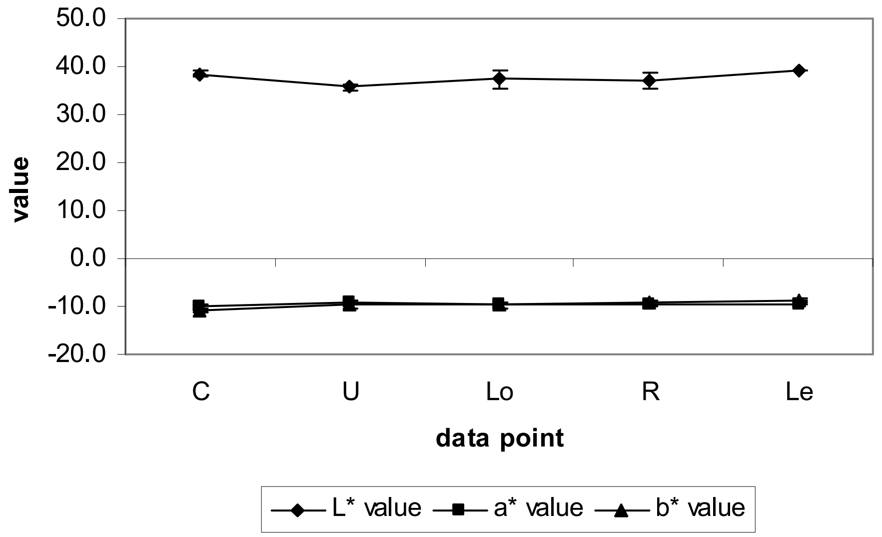

Figure 42 The change in color values of the samples according to the data points processed with the rotating drums at 100% power level and for 3 min

The effects of power level, time, location and operation type on color uniformity were analyzed using variances calculated for L*, a* and b* values. Variance is a measure of variability which shows how the data spread out. The higher the variance of color values measured is, the lower the uniformity present in color distribution. Significance of the differences between the variances was used to analyze the effects of power level, time, location and type on uniformity.

Table 3 Variances of L* values for data obtained from the turntable and the rotating drum experiments

	Var-L* value			Var-L* value		
	Turntable			Rotating Drums		
	time(min)			time(min)		
	1	2	3	1	2	3
Location A						
40% power	8.190	9.121	7.823	2.632	0.991	0.217
60% power	5.786	8.994	7.365	2.294	3.977	6.859
80% power	14.086	10.068	5.941	1.528	1.929	1.488
100% power	12.034	5.760	25.077	1.467	0.346	2.743
Location B						
40% power	5.877	4.787	8.937	3.110	1.263	0.150
60% power	7.342	9.783	9.457	3.722	1.355	1.950
80% power	17.920	2.780	4.436	1.603	2.257	1.108
100% power	17.793	9.852	25.603	4.448	0.214	1.626

Table 4 Variances of a* values for data obtained from the turntable and the rotating drum experiments

	Var-a* value			Var-a* value		
	Turntable			Rotating Drums		
	time(min)			time(min)		
	1	2	3	1	2	3
Location A						
40% power	12.000	13.308	11.084	0.313	0.258	0.044
60% power	14.996	21.362	15.603	0.252	0.047	0.173
80% power	21.126	15.672	16.743	0.351	0.269	0.383
100% power	15.175	9.304	11.756	0.132	0.119	0.155
Location B						
40% power	6.493	7.888	8.617	0.296	0.293	0.054
60% power	13.275	16.581	17.222	0.057	0.182	0.358
80% power	19.748	16.908	32.853	0.246	0.255	0.461
100% power	13.938	10.525	11.810	0.133	0.180	0.343

Table 5 Variances of b* values for data obtained from the turntable and the rotating drum experiments

	Var-b* value			Var-b* value		
	Turntable			Rotating Drums		
	time(min)			time(min)		
	1	2	3	1	2	3
Location A						
40% power	16.362	19.014	16.243	0.245	0.272	0.033
60% power	36.001	23.910	11.049	0.048	0.490	0.764
80% power	40.171	16.470	22.570	1.236	0.600	0.590
100% power	21.585	34.943	68.788	0.213	0.642	0.752
Location B						
40% power	11.979	12.815	11.054	0.041	0.120	0.025
60% power	20.652	23.792	47.023	0.068	1.010	1.041
80% power	34.766	12.262	22.683	0.653	0.456	0.237
100% power	24.181	45.088	65.381	0.212	0.745	1.470

3.2.1 Effect of the Power on the Uniformity of the Treatment

A. Analysis of Experiments Performed on the Turntable

Variances of the L* values at different power levels were analyzed and significant differences were detected. The power significantly affected uniformity in terms of lightness ($p<0.05$). At high power levels, higher variances were observed similar to the cases in previous studies (Pereira. 2007). It was stated in study that the higher the microwave power, the higher the standard errors of the color measurements of samples. Thus, with the turntable an increase in the non-uniformity with power was observed based on the fact that high power levels caused burning of some locations while the other parts was still blue or red.

In Figure 42 the change of L* values measured at the data points with power level is shown. Non-uniformity was observed at all power levels but especially the 80% power level gave the highest non-uniformity.

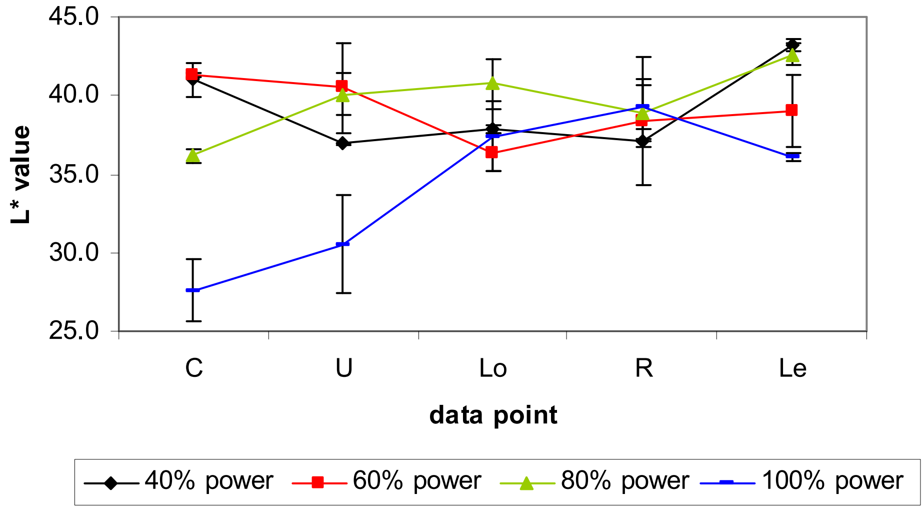

Figure 43 The L* values of the samples at data points processed on the turntable for 3 min at different power levels

The power levels also affected uniformity significantly in terms of the a* and b* values ($p<0.05$). The variances of these color values at the studied power levels were of considerable importance as shown in Figures 43 and 44.

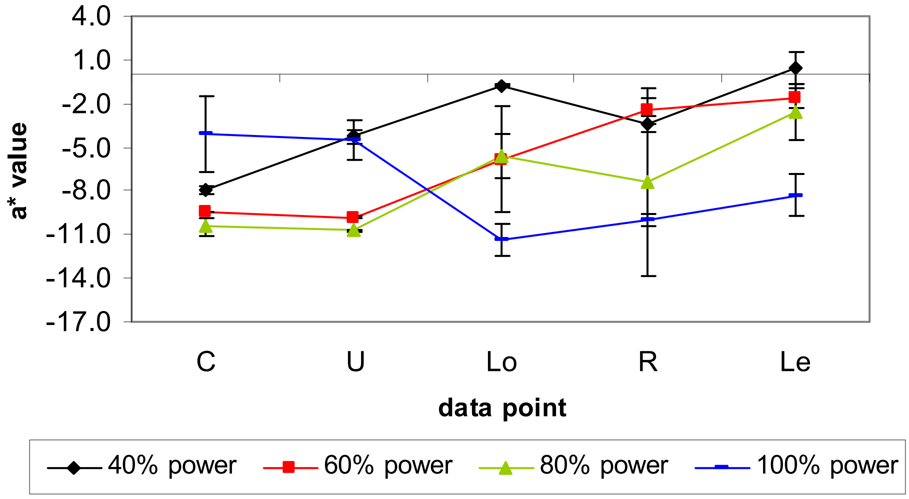

Figure 44 The a* values of the samples at data points processed on the turntable for 3 min at different power levels

Further for the b* value, at the lowest power level and the highest power levels, non-uniformities increased as can be seen from Table 4.

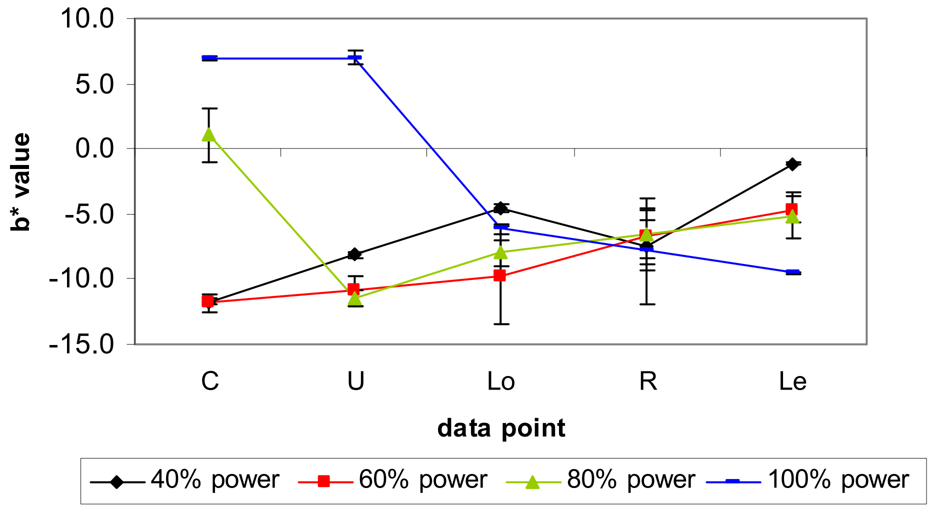

Figure 45 The b* values of the samples at data points processed on the turntable for 3 min at different power levels

For 1 min operation increasing power caused a decrease in the variance which indicates an increase in uniformity. At 40% power, locations which were less affected from microwaves still had a red color since power level was low while others parts became blue and this resulted in a high degree of non-uniformity. However, at higher power levels, less affected regions also turned blue and the product had less variation in the values.

B. Analysis of Experiments Performed with the Rotating Drums

The effect of power on uniformity in terms of the L* and a* values measured was found to be insignificant. The differences between variances of the L* and a* at the studied power levels were statistically insignificant. ($p>0.05$) Mixing in 3-D provided by the rotation of drums resulted in a highly uniform final product. However, power significantly affected the variances of the b* value and the variance increased with the power. At high power levels moisture removed from the macaroni beads condensed on the inner surface of the drums and caused local color changes which most probably resulted in higher variances.

Figures 45, 46, and 47 show the effect of power level on uniformity. The change in color values at different data points are given in figures.

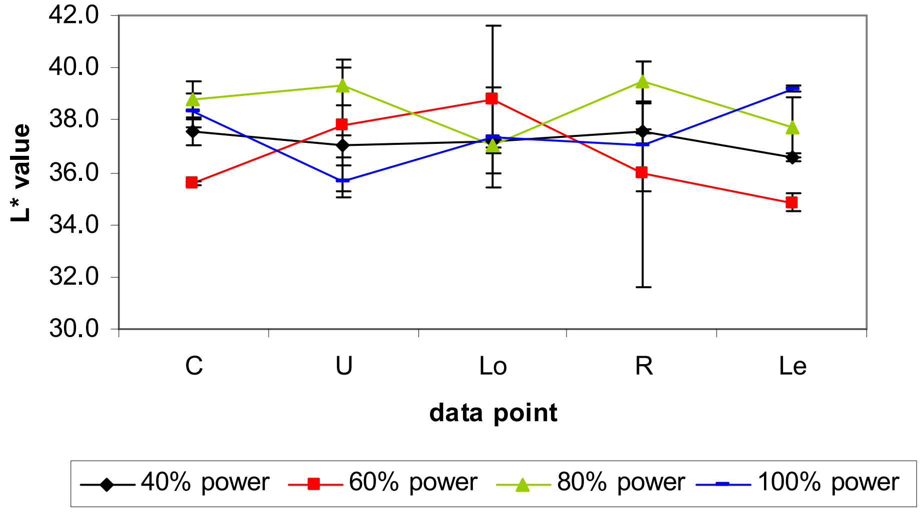

Figure 46 The L* values of the samples at the data points processed with the rotating drums for 3 min at different power levels

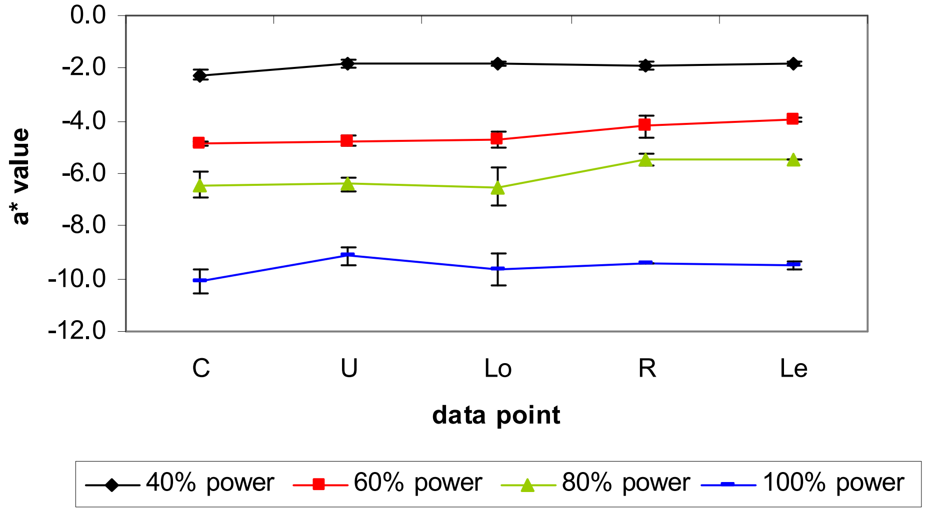

Figure 47 The a* values of the samples at the data points processed with the rotating drums for 3 min at different power levels

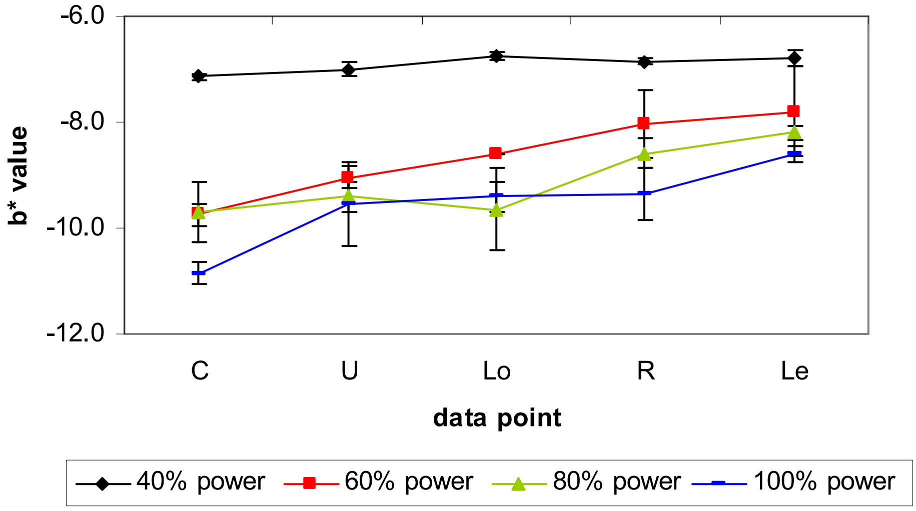

Figure 48 The b* values of the samples at the data points processed with the rotating drums for 3 min at different power levels

3.2.2 Effect of Time on the Uniformity of the Treatment

A. Analysis of the Experiments Performed on the Turntable

Variances of the L*, a* and b* values measured for 1. 2 and 3 min of processing times were analyzed statistically and no significant difference was detected which means that time did not affect uniformity significantly ($p>0.05$). For shorter operation time periods non-uniformity resulted from red-blue color differences between the regions. At longer times bluish regions started to burn and again non-uniformity was observed. Based on the variances in the values present in Table 3, 4, and 5 it was concluded that, non-uniformity was present in all of the operating conditions for the experiments performed with turntable. Trends of these variations could not be generalized. ANOVA tables were given in Appendix B.

B. Analysis of the Experiments Performed with the Rotating Drums

Time did not affect uniformity also for the experiments performed with new design. All products processed at different time periods in the rotating drums had similar uniformity properties. No difference was detected between the variances calculated for L*, a* and b* at 1, 2 and 3 min. ($p>0.05$). ANOVA tables are given in Appendix B.

3.2.3 Effect of the Location on the Uniformity of the Treatment

A. Analysis of the Experiments Performed on the Turntable

The effect of location on uniformity of color distribution of the final product was analyzed and no significant difference was detected between variances of L*, a* and b* values at the both locations studied on the turntable. The samples processed on the turntable had non-uniform color distribution and the location of the petri dish on the carousel did not improve this non-uniformity significantly. ANOVA tables are given in Appendix B.

B. Analysis of the Experiments Performed with the Rotating Drums

Samples processed with the rotating drums had generally uniform color distribution and the location of rotating drums inside the oven cavity did not significantly affect this uniformity. Variances of L*, a* and b* values at A and B locations were not significantly different. ($p>0.05$)

3.2.4 Effect of the Operation Type on the Uniformity of the Treatment

The main interest of this study was to investigate the contribution of the new design to the uniformity of the treatment in terms of the color of the final product. Variances of the L*, a* and b* values were analyzed separately and it was found that operation type affects the color uniformity in terms of all parameters (L*, a* and b*) significantly. The results of ANOVA were given in Appendix B.

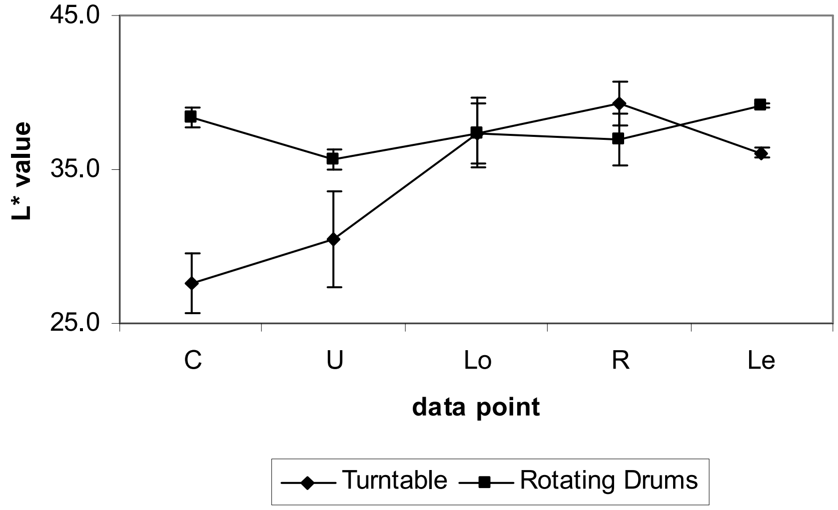

Figure 49 Comparison of the L* value distribution between the two operation types at 100% power level and 3 min

Using the rotating drums instead of turntable improved the uniformity. In Figures 48, 49 and 50 the L*, a* and b* value distribution of the samples processed for 3 min at 100% power level with the turntable and the rotating drums are shown; respectively. The horizontal trend in the a* value and b* values of the samples processed with rotating drums shows the high degree of uniformity achieved in the product. (Figs 49 and 50)

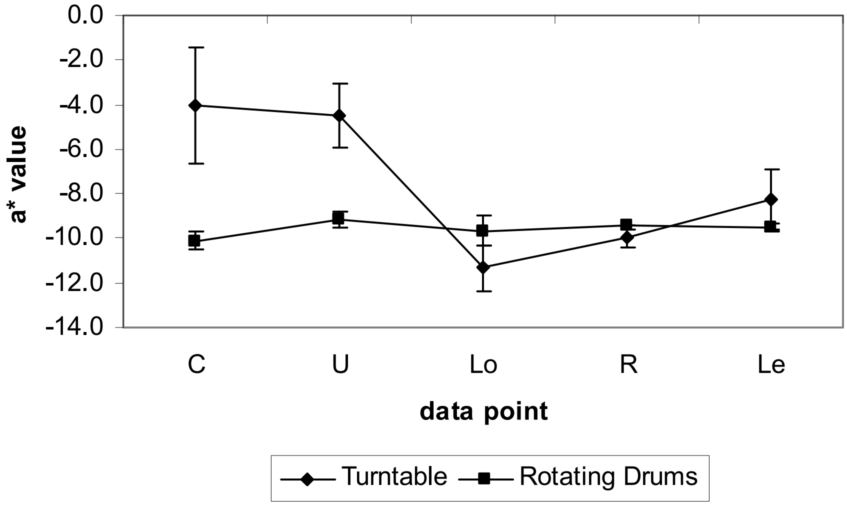

Figure 50 Comparison of the a* value distribution between the two operation types at 100% power level and 3 min

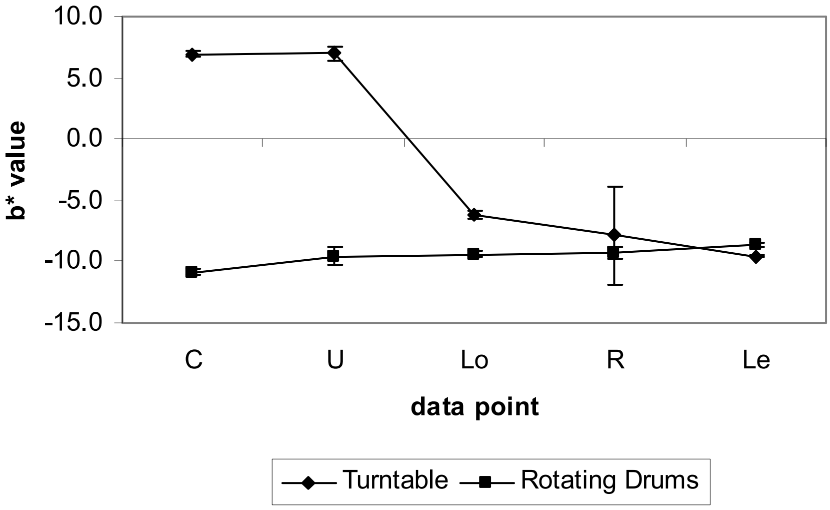

Figure 51 Comparison of the b* value distribution between the two operation types at 100% power level and 3 min

In the previous studies, in order to express the contribution of the new design on uniformity of the treatment quantitatively, Coefficient of variation (COV) which is the ratio of standard deviation to mean was used. Geedipalli et. al. (2007) found that the turntable increased the temperature uniformity by 43% when compared to a stationary processing condition with a similar calculation method. However this method can be used only if the data set has all positive values. In color measurements, a* and b* values were both positive and negative. Therefore COV was not applicable for present study. Instead of COV, variance was used to calculate the uniformity improvement quantitatively. The improvement in uniformity provided by rotating drums was found to be 94.7%. Detailed calculations are given in Appendix C.

3.3 AVERAGE MOISTURE CONTENT ANALYSIS

3.3.1 Effect of Operation Type on Average Final Moisture Content

The average moisture content data were analyzed statistically and the results showed that operation type affected significantly the final moisture content ($p<0.05$). In Figures 51, 52 and 53 the final moisture content data obtained from turntable experiments and rotating drum experiments were compared.

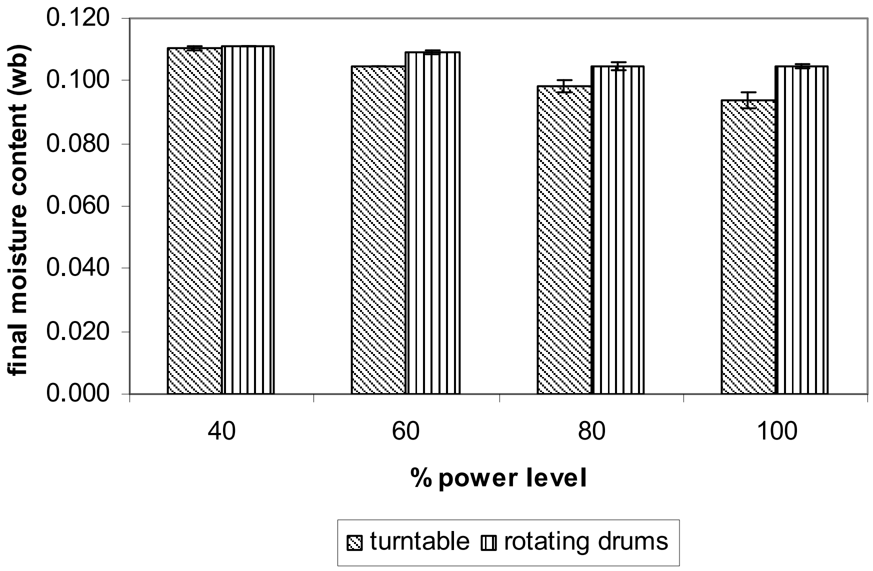

Figure 52 Comparison of the final moisture content at different power levels for 1 min operation

In all experiments performed, the final moisture content (wet basis) of samples processed in petri dishes on turntable were lower than the ones processed in rotating drums. The difference in final average moisture content values between samples processed on turntable and in rotating drums was higher at higher power levels and longer processing times (Fig. 52). This fact was mainly due to direct subjection of samples in petri dish to the microwaves while samples processed with new design were in rotating drums. Although glass mostly transmits the microwaves, partial reflection could occur.

Moreover, drums restricted the moisture removal since the perforations were not adequate. Removed moisture from the samples partially condensed on the inner surface of the drums, could partly be revaporized with the effect of microwaves. This resulted in an increase in humidty inside the drums and caused higher moisture content of the final product when compared with the ones processed on turntable.

The presence of burnt sections on the macaroni beads processed in petri dishes on the turntable also made those samples have lower final moisture content values than the ones processed in rotating drums.

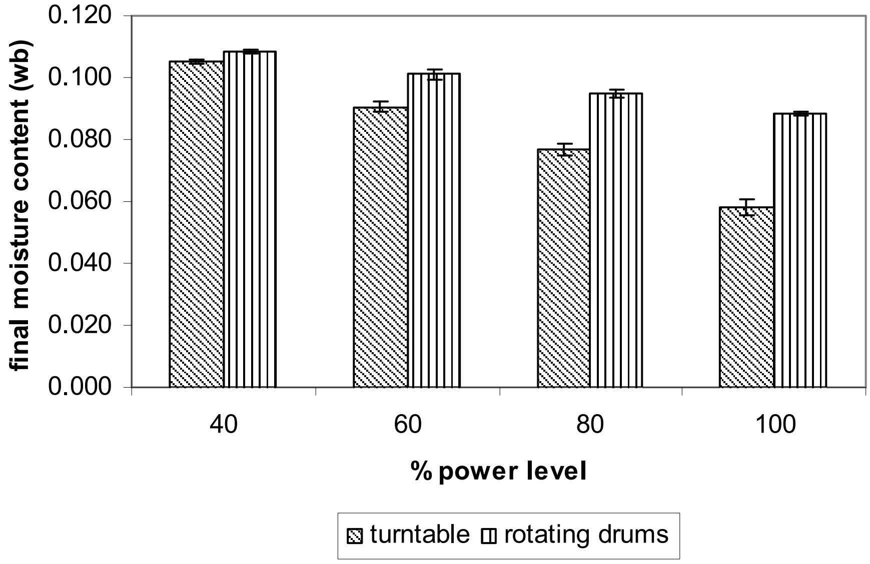

Figure 53 Comparison of the final moisture content at different power levels for 2 min operation

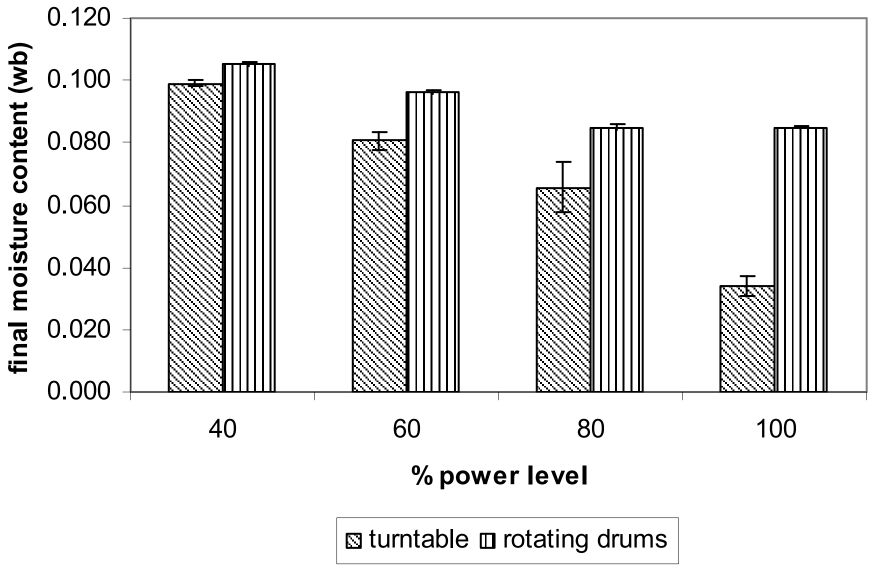

Figure 54 Comparison of the final moisture content at different power levels for 3 min operation

Alhough the final average moisture content was lower in samples processed on turntable, the moisture content distribution inside the petri dish was not uniform beacuse of the presence of burnt sections. However, the samples processed in rotating drums had more uniform moisture content distribution.

CHAPTER 4

CONCLUSIONS AND RECOMMENDATIONS

4.1 CONCLUSIONS

In the light of the experimental results obtained, it was concluded that, the average color values, L*, a*, and b* measured were not significantly affected from the locations studied inside the cavity for both operation types. The changes in color values significantly depend on the altering power level in both operation types for the three color parameters. The time also changed the average color values significantly for samples processed on the turntable in terms of L*, a* and b* values and in the rotating drums in terms of a* and b* values only. Lightness of samples processed in rotating drums was not affected by time.

Operation with the rotating drums was increased the average L* values of the final product as it kept the sample from burning and the operation type has an insignificant effect on the average a* and b* values.

Further, this design appeared to be superior to the turntable in avoiding non-uniform treatment with about 95% improvement

Non-uniformity in the product processed with the turntable significantly changed with the power level. Power level affected the uniformity of final product in terms of b* value only for the samples processed with the rotating drums. Time or location seems not affecting uniformity significantly in the both operation types.

The new design significantly affected final moisture content values of the samples. The final average moisture contents of samples processed on the turntable are lower than the ones processed with the new design owing to inadequate vapor removal in the latter. Higher power levels resulted in higher differences between the moisture content values of samples processed with turntable and rotating drums.

4.2 RECOMMENDATIONS

The new design significantly increased the uniformity of final product. For future studies the rotating drums can be used for different applications of microwaves in processes like drying, roasting or defrosting. For drying purposes, it can be recommended to use combination heating, such as infrared assisted microwave heating in order to overcome the problem in removing the moisture from the drums. The effect of proposed design on the quality parameters of the final product can also be studied.

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APPENDIX A

POWER MEASUREMENT BY IMPI 2-L TEST

The oven was operated at the highest power level with load of 2000±5 g water placed in two 1-L Pyrex beakers. Initial temperature of water was 20±2 °C. Final temperatures of water were measured immediately after 2 min and 2 s of heating. The power was calculated from the following formula:

$$P\ (W) = (70(\Delta T_1 + \Delta T_2))/2$$

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

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

Table 6 Results of IMPI 2-L Test

Run	**ΔT_1**	**ΔT_2**	**Power (W)**
1	9.7	9.4	668.5
2	9.9	9.5	679.0
3	9.8	9.9	689.5
Average			**679.0**

APPENDIX B

RESULTS OF STATISTICAL ANAYSIS

B.1 Statistical Analysis of Color Value Data Obtained From Turntable Experiments

Table 7 ANOVA (G.L.M.) table for the effects of power level, time and location on L* value in turntable experiments

Source	DF	Seq SS	Adj SS	Adj MS	F	P
power level	3	34.214	34.214	11.405	4.98	0.005
time	2	74.99	74.99	37.495	16.37	0.000
location	1	0.041	0.041	0.041	0.02	0.894
Error	41	93.894	93.894	2.29		
Total	47	203.139				

Table 8 ANOVA (G.L.M.) table for the effects of power level, time and location on a* value in turntable experiments

Source	DF	Seq SS	Adj SS	Adj MS	F	P
power level	3	225.736	225.736	75.245	115.62	0.000
time	2	167.025	167.025	83.513	128.32	0.000
location	1	0.025	0.025	0.025	0.04	0.845
Error	41	26.684	26.684	0.651		
Total	47	419.47				

Table 9 ANOVA (G.L.M.) table for the effects of power level, time and location on b* value in turntable experiments

Source	DF	Seq SS	Adj SS	Adj MS	F	P
power level	3	108.51	108.51	36.17	8.79	0.000
time	2	28.455	28.455	14.227	3.46	0.041
location	1	0.008	0.008	0.008	0	0.966
Error	41	168.677	168.677	4.114		
Total	47	305.65				

B.2 Statistical Analysis of Color Value Data Obtained From Rotating Drum Experiments

Table 10 ANOVA (G.L.M.) table for the effects of power level, time and location on L* value in rotating drum experiments

Source	DF	Seq SS	Adj SS	Adj MS	F	P
power level	3	42.361	42.361	14.12	10.31	0.000
time	2	2.454	2.454	1.227	0.90	0.416
location	1	1.235	1.235	1.235	0.90	0.348
Error	41	56.179	56.179	1.37		
Total	47	102.228				

Table 11 ANOVA (G.L.M.) table for the effects of power level, time and location on a* value in rotating drum experiments

Source	DF	Seq SS	Adj SS	Adj MS	F	P
power level	3	335.097	335.097	111.699	362.63	0.000
time	2	199.862	199.862	99.931	324.43	0.000
location	1	0.002	0.002	0.002	0.01	0.938
Error	41	12.629	12.629	0.308		
Total	47	547.59				

Table 12 ANOVA (G.L.M.) table for the effects of power level, time and location on b* value in rotating drum experiments

Source	DF	Seq SS	Adj SS	Adj MS	F	P
power level	3	257.722	257.722	85.907	74.41	0.000
time	2	113.593	113.593	56.796	49.19	0.000
location	1	1.367	1.367	1.367	1.18	0.283
Error	41	47.338	47.338	1.155		
Total	47	420.02				

B.3 Statistical Analysis of Color Value Data Based On Operation Type

Table 13 ANOVA (G.L.M.) table for the effects of operation type on L* value

Source	DF	Seq SS	Adj SS	Adj MS	F	P
type	1	95.8	95.8	95.8	29.49	0.000
Error	94	305.367	305.367	3.249		
Total	95	401.167				

Table 14 ANOVA (G.L.M.) table for the effects of operation type on a* value

Source	DF	Seq SS	Adj SS	Adj MS	F	P
type	1	23.8	23.8	23.8	2.31	0.132
Error	94	967.06	967.06	10.29		
Total	95	990.86				

Table 15 ANOVA (G.L.M.) table for the effects of operation type on b* value

Source	DF	Seq SS	Adj SS	Adj MS	F	P
type	1	12.113	12.113	12.113	1.57	0.213
Error	94	725.67	725.67	7.72		
Total	95	737.782				

B.4 Statistical Analysis of Uniformity Based on Color Values at Data Points Obtained from Turntable Experiments

Table 16 ANOVA (G.L.M.) table for the uniformity analysis based on L* value in turntable experiments

Source	DF	Seq SS	Adj SS	Adj MS	F	P
data point	4	591.21	591.21	147.8	14.56	0.000
Error	235	2385.3	2385.3	10.15		
Total	239	2976.5				

Table 17 ANOVA (G.L.M.) table for the uniformity analysis based on a* value in turntable experiments

Source	DF	Seq SS	Adj SS	Adj MS	F	P
data point	4	1397.92	1397.92	349.48	23.24	0.000
Error	235	3533.47	3533.47	15.04		
Total	239	4931.39				

Table 18 ANOVA (G.L.M.) table for the uniformity analysis based on b* value in turntable experiments:

Source	DF	Seq SS	Adj SS	Adj MS	F	P
data point	4	1026,95	1026,95	256,74	10,45	0,000
Error	235	5775,33	5775,33	24,58		
Total	239	6802,28				

B.5 Statistical Analysis of Uniformity Based on Color Values at Data Points Obtained from Rotating Drum Experiments

Table 19 ANOVA (G.L.M.) table for the uniformity analysis based on L* value in rotating drum experiments

Source	DF	Seq SS	Adj SS	Adj MS	F	P
data point	4	3.894	3.894	0.974	0.25	0.907
Error	235	901.912	901.912	3.838		
Total	239	905.807				

Table 20 ANOVA (G.L.M.) table for the uniformity analysis based on a* value in rotating drum experiments

Source	DF	Seq SS	Adj SS	Adj MS	F	P
data point	4	14.07	14.07	3.52	0.3	0.877
Error	235	2747.65	2747.65	11.69		
Total	239	2761.72				

Table 21 ANOVA (G.L.M.) table for the uniformity analysis based on b* value in rotating drum experiments

Source	DF	Seq SS	Adj SS	Adj MS	F	P
data point	4	55.049	55.049	13.762	1.51	0.200
Error	235	2143.871	2143.871	9.123		
Total	239	2198.92				

B.6 Statistical Analysis of Uniformity Based on Variances Calculated from Turntable Experiments

Table 22 ANOVA (G.L.M.) table for the effects of power level, time and location on uniformity based on L* value in turntable experiments

Source	DF	Seq SS	Adj SS	Adj MS	F	P
power level	3	560.56	560.56	186.85	5.25	0.004
time	2	160.91	160.91	80.45	2.26	0.117
location	1	1.56	1.56	1.56	0.04	0.835
Error	41	1459.28	1459.28	35.59		
Total	47	2182.3				

Table 23 ANOVA (G.L.M.) table for the effects of power level, time and location on uniformity based on a* value in turntable experiments

Source	DF	Seq SS	Adj SS	Adj MS	F	P
power level	3	802.63	802.63	267.54	4.95	0.005
time	2	25.57	25.57	12.79	0.24	0.790
location	1	0.43	0.43	0.43	0.01	0.929
Error	41	2215.52	2215.52	54.04		
Total	47	3044.15				

Table 24 ANOVA (G.L.M.) table for the effects of power level, time and location on uniformity based on b* value in turntable experiments

Source	DF	Seq SS	Adj SS	Adj MS	F	P
power level	3	5098.2	5098.2	1699.4	7.47	0.000
time	2	803.9	803.9	402	1.77	0.184
location	1	1.7	1.7	1.7	0.01	0.931
Error	41	9331.9	9331.9	227.6		
Total	47	15235.7				

B.7 Statistical Analysis of Uniformity Based on Variances Calculated from Rotating Drum Experiments

Table 25 ANOVA (G.L.M.) table for the effects of power level, time and location on uniformity based on L* value in rotating drum experiments

Source	DF	Seq SS	Adj SS	Adj MS	F	P
power level	3	11.254	11.254	3.751	1.76	0.170
time	2	13.282	13.282	6.641	3.11	0.055
location	1	0.005	0.005	0.005	0.00	0.961
Error	41	87.445	87.445	2.133		
Total	47	111.986				

Table 26 ANOVA (G.L.M.) table for the effects of power level, time and location on uniformity based on a* value in rotating drum experiments

Source	DF	Seq SS	Adj SS	Adj MS	F	P
power level	3	0.18253	0.18253	0.06084	2.58	0.066
time	2	0.01684	0.01684	0.00842	0.36	0.702
location	1	0.01095	0.01095	0.01095	0.47	0.499
Error	41	0.96547	0.96547	0.02355		
Total	47	1.1758				

Table 27 ANOVA (G.L.M.) table for the effects of power level, time and location on uniformity based on b* value in rotating drum experiments

Source	DF	Seq SS	Adj SS	Adj MS	F	P
power level	3	2.3268	2.3268	0.7756	4.48	0.008
time	2	0.6487	0.6487	0.3244	1.88	0.166
location	1	0.0031	0.0031	0.0031	0.02	0.894
Error	41	7.0914	7.0914	0.173		
Total	47	10.07				

B.8 Statistical Analysis of Uniformity Based on Variances for Operation Type

Table 28 ANOVA (G.L.M.) table for the effect of operation type on uniformity based on L* value

Source	DF	Seq SS	Adj SS	Adj MS	F	P
type	1	1671	1671	1671	68.46	0.000
Error	94	2294.3	2294.3	24.4		
Total	95	3965.2				

Table 29 ANOVA (G.L.M.) table for the effect of operation type on uniformity based on a* value

Source	DF	Seq SS	Adj SS	Adj MS	F	P
type	1	5064.3	5064.3	5064.3	156.32	0.000
Error	94	3045.3	3045.3	32.4		
Total	95	8109.7				

Table 30 ANOVA (G.L.M.) table for the effect of operation type on uniformity based on b* value

Source	DF	Seq SS	Adj SS	Adj MS	F	P
type	1	17432	17432	17432	107.48	0.000
Error	94	15246	15246	162		
Total	95	32678				

Table 31 ANOVA table for final average moisture content

Source	DF	SS	MS	F	P
type	1	0.005177	0.005177	17.96	0.000
Error	94	0.027094	0.000288		
Total	95	0.032272			

APPENDIX C

QUANTIFICATION OF UNIFORMITY IMPROVEMENT

	TURNTABLE	ROTATING DRUMS
	Average variance	Average variance
L*	10.200	2.053
a*	14.749	0.223
b*	27.450	0.498
Average	17.466	0.923

$$\%improvement = \frac{(\text{average variance})_{\text{turntable}} - (\text{average variance})_{\text{rotating drums}}}{(\text{average variance})_{\text{turntable}}}$$

$$\frac{17.466 - 0.923}{17.466} = 0.947$$

% 94.7 improvement in uniformity

APPENDIX D

PHOTOS OF THE DESIGNED SYSTEM

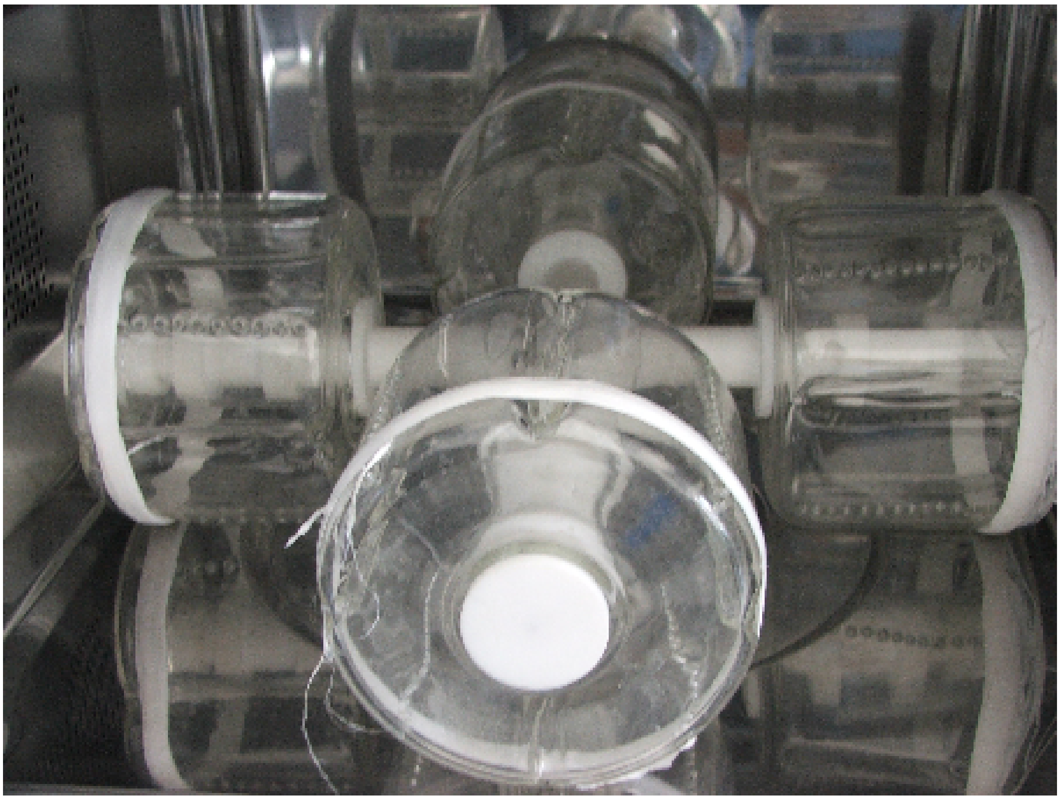

Figure 55 The system of the Rotating Drums

Figure 56 The placement of the design inside the oven