USAGE OF SPOUTED BED AND MICROWAVE ASSISTED SPOUTED BED DRYERS IN BULGUR PRODUCTION

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I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

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ABSTRACT

USAGE OF SPOUTED BED AND MICROWAVE ASSISTED SPOUTED BED DRYERS IN BULGUR PRODUCTION

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The main objective of this study was to investigate the effect of spouted bed and microwave assisted spouted bed drying on drying rates and quality parameters of bulgur. The drying experiments were performed at three air temperatures (50, 70, 90^{o}C) and at two microwave powers (288 W, 624 W). Quality parameters were selected as bulk density, apparent density, apparent porosity, internal porosity, microstructure analysis, and color for dried cooked wheat; yield and water absorption capacity for bulgur.

The drying rate increased with air temperature and microwave power. Microwave assisted spouted bed drying at microwave power of 288W and 624 W reduced drying time by at least 60% and 85%, respectively compared to spouted bed drying.

The effective moisture diffusivities of bulgur in the spouted bed and microwave assisted spouted bed drying were found to be 2.356×10^{-10} and 8.398×10^{-10} m^2/s on the average, respectively.

The effect of air temperature on product quality except color was not significant in spouted bed drying. Interior kernel porosity, sphericity and L* value of dried cooked wheat increased with air temperature and microwave power. Yield and water absorption capacity of bulgur tended to decrease as microwave power increased.

According to SEM analysis, more porous structure was observed in wheat samples dried in microwave assisted spouted bed compared to air dried ones. In microwave assisted spouted bed drying, lower water absorption capacity, bulk density and apparent density, higher sphericity and lighter color were observed as compared to spouted bed drying.

Keywords: Bulgur, microwave, spouted bed drying, effective diffusivity, wheat

ÖZ

BULGUR ÜRETİMİNDE FISKIYELİ YATAKLI VE MİKRODALGA YARDIMLI FISKIYELİ YATAKLI KURUTUCULARIN KULLANILMASI

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Bu çalışmanın asıl amacı fıskıyeli yataklı ve mikrodalga yardımlı fıskıyeli yataklı kurutucuların bulgurun kuruma hızı ve kalite parametreleri üzerine etkisini araştırmaktır. Kuruma deneyleri üç hava sıcaklığı (50, 70, 90^{o}C) ve iki mikrodalga gücünde (288 W, 624 W) gerçekleştirilmiştir. Kalite parametreleri, haşlanıp kurutulmuş buğday için yığın yoğunluk, görünen yoğunluk, görünen gözeneklilik, iç gözeneklilik, mikroyapı ve renk; bulgur için verim ve su emme kapasitesi olarak seçilmiştir.

Kuruma hızı hava sıcaklığı ve mikrodalga gücüyle artmıştır. Mikrodalga yardımlı fıskıyeli yataklı kurutucu, 288 W ve 624 W mikrodalga güçlerinde kuruma süresini fıskıyeli yataklı kurutucuya göre sırasıyla en az %60 ve %85 düşürmüştür.

Fıskıyeli yatakta ve mikrodalga yardımlı fıskıyeli yatakta bulgurun etkin nem yayınma katsayılarının ortalama olarak sırasıyla 2.356×10^{-10} ve 8.398×10^{-10} m^2/s düzeyinde olduğu bulunmuştur.

Fıskıyeli yataklı kurutmada hava sıcaklığının renk dışındaki kalite parametrelerine etkisi önemli olmamıştır. Haşlandıktan sonra kurutulan buğdayın iç tane gözenekliliği, küreselliği ve L* değeri hava sıcaklığı ve mikrodalga gücüyle artmıştır. Bulgurun verimi ve su emme kapasitesi mikrodalga gücü arttıkça azalma eğilimi göstermiştir.

SEM analizlerine göre mikrodalga yardımlı fıskıyeli yataklı kurutucuda kurutulan numunelerin hava ile kurutulanlara göre daha gözenekli olduğu gözlenmiştir. Mikrodalga yardımlı fıskıyeli yataklı kurutmada fıskıyeli yataklı kurutmaya göre daha düşük su emme kapasitesi, yığın yoğunluk ve görünen yoğunluk, daha yüksek küresellik ve daha açık renk gözlenmiştir.

Anahtar sözcükler: Bulgur, mikrodalga, fıskıyeli yataklı kurutma, etkin yayınma, buğday

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INTRODUCTION

1.1 Bulgur

Bulgur (in general produced from *Triticum durum*) is a very famous industrially processed ancient wheat product around the world. The first historical findings related to bulgur was discovered in the Çatalcahöyük (Anatolia) archaeological studies (the history of Çatalcahöyük goes back to 7000–8000 years ago) (Bayram and Oner, 2007). It is an ancient wheat food of Near Eastern, Mesopotamia and Mediterranean origin that referred as ‘‘Arisah’’ in the Old Testament and it is the major source of both protein and calories in the ancient world. The Roman word for bulgur is ‘‘cerealis’’, after Ceres, the goddess of harvest; Israelites called it ‘‘dagan’’, a word meaning ‘‘bursting kernels of grain’’; other Mid-Easterners called it ‘‘arisah’’, and in the Bible Biblical scholars translate ‘‘arisah’’ as ‘‘the first of the coarse meal’’ and, according to Biblical archeologists, was a porridge or gruel prepared from parboiled and sun-dried wheat (Bayram et al., 2004a). The product is referred to as bulgur in Turkey and North America whereas, in Near Eastern countries and North Africa, burghul is the commonly used term (Ozboy and Köksel, 2002).

Bulgur is a cleaned, washed, cooked, dehulled, ground and sifted wheat product. It is a nutritious and versatile product with a pleasant, nut-like flavor and an extended shelf life (Elgun et al., 1990; Ozkaya et al., 1996). Bulgur is the main ingredient used in more than 250 delicious meals due to its long shelf-life, low cost, ease of preparation, high nutritional value, taste and resistant to radiation, insect, mites and microorganisms. With these properties (its pre-processing operations)

bulgur can be categorized either as a semi-ready-to-eat food (pilaf etc.) or a ready-to-eat food (kofte, kısır etc.) (Bayram, 2000). Besides, bulgur is an important food source for Turkish, Arabic, Mediterranean, North African, and East European populations due to its nutritional and economic properties (Bayram, 2000; Bayram and Oner, 2002).

One of the most important parameter affecting bulgur quality severely is the wheat type. In general, hard wheat types are used in the bulgur production. Hard wheat types used in macarroni production are the most commonly preferred ones in bulgur production since they are rich in nitrogen and color pigments. Excess amount of nitrogen in wheat ensures more hard texture in the final product as nitrogen residues cause starch and protein to interact more intensively. Excess color pigments result in more desirable color in bulgur (Tekeli, 1964; Elgun and Ertugay, 1992).

Durum wheat is the main wheat type used to produce bulgur owing to its good milling properties; light yellow color; nitrogen and starch compounds that form a hard texture; uniform water absorption; and good texture and chewing characteristics. Besides, there is no disruption or adhesiveness due to durum's hard structure and high protein content (gluten) at the final stage. Bulgur is ground into different sizes to obtain different textures and cooking properties for various foods. The bulgur types involve coarse, medium, fine, double fine and ultra fine grinds (Bayram and Oner, 2002).

1.1.1 Nutritional and Functional Properties of Bulgur

Bulgur, one of the oldest cereal-based food, is more stable than wheat in hot and humid environments (Bayram et al., 1996) Although there are some changes in its nutrient values during processing, and it has nutrient values nearly the same nutrient values as wheat. Protein value was found to be completely unchanged (Shammas and Adolph, 1954); crude fat and fiber was generally lower compared to wheat grain (Pence, 1969); vitamin and mineral contents almost retained; thiamine content of bulgur was retained up to 98% of the original wheat (Shammas and

Adolphl, 1954); niacin almost completely retained but riboflavin of bulgur was approximately 73% of the original wheat; the ash content of the parboiled wheat was slightly less than whole wheat due to the debranning process; however, the iron and calcium content was greater than that of wheat (Pence et al., 1964); the phosphorus content generally decreased (Pence et al., 1964, 1965).

Bulgur is an important wheat product due to its high dietary fibre content, having 18.3 g dietary fibre per 100 g. Its dietary fibre content is 3.5, 6.8, 1.1, 1.8, 7.0, 15.3, 9.2, 2.3, 1.3 and 4.3 times higher than rice, wheat flour, barley, oat meal, spinach, tomato, turnip, whole wheat bread, soybean and pasta, respectively (Dreher, 2001). It is considered as a cereal preventing some diseases, generally called "diseases of civilization" due to its rich diet fibre (Ozkaya, 1997). In addition to its high dietary fiber, it contains easily absorbed minerals and vitamins, such as iron and calcium. Moreover, bulgur is easier to digest than other grains since it is pre-cooked form of wheat (Bayram et al., 2004a).

The amount of protein in bulgur is in the range of 12% to 15%. Rich in B-vitamins, iron, phosphorous and manganese, it complements the protein profile of legumes such as pinto beans and its B-vitamins complement the folate in vegetables, such as spinach, asparagus, broccoli or brussel sprouts. Since bulgur has richer vitamin source rather than rice, it has been preferred to be consumed instead of rice in countries where rice is widely consumed (Bayram et al., 2004a). Additionally, bulgur is a good source of folic acid (Bayram, 2002).

In Table 1.1, nutritional value of bulgur was compared with that of other cereals (Ozkaya et al., 1993). In general, bulgur was found to have the highest values in protein and vitamin B (riboflavin and thiamin).

Table 1.1 Comparison of nutritional properties of bulgur and some cereals (Ozkaya et al., 1993)

Product	Protein (%)	Carbohydrate (%)	Ash (%)	Riboflavin (%)	Thiamin (%)	Ca*	P*	Fe*
Rice	7.6	79.4	0.40	0.03	0.07	24	136	0.8
Rye flour	9.4	77.9	0.70	0.07	0.15	22	185	1.1
Wheat flour	10.5	76.1	0.43	0.05	0.06	16	87	0.8
Rye bread	9.1	52.4	2.00	0.08	0.18	72	147	1.6
Bread	8.5	51.8	1.80	0.11	0.05	79	92	0.6
Macaroni	12.8	76.5	0.70	0.06	0.09	22	165	1.5
Wheat	10.9	-	1.65	0.87	3.57	69	284	2.9
Bulgur	10.5	-	1.50	0.32	2.75	61	325.4	2.5

* mg/ 100g

Functional properties of the bulgur can be listed as follows; (Bayram, 2000; Bayram and Oner, 2002; Bayram et al., 2004a)

- long shelf-life
  - stopped respiration;
  - inactivation of enzymes and microorganisms due to the cooking and drying operations,
  - resistance to mold contamination and insect attacks,
- numerous nutritional benefits;
  - low fat, high protein, whole grain food,
  - high dietary fiber contents (18.3 g per 100 g),
  - excessive folic acid,
  - the best processing method to decrease the available phytic acid content in contrast to increasing the bran content (high mineral).
- appealing taste,
- easy preparation and semi- or ready- to- eat food,
- inexpensive and economical.

1.1.2 Consumption and Production of Bulgur in World

In Turkey, bulgur is a traditional wheat product which is widely produced and consumed in villages and homes. The number of bulgur plant has increased to 500 with total production of nearly one million tonnes (~800,000) annually. This production is approximately 2.5 and 2.0 times greater than that of pasta and rice in Turkey, respectively. Besides, the annual consumption of bulgur is about 12 kg/person (Bayram, 2000; Bayram and Oner, 2006). This consumption is extremely huge in the East and South Parts of Turkey, Syria, Iraq, Iran, Israel, Lebanon, and Arabia (25–35 kg/person) (Bayram 2000;Bayram and Oner, 2002). Bulgur production in the countries other than Turkey is also important. Bulgur production data with number of bulgur plant in the world are summarized in the Table 1.2. The number of bulgur plant have been increasing day by day and some existed pasta and flour plants have changed and adapted their system to process bulgur (Bayram, 2000; Bayram and Oner, 2005).

Table 1.2 Bulgur production in the world (Bayram and Oner, 2005).

Country	**Number of Bulgur Plant**	**Annual Production (tonnes)**
Turkey	500	1,000,000
US & Canada	15- 20	250,000- 300,000
Arabic Countries	10- 15	100,000- 120,000
EU	4 – 6	60,000- 80,000

As seen in Table 1.2, Turkey is the leader bulgur producer in the world. Due to the significant and increasing tendency to produce and consume bulgur in developing and developed countries, some technological developments and improvements are required to increase quality. Thus, each step in the bulgur production should be considered carefully and compensated with new technologies. One of the most important processing steps is the drying of bulgur which has been investigated in this study.

1.1.3 Processing of Bulgur

Bulgur is still produced by the ancient preparation techniques in small villages in the Eastern Mediterranean. Wheat is boiled in huge pots first until thoroughly cooked, then spread out flat on rooftops to dry in the sun. Then the kernels are cracked into coarse pieces and sieved into different sizes for various uses (Ercan, 1986; Bayram and Oner, 2002).

In Turkey, in bulgur production two methods,which are Antep and Mut (Karaman) methods, are preferred most commonly. Wheat is dehulled and ground after dry cleaning, cooking and drying in the Antep type. In the Karaman type production, wheat is dry- and wet-cleaned, cooked, dried, tempered, stone peeled and ground, then re-dried, cleaned and sized. The Antep system is oftenly used due to easy processing, good control, shelf-life extension and easy control of moisture content (Bayram and Oner, 2002).

The cooked and dried wheat is tempered up to 15–17% and 20–24% moisture during 15–20 min and 10–14 h for Antep and Mut (Karaman) methods, respectively. Dehulling and milling of dried cooked wheat in the Antep system is accomplished separately using a vertical emery dehuller and disc or hammer mills, respectively. Stone mill is used in the dehulling and milling stages of the Mut (Karaman) system. These differences between the two bulgur production systems affect the colour, shape and size of the bulgur particles. Due to the abrasive effect of the stone mill, Mut (Karaman) bulgur has a light yellow colour and an oval shape however, the control of process conditions (labour, maintenance, energy consumption and high moisture level) is difficult so that 70% of the total world’s bulgur is produced using the Antep milling system (Bayram and Oner, 2005).

Following processing steps are performed in the bulgur production;

a) Cleaning of raw material

The impurities and foreign seeds by dimensions, weight and form are separated (Bizarre and Morelli, 1980). Dust and foreign materials are removed by sieves, washers, triors and separators. Removed broken wheat kernels and foreign cereals are used as animal feed (Bayram and Oner, 2002).

b) Cooking

One of the most critical step in bulgur production is the cooking operation (Bayram et.al, 2004b). Cooking operation should ensure the two most important criterias. There should be no deformation, and complete cooking of wheat, which is realized by the absence of an opaque white centre (100% gelatinization, the gelatinized endosperm is essentially translucent but the ungelatinized starch appears in the endosperm as central white spots) should be achieved. Usage of deformed wheat in the subsequent processing steps i.e. drying, milling etc. ends up with a lot of problems (Bayram et.al, 2004a; 2004b; 2004c). Thus, cooking conditions should be well arranged to provide the complete gelatinization without darkening the product or making it so sticky as to interfere with the following drying process (Bayram, 2006).

Wheat is cooked either traditionally by the addition of water at a ratio of 1.5-2.0 or by pressurized cooking of soaked wheat at high temperature and pressure in an autoclave. In traditional cooking, bright yellow color of bulgur is ensured since temperature does not exceed 85-90^{o}C despite of deformed wheat kernels. Soaking of wheat prior to cooking prolongs processing time in autoclave cooking besides, high pressure and temperature applied in autoclave cooking results in darkening of final product color which are undesirable. On the other hand, as wheat deformation is minimized in autoclave cooking, it is most commonly preferred in industrial operations (Koca and Anıl, 1996). Cooking temperature should be lower than 95^{o}C to avoid denaturation of nutritional compounds (Cömden, 1986; Öktem, 1984). Besides, the amount of water added in cooking process is also critical. Too low water

content, results in partially gelatinized wheat or occurance of white center in the cooked wheat. On the other hand, if water content is too high in cooking system, solubilized vitamin B is leached out from wheat which decreases nutritional properties of wheat. As a result of cooking, moisture content should be higher than 40% (Cömden, 1986).

Koca and Anıl (1996) investigated the effect of different wheat types (*Triticum aestivum* and *Triticum durum*) and cooking methods (traditional cooking method; autoclave cooking method I: 110^{o}C for 15 minutes; autoclave cooking method II: 121^{o}C for 5 minutes) on physical (hectoliter weight, bulgur yield, grain hardness), chemical (ash, protein, crude fat, crude fiber starch contents) and organoleptic properties of bulgur. While ash, protein contents and organoleptic properties were found to be higher in the bulgur cooked with traditional method, ash contents in the bulgur cooked by autoclave method I and protein, crude fat and total bulgur yield in the bulgur cooked by autoclave method II were found to be higher.

Köksel et al. (1999) used three barley cultivars (*Hordeum vulgare* L.) to process into bulgur by pressure cooking or cooking at atmospheric pressure and investigate the effect of processing on levels of thiamine, riboflavin, minerals (Fe, Cu, Zn, Mn, Ca, Mg), the phytic acid and β-glucan. It was found that the processing of raw barley into bulgur decreased the levels of riboflavin, thiamine, Mn and Ca with significantly lower levels of phytate P suggesting better bioavailability of other minerals in the product.

Kadakal et. al (2007) determined the effect of cooking in beaker (90 and 100^{o}C) and in autoclave at 121^{o}C for 17 min on the content of several water-soluble vitamins [thiamin (vitamin B1), niacin, panthothenic acid (vitamin B5), pyridoxine (vitamin B6), and riboflavin (vitamin B2)] and found that the cooking in autoclave resulted in a more significant decrease on the thiamin, niacin, panthothenic acid, pyridoxine, and riboflavin content of the samples, when compared with cooking at 90 and 100^{o}C. As the cooking temperature increased, the concentrations of water-soluble vitamins in the samples decreased.

A lot of quality parameters such as cooking degree, colour, size, shape etc. are provided during cooking operation. The centre cutting of the wheat kernel, color of evaporated water or the smelling of steam from cooker are the traditional methods used in the control of cooking. However, these methods depend on experience and quality of operator which increases operation cost. Therefore, alternative, automated methods should be developed to control the cooking operation for bulgur production (Bayram, 2006).

Stapley et al. (1997) performed differential scanning calorimetry (DSC) scans for whole wheat grains that had been boiled or steamed for various times at either 100 ^{o}C or 120 ^{o}C. Scans were also obtained for raw grains that had been soaked and equilibrated to different moisture contents. Raw grains indicated moisture dependent peak temperatures. It was concluded that power-compensated differential calorimetry can be used successfully to investigate of the gelatinization behaviour of the starch that remains unconverted in wheat grains after processing by boiling and steaming. It was also found that grain moisture content was the most dominant factor other than effect of cooking in specific heat capacities of grains.

Thermodynamics and physical properties of the dimensional changes (changes of the length (*x*-dimension), two widths (*y*- and *z*-dimensions), weight, volume and density) in the wheat kernel during cooking was determined for bulgur production at 87, 92 and 97 °C for 140 min by Bayram et al. (2004a). It was found that the effect of cooking temperature on the physical properties of the wheat kernel showed that the rate of change in the secondary width (*z*-dimension), weight and density of the wheat kernel were more temperature dependent due to their greater activation energies althought the *y*-dimension of width of the wheat kernel required a lower amount of energy due to crease side.

Bayram (2005) derived nonlinear models (Sigmoid, Logistic, Gompertz, Hill and Chapman models) to model the cooking operation using centre cutting, light scattering and amylose/iodine values, and deformation degree of the intact wheat kernel. It was obtained that the best fitting models were the Sigmoid Chapman and

Gompertz for centre cutting and light scattering, amylose/ iodine and deformation degree, respectively.

Bayram (2006) concluded that the amylose/iodine and light scattering methods can be used to determine the cooking degree based on starch gelatinization for the production of bulgur as an alternative to traditionally used centre cutting method.

c) Drying

Drying is one of the most critical step in the bulgur production. Bulgur is traditionally sun-dried in open air. Commercially, hot air drying is used (Hayta, 2001). Tower, rotary, tunnel or fluidized bed dryers are often used in bulgur drying industrally. Dryers are preferred most commonly due to ease of scale-up, sanitation benefits, and elimination of reliance on suitable drying climatic conditions.

Hayta (2002) investigated the effects of different drying methods (tray, microwave, solar, sun drying) on the physicochemical (moisture content, bulk density, protein extractability, pilaf and fine bulgur yield, water and oil absorption, color) and sensory properties of bulgur. It was stated that although drying methods did not show any difference in the sensory properties, physicochemical properties were affected by drying methods in some extents.

Kadakal et al. (2007) investigated the effect of drying in hot-air oven (60, 70, and 80^{o}C) or sun-drying in open air, on several water-soluble vitamins [thiamin (vitamin B1), niacin, panthothenic acid (vitamin B5), pyridoxine (vitamin B6), and riboflavin (vitamin B2)]. It was found that the decrease in water-soluble vitamins was higher with open-air sun drying than with hot-air oven drying at 60, 70, and 80^{o}C.

d) Tempering

Tempering is accomplished by the addition of moisture to wheat. Objectives of tempering are as follows (Fang and Campbell, 2003);

- to soften the endosperm, enhancing its millability;
- to facilitate separation of bran from endosperm;
- to toughen the bran, reducing formation of bran powder during the size reduction process.

Structure, type and initial moisture content of wheat as well as season of year affect the time and moisture required for tempering (Bizarre and Morelli, 1980).

e) Dehulling

Dehulling is achieved by removal of bran. Aluerone layer should not be damaged since it is a protective layer for endosperm. As the pericarp is high in cellulose, amount of cellulose is decreased during dehulling. There are many dehullers used in bulgur production as abrasive type mill, konoz, stone mills (Bayram, 2000).

Bran is completely removed before milling the cooked kernel. Removal of bran increases the penetration rate of water into the kernel. Therefore, water absorption into the cooked wheat kernel is faster than in tempering uncooked wheat for flour or semolina production (Bayram and Oner, 2005).

f) Milling

The aim of milling is to produce granular small particles from larger ones. Bulgur is milled from cooked wheat to give particles with a range of dimensions which are then categorized by size (Bayram and Oner, 2005). In bulgur milling, stone mills are used traditionally as disc and roller mills are preferred industrially.

Milling techniques (stone, disc, roller, etc.) used in bulgur production influence the significant properties of bulgur (colour, shape, taste and size) (Yıldırım et.al, 2008).

In literature, milling of wheat has recently been involved in detail. Bayram and Oner (2005) compared the effects of mill types (stone, disc and hammer mills) on the milling quality of bulgur (appearance, surface structure, dimensions (max., min., mean, standard deviations and coefficient of variance), particle size distribution, bulk density and one-thousand particles weight). It was concluded that hammer milling is not suitable for bulgur preparation due to the loss of quality.

Bayram and Oner (2007) used roller, double disc and vertical disc mills to determine their effects on the quality of bulgur (surface characteristics, shape, dimension (x, y, z), particle volume (V), bulk density, one-thousand particles weight and size). It was found that the roller mill had the highest milling yield with nonuniform shape in contrast to double disc mill in which low surface quality with ovoid or elliptical shape was obtained. Besides, it was stated that ellipticity (ovoid) of bulgur particles in vertical disc mill was found to be lower than that of the double disc mills although the milling yield of vertical disc mill was higher than the double disc mill.

Yıldırım et. al (2008) investigated the effect of ternary roller mill (four rolls and three gaps) on the selected quality parameters of bulgur (Particle size, color, ash content, hectolitre-weight, yield and loss). It was stated that a high production yield and capacity with uniform particle size were obtained with low energy consumption in the roller mill.

g) Classification

According to Turkish Standards, bulgur types are defined as follows (TSE, 2003);

Type I: Bulgur for pilaf (Diameters between 3.55-1.60 mm)

Type II: Bulgur for kofte(Diameters between 2.00-0.50 mm)

1.2 Spouted Bed Drying

Terms as spouted bed and spouting were first introduced at the National Research Council of Canada in 1954 by Mathur and Gishler (Mathur and Epstein, 1974). Spouted bed system developed after unsuccessful application of a conventional fluidized bed which caused the poor quality of fluidization (bubbling and slugging) for such coarse particles of relatively uniform size (Gishler, 1983). As spouted bed drying was developed for wheat drying, this technique was first applied to dry wheat grains (Mathur and Gishler, 1955). The spouted beds have been implemented to many other thermal, mechanical and chemical processing applications such as drying of a large variety of other coarse particles, suspensions or solutions, particle coating and granulation, blending, heating, cooling, grinding, combustion, gasification, heterogeneous reactions, etc. (Jumah, 1995).

1.2.1 Mechanism of Drying

In spouted bed, the heated gas is injected vertically through a nozzle at the base of a conical, cylindrical or conical-cylindrical vessel containing relatively coarse particulate solids (Figure 1.1). If fluid injection rate is sufficiently high, the resulting jet causes a stream of particles to rise rapidly through a hollowed central core, called spout. Spouted particles, after rising to a height above the surface of surrounding packed bed, or annulus, rain back as a foundation onto the annulus, where they slowly move downward and to some extent inward as a loosely packed bed (Mathur and Epstein, 1974; Fayed and Otten, 1997).

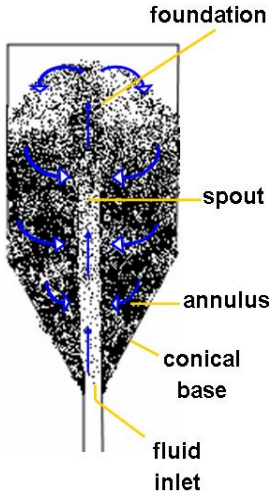

Figure 1.1 Schematic representation of a spouted bed

The mechanism of flow of solids as well as of gas in spouted bed technique is different from fluidization, but it appears to achieve the same purpose for coarse particles as fluidization does for fine particles (Mathur and Epstein, 1974). In spouted bed, fluid is moving through the core region using a nozzle rather than a porous or perforated distributor as in the fluidized bed. A fluidized bed can be considered as consisting of two phases, the bubble and emulsion. A spouted bed on the other hand, has three well defined regions, the annulus, the spout, and the fountain (Salam and Bhattacharya, 2006). Furthermore, a spouted bed can be considered as a special fluidization method suitable for handling Group D particles in the Geldart classification of particles (Geldart, 1973)(Figure 1.2). Group D particles are coarse particles that can not be fluidized well in conventional fluidized beds. Many particulate food and agricultural products categorize in this group. In an ordinary fluidized bed, particles experience a localized oscillatory and somewhat random movement (Feng et. al, 1999). In a spouted bed, the particles move through a macroscopic circulation that exhibits upward "spouts" and a downward annulus (Mathur and Epstein, 1974). The trajectory of an individual particle forms a three-dimensional pattern in the spouted bed over a certain period, but the position of the particle at any moment is random. Such characteristics result in the contact time between particles and fluid stream being very short in the spout region, and relatively longer in the downcomer zone. These unique characteristics make various types of

spouted bed popular for drying heat-sensitive materials (Prachayawarakorn et.al, 2006).

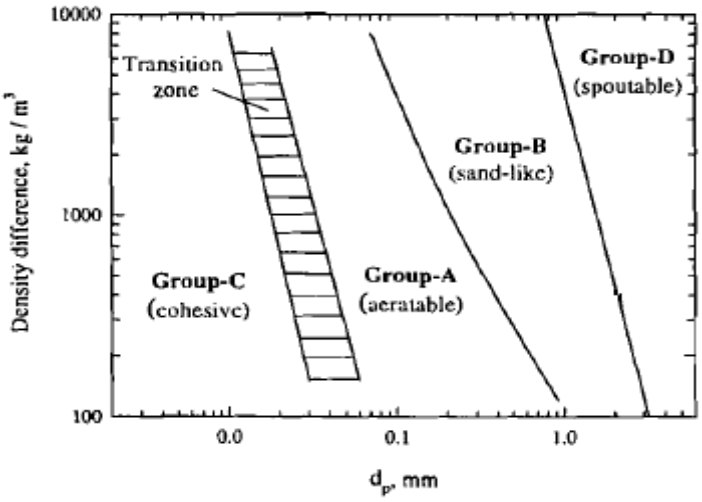

Figure 1.2 Modified Geldart classification chart for particles

Spouted bed drying is one of the convective drying mechanisms. There are two basic rate periods as constant rate and falling rate in convective drying. In the constant rate drying period, continuous thin layer of water covers the surface of the drying surface and so, the surface of the solid is initially very wet. Water on the surface is completely unbound. The rate of evaporation under the given air conditions is independent of the solid (Geankoplis, 2003). As evaporation of moisture absorbs latent heat, the liquid surface will reach to and stay at an equilibrium temperature where the rate of the heat flow from the surroundings to the surface exactly equals to the rate of heat absorption. If the solid is porous, most of the water evaporated is provided from the interior. The rate of evaporation remains constant until the average moisture content attains a value X_c, the critical moisture content. The constant rate period can be absent in some systems, depending on the type and the initial moisture content of the product. The rate of drying is mainly influenced by inlet temperature, humidity, and flow rate of the air (Treybal, 1980 ; Geankoplis, 2003).

At the critical moisture content, there is not enough water on the surface to keep a continuous film of water (Geankoplis, 2003). Thus, when the average moisture content of the solid has attained the critical moisture content, the surface film of moisture has been so insufficient. Further drying results in dry spots to form on the surface; these spots occupy larger portions of the exposed surface as drying proceeds. Finally, the original surface film of liquid will have entirely evaporated. This is the first part of the falling-rate period, the period of unsaturated surface drying. Since the mechanism of evaporation during this period is the same as that in the constant-rate period, the effects of such variables as temperature, humidity and velocity of the gas are the same as for constant-rate drying (Treybal, 1980).

The first falling rate period is a rapid falling rate period, where the drying rate declined sharply within a short time. This is followed by a slower falling rate period when the drying process proceeded slowly and eventually achieved its equilibrium state (Ng et. al, 2006). If drying proceeds further, the plane of evaporation slowly recedes from the surface. Heat for the evaporation is transferred to the zone of vaporization. Vaporized water moves through the solid into the air stream (Geankoplis, 2003). In this period, diffusion in the solid governs the rate of drying. Therefore, the rate at which moisture can move through the product, as a result of concentration gradients existing between the internal parts and the surface of the solid, is the controlling step. The rate of internal movement of the moisture decreases more rapidly than before as the moisture content of the solid is lowered by drying until the equilibrium moisture content, X_e, is attained, where the drying ceases. This is the second part of the falling-rate period and known as the internal diffusion-controlling step. In the falling rate period, the drying rate is based mostly on the physical structure and chemical composition characteristics of the solid (Treybal, 1980).

The study of Luikov (1966) for porous media transport stated that temperature (T), moisture content (X) and gas pressure (P) were primary variables and the equations were as follows;

$$\frac{\partial T}{\partial t} = K_{11}\nabla^2 T + K_{12}\nabla^2 X + K_{13}\nabla^2 P \qquad 1.1$$

$$\frac{\partial X}{\partial t} = K_{21}\nabla^2 T + K_{22}\nabla^2 X + K_{23}\nabla^2 P \qquad 1.2$$

$$\frac{\partial P}{\partial t} = K_{31}\nabla^2 T + K_{32}\nabla^2 X + K_{33}\nabla^2 P \qquad 1.3$$

where t is the time and K_{mn} values are the coefficients.

In equations through 1.1 to 1.3, effect of two different variables on the transport of the third variable are observed. According to Luikov's analysis (Luikov, 1966), concentration gradients can cause heat conduction (Dufour effect) in equation 1.1 and temperature gradients can cause mass diffusion (Soret effect) as seen in equation 1.2 resulting in a coupled set of nonlinear partial differential equations. The effects of thermal and momentum diffusion are often neglected due to their poor contribution to transport in convective drying (Keey, 1972). As a result, equation 1.2 is simplified to:

$$\frac{\partial X}{\partial t} = K_{22}\nabla^2 X \qquad 1.4$$

This equation is another form of Fick's second law (Bird et.al, 1960):

$$\frac{\partial X}{\partial t} = \nabla \cdot D_{eff} \nabla X \qquad 1.5$$

where D_{eff} (m^2/s) is the effective diffusivity that includes the effects of all possible mechanisms of transport of moisture in both liquid and vapor form. Since thin-layer drying occurred in the falling rate period only and liquid diffusion dominates the process, Fick's second law can be used to describe the drying. The general series of Fick's law with spherical coordinates is given below (Mohapatra and Rao, 2005):

$$\frac{X - X_e}{X_0 - X_e} = \frac{6}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{n^2}\exp\left[-\frac{n^2 D_{eff}\pi^2}{R^2}t\right] \qquad 1.6$$

where, X is the moisture content at time t, X_e is the equilibrium moisture content, X_o is the initial moisture content, R(m) is the radius of the particle. Dimensionless Fourier number is equivalent to the group of $\frac{D_{eff}t}{R^2}$ for the mass transfer. When Fourier number is greater than about 0.1, the terms higher than the first can be ignored and taking the natural logarithm of both sides reduces the relation into the form:

$$In\left(\frac{X - X_e}{X_0 - X_e}\right) = In\left(\frac{6}{\pi^2}\right) - \frac{\pi^2 D_{eff}}{R^2}t \qquad 1.7$$

Equation 1.7 can be used to determine D_{eff} from the slope of the $In\left(\frac{X - X_e}{X_0 - X_e}\right)$ versus time plot.

1.2.2 Drying of Wheat in Spouted Bed

The most popular application of spouted beds has been drying of coarse, heat-sensitive granular materials which involve agricultural products and various polymeric materials. Eventhough the range of moisture and drying conditions changes widely, there is always a huge temperature difference between the hot air and the bed. This makes spouted beds suitable in drying of heat-sensitive particles (Mathur and Epstein, 1974).

The pilot wheat drier used by Mathur and Gishler (1955) could be thought as a typical continuous granular-solids drying system. Up to 270 kg/hour of wheat, through a dry basis moisture content range of 4% could be dried in a system with 38

cm in column diameter, using 177^{o}C inlet air. The first detailed analysis of the wheat drying in a spouted bed was performed by Becker and Sallans (1960). In this study, Becker and Sallans investigated the mathematical treatment of the continuous drying of wheat in a spouted bed in the case where diffusion within the solids governs the drying rate. Besides, they assumed that the bed was deep sufficiently so that the exit gas was in thermal equilibrium with wheat in isothermal bed and concluded with the non-isochronal diffusion equation for drying rate and the relation for critical grain temperature. Analysis of continuous spouted bed wheat drying (Becker and Sallans, 1960) was subsequently extended to well-stirred batch drying of wheat by Becker and Isaacson (1970) and Viswanathan et. al (1984). In all of these studies, surface moisture content of grain was taken as constant.

Unlike previous studies, Zahed and Epstein (1992) assumed that the surface moisture content of grains was not constant in batch and continuous spouted bed drying of three cereal grains, one of which was wheat. In this study, numerical predictions of grain temperature and moisture content with time for batch drying of well mixed deep beds as well as the exit grain and air moisture contents and temperatures for continuous drying were performed and results were consistent with both batch and continuous spouted bed drying data from the literature.

The spouted bed technique, as defined by Mathur and Gishler (1955), is a modified form of conventional fluidization techniques which facilates agitation of relatively coarse particles. The advantage of such well-agitated bed is that particle temperatures are uniform throughout the bed (Becker and Sallans, 1960). The most crucial limitation in drying of wheat is the grain temperature and thus, this advantage is of decided importance (Becker and Sallans, 1956). Other advantages and limitations of conventional spouted beds are listed below (Jumah, 1995);

Advantages

- Can handle coarse particles (diameter greater than 1 mm)
- Predictable and reproducible solids and gas flow patterns
- Regular cyclic movement of solids
- Intensive particle circulation
- Lower pressure drop compared to fluid beds
- Low gas residence time
- Simple construction and maintenance with no mechanical moving parts
- Low investment cost
- Small space requirements

Limitations

- Gas flow rate governed by the requirements of spouting rather than heat/mass transfer or chemical kinetics
- Low bed-to-wall or bed-to-surface heat transfer rates
- High pressure drop prior to onset of spouting
- Limitations on vessel size and maximum spoutable bed height
- Difficulty of scale-up

1.3 Microwave Drying

Microwaves are electromagnetic waves which involve electric and magnetic fields. Microwave heating occurs at frequencies between 300 MHz and 300 GHz with wavelenghts ranging from 1 mm to 1m (Schiffman, 2007). In food applications, two frequencies are used in microwave ovens as 915 MHz for industrial purposes and 2450 MHz for home purposes.

Microwaves are the forms of radiant energy that are converted into heat through their interaction with materials. There are two main mechanisms responsible

for this energy conservation in the food materials; ionic conduction and dipolar rotation due to alternating electric field (Sahin and Sumnu, 2006).

In ionic interaction, there is a two step energy conservation. At first, electric field energy is converted to induced ordered kinetic energy which occurs when electric field causes ions (eg. salt ions in food) to move in the direction opposite to their own polarity. This induced ordered kinetic energy is converted to disordered kinetic energy or heat as ions collide with unioinized molecules like water molecules in food materials, giving up kinetic energy and causing them to collide with other water molecules in billard ball fashion (Schiffman, 2007).

Water molecules in food is the main reason for dipolar rotation if they are placed in an alternating electric field. They will undergo a torque or rotational force attempting to orient them in the direction of the field. When the field is applied, the molecules try to orient themselves in the initial field direction and collide randomly with their neighbors. When the field reverses, they attempt to reverse direction and further collisions occur. This ends up with thermal agitation and so heating (Sahin and Sumnu , 2006).

1.3.1 Mechanism of Microwave Drying

In microwave drying, heating takes place directly at regions within a material where free ionic or dipolar molecules exist. The volumetric absorption of electromagnetic energy by a wet solid is owing to the response of the unbound liquid to the applied electric field. Water and some solvents are able to absorb energy due to their polar structure and the presence of salts dissolved in the liquid. Selective absorption of electromagnetic energy by water molecules throughout the particle increases both temperature and water vapor pressure (Jumah and Raghavan , 2001). As the temperature inside the material approaches the boiling point of water, pressure development becomes significant. This pushes moisture from inside toward the surface leading to Darcy's flow. Generally, it results in a much higher surface moisture level than due to the diffusion alone (Ni, 1997). In general, much higher

drying rates can be maintained toward the later part of a drying process. Thus, when the drying rate under convective heating is substantially reduced, the rate of moisture removal would be increased if electromagnetic energy were used as a supplementary heat source (Jumah and Raghavan, 2001).

In microwave drying, pressure gradient has a major effect on the moisture transport and Luikov's equation (1.2) can be rewritten as follows;

$$\frac{\partial X}{\partial t} = K_{23}\nabla^2 P \qquad 1.8$$

Microwave drying, like conventional drying, is caused by water vapor pressure differences between interior and surface regions, which creates a driving force for moisture transfer, and it is most effective at product moisture contents below 20%, as used in a number of drying processes (Mudgett, 1989).

In general, four major requirements in drying of foods can be provided with microwave-related drying as speed of operation, energy efficiency, cost of operation, and quality of dried products (Gunasekaran, 1999). To overcome the limitations of other slow drying processes, microwave drying can significantly affect the drying process by the following unique advantages (Feng and Tang, 1998; Nijhuis et al., 1998; Torringa et al., 2001; Zhanga et. al, 2006):

- adjustment of energy absorption level by the wet products automatically-moisture-leveling effect of microwaves;
- possible selective heating of the interior portions- microwave focusing effect;
- rapid energy dissipation throughout the material;
- relatively minor migration of water-soluble constituents;
- lower product temperatures in combination with vacuum;
- more efficient drying in the falling rate period.

Microwave drying alone has some major drawbacks that involves the inherent non-uniformity of the electromagnetic field within an microwave cavity and possible textural damage (Feng and Tang, 1998), scorching due to overheating (Clark, 1996; Nijhuis et al.,1998), limited product penetration depth of the microwave radiation into the product (Feng and Tang, 1998). Other drying methods can be combined to compensate for these drawbacks like spouted bed drying.

1.3.2 Microwave Assisted Spouted Bed Drying

Increasing problems related to product quality and production costs have resulted in more investigations on drying technologies. To overcome the problems, one of the novel application is the combination of microwave energy with conventional drying systems. The advantages of microwave assisted drying systems can be summarized as follows: shorter drying time, improved product quality, and flexibility in producing a wide variety of dried products even though drawbacks can be listed as follows: high start-up costs and relatively complicated technology as compared to conventional convection drying. Microwave assisted drying combines the advantages of conventional drying methods and microwave heating, leading to better processes than microwave drying alone (Zhanga et al., 2006).

One of the most important limitations in the microwave drying alone is the occurance of non-uniform heating. Heating uniformity can be achieved by either through pneumatic agitation (Feng and Tang, 1998) or mechanical means (Torringa et al., 2001). Pneumatic agitation for particles in the drying column can be provided by fluidization. It also enhances heat and mass transfer as surface boundary layers change constantly. Thus, microwave assisted fluidized or spouted bed drying can be a solution for the non-uniform heating of microwave drying alone (Zhanga et al., 2006).

Spouted bed can be used to fluidize coarse particles which is not possible for a conventional fluidize bed since coarse food particles are difficult to fluidize, especially when their moisture content is relatively high and surface is relatively

sticky (Feng and Tang, 1998). In general, the system of microwave assisted spouted bed drying involves microwave power source, cavity, hot-air source and spouted bed. In literature, granular or diced (or sliced) products of fruits such as diced apple (Feng and Tang, 1998) and blueberries (Feng and Tang, 1999) or vegetables such as sliced asparagus (Nindo et al., 2003) were dried by using microwave assisted spouted bed.

Feng and Tang (1998) investigated the possibility of combining microwave heating with a spouted bed to achieve uniform heating to dry diced apples. Drying temperature uniformity in diced apples was greatly improved. The diced apples with microwave assisted spouted bed finish drying (from 24% moisture content to about 5%) showed a much smaller temperature variation as compared to that with a stationary bed during microwave drying. The diced apples also had lower bulk density, less discoloration and higher rehydration rates compared to conventional spouted bed drying. Drying time was reduced by more than 80% compared with spouted bed drying alone. In the study on frozen blueberries, microwave assisted spouted bed drying indicated a lower bulk density, more acceptable color, and higher rehydration ratio compared with other drying methods (Feng and Tang, 1999). In addition to the development of a heat- and mass transfer model to simulate microwave assisted spouted bed drying, the effect of microwave power and hot air temperature on drying rate and product temperature of diced apples in a laboratory microwave and spouted-bed combined dryer was investigated by Feng et. al (2001). In this study, uniform product color and product temperature were considered as an evidence of uniform microwave heating and it was shown that drying rates increased with increasing spouted-bed air temperature or microwave power level.

Microwave assisted spouted bed drying was used to evaluate the effect of different drying methods (tray drying; spouted bed drying; microwave assisted spouted bed drying; refractance window drying; freeze drying) on the retention of physical quality and antioxidants in sliced asparagus (Nindo et al., 2003). It was found that microwave assisted spouted bed dried asparagus particles had good rehydration and color characteristics and microwave assisted spouted bed drying was the fastest method among the other methods.

Jumah and Raghavan (2001) analyzed the heat and mass transfer phenomena during the combined microwave-convective batch spouted bed drying of wheat by using the numerical method of lines. In this study, microwave assisted spouted bed drying gave a higher drying rate than in convective drying alone. Besides, increasing the microwave electric field strength, frequency, and inlet air temperature resulted in higher sample temperature with increased drying rates and reduced drying time. Although air velocity did not cause any difference in the drying rate appreciably, it influenced the particle temperature profile.

Up to now, it is shown in the literature that microwave assisted spouted bed drying reduces the drying time sharply and improves product quality, compared to conventional hot air drying methods.

In the microwave assisted spouted bed drying, Luikov's equation (1.2) involves both moisture gradient due to convective spouted bed drying and pressure gradient due to microwave drying. Final form of the equation is as follows;

$$\frac{\partial X}{\partial t} = K_{22}\nabla^2 X + K_{23}\nabla^2 P \qquad 1.9$$

1.4 Objectives of the Study

Bulgur is a traditional wheat product which has been produced and consumed widely in Turkey as well as in world. The main reasons for this are the inexpensiveness and high nutritional properties of bulgur. However, the studies on bulgur processing are limited in the literature. Thus, new methods should be considered in the processing of bulgur to increase the quality of the product.

Although microwave assisted spouted bed combines the advantages of both conventional and microwave drying, there are few studies concerning the usage of microwave assisted spouted bed in food drying in literature. Moreover, spouted bed drying was performed several times in wheat drying owing to its high quality final product. Despite of various advantages of both spouted bed and microwave assisted spouted bed, they have never been used in drying of wheat for bulgur production up to this study.

The main objective of this study is to investigate the effect of spouted bed and microwave assisted spouted bed drying on drying rates and quality parameters of bulgur. In addition, the drying rates for spouted bed and microwave assisted spouted bed drying at different conditions were compared. Furthermore, the effective diffusivities were calculated and their temperature dependency were expressed using Arrhenius type of equation.

The independent variables used in the study were air temperature for both drying methods and microwave power levels for microwave assisted spouted bed drying. Quality parameters were selected as bulk density, apparent density, apparent porosity, internal porosity, microstructure analysis, and color for dried cooked wheat; yield and water absorption capacity for bulgur. Microstructure analysis and pore size distribution of bulgur have not been investigated up to now. In this study, SEM and pore size distribution analysis of bulgur were performed for the first time.

CHAPTER 2

MATERIALS AND METHODS

2.1 Materials

Triticum Durum wheat sample Kunduru-1149 purchased from a local market was used in this study.

2.2 Experimental Setup

A schematic diagram of the experimental setup is illustrated in Figure 2.1. The column of spouted bed was made of glass with an inner diameter, D_c of 140 mm, outer diameter of 150 mm, length, H of 25 cm and a cone angle,α of 90^o (Figure 2.2). Glass column was selected in order to make visual observations during movement of the bed and to ensure microwaves to pass through the column. The air inlet nozzle was located at the center of the bottom cone. The nozzle diameter,D_i of 20 mm was used in the study. A screen was used as a support under the nozzle to prevent falling of particles and provide a pass for hot air. A blower (TMM, KB-6, 2.2 kW, Ankara, Turkey) provided maximum air flow rate of 250 m^3/ hour was used to supply air to the system. An adjustable air heater manufactured by Seher Electric Ltd. (Ankara, Turkey) rated at 4.5 kW was used to attain the desired air temperature. Inlet air temperature was monitored by a thermocouple which was connected to heater controller. Ball valves were used to adjust the air velocity. The air velocity was measured by an anemometer (Turbo Meter, Davis Instruments, Hayward, California, USA). The relative humidity of air was monitored using a digital hygrometer (Testo 610, Testo Ltd, Alton, England), sensitive to changes of 0.1% RH.

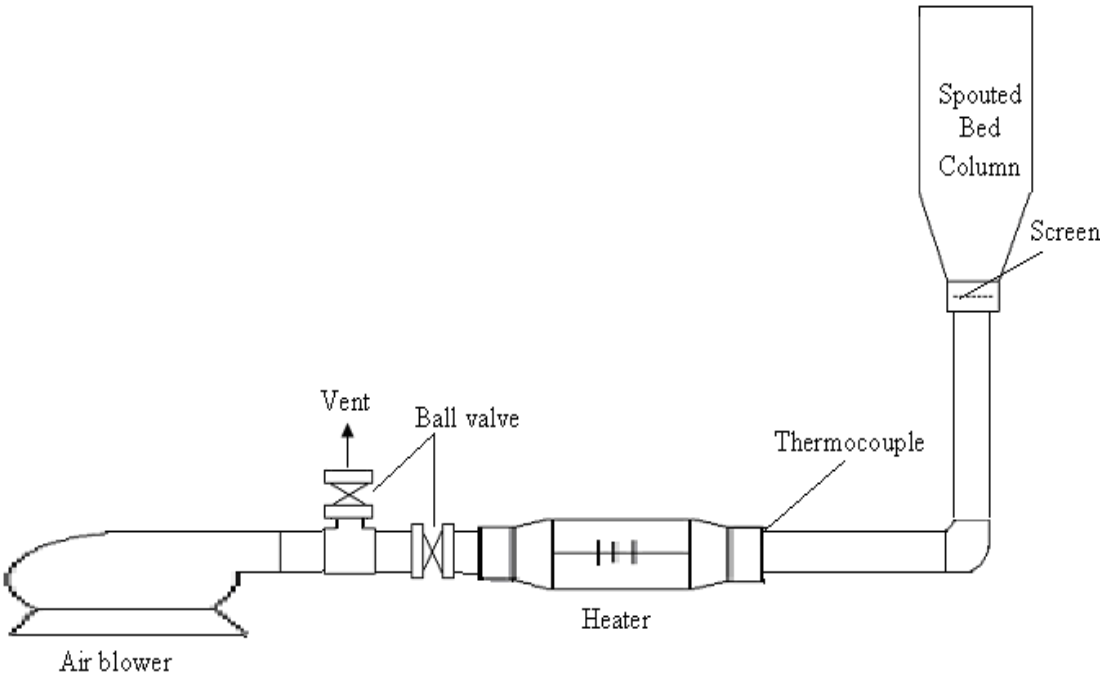

Figure 2.1 Schematic representation of spouted bed drying experimental setup

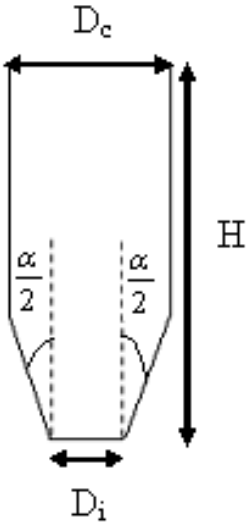

Figure 2.2 Dimensions of spouted bed column

The only difference in microwave assisted spouted bed experimental setup shown in Figure 2.3 was the addition of a domestic microwave oven (White-Westing House Type: SJ Model: KM 90 VP-63103, Pittsburgh, PA, USA) with a frequency of

2450 MHz into the spouted bed experimental setup. The cavity of microwave oven had a dimension of $400 \times 350 \times 340$ mm. A hole of 24 mm in diameter was made at the bottom of the microwave oven for elongated nozzle part to pass through the hole and attach to the pipe out from the bottom. By this way, spouted bed column was able to be put into the oven cavity for the microwave assisted spouted bed drying experiments. The hole was then closed by a teflon bung to minimize microwave leakage. On the top of the oven, there was another hole to remove the moisture during the experiments.

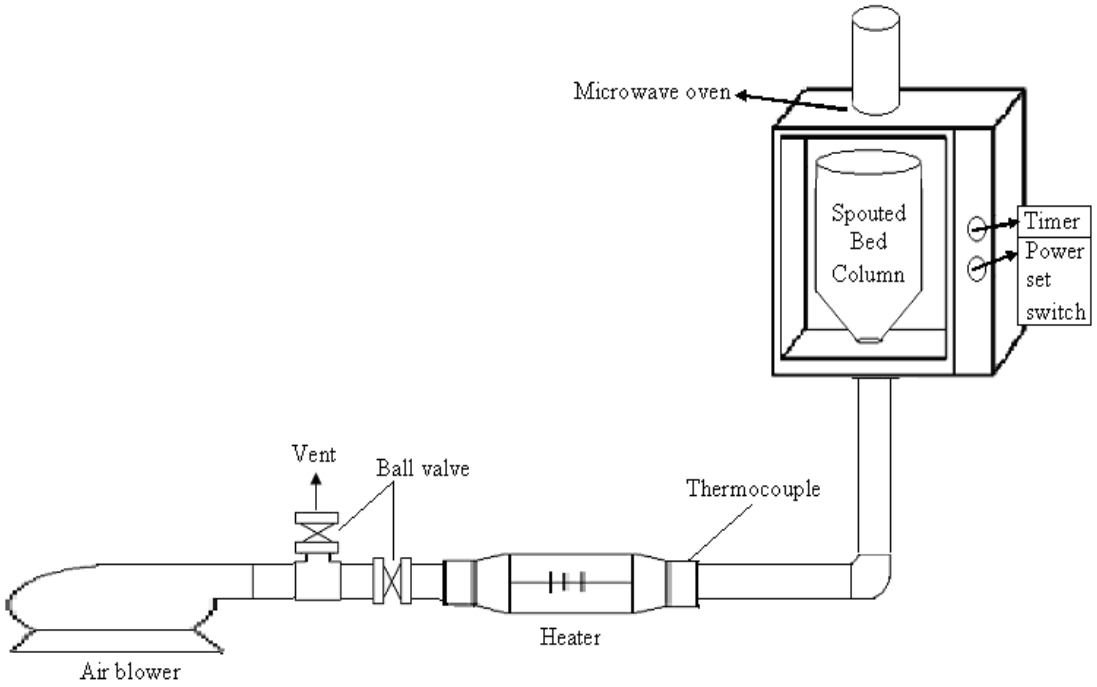

Figure 2.3 Schematic representation of microwave assisted spouted bed drying experimental setup

2.3 Minimum Spouting Velocity Determination

The system shown in Figure 2.4 was used in minimum spouting velocity determination. An open U-tube manometer containing water was placed to the bottom nearest part of spouted bed column to monitor the pressure drop in the bed as air velocity increased. Two ball valves were located at the exit of air blower to adjust air velocity during experiment. In the determination of minimum spouting air

velocity experiments, 200 g of parboiled wheat was weighted by an electronic balance (Sartorius, BP610, Göttingen, Germany) and loaded into the column to obtain maximum of minimum spouting velocity. The air blower was operated and the ball valve was gradually opened with stepwise increments up to no further change in level of water in manometer observed. The experiment was done at room temperature (25^{o}C). An anemometer (Turbo Meter, Davis Instruments, USA) was used to measure the air velocity and corresponding pressure drop values to that velocity were calculated from changes in the level of water in the manometer. Then, the procedure was reversed by gradually closing the valves and monitoring changes in the pressure drop. A plot of bed pressure drop versus superficial air velocity was used to determine minimum spouting velocity.

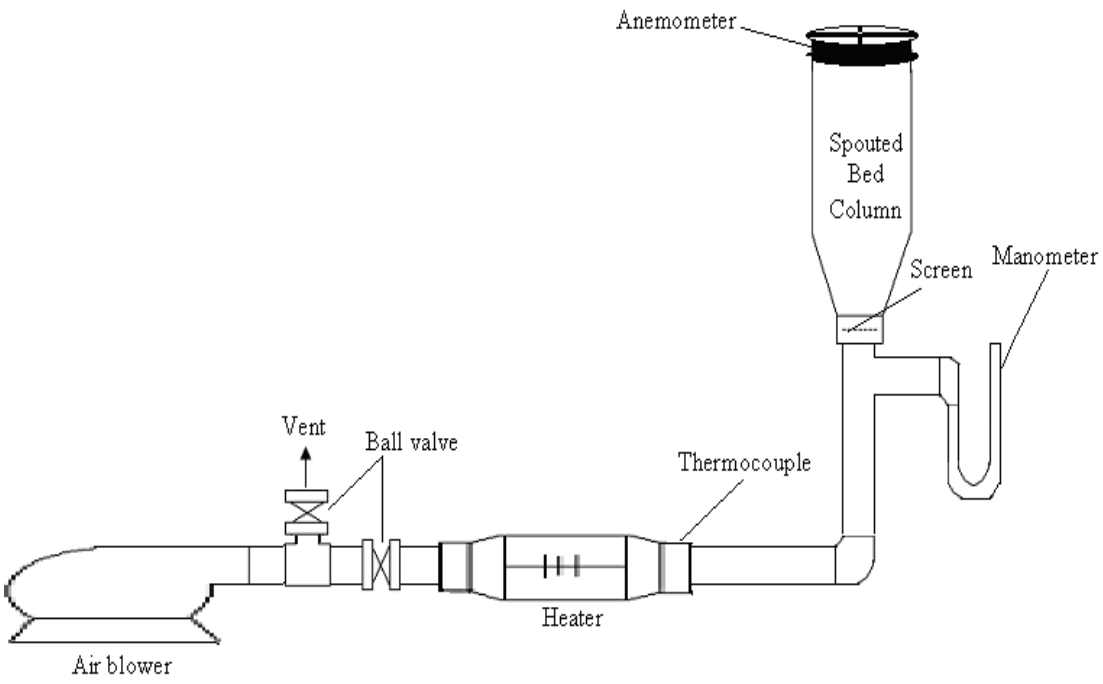

Figure 2.4 Schematic of system in minimum spouting velocity determination

2.4 Preparation of Bulgur

2.4.1 Cleaning

Durum wheat samples were screened through 2 mm and 4mm sieves to eliminate foreign materials, seeds, broken kernels and husk. Samples remained on 2 mm sieve were cleaned further manually to separate same sized foreign materials.

2.4.2 Boiling

Cleaned wheat kernels were cooked in boiling water at a ratio of 1:5 (weight basis). To determine boiling time for entire starch gelatinization, wheat samples were boiled on a hot plate (Karl Kolb Scientific Technical Supplies, Frankfurt., Germany) for different times, 60, 70, 80, 90, 100 minutes, respectively. Differential scanning calorimeter (DSC) (TA Instruments DSC-Q20, New Castle, Delaware, USA) was used to ascertain boiling time. Boiled wheat samples were freeze-dried for 24 hours prior to DSC analysis. Freeze dried wheat samples were ground and loaded into aluminium hermetic pans with a ratio of 1:3 (sample: water ratio). The pan was hermetically sealed. An empty sample pan was used as reference. The DSC was performed by heating from 40 to 120 °C at a heating rate of 10 °C/min. As a result of DSC analysis, time of boiling was determined as 90 minutes (Section 3.1).

Throughout the experiments, cooked wheat kernels were prepared as follows: wheat kernels, separated from foreign materials were cooked at boiling water at 95^{o}C, at a ratio of 1:5 for 90 minutes. Cooked wheat kernels were kept for half an hour in ambient air prior to drying in order to evaporate surface moisture and to separate damaged and different variety kernels by the help of color difference.

2.4.3 Drying

2.4.3.1 Spouted Bed Drying

The system used in spouted bed drying was illustrated in Figure 2.1. Air blower was operated and air velocity in all experiments was adjusted to 0.95 m/s by the help of ball valves. Air velocity was checked by anemometer. Heater was operated for a sufficient time to reach the desired temperature. Inlet air temperature was controlled by thermocouple in the heater controler and thermometer at the same time. Then, cooked wheat kernels were put into the spouted bed column. The weight data was taken in every fifteen minutes by displacing and replacing spouted bed column as fast as possible. For weight measurements of samples, a portable electronic balance with 610 g ± 0.01 g (Sartorius, BP610, Göttingen, Germany) was used. The experiments were performed at the air temperatures of 50, 70 and 90°C until the moisture content of the wheat kernels were reduced below 12% in wet basis.

2.4.3.2 Microwave Assisted Spouted Bed Drying

The system shown in Figure 2.2 was used in microwave assisted spouted bed drying. The spouted bed column was placed into the microwave oven as illustrated in Figure 2.2 . The other parts of the system were the same as the ones in the spouted bed drying system. Air blower was operated and outlet air velocity was brought to 0.95 m/s using the ball valves. The heater was adjusted to obtain the desired air temperature. The cooked wheat kernels were loaded into the spouted bed column and placed in the microwave oven. Then air pipe line was attached to the system. The microwave oven was set to the specified microwave power and then turned on. The weight data was taken in five minute intervals until the moisture content of the wheat kernels were reduced below 12% in wet basis. The experimental procedure was followed for air temperature of 50, 60 and 70°C with two microwave powers: 288 W and 624 W which were determined by IMPI-2L test (Appendix A). The maximum power of the oven was 624 W.

2.4.4 Tempering and Dehulling

Dried cooked wheat was tempered prior to dehulling in order to facilate bran separation. All wheat samples were tempered to 17% moisture content (wet basis) for 16 hours by the addition of sufficient water (Yıldırım, 2004).

Bran separation in tempered wheat was performed by dehuller (Poyraz Degirmen Makinaları, Konya, Turkey). Tempered wheat samples were dehulled for 3 minutes.

2.4.5 Grinding and Shifting

Bran separated wheat samples were ground in a laboratory type roller mill (Maxi C, Batsak Co, Ankara, Turkey). Mill was powered by 0.63 kW. According to TSE, fine bulgur is defined as the bulgur obtained between 2.000 mm and 0.425 mm sieves (TSE, 2003). Therefore, 2.000 mm and 0.425 mm sieves (Endecotts Ltd., London, England) were attached to Octagon 200 Test Sieve Shaker (London, England) where shifted for 5 minutes at amplitude of 8 out of 10 .

2.5 Measurement Methods

2.5.1 Moisture Content

A laboratory oven (Dedeoğlu, TS-5050, Ankara, Turkey) operated at 105°C was used for moisture determination. 10 grams of cooked wheat sample was weighed in an electronic balance (Sartorius, BP610, Germany) and put into the dried petri plate. The dry weights of the samples were determined by heating at 105°C till the constant weight was attained. This procedure was repeated for each of the experimental run.

2.5.2 Bulk Density

The cylindrical glass container with known volume (36 ml) and weight (43.2 g) was filled completely with dried cooked wheat kernels. The container was tapped several times and the excess wheat grains were removed by sweeping the surface of the cylinder with a ruler and the grains were not compressed. Then, sample filled container was weighted by an electronic balance (Sartorius, BP610, Göttingen, Germany) until the weight of sample filled container remained approximately constant. The bulk volume of the dried cooked wheat samples was taken as equal to that of the container. The weight of samples at that volume was calculated by subtracting the weight of empty container from that of sample filled container. Bulk density (g/ml) was then calculated as the ratio between the kernels weight and the volume of the cylinder.

2.5.3 Apparent Density

The apparent volume was measured using the liquid-displacement technique. The burette (100ml) was filled with 50 ml water. The volume displacement of pre-weighed (5 g) dried cooked wheat immersed in the water was measured. Apparent density (g/mL) was then determined by dividing the weight of the dried cooked wheat by its apparent volume.

2.5.4 Porosity

2.5.4.1 Bulk Porosity

Bulk porosity (ε) was calculated using the relationship between bulk (ρ_{bulk}) and apparent densities ($\rho_{apparent}$) according to Sahin and Sumnu (2006) as follows:

$$\varepsilon = 1 - \frac{\rho_{bulk}}{\rho_{apparent}} \qquad 2.1$$

2.5.4.2 Mercury Porosimetry

Porosity and pore size distribution within the kernels were measured by using a porosimeter (Poremaster 60, Quantichrome Corp., Florida, USA) which automatically performed complete porosimetry runs (intrusion and extrusion). About 0.7 g of dried cooked wheat grains were placed in a sample holder. The sample holder was then placed in the mercury porosimeter and the run parameters were entered. The run mode was set at autospeed and the maximum pressure was set to 300 MPa. For all calculations mercury surface tension (γ) was taken as 480 erg/cm^2 and mercury contact angle (α) as 140^o. Relation between pressure (P) and pore diameter (D) was explained by Washburn equation (Adamson, 1990) which describes a linear relationship between the size of an intrudable circular pore and the applied mercury pressure in the mercury porosimeter;

$$D = \frac{-4\gamma\cos\alpha}{P} \qquad 2.2$$

2.5.5 Microstructural analysis

The dried cooked wheat kernels were frozen with liquid nitrogen and then cut vertically into two pieces, mounted on an aluminum platform with an adhesive and coated with gold. SEM images were obtained at two different magnifications (14×, 300×). All SEM images were obtained at a voltage of 20 kV using a scanning electron microscope (JSM-6400-NORAN, Tokyo, Japan).

2.5.6 Sphericity

A micrometer (Mitutoyo, CD-15D, Japan) was used to determine length (L), width (W) and thickness (T) of 10 randomly selected dried cooked wheat grains from each experimental run. The geometric mean, D_g, equivalent, D_p and arithmetic diameter, D_a, in mm was calculated by considering prolate spheroid shape for a wheat grain (Mohsenin, 1986):

$$D_g = (LDT)^{\frac{1}{3}} \quad 2.3$$

$$D_p = \left[L \frac{(W+T)^2}{4} \right]^{\frac{1}{3}} \quad 2.4$$

$$D_a = \frac{(L+W+T)}{3} \quad 2.5$$

The sphericity (Θ) defined as the ratio of the surface area of the volume of sample which is assumed to be equal to the volume of the triaxial ellipsoid having equivalent diameters the volume of the circumscribed sphere, was determined through the equation (Mohsenin, 1986):

$$\Theta = \frac{(LDT)^{\frac{1}{3}}}{L} \quad 2.6$$

2.5.7 Color

The color of dried cooked wheat samples were measured by a color reader (Minolta, CR10, Osaka, Japan). The CIE color values expressed as L* (whiteness/ darkness), a* (redness/greenness) and b* (yellowness/blueness) for the respective samples were determined.

2.5.8 Yield

Bran separated dried cooked wheat was ground in a laboratory type roller mill (Maxi C, Batsak Co, Ankara, Turkey) and sifted through 2.0 and 0.5 mm sieves for 5 minutes. The ground material was then classified as fine bulgur (0.5 to 2 mm). The percentage of the materials remaining on the sieve was expressed as yield;

$$\text{Yield (\%)} = \frac{\omega_b}{\omega_w} \times 100 \quad 2.7$$

where ω_b and ω_w are the weight of the fine bulgur and dried cooked wheat, respectively.

2.5.9 Water Adsorption Capacity

Bulgur samples (10 gr) was poured into 30 ml of water in the centrifugal tubes. The sample in the tubes was put into water bath at 75°C for 20 minutes and then centrifuged (Sigma-2-16 PK, Germany) at 4000×g for 10 minutes. Water absorption capacity value is expressed as;

$$\text{Water absorption(g water / g bulgur)} = \frac{W_2 - W_1}{W_1} \qquad 2.8$$

where W_2 is the weight (g) of bulgur after centrifugation and W_1 is the initial weight (g) of bulgur (Hayta, 2002).

2.6 Data Analysis

The effects of drying conditions were determined by using analysis of variance (ANOVA) and Tukey's Comparison Test ($p<0.05$). All statistical analysis were performed by using Minitab statistics programme (MINITAB for Windows, Version 15, Minitab Inc., State College, Pa., USA).

CHAPTER 3

RESULTS AND DISCUSSION

Drying is one of the most important steps in bulgur production since it affects various quality parameters as well as storage properties of bulgur. Spouted bed dryer has not been used in production of bulgur up to now although there are some studies on drying of raw wheat in literature (Mathur and Gishler, 1955; Thorley et al., 1959; Becker and Sallans, 1961; Kugo et al., 1965; Viswanathan et al. ,1986; Gong et al., 1997; Go et al., 2007). In addition, microwave assisted spouted bed dryer offers additional benefits by minimizing possible drawbacks of both spouted bed and microwave drying. In this study, the effects of different drying methods such as spouted bed and microwave assisted spouted bed drying on drying rate curves and quality parameters of dried cooked wheat and bulgur were investigated. Measured quality parameters for dried cooked wheat were bulk density, apparent density, porosity, sphericity and color; for bulgur were yield and water absorption capacity. Microstructure analysis was also performed for dried cooked wheat.

3.1 Determination of Boiling Time of Raw Wheat

Complete wheat starch gelatinization without deforming wholeness of the wheat is the aim of the cooking process since dispersed wheat kernel as a result of cooking may affect following operations i.e. drying, milling etc. severely in bulgur production and so the final product quality (Bayram et al. 1996, 2004a, 2004b). Three gelatinization measuring methods i.e. centre cutting, light scattering and amylose/iodine, were used to control the cooking of wheat (*Triticum durum*) for bulgur processing in the literature (Smith et al., 1964; Singh and Dodda, 1979; Bayram, 2005, 2006). In this study, instead of these three methods, differential scanning calorimeter was employed to determine the boiling time of wheat (60, 70, 80, 90, 100 minutes) at which 100% starch gelatinization occured. The interaction

between starch and water involves both the melting of starch crystallites and the glass transition of amorphous regions (Slade and Levine, 1988). Both of these can be examined by differential scanning calorimetry (DSC). As cooking time increased, enthalpy of gelatinization decreased since longer cooking time resulted in more gelatinized wheat samples (Figure 3.1). Gelatinization temperature was slightly increased with cooking time. This can be attributed to gelatinization of weaker granules first (Garcia et al.,1996). In a typical DSC-profile for durum wheat starches, gelatinization peak can be noticed around 55–60 °C (Vansteelandt and Delcour, 1999) which was consistent with the gelatinization temperature observed around 55^{o}C in Figure 3.1. The endothermic gelatinization peaks were observed up to 90 minutes which indicated that complete starch gelatinization was achieved when raw wheat was cooked for 90 minutes. Thus, all cooking experiments were carried out for 90 minutes.

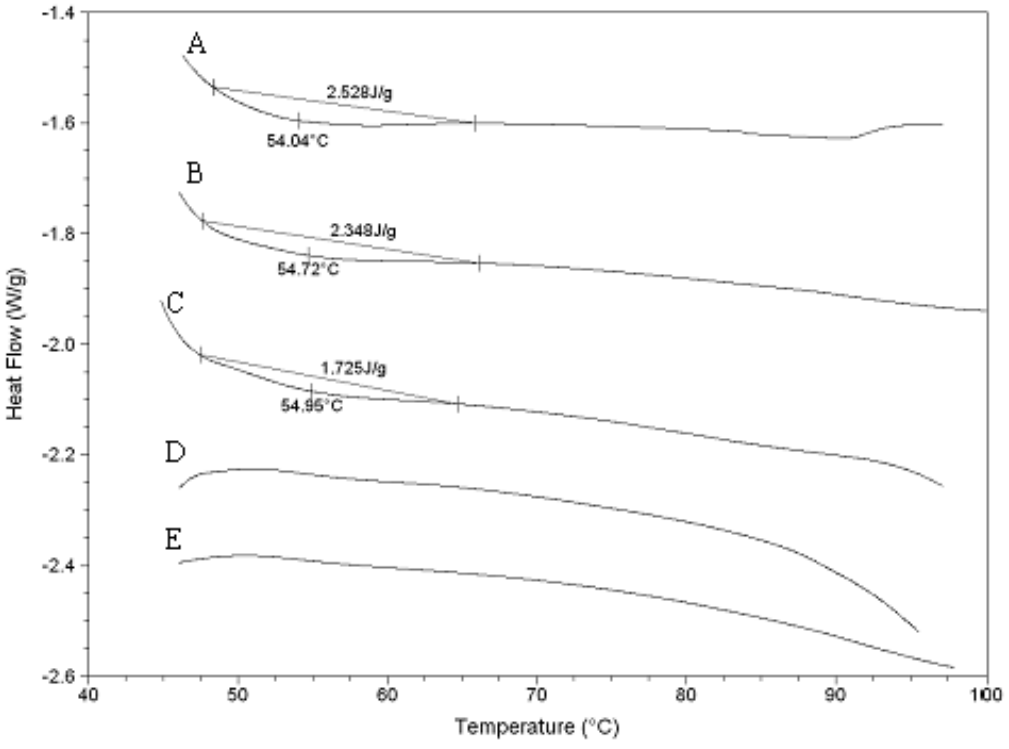

Figure 3.1 DSC thermogram of cooked wheat at different boiling times (A:60; B:70; C:80; D:90; E:100 minutes)

3.2 Minimum Spouting Velocity

As steady spouting of wheat was observed in the bed for 200 g of cooked wheat, the weight of cooked wheat in all drying experiments was selected as 200 g. In the determination of minimum spouting air velocity experiments, 200 g of parboiled wheat was loaded into the column to obtain maximum of minimum spouting velocity. Besides, experiment was done at room temperature ($25^{o}C$) instead of studied drying temperatures so as to avoid changes in the height of the bed. During drying at high temperatures, height of bed decreases since most of the moisture within the particle is evaporated which also causes a decrease in the minimum spouting air flow requirement. In this way, it is provided that air flow rate will always be higher than minimum spouting flow requirement. To determine minimum spouting velocity, a plot of bed pressure drop versus superficial air velocity was used (Figure 3.2 referring to data in Appendix B). Minimum spouting velocity is obtained by slowly decreasing the air flow. Spouting conditions is observed until point C. After point C, there is a pressure drop increase which is an indication of collapse of spout.

Following sequence of events was observed as air flow rate was increased. From starting point to point A, pressure drop increased almost linearly with increasing air velocity. Small air cavity started to form at the air inlet of the column. This cavity compressed particles inside the bed and caused them to form a compact arch which brought about a resistance to flow and so increased the pressure drop. At point A, maximum pressure drop was observed. After point A, pressure drop did not rise with air velocity since dimensions of hollow internal cavity(spout) became large compared to the packed solids above it. Thus, pressure drop reduced up to point B. At point B, onset of spouting occured which meant further increasing air velocity did not have an effect on pressure drop since air easily passed through the bed as bed became mobile (Mathur and Epstein, 1974).

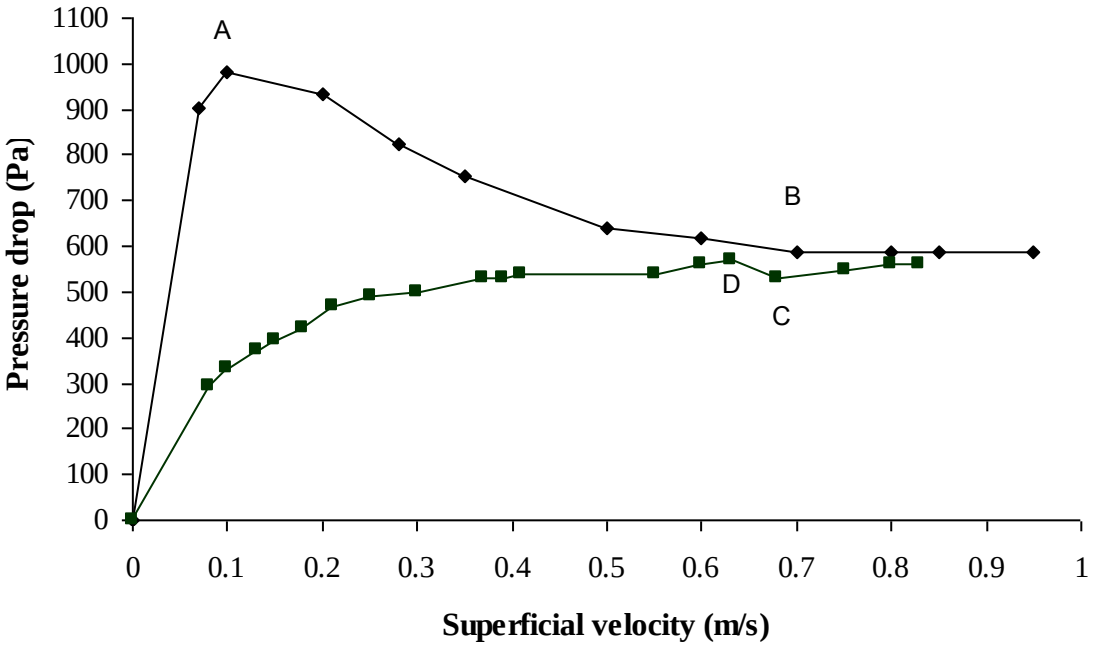

Figure 3.2 Spouting characteristics of parboiled wheat, A: maximum pressure drop; B: onset of spouting ; C: minimum spouting point; D: spout collapse

(♦) increasing flow (■) decreasing flow

In the plot, point C corresponds to a superficial air velocity of 0.68 m/s. In order to ensure steady spouting, superficial air velocity of 0.95 m/s, nearly 1.4 times minimum spouting velocity, was used in all the experiments. Minimum spouting velocity was also calculated by the Mathur-Gisher equation to verify experimentally found one (Mathur and Epstein, 1974):

$$U_{ms} = \left(\frac{d}{D_c}\right)\left(\frac{D_i}{D_c}\right)^{1/3}\sqrt{\frac{2gH(\rho_p - \rho_f)}{\rho_f}} \qquad 3.1$$

where d, D_c and D_i are the particle, column and nozzle diameters (m), respectively; g is the gravimetric acceleration (m/s^2); H is the height of the bed (m); $\rho_p$and ρ_f are the density of particle and air (kg/m^3), respectively. Values of all variables in the equation given in Appendix B. Minimum spouting velocity was calculated as 0.75 m/s empirically which is close to the experimental result.

3.3 Drying Rate Curves

In this study, drying rate curves were prepared for spouted bed and microwave assisted spouted bed drying of cooked wheat. Although drying is one of the crucial steps which affects its quality, reported studies about drying characteristics of bulgur were limited.

3.3.1 Spouted Bed Drying

In this part of the study, the effect of inlet air temperature (50, 70, 90^{o}C) on drying rate curves was investigated. The weight data taken in the spouted bed drying experiments are given in Table C.1. This data were converted into the moisture content in the dry basis which was also given in Table C.2. The drying curve obtained at different inlet air temperatures in spouted bed drying can be seen in Figure 3.3. Large temperature difference between the grain surface and the evaporation front makes the release of moisture easier. Therefore, dring was achieved in a shorter time when higher inlet air temperature was used.

The effect of air temperature on spouted bed drying can also be observed from drying rate curve (Figure 3.4). As the temperature of drying increased, drying rate increased throughout drying period. As a result, drying time decreased (Figure 3.3). The increase in temperature brings about rise in evaporation rate and effective mass diffusivity which result in higher drying rate. In addition, the total drying process was observed to be occured in falling rate period which means that moisture diffusion was the main mechanism of wheat drying in a spouted-bed dryer. Internal moisture diffusion resistance is very high as compared to external convective resistance. Mass transfer Biot number is typically in the order of 10^{6}-10^{7} for cereal grains under spouting conditions (Mathur and Epstein, 1974).

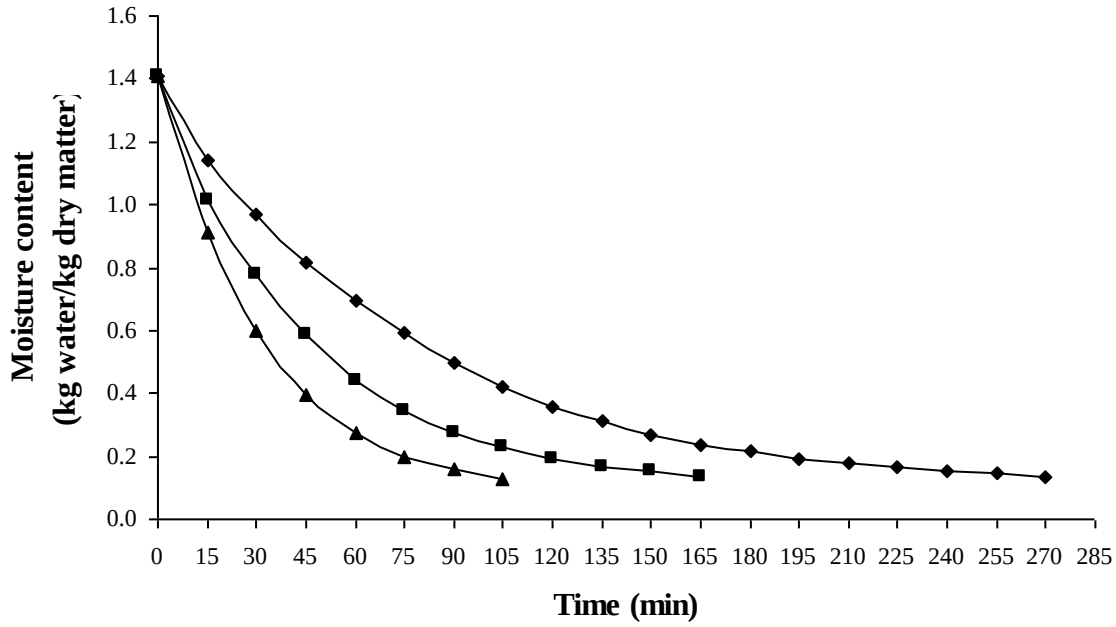

Figure 3.3 Spouted bed drying curves at different temperatures

(♦) 50°C (■) 70°C (▲) 90°C

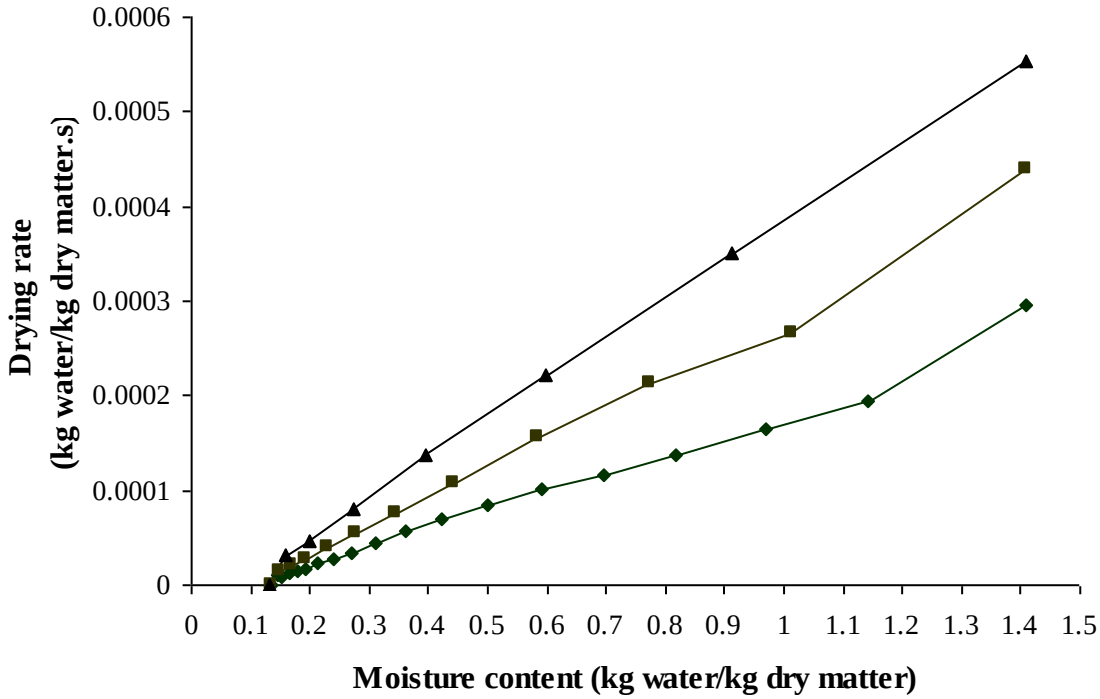

Figure 3.4 Drying rate curves for spouted bed drying at different temperatures

(♦) 50°C (■) 70°C (▲) 90°C

3.3.2 Microwave Assisted Spouted Bed Drying

In this part of study, the influence of microwave power (288 and 624 W) combined with hot air drying (50, 70 and 90^{o}C) was investigated.

The weight loss data taken in the microwave assisted spouted bed drying are given in Table C.3 and C.4. This data were converted into moisture content in dry basis data given in Table C.5 and C.6. Dring rate curves obtained at different conditions can be seen in Figures 3.5- 3.9.

Figures from 3.5 to 3.7 shows that as microwave intensity increased, drying rate increased significantly. This can be due to an increase in the temperature of the moisture inside the particles, caused by a higher steam pressure developed at higher microwave intensity. Relatively large amounts of internal heating when microwave was used results in higher moisture vapor generation inside the grain. This creates significant internal pressure and concentration gradients.

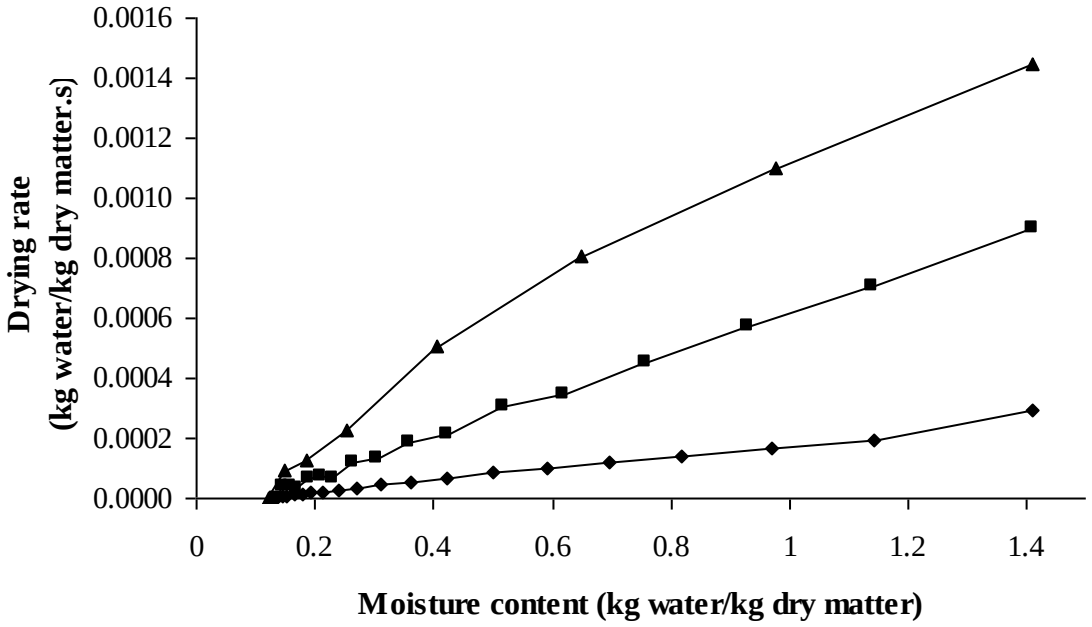

Figure 3.5 Drying rate curves for spouted bed drying and microwave assisted spouted bed drying at 50^{o}C.(♦) Spouted bed only (■) 288 W (▲) 624 W

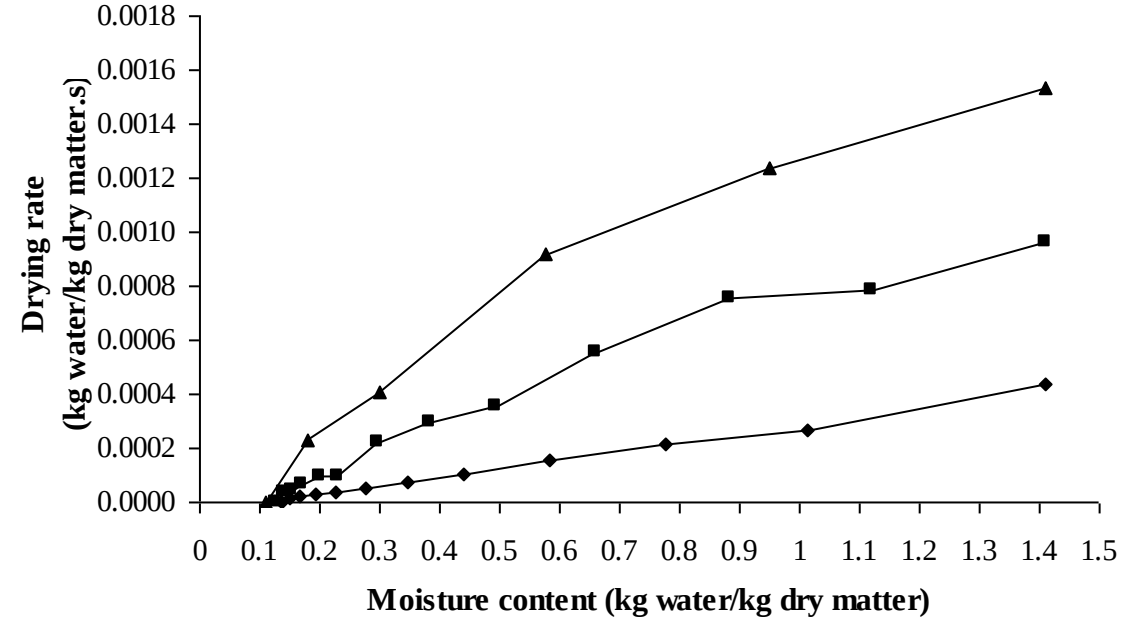

Figure 3.6 Drying rate curves for spouted bed drying and microwave assisted spouted bed drying at 70°C.(♦) Spouted bed only (■) 288 W (▲) 624 W

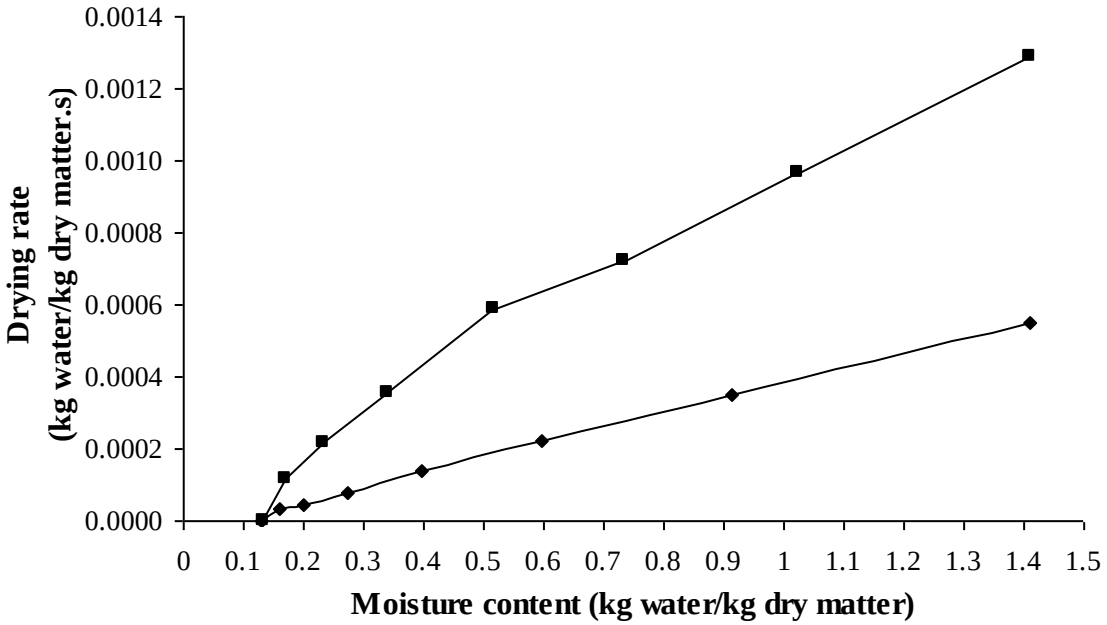

Figure 3.7 Drying rate curves for spouted bed drying and microwave assisted spouted bed drying at 90°C.(♦) Spouted bed only (■) 288 W

Figure 3.8 and 3.9 indicates that increasing temperature caused a rise in drying rate for microwave assisted spouted bed drying. The effect of temperature on drying rate was hardly observed below 20% (db) moisture content. This is because the internal heat generation by microwave power is a very effective process for the evaporation and removal of water even at low moisture levels or in the falling rate period. In other words, because of large amount of heating, moisture evaporates inside the material creating significant interior pressure. Thus, mass transfer in microwave drying is mostly dependent on pressure gradient other than moisture gradient or diffusion. Below 20% moisture content, drying takes place dominantly by microwave since moisture gradient became negligible compared to pressure gradient inside the wheat kernel.

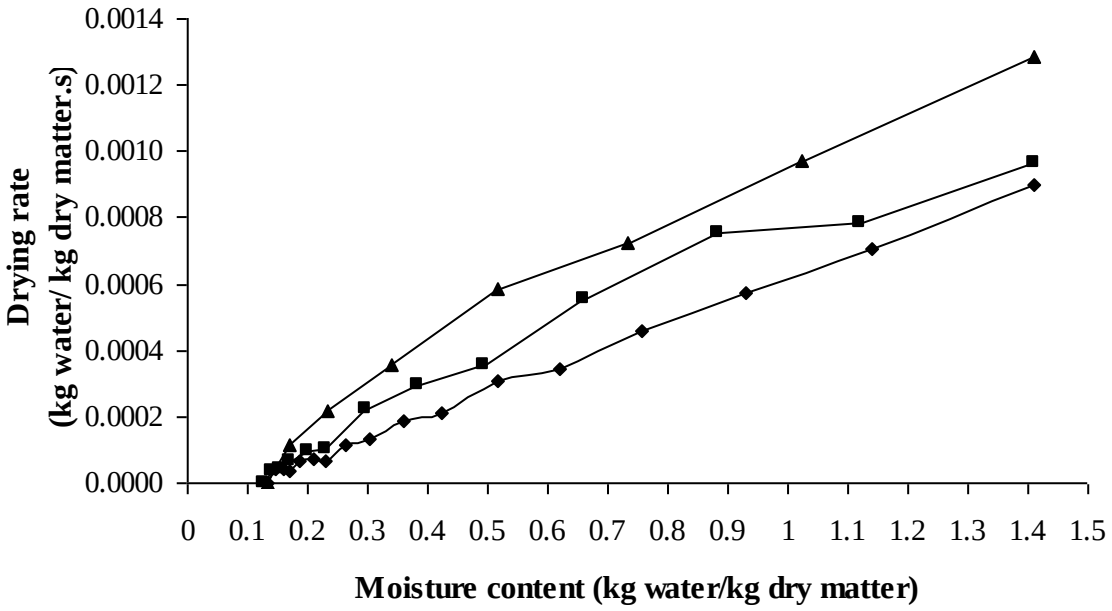

Figure 3.8 Drying rate curves for microwave assisted spouted bed drying at 288 W (♦) 50°C (■) 70°C (▲) 90°C

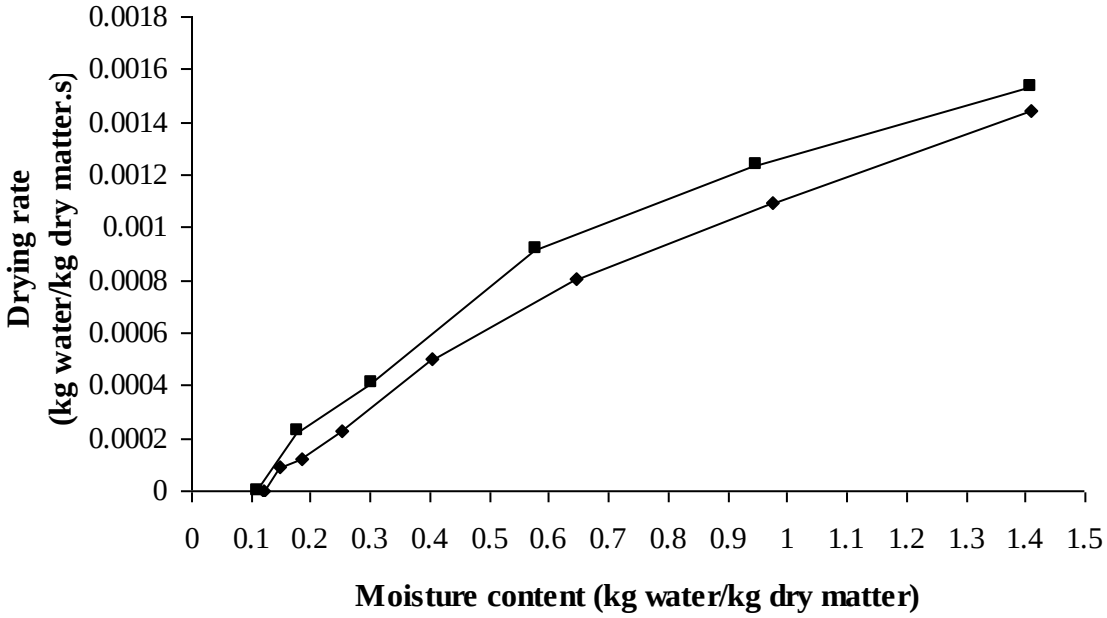

Figure 3.9 Drying rate curve for microwave assisted spouted bed drying at 624 W (♦) 50°C (■) 70°C

Table 3.1 Drying times for different drying methods

Microwave Power	50°C	70°C	90°C
NO	270 min	165 min	105 min
288 W	80 min	60 min	35 min
624 W	35 min	25 min	------

Effects of temperature and microwave powers on different drying conditions can easily be observed by the help of Table 3.1. Increase in the microwave power increases the vapor pressure of the moisture within the grains creating a higher vapor pressure gradients which results in higher drying rate and as a result lower drying time. Microwave assisted spouted bed drying at microwave power of 288W and 624 W resulted in time reduction of at least 60% and 85%, respectively compared to spouted bed drying. When temperature increased in spouted bed from 50°C to 70°C,

reduction of time was 39%. Increasing temperature in spouted bed from 50°C to 90°C caused time reduction of 61%. As a result, it can be said that combining spouted bed drying with microwave decreases time of processing more than increasing temperature in hot air spouted bed drying.

3.4 Determination of Effective Diffusivity

Equilibrium moisture contents were determined according to information given in Appendix C. The relative humidity and the corresponding calculated equilibrium moisture contents are given in Table C.7. Moisture content data and equilibrium moisture contents given in Appendix C were substituted into the equation (Equation 1.7) to draw the curves to obtain the effective moisture diffusivities (Figure 3.10-3.12).

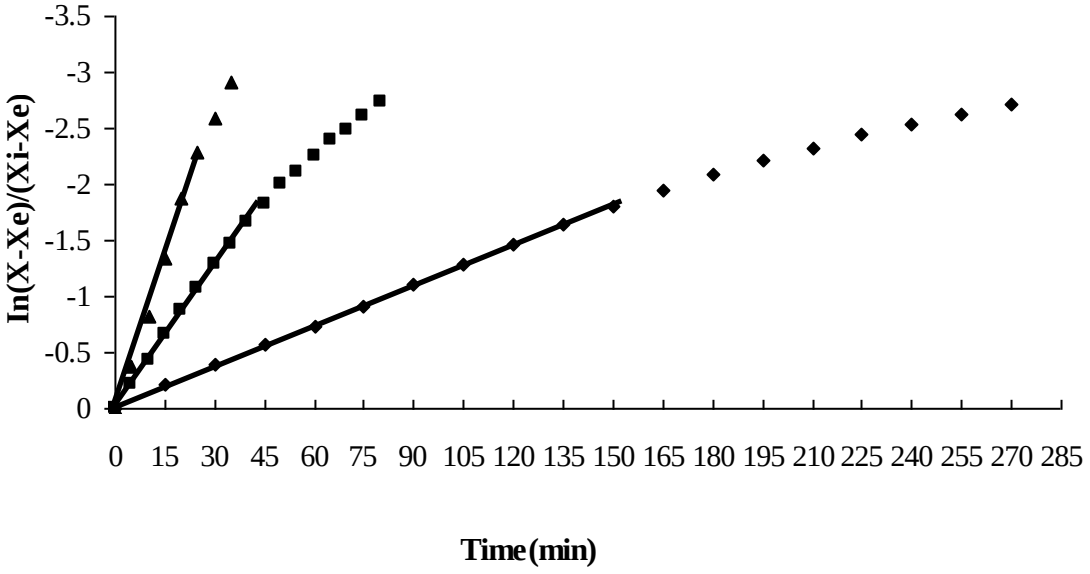

Figure 3.10 Variation of dimensionless moisture content with time for the spouted bed and microwave assisted spouted bed drying at 50°C
(♦) Spouted bed only (■) 288 W (▲) 624 W

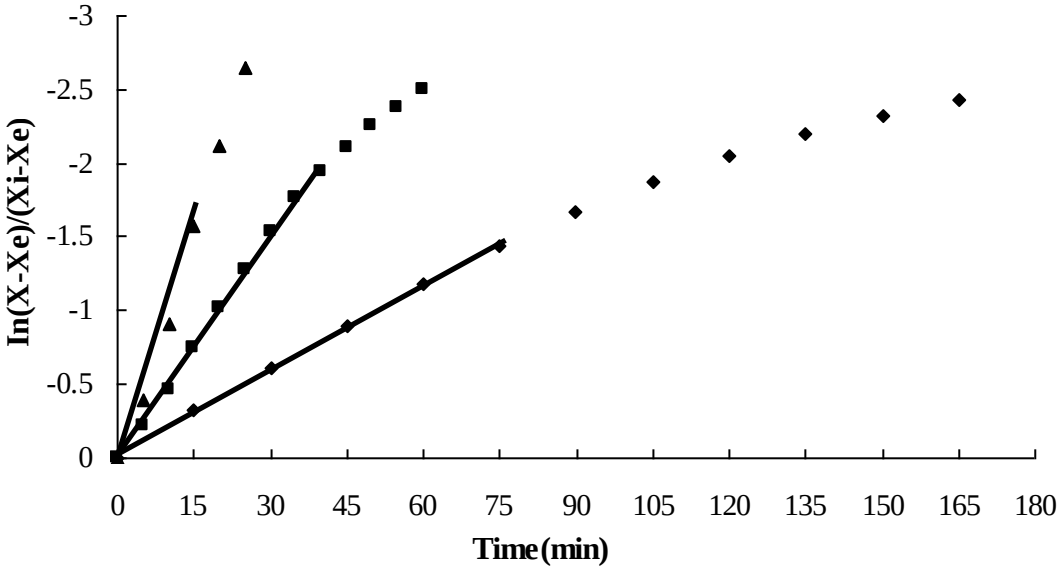

Figure 3.11 Variation of dimensionless moisture content with time for the spouted bed and microwave assisted spouted bed drying at 70°C

(♦) Spouted bed only (■) 288 W (▲) 624 W

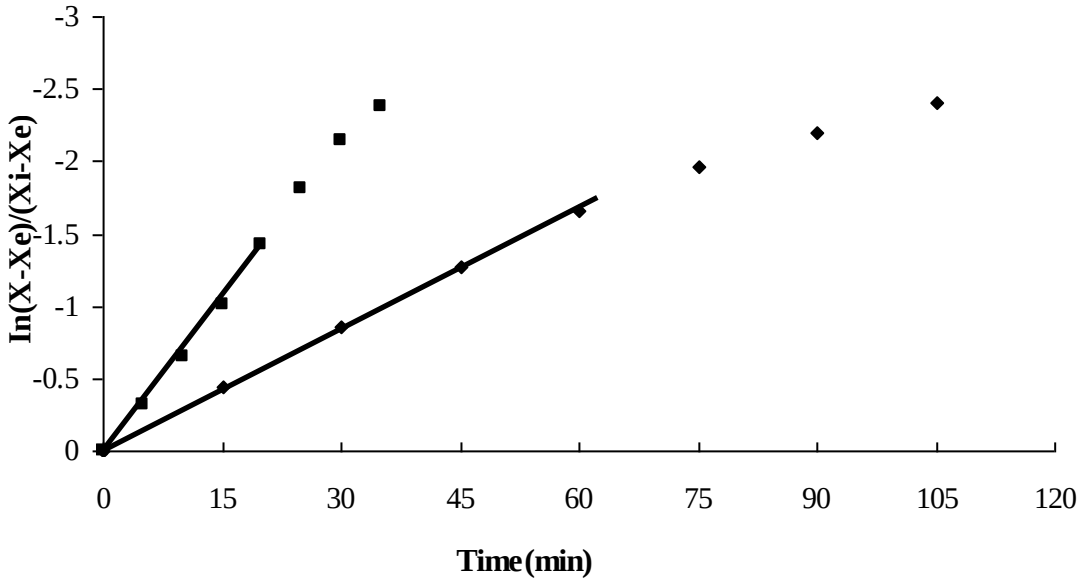

Figure 3.12 Variation of dimensionless moisture content with time for the spouted bed and microwave assisted spouted bed drying at 90°C

(♦) Spouted bed only (■) 288 W

It can be seen from figures that there was more than one falling rate period. The reason for this was the higher moisture content of cooked wheat which shrunk considerably during drying. Turhan et.al (2001) also observed two falling rate periods for the whole grains of gelatinized durum wheat dried by forced and natural convection by using a simple mathematical model based on overall moisture balance instead of Fick's second law. Fick's second law for unsteady state diffusion can be used since liquid diffusion of moisture controls the rate of drying in the falling rate period. By assuming long drying times, only the first term in the solution of Fick's second law for unsteady state diffusion was taken into consideration. Slopes of the lines were determined by regression analysis and effective diffusivity values were calculated for the first falling rate period only. The first linear portion of the curve was taken to ignore the effect of shrinkage on effective diffusivity. The results are tabulated in Table 3.2.

Table 3.2 D_{eff} values for the first falling rate period

Drying Method	Drying Conditions	$D_{eff} \times 10^{10}(m^2/s)$	r^2	Fo
Spouted	50°C	1.44	0.999	0.32
bed	70°C	2.31	0.998	0.32
drying	90°C	3.32	0.999	0.29
Microwave	50°C- 288 W	5.06	0.999	0.34
assisted	50°C- 624 W	11.3	0.995	0.33
spouted	70°C- 288 W	6.21	0.999	0.31
bed	70°C- 624 W	10.9	0.995	0.23
drying	90°C- 288W	8.52	0.997	0.25

Fourier number was also taken into consideration to check the long drying time assumption and it was found to be greater than 0.1 for all cases since time was relatively long enough. Effective diffusivities found were within the range (10^{-9} to 10^{-11} m^2/s) that were reported for the drying of food products (Madamba et. al., 1996).

The increase in effective diffusivity with temperature and microwave power level can be seen from Table 3.2. In fact, this increase became obvious as microwave power increased. The effective diffusivities of cooked wheat samples dried in microwave assisted spouted bed were higher than that in spouted bed. The effective diffusivity depends mainly on moisture content, temperature and the physical structure of the product (Feng et al.,1999). As final moisture content of all samples were approximately the same, the increase in effective diffusivity with temperature and microwave power level can be attributed to the change in physical structure of the samples. Porosity is one of the most crucial structural factors affecting the diffusion of moisture in the food polymer matrix for porous food products (Feng et. al, 1999). Thus, rapid heating in microwave drying may result in higher vapor pressure inside the sample which may enhance pore formation and end up with faster moisture diffusion through the surface of sample and so higher effective moisture diffusivities. This internal vaporization may promote with increase in microwave power and cause effective diffusivity to increase with microwave power. In literature, this was also observed in the effective diffusivities of some food products: diced apple (Feng et al., 1999); garlic cloves (Sharma and Prasad, 2004); apple pomace (Wang et al., 2007).

The effect of temperature on effective diffusivity is generally expressed using an Arrhenius-type relationship, since temperature has the significant effect over the drying process rather than initial moisture content of the product;

$$D_{eff} = D_0 \exp\left[-\frac{E_a}{RT}\right] \qquad 3.10$$

where, D_o is a diffusivity at infinite high temperature, E_a is the activation energy (kJ/kg mol), R is universal gas constant, 8.314 kJ/kgmol.K.

In(D_{eff}) versus 1/T graph was plotted to determine D_o and Ea values (Figure 3.13). The slope of the curve gives the Ea/R, while the intercept gives the D_o. D_o and activation energy were found as 2.89×10^{-7} m^2/s and 20404 kJ/kgmol, respectively.

Temperature dependency of effective diffusivity expressed using Arrhenius equation is;

$$D_{eff} = 2.89\times10^{-7}\exp\left[-\frac{2454.15}{T_{abs}}\right] \qquad 3.3$$

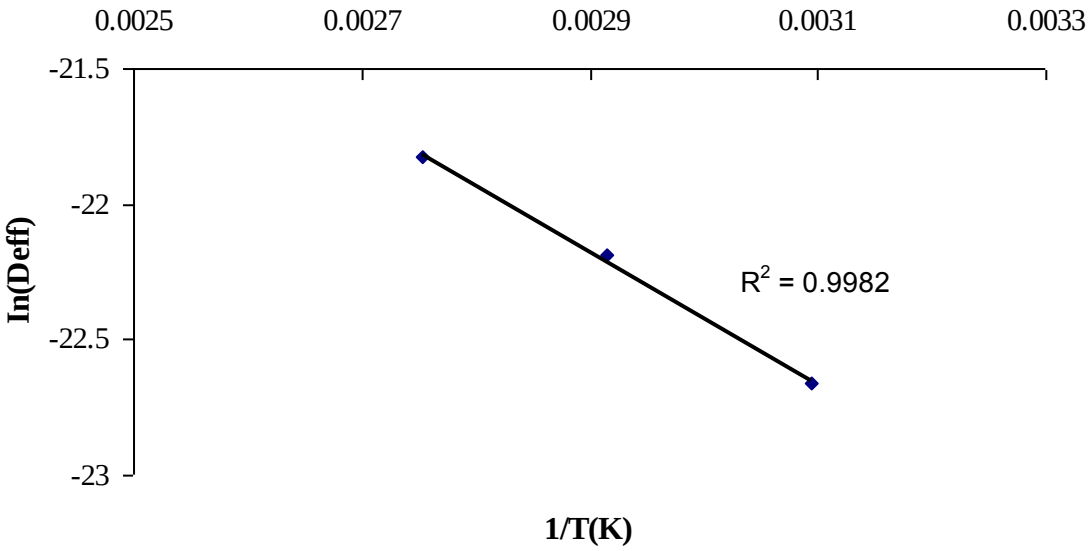

Figure 3.13 Arrhenius plot for the spouted bed drying

This activation energy is 2.2 times lower than the value of 37013 kJ/kgmol reported earlier for drying of parboiled wheat (Mohapatra and Rao, 2005). This can be explained by differences in drying methods (temperature ranges), variety of wheat and initial moisture content of wheat. Thermodynamically, activation energy is related to the ease with which the water molecules pass the energy hurdle when migrating within the product. A lower activation energy means to a higher drying rate in a drying process (Adu and Otten, 1996). Spouted bed or well- agitated bed ensures uniform particle temperature(Becker and Sallans, 1960). This may result in less energy for the removal of moisture and so lower activation energy.

3.5 Quality Parameters

The quality of dried products mainly depends on drying methods and conditions. For this reason, the effect of drying methods and conditions should be investigated to obtain high quality final product. The quality parameters can be categorized as (Krokida and Maroulis, 1999);

- Thermal properties (state of product: glassy, crystalline, rubbery)
- Structural properties (density, porosity, pore size, specific volume)
- Textural properties (compression test, stress relaxation test, tensile test)
- Optical properties (color, appearance)
- Sensory properties (aroma, taste, flavor)
- Nutritional characteristics (vitamins, proteins)
- Rehydration properties (rehydration rate, rehydration capacity)

In this study, apparent density, bulk density, porosity, microstructure and sphericity (structural properties), color (optical properties), water absorption capacity (rehydration properties) and yield were examined as quality parameters for spouted bed and microwave assisted spouted bed drying.

3.5.1 Bulk Density

The values of bulk density of cooked wheat dried in the spouted bed and microwave assisted spouted bed dryers at different conditions are illustrated in Table 3.3. ANOVA and Tukey's test results are given in the Appendix D.1.

Bulk density values of dried cooked wheat did not change significantly with air temperature in the spouted bed drying as seen in Table 3.3 ($p>0.05$). Hatamipour and Mowla, (2003) showed that air temperature, inert material, and air velocity had no significant effect on physical properties of maize and green peas and therefore, shrinkage and density are only functions of moisture content in the fluidized bed with inert particles. Besides, bulk density of dried cooked wheat in spouted bed and microwave assisted spouted bed at low microwave power (except air temperature of

90^{o}C) were not significantly different from each other in terms of drying method and drying temperatures. In microwave assisted spouted bed drying, the increase in microwave power decreased bulk density significantly. This can be due to improved puffing effect or volumetric expansion at high microwave power levels. Krulis et al. (2005) indicated that increase in microwave power resulted in higher percent of puffed particles and so lower bulk density of microwave vacum dried strawberry. The bulk densities of cooked wheat dried at 70^{o}C with 624 W and 90^{o}C with 288 W in microwave assisted spouted bed drying were significantly lower than that of the others ($p<0.05$). In general, hot air combined with higher microwave power resulted in lower bulk densities. This can be attributed to puffing effect of microwave which is caused by internal vapor generation. Puffing effect may cause wheat grain to swell during drying and result in volume increase at the end of drying. It was also reported by Krokida and Maroulis, (1999) that the bulk density of microwave dried material was lower than that of conventionally air dried materials.

Table 3.3 Bulk density values for dried cooked wheat

Drying Method	Drying Condition	Bulk Density(kg/m^3)
Spouted bed	50^{o}C	691.56± 13.199^{ab*}
	70^{o}C	689.83± 26.163^{ab}
	90^{o}C	667.36± 2.082^{b}
Microwave assisted spouted bed	50^{o}C, 288W	739.89± 9.428^{a}
	50^{o}C, 624W	678.97± 14.260^{b}
	70^{o}C, 288W	697.72± 1.257^{ab}
	70^{o}C, 624W	590.67± 1.109^{c}
	90^{o}C, 288W	606.44± 21.135^{c}

*Values with different superscripts means that drying conditions are significantly different ($p< 0.05$)

3.5.2 Apparent Density

The apparent density values for dried cooked wheat in the spouted bed drying and microwave assisted spouted bed drying are tabulated in Table 3.4. Anova table and Tukey's test results for apparent density are given in Appendix D.2.

Table 3.4 Apparent density values for dried cooked wheat

Drying Method	Drying Condition	Apparent Density(kg/m^3)
Spouted bed	50^oC	1190.5 ± 0.00^a
	70^oC	1206.4 ± 61.66^a
	90^oC	1149.6 ± 21.94^a
Microwave assisted spouted bed	50^oC, 288W	1203.8 ± 18.81^a
	50^oC, 624W	1100.1 ± 18.65^{ab}
	70^oC, 288W	1188.1 ± 0.00^a
	70^oC, 624W	1021.4 ± 1.44^b
	90^oC, 288W	1020.8 ± 29.46^b

As illustrated in the Table 3.4, the effect of temperature on the apparent density in spouted bed drying was not found to be significant. Apparent density of continuous materials is dependent on the moisture content and on the shrinkage resulted by the water removing method (Krokida and Maroulis , 2000). Ramallo et al. (2001) showed that apparent density of leaves varied greatly with moisture content, but this variation did not depend on drying temperature between 100 and 130^oC when the experiments were carried out in a convective cross-flow air dryer. In this study, only final products were subjected to apparent density measurement. As final moisture content of all dried cooked wheat were approximately the same (10% to 12% in wet basis), the effect of moisture content on apparent density was not investigated. Besides, the influence of drying methods on apparent density were observed in microwave assisted spouted bed drying at high temperatures combined with high microwave powers. Apparent densities of dried cooked wheats at 70^oC

with 624 W of microwave power and 90^{o}C with 288 W of microwave power were significantly different than that of other wheat samples ($p<0.05$). Apparent density tended to decrease with an increase in microwave power. Lower apparent densities can be an indication of pore formation. This can be explained by puffing effect of microwave drying which results in greater apparent volume of microwave dried product than that of the air dried ones and decrease in apparent density. Puffing effect of microwave in apparent density was reported by Feng and Tang, (1998) in the study of drying of diced apples in a microwave assisted spouted bed. This was also observed by Feng and Tang, (1999) for the drying of blueberries in microwave assisted spouted bed drying.

3.5.3 Porosity

Information on the characteristics of pores and the mechanical properties of dried food products is necessary for process design, estimating properties such as thermal conductivity, density and moisture diffusivity, and determining food quality (Rahman, 2001). In this part of the study, characteristics of both spouted bed and microwave assisted spouted bed dried cooked wheat were investigated by calculating bulk porosity from the measured bulk and apparent densities and internal porosity, and pore size distribution determined with mercury porosimeter.

3.5.3.1 Bulk Porosity

Bulk porosity values of dried cooked wheat in terms of drying conditions are given in Table 3.5. Related statistical results are in Appendix D.3.

As expected, bulk porosity did not change in spouted bed drying with temperature since the effect of spouted bed air-drying temperature was insignificant on bulk density and apparent density values of dried cooked wheat (Table 3.3& 3.4). Both bulk and apparent density depend mostly on moisture content and drying methods rather than drying air temperature.

Table 3.5 Bulk porosity values for dried cooked wheat

Drying Method	Drying Conditions	Bulk Porosity
Spouted bed	50°C	0.42± 0.011[a]
	70°C	0.42± 0.007[a]
	90°C	0.42± 0.009[a]
Microwave assisted spouted bed	50°C, 288W	0.38± 0.000[b]
	50°C, 624W	0.38± 0.002[b]
	70°C, 288W	0.41± 0.001[a]
	70°C, 624W	0.42±0.000[a]
	90°C, 288W	0.40 ±0.003[ab]

In microwave assisted spouted bed, bulk porosity did not change with increase in microwave power at specified temperature. Although bulk and apparent densities at 70°C with 624 W microwave power and 90°C with 288 W microwave power in microwave assisted spouted bed were significantly lower than that of other wheat samples, bulk porosity of dried cooked wheat did not show any significant difference at these drying conditions. Any significant difference in densities may become negligible during the calculation of bulk porosity. On the other hand, bulk porosity values of dried cooked wheat at 50°C in microwave assisted spouted bed drying were observed to be smaller than that of others. Besides, bulk porosity of dried cooked wheat at 50°C in spouted bed tended to decrease significantly when spouted bed combined with microwave power. This tendency became negligible as air temperature and microwave power increased in microwave assisted spouted bed drying. This can be explained by relationship between porosity and sphericity. Rogers and Head, (1961) explained this fact that larger grains have a higher sphericity and tend to pack more closely together than smaller and more irregularly shaped grains. Sphericity of dried cooked wheat in spouted bed drying combined with microwave was higher than that in spouted bed drying (Section 3.5.4). Therefore, microwave assisted spouted bed drying may end up with lower bulk porosity. Baysal et al. (2003) also observed that the tapped porosity values of carrot

were found to be the lowest for microwave dried samples as compared to hot air dried ones.

3.5.3.2 Pore Size Distribution

The parameters describing the pore structure obtained from mercury porosimeter are presented in Table 3.6. ANOVA tables and Tukey's test results are given in Appendix D.4.

Table 3.6 Pore size characteristics summary of high pressure mercury porosimeter

Drying Method	Drying Conditions	Total Volume ($m^3/kg) \times 10^6$	Surface Area ($m^2/kg) \times 10^{-3}$	Porosity (%)
Raw		31.6 ± 6.15^{c}	9.40 ± 2.304^{a}	3.32 ± 0.362^{b}
Spouted bed drying	50°C	41.8 ± 0.00^{c}	9.40 ± 0.213^{a}	4.18 ± 0.806^{b}
	70°C	38.5 ± 11.67^{c}	9.36 ± 2.657^{a}	4.56 ± 0.756^{b}
	90°C	41.5 ± 2.19^{c}	8.17 ± 1.489^{a}	3.65 ± 0.081^{b}
Microwave assisted spouted bed	50°C, 288W	54.5 ± 5.66^{bc}	9.57 ± 1.860^{a}	5.88 ± 1.463^{ab}
	50°C, 624W	77.9 ± 19.73^{ac}	10.84 ± 1.096^{a}	6.49 ± 0.584^{ab}
	70°C, 288W	68.2 ± 17.89^{ac}	9.12 ± 0.727^{a}	7.56 ± 1.233^{ab}
	70°C, 624W	104.3 ± 0.00^{ab}	9.77 ± 0.000^{a}	7.79 ± 0.000^{ab}
	90°C, 288W	119.9 ± 29.06^{a}	8.46 ± 0.718^{a}	10.87 ± 3.567^{a}

As seen in Table 3.6, pore size distribution characteristics did not change significantly in spouted bed drying with air temperature. Chang (1988) found that interior kernel porosity of hard wheat (13.8 %, wb) was about 3.6 to 5 % by using helium gas pycnometer. The obtained interior porosity values with mercury porosimetry were also in this range for dried cooked wheat in spouted bed drying. The lowest porosity and total volume of pores were observed in raw wheat. This can be attributed to increased porosity of wheat owing to starch gelatinization during cooking prior to drying. In addition, pores also developed during drying.

In microwave assisted spouted bed, interior kernel porosity tended to increase with temperature and microwave power. In general, this can be attributed to sharp decrease in drying time with increase in air temperature and microwave power (Table 3.1). As drying time decreased, less collapse of structure occured. In addition, increase in the porosity with microwave power can be ascribed to puffing effect caused by internal vapor generation. Interior kernel porosity did not change significantly with drying methods, except for drying at 90^{o}C in spouted bed and microwave assisted spouted bed drying.

The plot of cumulative volume of mercury intruded versus pore size or versus pressure is called as cumulative intrusion curve. This curve can be used to determine the total volume of mercury intruded, the pore volume in any pore size range and the threshold diameter (the diameter above which comparitively low mercury intruded) (Aligizaki, 2006). The cumulative volumes of mercury intruded as a function of pore size (nm) and pressure (psia) of dried cooked wheat are shown through Figures 3.14 to 3.16 for different air temperatures in spouted bed drying. Initially, there was a sharp rise in intrusion volume and then a relatively constant region with increasing pressure in all graphs. Similar pattern in intrusion curves was observed for wheat straw and grain (Chesson et al., 1997), dried tuna (Rahman et al., 2002), deep-fat-fried chicken meat (Kasamsa and Ngadi, 2005) and dried apple (Rahman et al., 2005) in the literature. Initial steep rise in intrusion volume can be an indication of macro pores existance on the surface. A gradual rise on the slope can be explained by decreasing pore size through the wheat. A sharp rise in the slope indicates very large number of uniform size pores. A vertical line indicates that the pores are exactly same size (Rahman et al., 2002).

Similar pattern was also observed for the cumulative intrusion curves of dried cooked wheat for different air temperatures combined with different levels of microwave power in microwave assisted spouted bed drying (Figures 3.17-3.21). There was a sharp increase in intrusion volume initialy and then a gradually constant region with increase in pressure in all graphs. This sharp increase was observed to be steeper in microwave assisted spouted bed drying at 70^{o}C with 624 W microwave

power and at 90^{o}C with 288 W microwave power. This can be attributed to the existance of more macro pores on the surface due to less collapse of structure as a result of reduction in the drying time in these drying conditions.

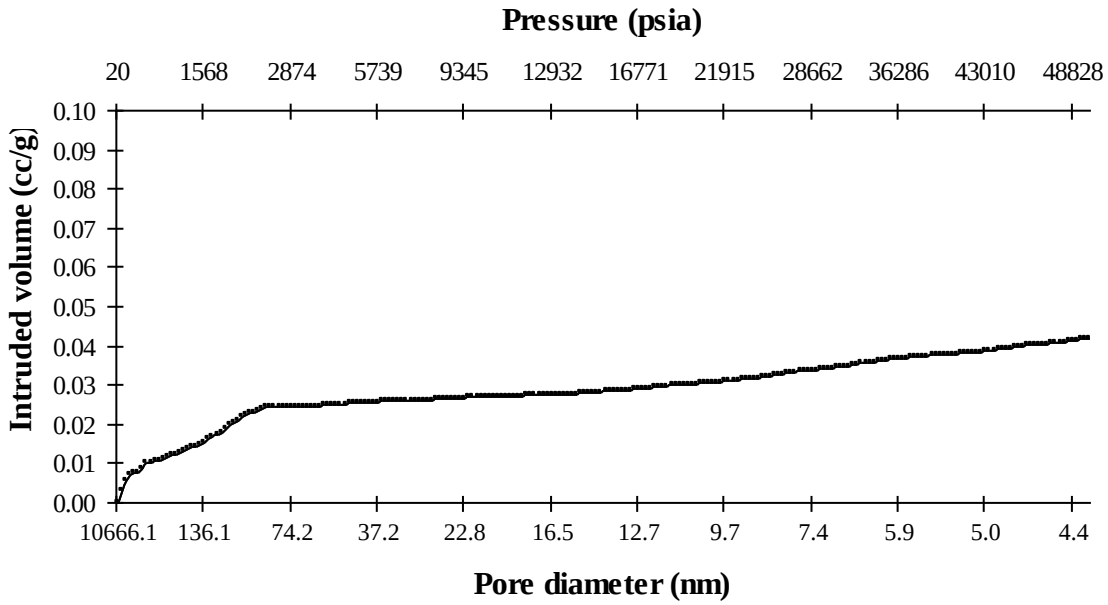

Figure 3.14 Cumulative intrusion curve for spouted bed drying at 50^{o}C

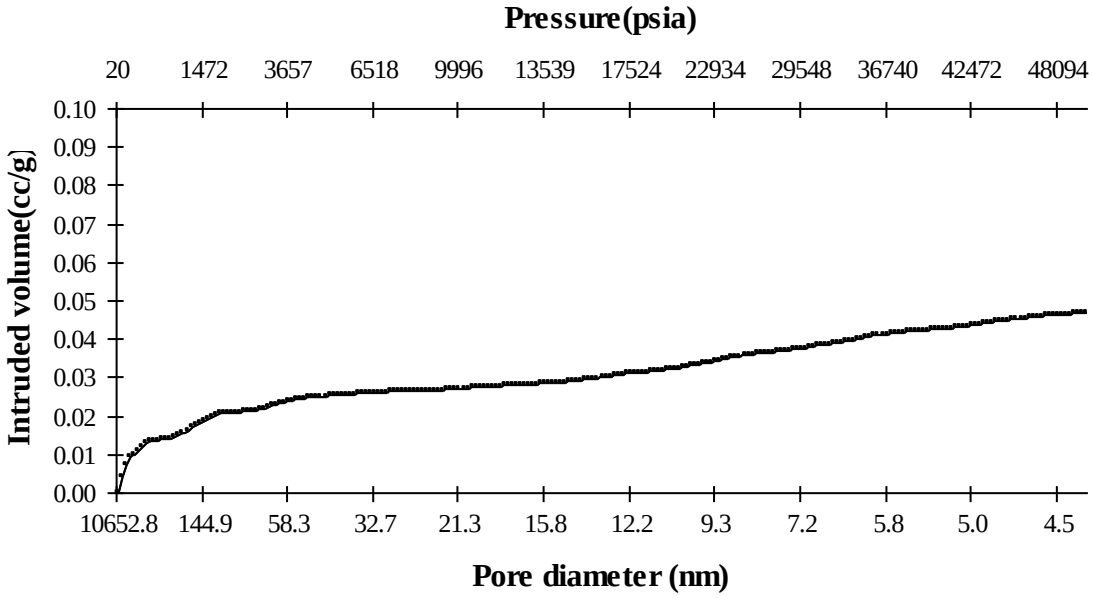

Figure 3.15 Cumulative intrusion curve for spouted bed dying at 70^{o}C

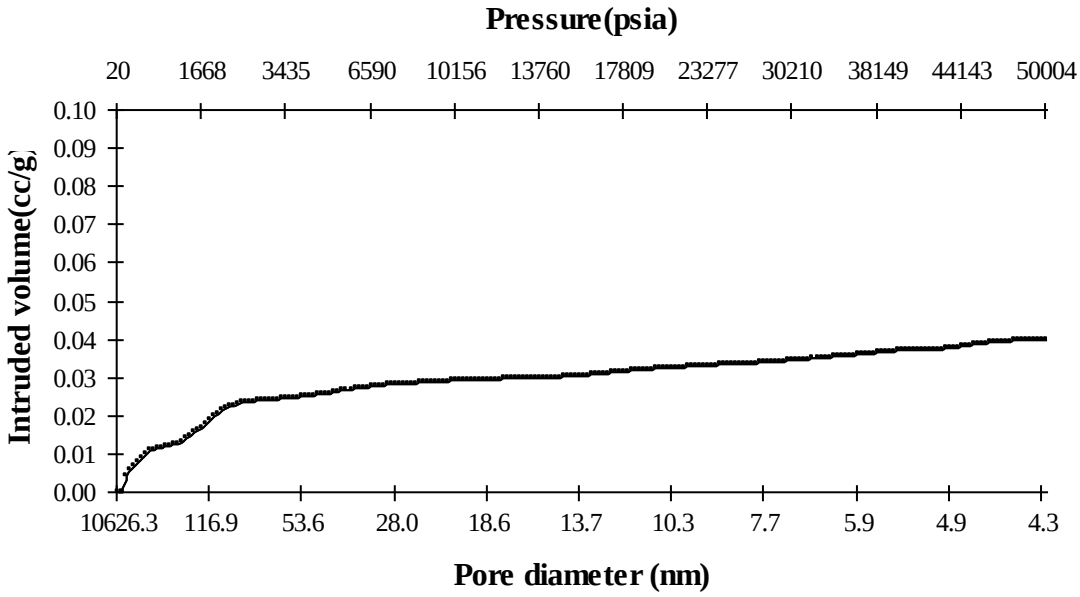

Figure 3.16 Cumulative intrusion curve for spouted bed drying at 90^{o}C

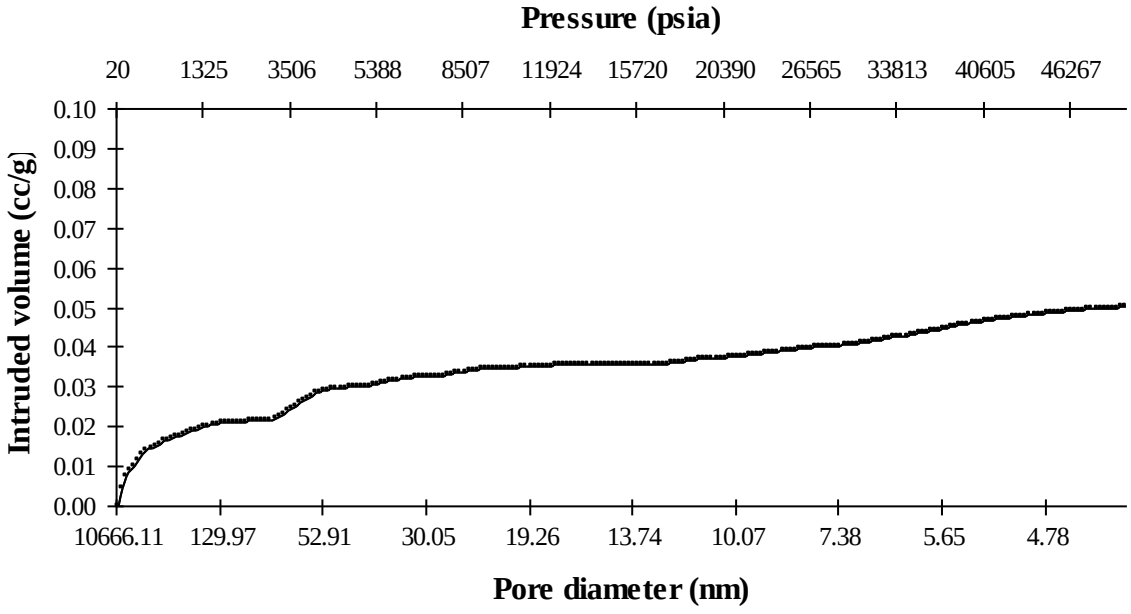

Figure 3.17 Cumulative intrusion curve for microwave assisted spouted bed drying at 50^{o}C, 288 W

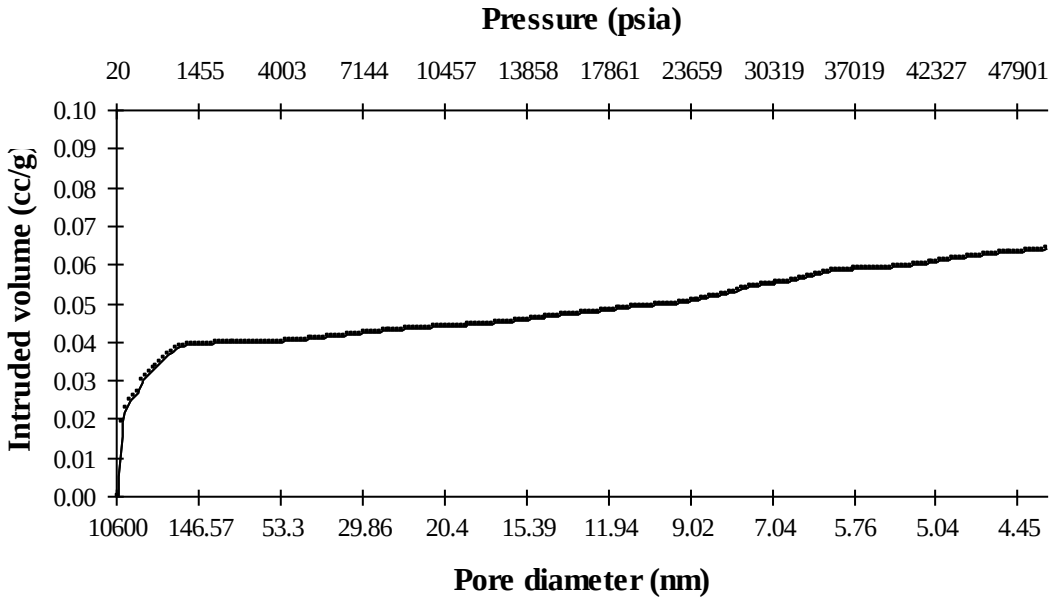

Figure 3.18 Cumulative intrusion curve for microwave assisted spouted bed drying at 50^{o}C, 624 W

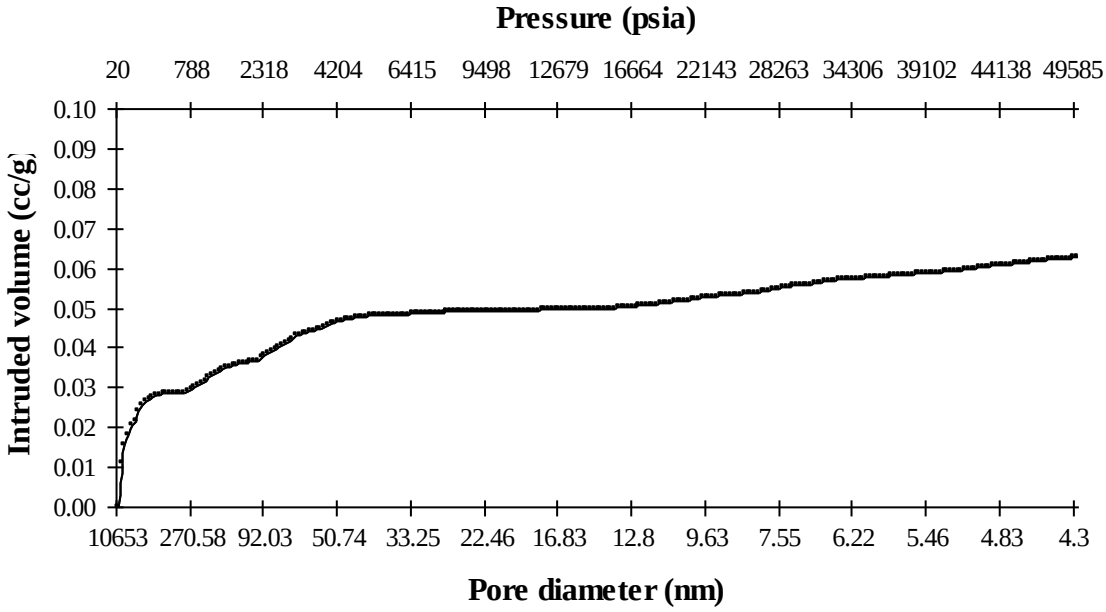

Figure 3.19 Cumulative intrusion curve for microwave assisted spouted bed drying at 70^{o}C, 288 W

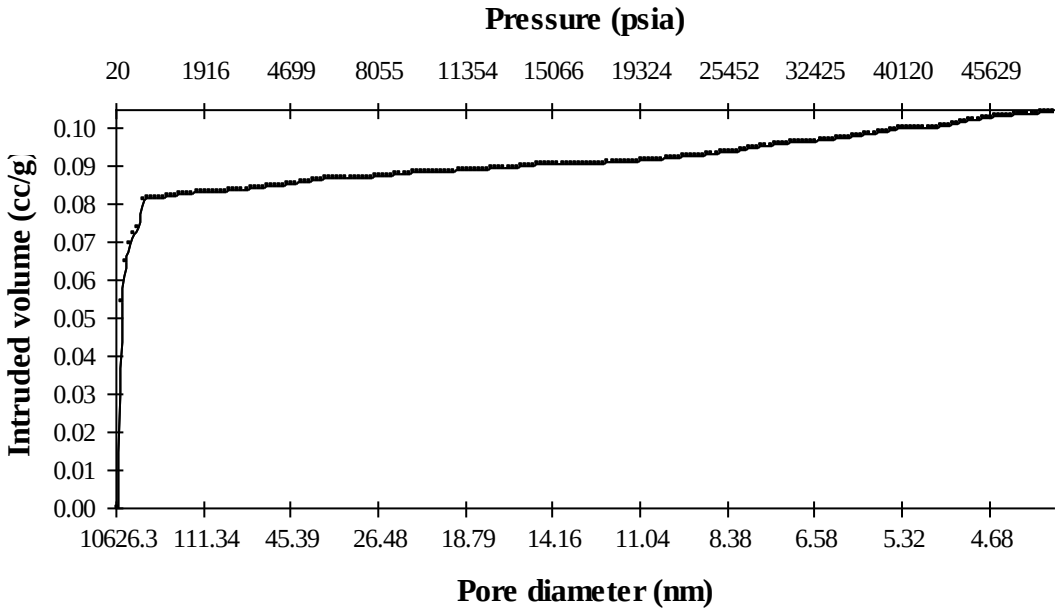

Figure 3.20 Cumulative intrusion curve for microwave assisted spouted bed drying at 70^{o}C, 624 W

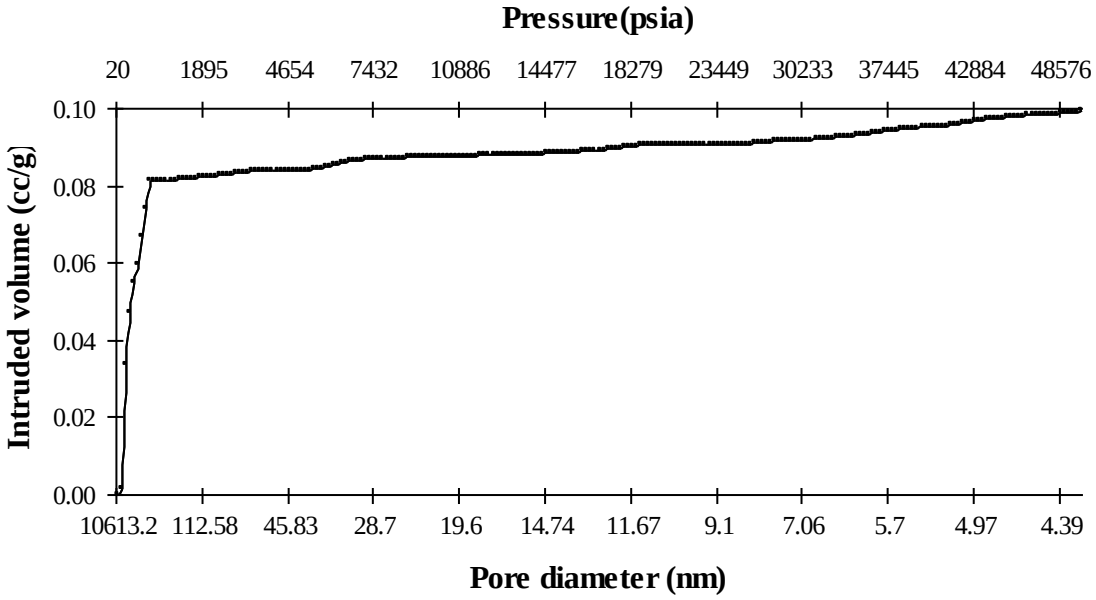

Figure 3.21 Cumulative intrusion curve for microwave assisted spouted bed drying at 90^{o}C, 288 W

Cumulative intrusion curves showed that pore size ranges for spouted bed drying at 50^{o}C, 70^{o}C, 90^{o} C were from 10666.11 to 4.27 nm at pressure range of 20 to 49961 psia; from 10652.82 to 4.26 nm at pressure range from 20 to 50039 psia; from 10626.34 to 4.27 at pressure range from 20 to 50004 psia, respectively. Pore size ranges of dried cooked wheat were close to each other under similar pressure ranges for spouted bed drying at different temperatures. Besides, threshold pore sizes were 89.09, 53.59 and 46.88 nm at 50^{o}C, 70^{o}C and 90^{o}C, respectively. Increasing pressure above threshold pore sizes resulted in lower mercury intrusion compared to amount intruded below threshold values. As drying temperature increased, threshold pore size decreased slightly. This can be a result of enhanced shrinkage due to increased temperature. Pore size range of microwave assisted spouted bed dried wheat samples were similar and changed approximately between 10600 to 4.27 nm at pressure range of 20 to 50000 psia.

Pore size distribution was found by using the relation between pore radius and pore volume, assuming cylindrical pores (Lowell and Shields, 1984). The pore size distribution function can be defined as;

$$D_v = \left(\frac{P}{r}\right)\left(\frac{dV}{dP}\right) \qquad 3.4$$

where D_v is the volume pore size distribution function, defined as the pore volume per unit interval of pore radius (cc/g ml), and dV is the volume of intruded mercury in the sample (considered to be exactly equal to the volume of pores). The intruded volume is expressed as cc/g. The term dV/dP is the first derivative (slope) of the volume versus pressure data. Pore-size distribution curves (D_v versus pore diameter) for spouted bed dried cooked wheat are given in Figures 3.22–3.24. The volume size distribution functions below 200 nm were too small and consistent to be ignored for all drying conditions. In the literature, this curve is usually characterized on the basis of the number, size and shape of peaks. A sharp peak indicates the extent of similar size pores, and higher the height, the more pores at this size (Rahman et al., 2002). Dried cooked wheat for spouted bed drying at 50^{o}C showed one sharp peak at 4.29 nm. Dried cooked wheat at 70^{o}C and 90^{o}C also showed one sharp peak at 4.9 and 4.72 nm, respectively. Besides, all curves were skewed to the right (to lower pore diameter) and the heights of peaks were approximately the same. Karathanos et al. (1996) found two peak for amioca starch when using the low-pressure mercury porosimetry, one in the region 6–8 μm and the other at around 1 to 3.5 μm; another peak was observed using the high-pressure mercury porosimetry at very small pore sizes (3 nm). In the literature, the high-pressure mercury porosimetry results for foods are lacking due to the complexity of measurement and the difficulty in interpretation of results.

Pore size distribution curves for cooked wheat samples dried in microwave assisted spouted bed drying were illusturated in Figures 3.25-3.29. Dried cooked wheat for microwave assisted spouted bed drying at 50^{o}C with two different microwave powers, 288 W and 624 W was indicated one sharp peak at 4.27 and 4.89

nm, respectively. One sharp peak in pore size distribution curves of microwave assisted spouted bed drying at 70°C with 288 W and 624 W microwave power was observed at 4.53 and 4.82 nm, respectively. Two peaks were obtained for 90°C at 288 W in microwave assisted spouted bed drying; one sharp peak at 5.01 nm and another shorter one at 11.96 nm. As in spouted bed dried wheat samples, all curves were observed to be skewed to the right (to lower pore diameter). As microwave power increased, peaks were slightly skewed to the left (higher pore diameter).

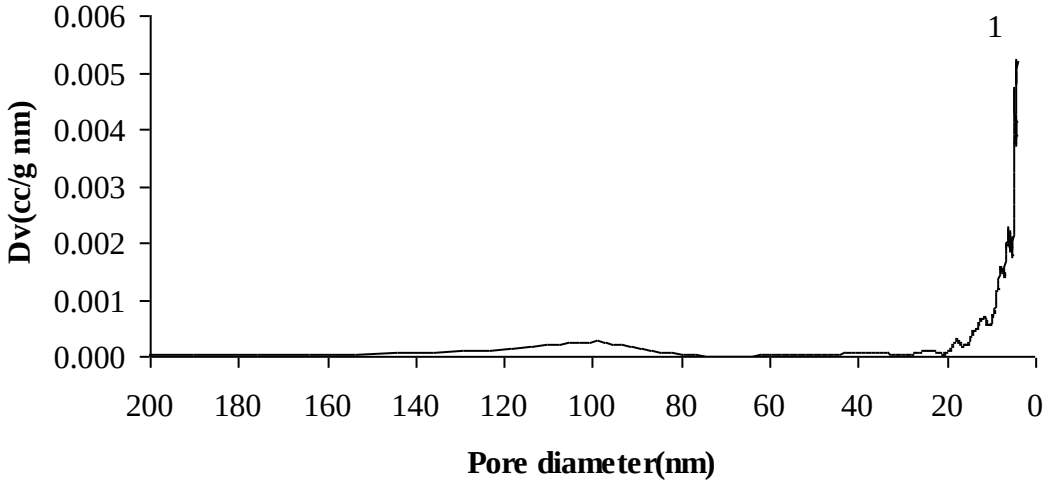

Figure 3.22 Pore size distribution curve for spouted bed drying at 50°C

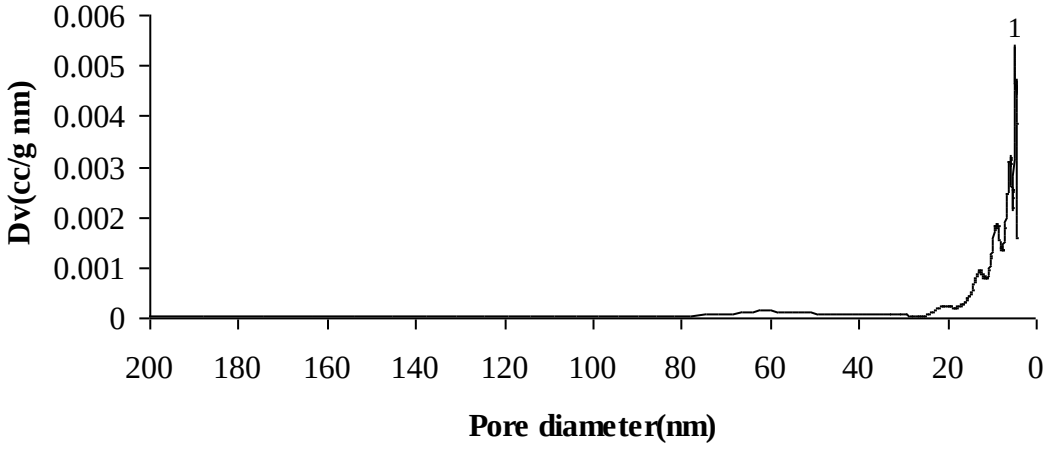

Figure 3.23 Pore size distribution curve for spouted bed drying at 70°C

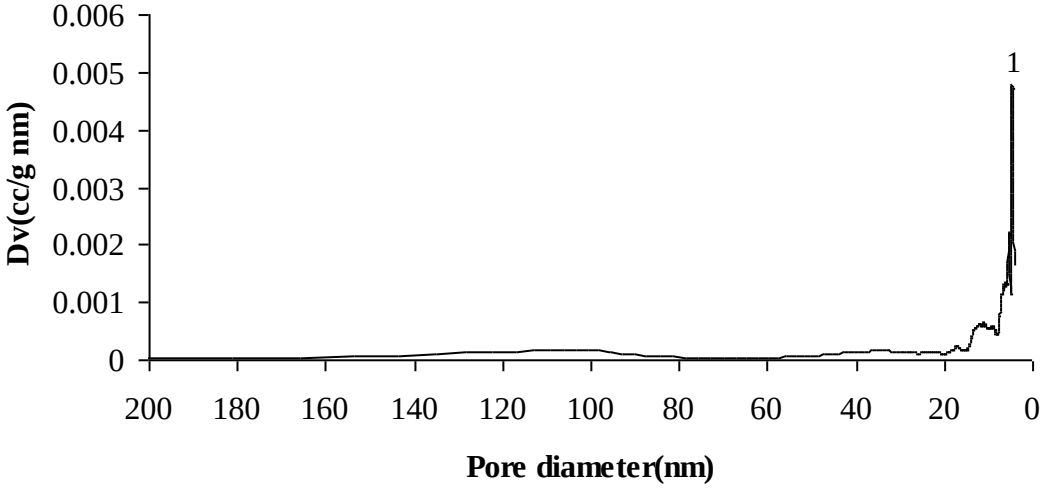

Figure 3.24 Pore size distribution curve for spouted bed drying at 90^{o}C

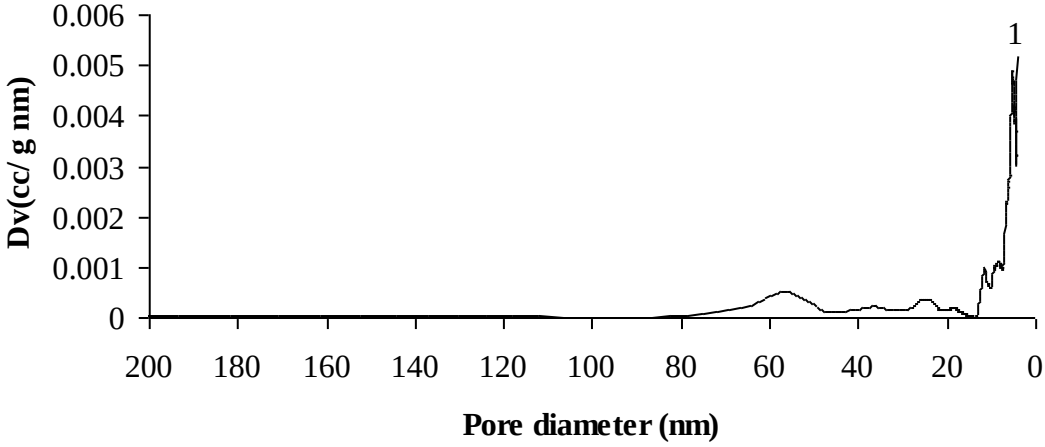

Figure 3.25 Pore size distribution curve for microwave assisted spouted bed drying at 50^{o}C, 288 W

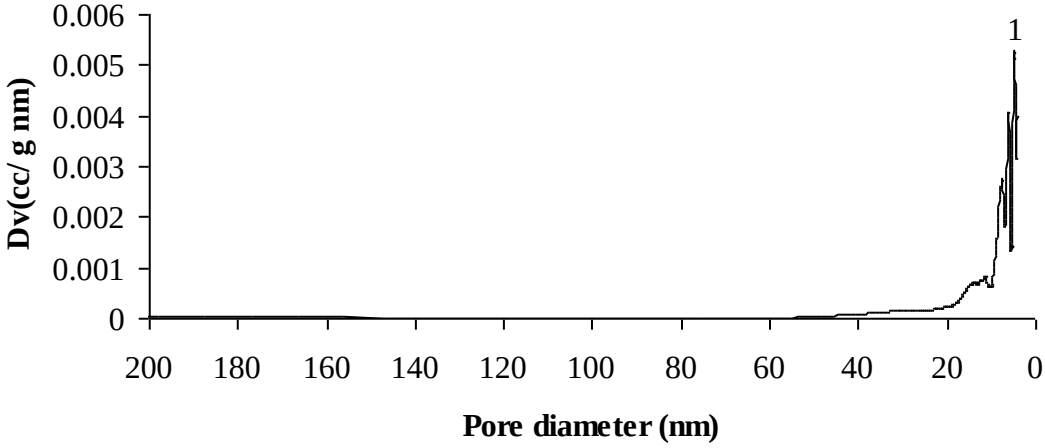

Figure 3.26 Pore size distribution curve for microwave assisted spouted bed drying at 50^{o}C, 624 W

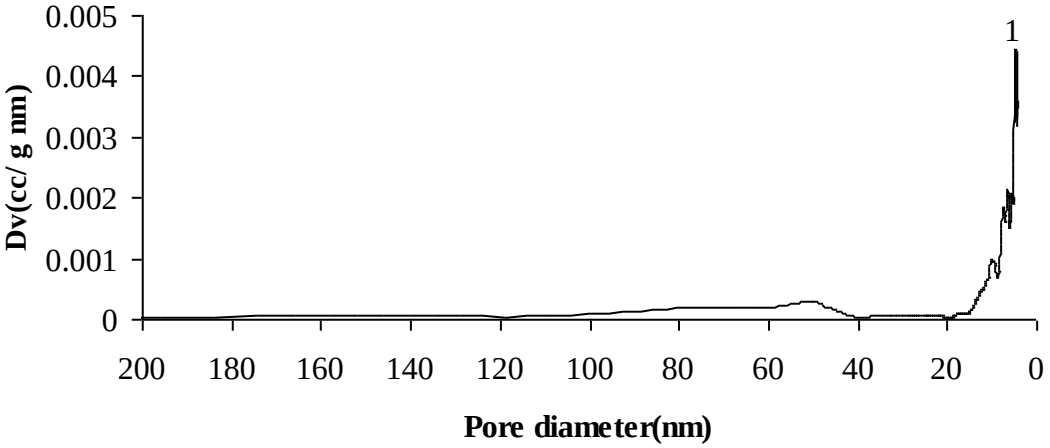

Figure 3.27 Pore size distribution curve for microwave assisted spouted bed drying at 70^{o}C, 288 W

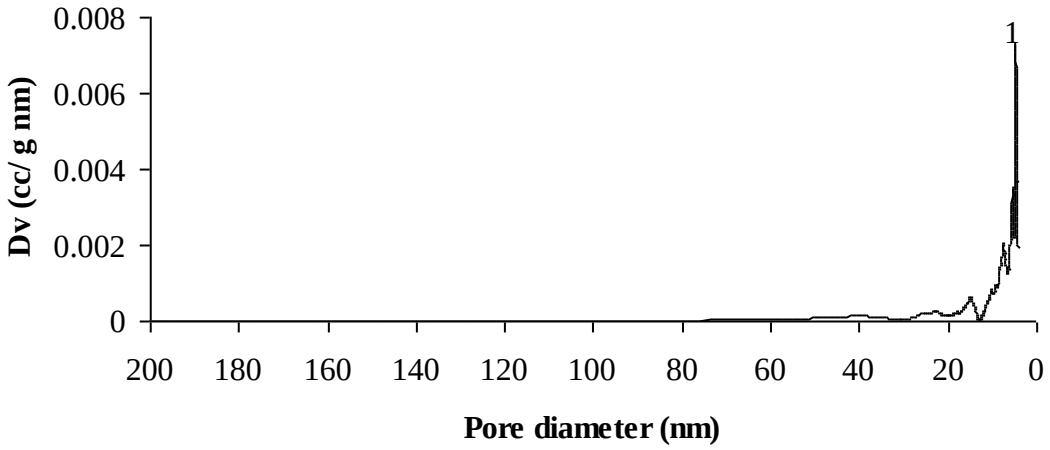

Figure 3.28 Pore size distribution curve for microwave assisted spouted bed drying at 70^{o}C, 624 W

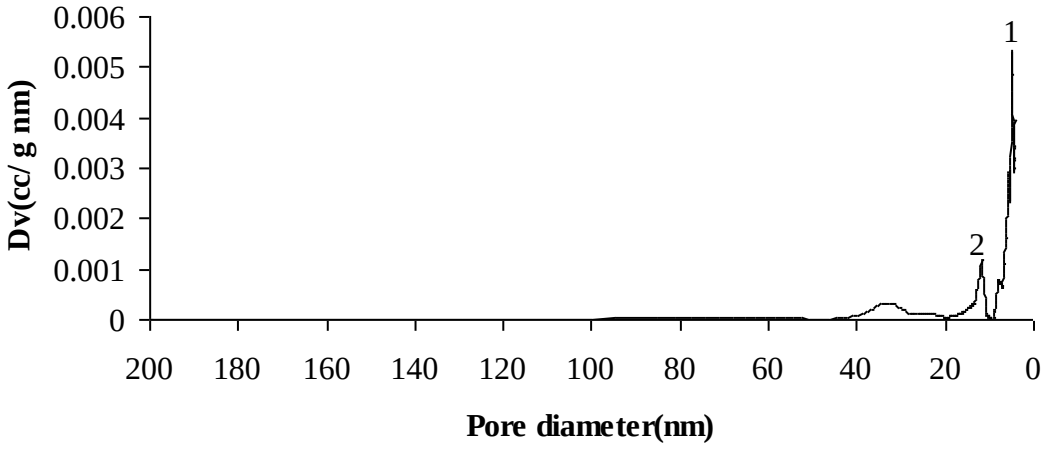

Figure 3.29 Pore size distribution curve for microwave assisted spouted bed drying at 90^{o}C, 288 W

Fractal analysis is used to characterize native and physically or chemically transformed food particles. The efficiency of the transformation process and food particle properties such as adsorption capacity, solubility, puffing ability, chemical reactivity, and emulsifying ability to optimize food ingredient selection for product development and process design can be predicted by the help of fractal analysis (Rahman, 1997). The fractal dimension can be estimated from the slope of the plot of log (dV/dP)vs log P (Ehrburger-Dolle *et al.*, 1994);

$$\frac{dV}{dP} \infty P^{\delta-4} \qquad 3.5$$

where δ, fractal dimension, is the characteristic size distribution of micropores in the same size particles. Fractal dimensions are tabulated in Table 3.7.

According to fractal geometry theory, fractal dimension of surface should be between 2 and 3. The values equal to or greater than 3 are nonphysical from a geometric point of view (Ehrburger-Dolle et al., 1994). More than one linear part was observed when log(dV/dP) was plotted against log P. Initial and final linear portion can be attributed to the mechanical properties of the solid and the fractal dimension can be higher than 3. Ehrbutger- Dolle et al.(1994) investigated three linear sections in log (dV/dP) of different active carbon particles and stated that only the middle linear segment will give the actual fractal dimension. Thus, only middle linear portion of the plot was taken into consideration while estimating fractal dimension. As seen in Table 3.7, fractal dimension of porous of dried cooked wheat was in the range between 2 and 3.

The differential distribution curve is a plot of dV/d(logD) versus D. As seen from differential pore size distribution curves, the pore size distribution of dried cooked wheat in spouted bed drying was dominated by small micropores in a very narrow diameter range of 4 to 20 nm (Figure 3.30- 3.32). This range in microwave assisted spouted bed was similar between 4 and 10 nm (Figure 3.33-3.37).

Table 3.7 Fractial dimensions of pores for dried cooked wheat in spouted bed drying

Drying Method	Drying Conditions	δ, fractal dimension
Spouted bed	50°C	2.74
	70°C	2.10
	90°C	2.58
Microwave assisted spouted bed	50°C, 288W	2.24
	50°C, 624W	2.12
	70°C, 288W	2.02
	70°C, 624W	2.55
	90°C, 288W	2.81

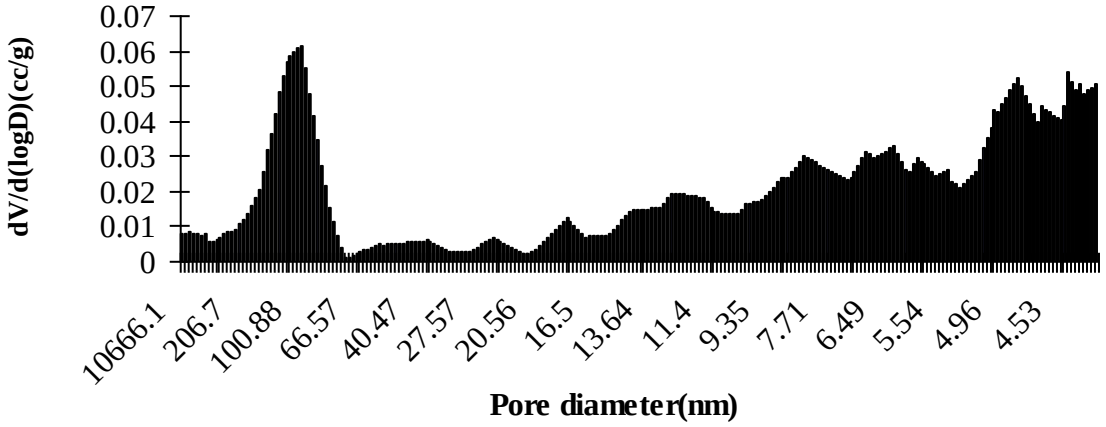

Figure 3.30 Differential pore size distribution curve for spouted bed drying at 50°C

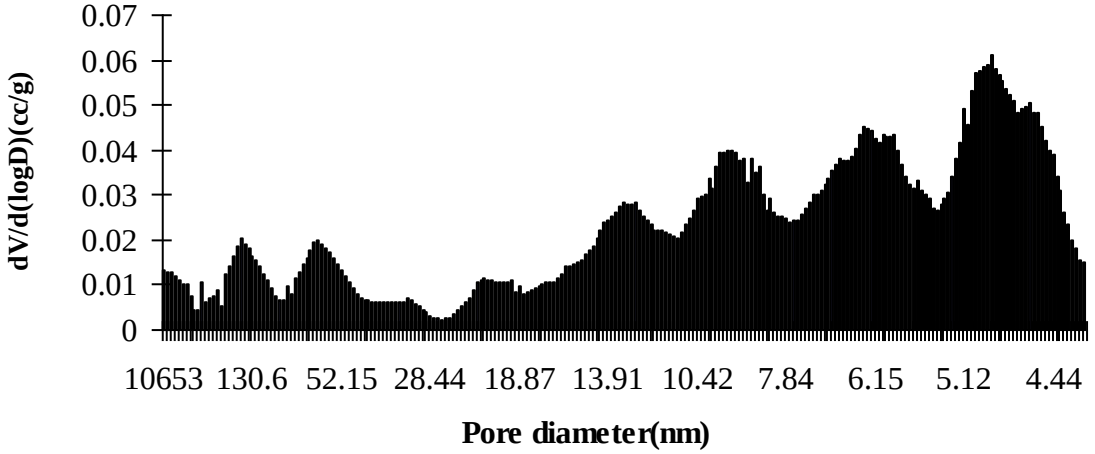

Figure 3.31 Differential pore size distribution curve for spouted bed drying at 70°C

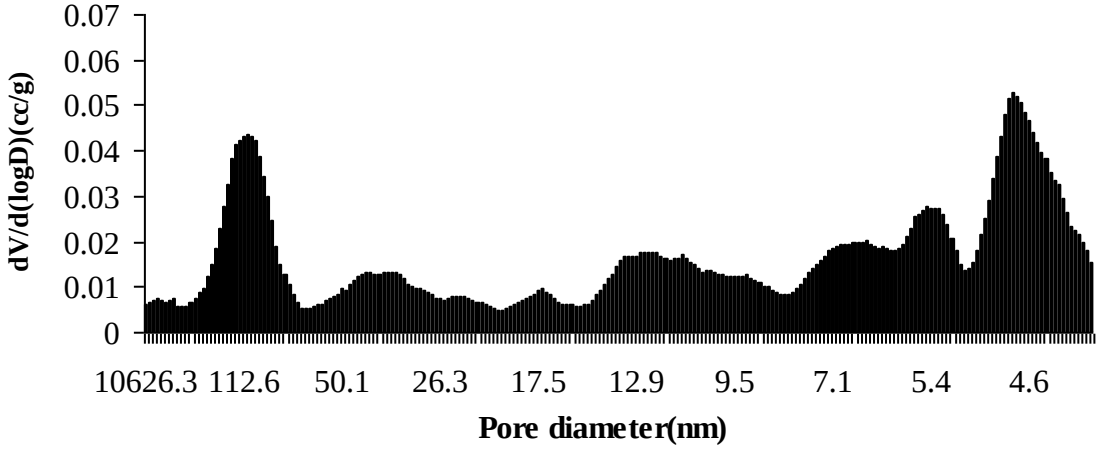

Figure 3.32 Differential pore size distribution curve for spouted bed drying at 90^{o}C

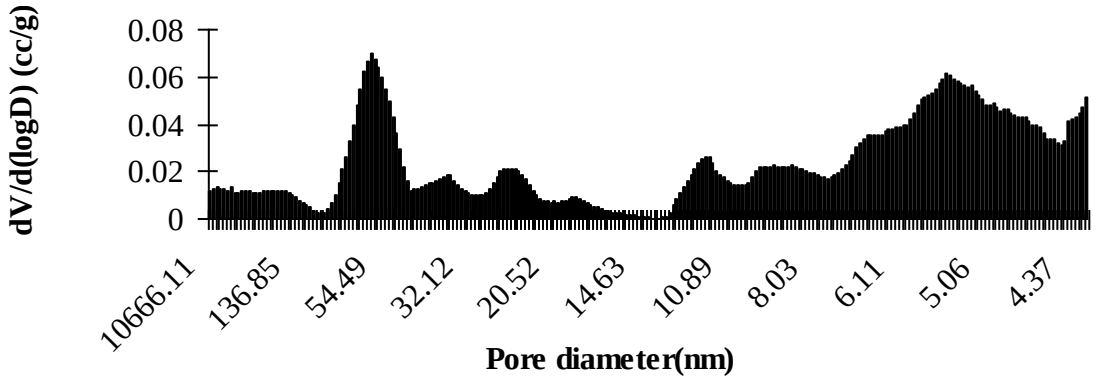

Figure 3.33 Differential pore size distribution curve for microwave assisted spouted bed drying at 50^{o}C, 288 W

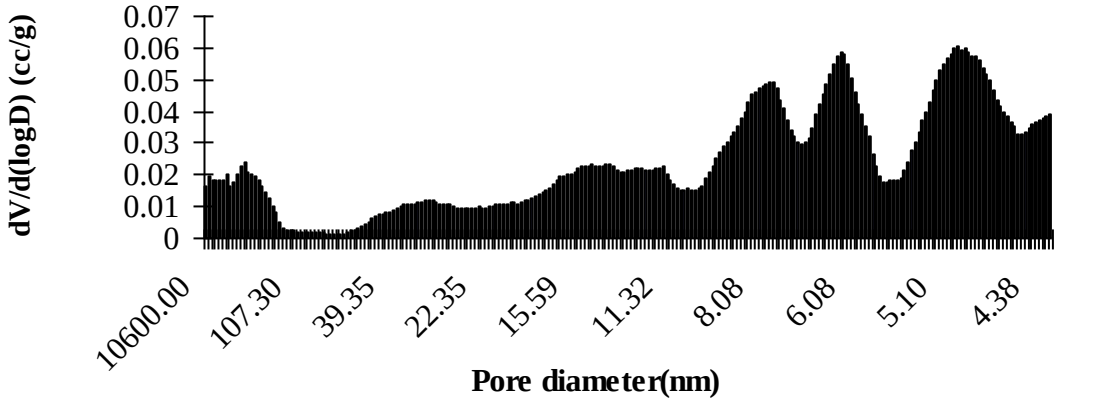

Figure 3.34 Differential pore size distribution curve for microwave assisted spouted bed drying at 50^{o}C, 624 W

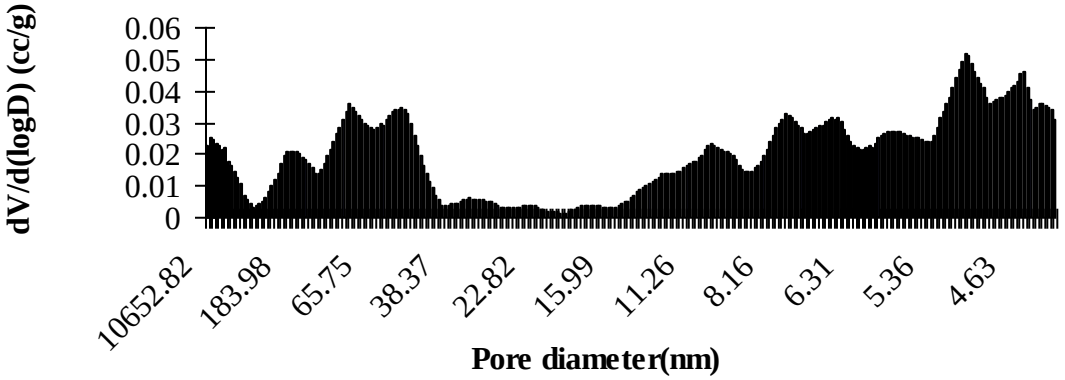

Figure 3.35 Differential pore size distribution curve for microwave assisted spouted bed drying at 70^{o}C, 288 W

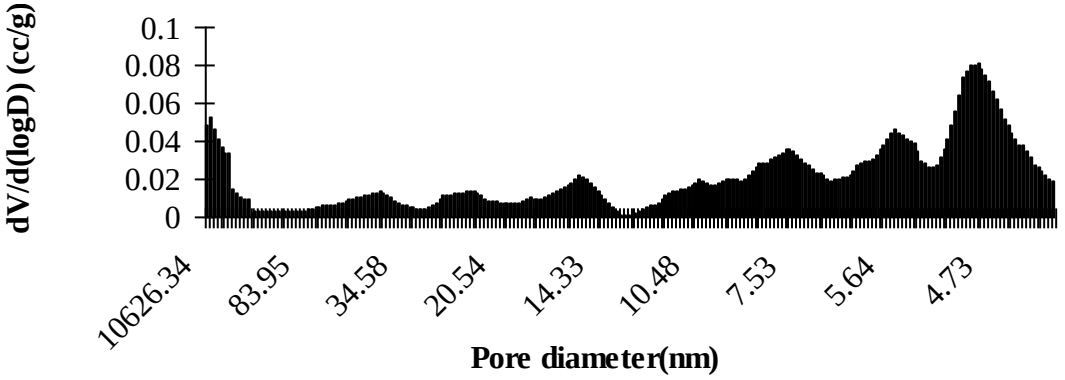

Figure 3.36 Differential pore size distribution curve for microwave assisted spouted bed drying at 70^{o}C, 624 W

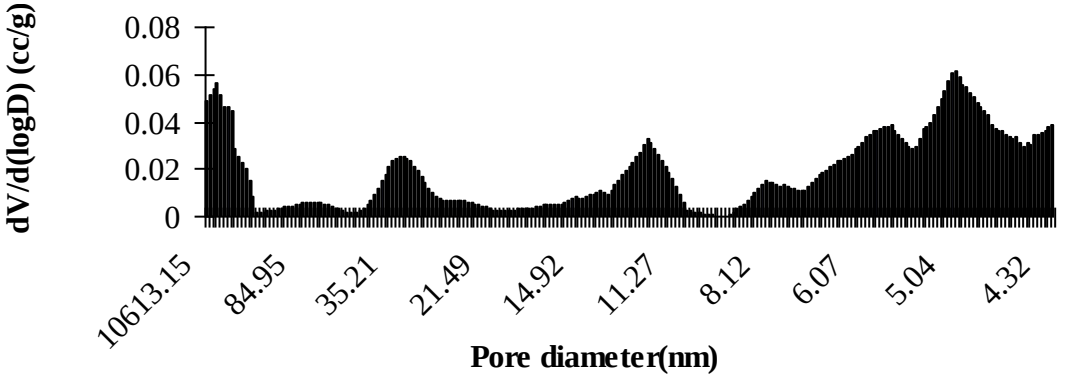

Figure 3.37 Differential pore size distribution curve for microwave assisted spouted bed drying at 90^{o}C, 288 W

3.5.4 Sphericity

Sphericity values as well as equivalent, D_p (mm), geometric mean, D_g (mm) and arithmetic D_a (mm) diameters of dried cooked wheat are tabulated in the Table 3.8. Tukey's comparison test results are given in Appendix D.5.

Table 3.8 Sphericity values of dried cooked wheat at different drying conditions

Drying Method	Drying Conditions	Sphericity	Equivalent Diameter	Geometric Diameter	Arithmetic Diameter
	50°C	0.602± 0.0313^{a}	4.4±0.21^{abc}	4.4±0.22^{abc}	4.2±0.22^{ab}
Spouted	70°C	0.602± 0.0309^{a}	4.2±0.37^{c}	4.2±0.36^{c}	4.5±0.37^{b}
Bed	90°C	0.617±0.0339^{ab}	4.4±0.29^{abc}	4.4±0.29^{abc}	4.7±0.30^{ab}
	50°C,288W	0.607±0.0349^{ab}	4.3±0.27^{bc}	4.3±0.27^{bc}	4.6±0.28^{b}
Microwave	50°C,624W	0.641±0.0405^{bc}	4.5±0.25^{ab}	4.5±0.25^{ab}	4.7±0.25^{ab}
Assisted	70°C,288W	0.6401±0.0418^{bc}	4.3±0.14^{bc}	4.2±0.13^{bc}	4.5±0.18^{b}
Spouted	70°C,624W	0.680± 0.0341^{d}	4.5±0.24^{a}	4.5±0.24^{a}	4.7±0.25^{ab}
Bed	90°C,288W	0.673±0.0344^{cd}	4.7±0.31^{a}	4.6±0.31^{a}	4.9±0.32^{a}

In spouted bed drying, there was no significant difference in sphericity with air temperatures. In literature, sphericity was considered as one of the moisture dependent physical properties of wheat (Al-Mahasneh and Rababah, 2007; Kheiralipour et al. 2008). Therefore, the effect of air temperature on dried cooked wheat dimensions as height, width, thickness and as a result on sphericity can not be observed as dimensions changes mainly with moisture content. This was also confirmed by the interior kernel porosity and bulk porosity (Tables 3.5 -3.6) which did not change significantly with air temperature in spouted bed drying. Sphericity increased with microwave power in microwave assisted spouted bed drying. This can also be seen from the pictures of dried cooked wheat (Appendix E). This can be attributed to volume expansion due to puffing effect of microwave caused by internal vapor generation. Puffing effect can be promoted with increased microwave power.

This can be ascribed to increased sphericity with microwave power. The equivalent, D_p, geometric mean, D_g and arithmetic D_a diameters of dried cooked wheat with drying methods did not change significantly with drying methods (Table 3.8).

3.5.5 Microstructure Analysis

The Scanning Electron Microscopy (SEM) images of cooked wheat dried in spouted bed and raw wheat were shown in Figure 3.38 and 3.39, respectively.

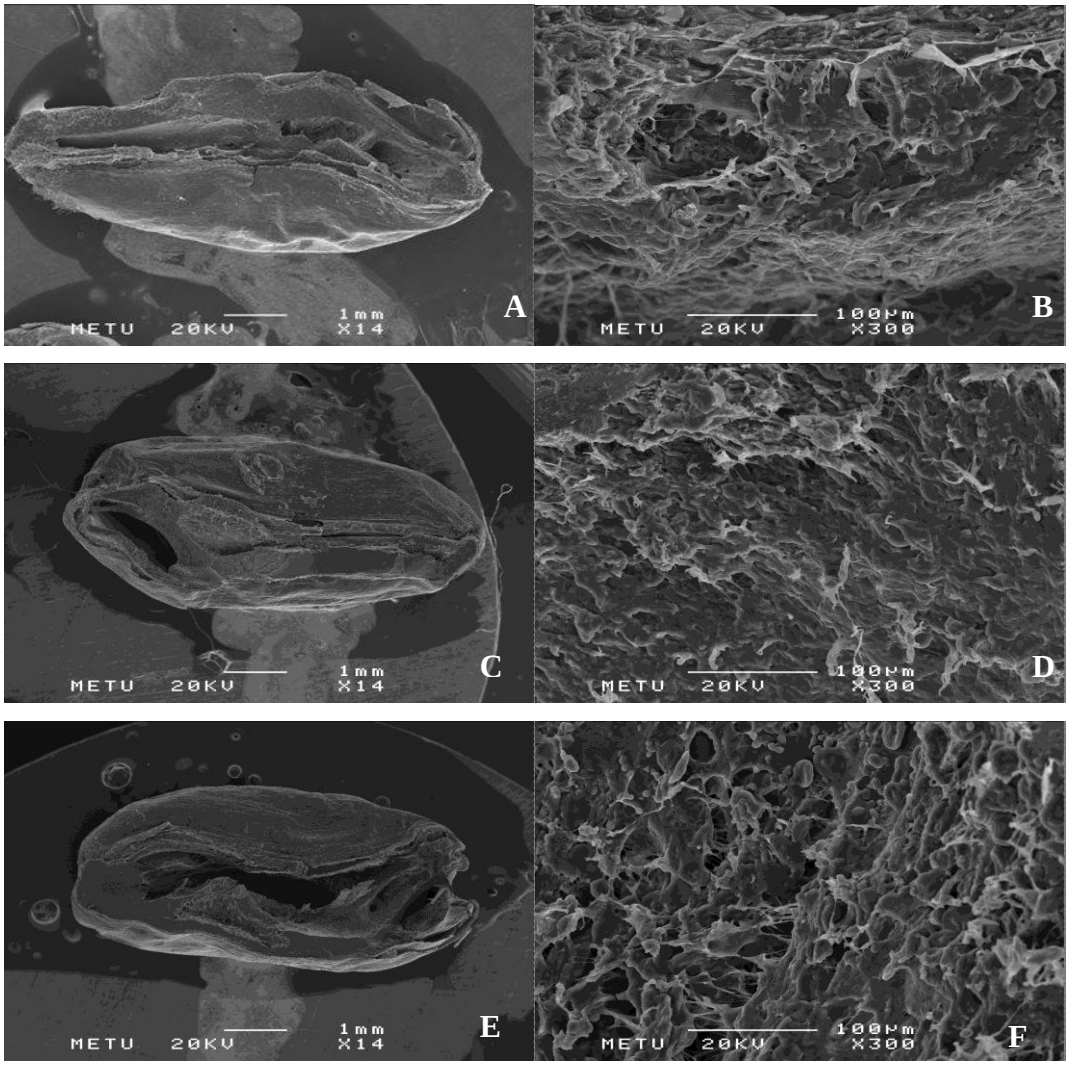

Figure 3.38 SEM images of cooked wheat dried in spouted bed at different temperatures (A, B: 50^{o}C, C,D :70^{o}C, E,F: 90^{o}C)

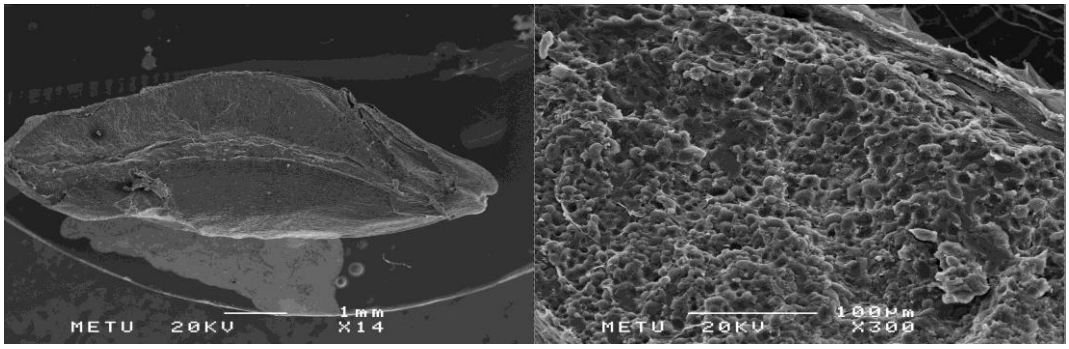

Figure 3.39 SEM images of raw wheat

When the SEM images of dried cooked wheat samples were compared to that of raw wheat, it was observed that raw wheat had more compact and smooth structure than dried cooked wheat. Starch granules can be easily observed on the SEM image of raw wheat. However, in dried cooked wheat, starch granules were largely deformed, swollen and became fragmented, but were still distinguishable. This can be due to cooking and drying stages which may alter wheat microstructure, especially wheat starch granules, wheat gluten, severely as a result of gelatinization and protein denaturation. Raw wheat was cooked in boiling water, approximately at 95°C in this study to provide 100% starch gelatinization prior to drying. Bilbao-Saintz et al. (2007) stated that the starch granules of wheat appeared disintegrated and melted together with an homogeneous appearance when the heating was applied to 95°C. Charles et al. (2003) stated that the intact starch granules of wheat are smooth, free from pores, cracks, or fissures, have round to oval shapes, and are relatively thick, whereas the gelatinized starch granules are either swollen or ruptured with cleaved surfaces.

There were no clear difference between SEM images of cooked wheat dried at different temperatures in terms of porosity but more porous structure was observed compared to raw wheat (Fig 3.38-3.39). Murthy et al. (2008) observed that the raw wheat had a closed structure and roasted wheat in fluidized bed had a porous structure. As can be seen in Figure 3.38, starch granules of dried cooked wheat showed more deformed and nonspherical shape.

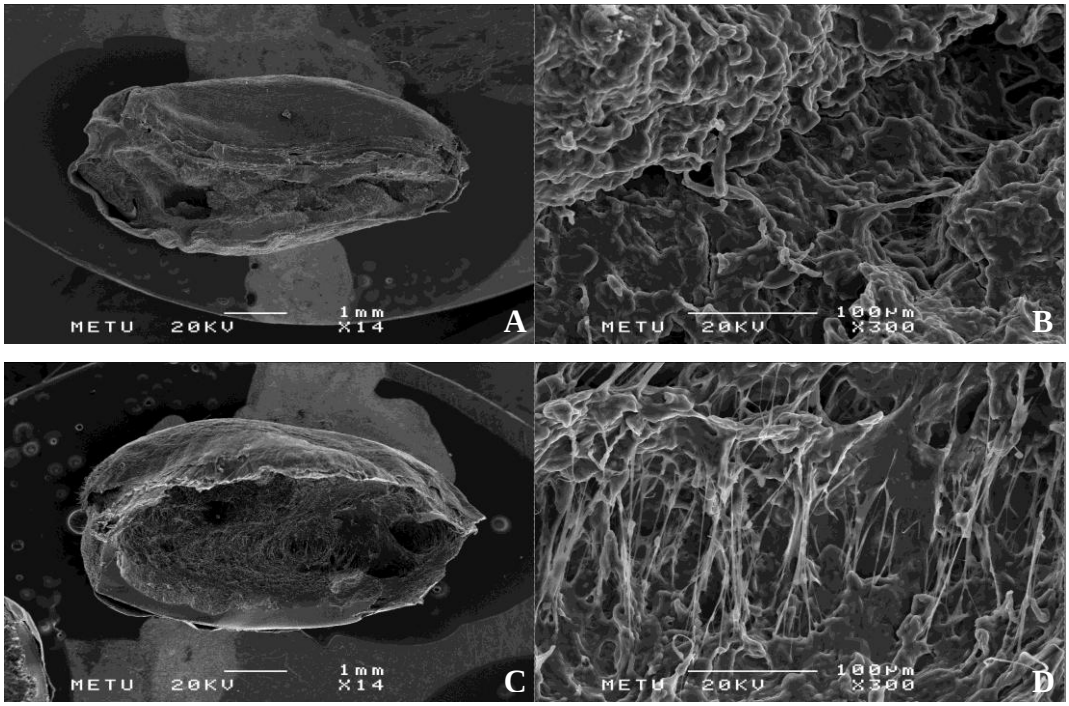

Figure 3.40 SEM images of cooked wheat dried in microwave assisted spouted bed at 70^{o}C with different microwave power levels (A,B; 288W; C,D;624 W)

The SEM images of cooked wheat dried in microwave assisted spouted bed at 70^{o}C with different microwave powers were shown in Figure 3.40. Microstructure of dried cooked wheat in microwave assisted spouted bed was different than that in spouted bed drying. As illustrated in Figure 3.40, more porous structure in wheat samples compared to air dried ones was clearly observed which was also consistent with obtained result of interior kernel porosity in Section 3.5.3.2. Besides, the microscopic observations indicated that porosity increased with microwave power. This was ascribed to puffing effect of microwave by internal vapor generation. Microwave treatment enhanced apperance of honeycomb-like network with empty hole which became more recognizable when images of the half kernel of dried cooked wheat were compared. Continuous matrix was observed in which distinction of starch granules became difficult as microwave power increased. In addition, fibrils of protein network increased and became more recognizable at the highest microwave power level which can be an indication of enhanced wheat gluten denaturation with microwave power. This can be due to the extent of either

denaturation of protein which is mainly based on the severity of the heat treatments and availability of water (Srivastava et al., 2002). Initial moisture content of all gelatinized cooked wheat samples were the same thus, the difference can be attributed to drying method. Combination of air drying with microwave power can result in more deformed protein network with more porous structure.

3.5.6 Color

In this study, dried cooked wheat was investigated in terms of color attributes. The effects of drying methods on CIE L*a*b* of dried cooked wheat are shown in Table 3.9. ANOVA tables and Tukey's results for color values are given in Appendix D.6.

Table 3.9 Color values for dried cooked wheat at different drying conditions

Drying Method	Drying Conditions	L*	a*	b*
Spouted Bed	50°C	41.8 ± 0.95^{cd}	10.1 ± 0.50^{b}	40.3 ± 0.76^{bcd}
	70°C	40.8 ± 0.26^{de}	9.9 ± 0.34^{b}	40.0 ± 0.61^{be}
	90°C	40.3 ± 0.82^{e}	13.2 ± 0.67^{a}	39.2 ± 0.98^{e}
Microwave Assisted spouted Bed	50°C,288W	40.9 ± 0.42^{de}	9.7 ± 0.36^{b}	39.5 ± 0.99^{de}
	50°C,624W	42.3 ± 0.33^{bc}	8.9 ± 0.46^{b}	40.1 ± 0.72^{bce}
	70°C,288W	41.7 ± 1.04^{cd}	9.4 ± 0.30^{b}	40.2 ± 0.59^{ce}
	70°C,624W	42.8 ± 0.62^{ab}	13.1 ± 0.41^{a}	40.7 ± 0.67^{abc}
	90°C,288W	43.7 ± 0.91^{a}	12.7 ± 3.22^{a}	41.6 ± 0.36^{a}

L* (lightness) and b*(yellowness) values of dried cooked wheat decreased with increased temperature while a* (redness) values tended to rise in spouting bed drying. This change was observed to be significant when values of lowest and highest temperature in spouted bed drying were compared. Browning reactions can be responsible for color change in dried cooked wheat. In general, browning reactions largely depend on moisture content, drying temperature and time. Thus,

drying at higher temperatures promoted the formation of browning pigments. As a result of this, dried cooked wheat became darker in color as temperature increased. According to Ozboy and Köksel (1998), color changes in bulgur and in parboiled rice can be ascribed to Maillard reaction between reducing sugars and aminoacids. Furthermore, β-carotenoid is the main pigment in durum wheat which is responsible for the yellow color (Kruger and Reed, 1988). High temperature also enhances the pigment degradation. Reduction in b* value (yellowness) of dried cooked wheat can be explained by increased β-carotenoid degradation due to high air temperature in spouted bed drying. Wachiraphansakul and Devahastin, (2005) observed that increasing of both the inlet air temperature and heating duration caused an increase of all color parameters (L, a, b) but at different extents for soy residue (okara) dried in jet spouted bed dryer. Niamnuy et al. (2007) considering the effect of drying temperature on color changes of shrimp in jet spouted bed drying found that the absolute lightness difference (ΔL) decreased but hue angle, chroma, and ΔE increased with an increase in the inlet air temperature.

In microwave assisted spouted bed drying, L* value increased significantly as microwave power increased. This can be attributed to decrease in drying time due to elevated drying rates in microwave assisted spouted bed dryer (Table 3.1). Drying time is one of the key parameters for the development of browning as well as drying temperature. Thus, reduction in drying time may result in less browning in final product. Besides, drying time also affects the extent of pigment degradation. There was no significant difference among the b value of cooked wheat dried in microwave assisted spouted bed. This could be attributed to less degradation of color pigment as a result of substantial reduction in drying time.

L* and b* values tended to increase when spouted bed drying was combined with high microwave powers or at the highest temperature (90^{o}C). No linear trend was observed in the a values when drying methods were compared.This was in agreement with the study of Feng and Tang, (1998) in which less discoloration (lower ΔE) and higher L values observed for evaporated diced apple dried in microwave assisted spouted bed than dried in spouted bed. Maskan (2000) showed

that ΔE and L values of banana was higher and more close to fresh samples when dried in microwave finish drying instead of hot air drying or microwave drying alone.

3.5.7 Yield

The effect of drying methods on yield values for fine bulgur are shown in Table 3.10. One-way ANOVA tables and Tukey's multiple comparison test results are given in Appendix D.7.

Table 3.10 Fine bulgur yield at different drying conditions

Drying Methods	Drying Conditions	Yield
Spouted bed	50°C	0.84± 0.006[a]
	70°C	0.81± 0.018[ab]
	90°C	0.79± 0.023[ab]
Microwave assisted spouted bed	50°C,288W	0.84± 0.004[a]
	50°C,624W	0.77± 0.000[b]
	70°C,288W	0.79± 0.011[ab]
	70°C,624W	0.77± 0.008[b]
	90°C,288W	0.77± 0.011[b]

Gyimes (2004) investigated the relationship between the kernel hardness and wheat milling yield and found that there was a positive correlation between them. This was explained with breaking characteristic of wheat kernel related to its hardness. If the breaking lines pass through the endosperm cells, more endosperm parts remain on the bran. In the soft wheat, the cells has less rigidity, the shear forces split the cell and a part of the endosperm on the bran remains and so less milling yields are observed. In this study, hard wheat (*Triticum durum*) was used thus, yield values were acceptable. Besides, hardness of the wheat can be related to its porosity. Dobraszczyk et al. (2000) showed that increased levels of porosity weakened the endosperm structure and so voids in porous materials can concentrate stresses and

cause a reduction in mechanical strength. In other words, increased porosity can bring about decrease in hardness and milling yield. Interior kernel porosity values of dried cooked wheat were not affected with temperature in spouted bed (Table 3.6). This was consistent with results of milling yield. As can be seen in Table 3.10, fine bulgur yield did not change significantly with air temperature. Besides, yield values at lower microwave power and air temperatures in microwave assisted spouted bed drying were similar to that of spouted bed drying. However, higher microwave power resulted in significantly lower yield values in microwave assisted spouted bed drying. This can be ascribed to the lowest interior porosity and so harder endosperm structure in spouted bed. When the microwave power was combined with spouted bed drying, there was a slight decrease in yield at lower microwave power level. This decrease became significant at low drying temperature as microwave power level increased which can also be attributed to increase in the interior kernel porosity with microwave power (Table 3.6). Increased interior porosity due to puffing effect of microwave may weaken the wheat structure and affect the breaking line which may cause more endosperm part to remain on the bran and thus decrease in yield.

3.5.8 Water Absorption Capacity

The effects of drying methods on water absorption capacity of bulgur are tabulated in Table 3.11. One-way ANOVA tables and Tukey's comparison test results are given in Appendix D.8.

As can be seen in Table 3.12, water absorption capacity did not change significantly with air temperatures in spouted bed drying. Water absorption capacities of spouted bed dried cooked wheat samples at lower air temperatures were observed to be higher significantly compared to that of microwave assisted spouted bed dried ones. Although microwave dried cooked wheat samples showed higher porosities compared to conventionally treated ones, they resulted in the lowest water absorption capacities. This could be explained by incomplete dehulling process since puffed wheat samples due to internal vapor generation in microwave drying were easily cracked by the dehuller. Therefore, dried cooked wheat in microwave assisted

spouted bed drying contained some portion of hull attached to the crack wheat after dehulling process. This may cause significantly lower water absorption capacity in microwave assisted spouted bed drying compared to spouted bed drying.

Table 3.11 Water absorption of fine bulgur at different drying conditions

Drying Methods	Drying Conditions	Water absorption (g water/g bulgur)
Spouted bed	50°C	2.32± 0.054^{ab}
	70°C	2.39± 0.102^{a}
	90°C	2.13± 0.016^{bc}
Microwave assisted spouted bed	50°C,288W	2.07± 0.028^{c}
	50°C,624W	1.98± 0.034^{c}
	70°C,288W	2.00± 0.001^{c}
	70°C,624W	1.96± 0.028^{c}
	90°C,288W	1.97± 0.056^{c}

CHAPTER 4

CONCLUSION AND RECOMMENDATIONS

The drying rate increased with air temperature in spouted bed drying and with both air temperature and microwave power in microwave assisted spouted bed drying. Besides, the effect of microwave was observed to be dominant in the falling rate period rather than the effect of air temperature in microwave assisted spouted bed drying. In general, spouted bed drying at higher temperatures and microwave assisted spouted bed drying shorten the drying time drastically.

The effect of air temperature on bulk density, apparent density and bulk porosity was not significant in spouted bed drying. In general, combination of hot air with higher microwave power caused lower bulk and apparent densities of cooked wheat dried in microwave assisted spouted bed. Microwave power seems to affect bulk density and apparent density more than air temperature.

Air temperature in spouted bed drying did not cause any significant change in pore size characteristics of dried cooked wheat. There was a tendency to increase in interior kernel porosity with microwave power. The cumulative intrusion curves and pore size distribution curves were similar for both drying methods.

SEM analysis showed that starch granules of cooked wheat dried in both spouted bed and microwave assisted spouted bed were deformed and swollen due to cooking and drying during production compared to raw wheat. More porous wheat structure with increased protein fibrils was observed in microwave assisted spouted bed drying. Microwave seems to change the structure of wheat severely.

L* and b* values of dried cooked wheat samples were decreased however, a* value increased with air temperature in spouted bed drying due to browning

reactions. L* value increased with microwave power in microwave assisted spouted bed drying. This shows that dried cooked wheat samples in microwave assisted spouted bed drying resulted in more desirable color.

Yield values of bulgur did not change in spouted bed drying with air temperature nevertheless, tended to decrease as microwave power increased in microwave assisted spouted bed drying. Water absorption capacity values of bulgur were lower in microwave spouted bed drying compared to that in spouted bed drying.

Microwave assisted spouted bed drying shortens the time of processing sharply besides, final product quality are expected to be compatible with that of spouted bed drying. Thus, it may be concluded that usage of microwave assisted spouted bed drying at lower temperature and microwave power such as 50^{o}C, 288 W in bulgur production is preferable in terms of energy saving with acceptable quality in final product.

For future studies, the effect of spouted bed and microwave assisted spouted bed on nutritional properties of bulgur may be investigated. Besides, novel drying methods like solar drying may be used to produce bulgur.

REFERENCES

Adamson, A.W.(1990) Physical Chemistry of Surfaces, 5th ed, New York: John Wiley & Sons Inc.

Adu, B., Otten, L. (1996) Diffusion characteristics of white beans during microwave drying, *Journal of Agricultural Engineering Research*, 64(1), 61-70.

Al-Mahasneh, M.A., Rababah, M.T.(2007) Effect of moisture content on some physical properties of green wheat, *Journal of Food Engineering*, 79, 1467-1473.

Aligizaki, K.K.(2006) Mercury intrusion porosimetry, Pore Structure of Cement-Based Materials: Testing Interpretation and Requirements, 60-108, Abingdon [England] ; New York : Taylor & Francis.

Bayram, M.(2000). Bulgur around the world. Cereal Foods World, 45, 80–82.

Bayram, M.(2002) Bulgur: The old new wheat, *World Grain*.

Bayram, M. (2005) Modelling of cooking of wheat to produce bulgur, *Journal of Food Engineering*, 71, 179-186.

Bayram, M. (2006) Determination of the cooking degree for bulgur production using amylose/iodine, centre cutting and light scattering methods, *Food Control*, 17, 331–335.

Bayram, M., Oner, M.D. (2002) The new old wheat: convenience and nutrition driving demand for bulgur. World Grain November: 51–53.

Bayram, M., Oner, M.D.(2005) Stone, disc and hammer milling of bulgur, *Journal of Cereal Science*, 41, 291–296.

Bayram, M., Oner, M.D.(2006) Determination of applicability and effects of colour sorting system in bulgur production line, *Journal of Food Engineering*, 74, 232–239.

Bayram, M., Oner, M. D.(2007) Bulgur milling using roller, double disc and vertical disc mills, *Journal of Food Engineering*, 79, 181–187.

Bayram, M., Öner, M.D., Eren, S. (1996) State of the art and problems encountered in bulgur production, *Food Technology-Turkey*, 1, 39–45.

Bayram, M., Öner, M.D., Eren, S. (2004a). Effect of cooking time and temperature on the dimensions and crease of the wheat kernel during bulgur production, *Journal of Food Engineering*, 64, 43–51.

Bayram, M., Öner, M.D., Eren, S. (2004b). Thermodynamics of the dimensional changes of the wheat kernel during the cooking operation for the bulgur production, *Food Science and Technology International*, 10, 243–253.

Bayram, M., Öner, M.D., Kaya, A. (2004c) Influence of soaking on the dimensions and colour of soybean for bulgur production, *Journal of Food Engineering*, 61, 331-339.

Baysal, T., Icier, F., Ersus, S.,Yıldız, H. (2003) Effects of microwave and infrared drying on the quality of carrot and garlic, *Eur Food Res Technol*, 218:68–73.

Becker H.A., Sallans H.R.(1956) A study of the relation between time, temperature, moisture content, and loaf volume by the bromate formula in the heat treatment of wheat and flour, *Cereal Chemistry*, 33:4, 254-265.

Becker, H.A., Sallans, H.R. (1960) Drying wheat in a spouted bed, *Chemical Engineering Science,*13:3, 97-112.

Becker, H.A., Sallans, H.R.(1961) On the continuous, moisture diffusion-controlled drying of solid particles ina well-mixed, isothermal bed, *Chemical Engineering Science,*13, 97.

Becker, H.A., Isaacson, R.A.(1970) Wheat drying in well-stirred batch and continuous-moving bed dryers, *Canadian Journal of Chemical Engineering*, 48, 560-567.

Bilbao-Sáinz, C.,Butler, M.,Weaver, T., Bent, J.(2007) Wheat starch gelatinization under microwave irradiation and conduction heating, *Carbohydrate Polymers*,69, 224–232

Bird R., Stewart W. E., Lightfoot E. N.(1960) Transport phenomena, John Wiley and Sons, Inc., U.S.A.

Bizarre O., Morelli A.(1980) Durum wheat chemistry and technology:Milling of durum wheat, Buhler Miag sp A, 161-18.

Chang, C.S.(1988) Measuring density and porosity of grain kernels by using gas pycnometer, *Cereal Chemistry*, 65, 13-15

Charles, A.L.,Kao, H.M., Huang, T.C.(2003) Physical investigations of surface membrane-water relationship of intact and gelatinized wheat-starch systems, *Carbohydrate Research*, 338, 2403-2408.

Chesson, A., Gardner, P.T., Wood, T.J.(1997) Cell wall and porosity and available surface area of wheat straw and wheat grain fractions, *Journal of the Science of Food* and *Agriculture*, 75: 289–295.

Clark D. E. (1996). Microwave processing of materials, *Annual Review of Materials Science*, 26, 299-331.

Cömden,M.(1986) Sürekli bulgur üretim tekniği ve bulgur kurutulması, Gıda Sanayi Araştırma ve Geliştirme'86 Sempozyumu, Ege Üniv., Gıda Müh.85-91.

Dreher, M. L. (2001) Dietary fiber overview. In S. Sungsoo (Ed.), Handbook of dietary fiber (pp. 21–36). New York, USA: Marcel Dekker Inc.

Dobraszczyk, B.J., Whitworth, M.B., Vincent, J.F.V., Khan, A.A. (2000) Single kernel wheat hardness and fracture properties in relation to density and the modelling of fracture in wheat endosperm, *Journal of Cereal Science*, 35, 245-263.

Ehrburger-Dolle, F., Lavanchy, A., Stoeckle, F. (1994)Determination of the surface fractal dimension of active carbons by mercury porosimetry, *Journal of Colloid and Interface Science,* 166, 451-461.

Elgun A., Ertugay Z., Certel M.(1990) Corn bulgur: Effects of corn maturation stage and cocking form on bulgur-making parameters and physical and chemical properties of bulgur products, *Cereal Chemistry*, 67:1-6.

Elgun A., Ertugay Z.(1992)Tahıl İşleme Teknolojisi Atatürk Üniversitesi, Ziraat Fakültesi Yayınları No:297, Ders Kitapları Seri, 52:346-348,Erzurum.

Ercan (1986) Bulgur işleme tekniği ve kimyasal bileşimi, *Gıda Dergisi*, 11(6), 319-321.

Fang C., Campbell G.M.(2003) On predicting roller milling performance V: Effect of moisture content on the particle size distribution from first break milling of wheat, *Journal of Cereal Science,* 37, 31-34.

Fayed, M. E., Otten, L. (1997) Handbook of powder science & technology. Spouting of Particulate Solids, New York, Chapman & Hall.

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

Feng, H., Tang, J. (1999) Microwave and spouted bed drying of frozen blueberries: The effect of drying and pretreatment methods on physical properties and retention of flavor volatiles, *Journal of Food Processing Preservation,* 23, 463-479.

Feng, H., Tang, J., Cavalieri, R. P. (1999) Combined microwave and spouted bed drying of diced apples: Effect of drying conditions on drying kinetics and product temperature, *Drying Technology*, 17:10, 1981 – 1998.

Feng, H., Tang, J., Cavalieri, R. P., Plumb, O. A. (2001) Heat and mass transport in microwave drying of hygroscopic porous materials in a spouted bed., *AIChE Journal*, 74(7), 1499-1511.

Garcia, V., Colonna, P., Lourdin, D., Buleon, A., Bizot, H., Ollivon, M. (1996) Thermal transitions of cassava starch at intermediate water contents, *Journal of Thermal Analysis and Calorimetry, 47*, 5, 1213–1228.

Geankoplis, C. J.(2003) Transport processes and unit operations, 4th ed. Prentice-Hall, Inc., U.S.A.

Geldart, D. (1973) Types of fluidization, *Powder Technology*, 7, 285-290.

Gishler, P.E.(1983) The spouted bed technique- Discovery and early studies at N.R.C., *Canadian Journal of Chemical Engineering*, 61, 267-268.

Go, A., Das, S.K., Srzednicki, G., Driscoll, R.H. (2007) Modeling of moisture and temperature changes of wheat during drying in a triangular spouted bed dryer, *Drying Technology*, 25: 575–580.

Gong, Z.X., Devahastin, S., Mujumdar, A.S. (1997) A two-dimensional finite element model for wheat drying in a novel rotating jet spouted bed, *Drying Technology*, 15:2, 575-592.

Gunasekaran, S. (1999) Pulsed microwave-vacuum drying of food materials, *Drying Technology*, 17(3), 395-412.

Gyimes, E. (2004) Investigation of relationship among the agro-physical features of wheat (*Triticum aestivum*) kernel varieties, PhD Thesis, University of West Hungary.

Hatamipour, M.S., Mowla, D.(2003) Correlations for shrinkage, density and diffusivity for drying of maize and green peas in a fluidized bed with energy carrier, *Journal of Food Engineering*, 59, 221–227.

Hayta, M.(2002) Bulgur quality as affected by drying methods, *Journal of Food Science*, 67:6, 2241-2244.

Jumah R.Y.(1995) Flow and Drying Characteristics of a Rotating Jet Spouted Bed, Ph.D. Thesis, McGiIl University, Canada.

Jumah, R. Y., Raghavan, G. S. V. (2001) Analysis of heat and mass transfer during combined microwave convective spouted-bed drying, *Drying Technology*,19:3, 485–506.

Kadakal, Ç., Ekinci, R., Yapar, A.(2007) The effect of cooking and drying on the water-soluble vitamins content of bulgur, *Food Science and Technology International*; 13; 349-354.

Karathanos, V.T., Kanellopoulos, N.K., Belessiotis, V.G.(1996) Development of porous structure during air drying of agricultural plant products. *Journal of Food Engineering*, 29, 167–183.

Kasamsa, L.S., Ngadi, M.O. (2005) Pore structure characterization of deep-fat-fried chicken meat, *Journal of Food Engineering*, 66, 369–375

Keey, R. B. (1972) Drying principles and practice, Pergamon Press, Hungary.

Kheiralipour, K., Karimi, M., Tabatabaeefar, A., Naderi, M., Khoubakht, G., Heidarbeigi, K. (2008) Moisture-Depend Physical Properties of Wheat (*Triticum aestivum* L.). *Journal of Agricultural Technology* ,4(1): 53-64.

Koca, A.F., Anıl, M.(1996) The effect of different wheat kinds and cooking methods on bulgur quality, *Gıda*, 21(5), 369-374.

Köksel, H., Edney, M.J.,Özkaya, B. (1999) Barley bulgur: effect of processing and cooking on chemical composition, *Journal of Cereal Science,* 29: 185–190.

Krokida, M. K. , Maroulis, Z. B. (1999) Effect of microwave drying on some quality properties of dehydrated products, *Drying Technology*, 17:3,449- 466

Krokida, M.K., Maroulis,Z.B. (2000) Quality change during drying of food materials, In *Drying Technology in Agriculture and Food Sciences*; Mujumdar, A.S.; Ed.; Science Publishers, Inc.: Enfield, NH.

Kruger, J.E., Reed, G. (1988) Enzymes and colors. In: Pomeranz Y, editor. Wheat: Chemistry and technology, (441-500), 3rd ed. Vol. II. ,St. Paul, Minn.

Krulis, M., Kühnert, S., Leiker, M., Rohm, H. (2005) Influence of energy input and initial moisture on physical properties of microwave-vacuum dried strawberries, *Eur Food Res Technol*, 221: 803–808.

Kugo, M., Watanabe, N., Uemaki, O., Shibata, T. (1965) Drying of wheat by spouting bed, Bull.Hokkaido Univ. Sapporo, Jap., 39, 95.

Lowell, S., Shields, J.E. (1984). Powder surface area and porosity (2nd ed.). London: Chapman and Hall

Luikov, A.V. (1966) Heat and mass transfer in capillary-porous bodies, Pergamon Press, Oxford.

Madamba, P.S., Driscoll, R.H., Buckle, K.A.(1996). Thin-layer drying characteristics of garlic slices, *Journal of Food Engineering*, 29, 75–97.

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

Mathur, K.B., Gishler, P.E. (1955) A study of the application of the spouted bed technique to wheat drying, *Journal of Applied Chemistry*, 5, 624.

Mathur, K.B., Epstein, N. (1974) Spouted Beds, Academic Press, New York.

Mohapatra, D., Rao, P.S.(2005) A thin layer drying model of parboiled wheat, *Journal of Food Engineering*, 66, 513–518.

Mohsenin, N.N. (1986) Physical Properties of Plant and AnimalMaterials. Gordon and Breach Science Publishers, New York.

Mudgett R. E. (1989) Microwave food processing, *Food Technology*, 117-126.

Murthy, K.V., Ravi, R., Bhat, K. K., Raghavarao, K.S.M.S. (2008) Studies on roasting of wheat using fluidized bed roaster, *Journal of Food Engineering*, 89, 339-342.

Ng P.P., Tasırın S.M., Law C.L. (2006) Thin layer method analysis of spouted bed dried Malaysian paddy–Characteristic drying curves, *Journal of Food Process Engineering*, 29:4, 414-428.

Ni, H.(1997) Multiphase moisture transport in porous media under intensive microwave heating. Ph.D. Thesis, Cornell University, U.S.A.

Nıamnuy, C., Devahastin, S., Soponronnarit, S.(2007) Effect of process parameters on quality changes of shrimp during drying in a jet spouted bed, *Journal of Food Science*, 72,9, 553-563.

Nijhuis H. H., Torringa H. M., Muresan S., Yuksel D., Leguijt C., Kloek W. (1998) Approaches to improving the quality of dried fruit and vegetables, *Trends in Food Science and Technology*, 9, 13-20.

Nindo, C., Ting, S., Wang, S. W., Tang, J., Powers, J. R. (2003) Evaluation of drying technologies for retention of physical and chemical quality of green asparagus (Asparagus officinalis L.), *LWT-Food Science and Technology*, 36(5), 507-516.

Oktem, R.(1984) Tarhana ve bulgur imalat tekniği geliştirme olanakları.9. IzmirGıda ve Tarım Fuarı, Gıda Sanayinde Teknolojik Gelimseler Sempozyomu, Ege Uni., Gıda Müh., Izmir, Turkey, 115-126.

Ozboy, Ö., Köksel, H. (1998) The effects of bulgur production on various chemical properties of wheats, *Gıda*, 23,6,449-457.

Ozboy Ö., Koksel H.(2002) An application of linear regression technique for predicting bulgur yield and quality of wheat cultivars, *Nahrung/Food*,46:1,21– 24.

Ozkaya, B.(1997) Bulgur İşleme Tekniğinin Besleme Kalitesi Açısından Önemi. 2. Un- Bulgur ve Bisküvi Sempozyumu. Karaman. 153-164.

Ozkaya, B., Ozkaya, H., Koksel, H.(1993) Bazı buğday ceşitlerinden farklı yöntemlerle üretilen bulgurların bazı vitamin ve mineral içerikleri ile proteinlerinin elektroforetik ve nişastalarının "Briefringence" özellikleri üzerinde araştırmalar,Tarla Bitkileri Merkez Araştırma Enstitüsü Dergisi, 2(4)36-56.

Ozkaya, B.,Koksel,H.,Ozkaya,H.(1996) Riboflavin-, thiamin-und minearlstoffgehalte in bulgur aus verschiedenen durum-weizensorten, Getreide Mehl und Brot, 50:347-349.

Pence, J.W.(1969) History and status-of specific protein-rich foods, Bulgur, WURLD wheat, and wheat protein beverages, Protein-enriched Cereal Foods for World Needs, Ed. Milner. M. Am. Assoc. of Cereal Chem., St. Paul, MN.-

Pence, J.W., Ferrel. R.E., Robertson. J.A.(1964) Effects of process on B vitamins and mineral contents of bulgur, *Food Technology*, 18: 171.

Pence, J.W., Ferrel. R.E., Hammes. P.A., Haley, W.L.(1965) The composition of commercial bulgur, *Cereal Science Today,* 10: 587.

Prachayawarakorn, S.,Ruengnarong, S., Soponronnarit, S.(2006) Characteristics of heat transfer in two-dimensional spouted bed, *Journal of Food Engineering* ,76, 327–333.

Rahman, M.S.(1997) Physical meaning and interpretation of fractal dimensions of fine particles measured by different methods, *Journal of Food Engineering*, 32, 447-456

Rahman, M.S. (2001) Toward prediction of porosity in foods during drying: a brief review, *Drying Technology*,19:1,1 -13.

Rahman, M.S., Al-Amri, O.S., Al-Bulushi, I.M.(2002) Pores and physico-chemical characteristics of dried tuna produced by different methods of drying. *Journal of Food Engineering* , 53: 301–313.

Rahman, M.S., Al-Zakwani, I., Guizan, N.(2005) Pore formation in apple during air-drying as a function of temperature: porosity and pore size distribution, *Journal of the Science of Food Agriculture*, 85:979–989

Ramallo, L.A. , Pokolenko, J. J., Balmaceda, G. Z., Schmalko, M. E. (2001) Moisture diffusivity, shrinkage, and apparent density variatıon during of leaves at high temperatures,*International Journal of Food Properties*,4:1,163- 170

Rogers, J. W., Head, W.B. (1961) Relationships Between Porosity, Median Size, and Sorting Coefficients of Synthetic Sands, *Journal of Sedimentary Research*, 31

Sahin S., Sumnu S.G.(2006) Physical properties of foods, New York : Springer.

Salam P.A., Bhattacharya S.C.(2006) A comparative hydrodynamic study of two types of spouted bed reactor designs, Chemical Engineering Science ,61, 1946 – 1957.

Schiffman, R.F.(2007) Microwave and dielectric drying, Handbook of Industrial Drying-edited by A.S. Mujumdar, 3rd edition, 289-290,Boca Raton, FL : CRC/Taylor & Francis.

Sharma, G.P., Prasad, S.(2004) Effective moisture diffusivity of garlic cloves undergoing microwave-convective drying, *Journal of Food Engineering*, 65(4), 609-617.

Shammas, E., Adolph, W.H. (1954) Nutritive value of parboiled wheat used in the Near East, Journal of American Diet. Association, 30: 982.

Singh, B., Dodda, L. M. (1979). Studies on the preparation and nutrient composition of bulgur from triticale, *Journal of Food Science*, 44, 449–452.

Slade, L., Levine, H. (1988). Non-equilibrium melting of native granular starch Part I. Temperature location of the glass transition associated with gelatinization of A-type cereal starches, *Carbohydrate Polymers*, 8, 183-208.

Smith, G. S., Barta, E. J., Lazar, M. E. (1964). Bulgur production by continuous atmospheric pressure process, *Food Technology*, 18, 89–92.

Srivastava, A.K., Meyer, D., Rao, H., Seibel, W. (2002) Scanning Electron Microscopic Study of Dough and Chapati from Gluten-reconstituted Good and Poor Quality Flour, *Journal of Cereal Science*, 35:119–128.

Stapley,A.G.F.,Gladden,L.F., Fryer,P.J.(1997) A differential scanning calorimetry study of wheat grain cooking, International Journal of Food Science and Technology, 32, 473-486.

Tekeli, T.(1964)Bulgur, Hububat Teknolojisi, Ankara Üniversitesi, Ziraat Fakültesi Yayınları, 103-109, Atatürk Üniversitesi Basımevi, Erzurum.

Thorley, B., Saunby, J.B., Mathur, K.B., Osberg, G.L.(1959) An analysis of air and solid flow in a spouted wheat bed, *Canadian Journal of Chemical Engineering*, 37, 184-192.

Treybal, R.E. (1980) Mass-transfer operations, 3rd ed. McGraw-Hill, Inc., New York.

TSE, (2003) Bulgur-TS2284. Turkish Standard Institute

Torringa E., Esveld E., Scheewe I., Van den Berg R., Bartels P. (2001) Osmotic dehydration as a pre-treatment before combined microwave-hot-air drying of mushrooms, *Journal of Food Engineering*, 49, 185-191.

Turhan, M., Gunasekaran, S., Lamsal, B.P. (2001) Drying of gelatinized whole wheat, *Drying Technology*,19:2,333- 342.

Turhan, M., Oymael B., Ekiz H.I. (2003) Water vapor adsorption of ready-to-cook wheat, *Journal of Food Engineering*, 57, 269-276.

Vansteelandt, J., Delcour, J.A.(1999) Characterisation of starch from durum wheat (Triticum durum), *Starch-Starke*, 51, 2-3, 73-80

Viswanahan K., Lyall M.S., Negi K.S., Raychaudhury B.C. (1984) Experimental and theoretical study of batch drying of wheat in spouted beds, Proc. 4th International Drying Semposium, Kyoto, 552-557.

Viswanathan, K., Lyall, M.S., Raychaudhuri, B.C. (1986) Spouted bed drying of agricultural grains, *Canadian Journal of Chemical Engineering*, 64, 22, 223-232.

Wachiraphansakul, S., Devahastin, S.(2005)Drying kinetics and quality of soy residue (Okara) dried in a jet spouted-bed dryer,Drying Technology,23:6,1229-1242.

Wang, Z., Sun, J., Chen, F, Liao, X., Hu, X. (2007) Mathematical modelling on thin layer microwave drying of apple pomace with and without hot air pre-drying, *Journal of Food Engineering*, 80:2, 536-544.

Yıldırım, A.(2004) Effect of different millling systems on selected quality parameters of Bulgur, M. Sc. Thesis, University of Gaziantep, Turkey.

Yıldırım, A., Bayram, M.,Öner, M.D.(2008) Ternary milling of bulgur with four rollers, *Journal of Food Engineering*, 84:394–399.

Zahed, A.H., Epstein, N.(1992) Batch and continuous spouted bed drying of cereal-grains - the thermal-equilibrium model, *Canadian Journal of Chemical Engineering*, 70(5), 945-953.

Zhanga, M., Tang, J., Mujumdar, A.S., Wang, S.(2006) Trends in microwave related drying of fruits and vegetables, *Trends in Food Science & Technology*, 17:524-534.

APPENDIX A

POWER MEASUREMENT OF MICROWAVE OVEN (IMPI-2L)

Operate the oven at its rated line voltage with oven set on high with a load of 2000 ± 5 g water placed in two 1-L beakers. The beakers should initially be at room ambient temperature. Initial water temperature should be 20°C ± 2°C, measured after water is placed in beakers and before placing in the microwave oven. The beakers are placed in the center of the oven, side by side in the width dimension of the cavity, and touching each other. The oven is turned on for 2 min and 2 s. The beakers are removed from the oven, and the final temperatures are measured and recorded.

The power is calculated from the following formula:

$$P(W) = 70 \times \frac{\Delta T_1(^oC) + \Delta T_2(^oC)}{2} \qquad \text{A.1}$$

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 the average of the three readings. If any individual measurement is more than 5% from the average, the complete test should be repeated.

The oven should be pre-warmed by heating 2L of water for 5 minutes, then wiping the shelf with a cold wet rag. The water in each vessel should be well stirred by plastic or wooden spoon before measuring the starting and final temperatures. The temperature should be measured with a thermometer with 0.1°C resolution (Buffler, 1993).

Table A.1 Power measurement test data

Replicate		**T_1 (^oC)**	**T_2 (^oC)**	**Power (W)**	**%deviation**
1	Ti	18.6	18.9	626	0.4
	Tf	26.9	28.5		
	ΔT	8.3	9.6		
2	Ti	19.0	20.4	623	0.2
	Tf	27.8	29.4		
	ΔT	8.8	9.0		
3	Ti	20.6	20.8	623	0.2
	Tf	28.8	30.4		
	ΔT	8.2	9.6		
Average P (W)				624	

APPENDIX B

MINIMUM SPOUTING AIR VELOCITY DETERMINATION

Table B.1 The variation of pressure drop in the bed with the increasing superficial air velocity.

Superficial air velocity (m/s)	Pressure drop (Pa)
0.00	0.00
0.10	981.00
0.15	1000.62
0.20	971.19
0.25	931.95
0.30	824.04
0.35	755.37
0.45	686.70
0.47	608.22
0.58	598.41
0.65	608.22
0.75	618.03
0.80	618.03
0.86	618.03
0.92	618.03
0.94	618.03

Table B.2 The variation of pressure drop in the bed with the decreasing superficial air velocity.

Superficial air velocity (m/s)	Pressure drop (Pa)
0.94	618.03
0.88	618.03
0.84	608.22
0.80	588.60
0.75	578.79
0.70	549.36
0.65	559.17
0.60	539.55
0.55	529.74
0.50	510.12
0.45	539.55
0.40	539.55
0.35	529.74
0.30	500.31
0.25	490.50
0.20	470.88
0.15	392.40
0.10	294.30
0.00	0.00

APPENDIX C

DRYING EXPERIMENTS

Table C.1 Weight data for spouted bed drying at different air temperatures.

Time (min)	50°C	70°C	90°C
0	200.02	200.05	200.02
15	177.92	167.23	158.73
30	163.36	147.37	132.51
45	151.00	131.43	115.92
60	140.79	119.68	105.65
75	132.03	111.67	99.64
90	124.42	106.02	96.21
105	118.06	101.96	93.85
120	112.90	98.97	
135	108.69	96.97	
150	105.43	95.45	
165	102.83	94.28	
180	100.80		
195	99.12		
210	97.80		
225	96.62		
240	95.70		
255	94.99		
270	94.26		

Table C.2 Dry basis moisture content data for spouted bed drying at different air temperatures.

Time (min)	50°C	70°C	90°C
0	1.410	1.410	1.410
15	1.143	1.014	0.912
30	0.968	0.775	0.596
45	0.819	0.583	0.396
60	0.696	0.442	0.273
75	0.591	0.345	0.200
90	0.499	0.277	0.159
105	0.422	0.228	0.131
120	0.360	0.192	
135	0.309	0.168	
150	0.270	0.150	
165	0.239	0.136	
180	0.214		
195	0.194		
210	0.178		
225	0.164		
240	0.153		
255	0.144		
270	0.136		

Table C.3 Weight data for microwave assisted spouted bed drying at 288 W and different air temperatures.

Time (min)	50°C	70°C	90°C
0	200.00	200.01	200.00
5	177.63	177.05	167.96
10	160.07	157.18	143.84
15	145.73	138.97	125.88
20	134.38	125.73	111.23
25	125.79	116.37	102.31
30	118.16	109.21	96.98
35	112.84	103.86	94.12
40	108.20	100.62	
45	104.94	98.14	
50	102.02	96.22	
55	100.44	94.84	
60	98.62	93.62	
65	97.04		
70	96.19		
75	95.18		
80	94.20		

Table C.4 Weight data for microwave assisted spouted bed drying at 624 W and different air temperatures.

Time (min)	50°C	70°C
0	200.00	200.03
5	164.04	161.83
10	136.73	130.95
15	116.60	108.04
20	104.05	97.92
25	98.37	92.28
30	95.25	
35	92.96	

Table C.5 Dry basis moisture content data for microwave assisted spouted bed drying at 288 W and different air temperatures.

Time (min)	50°C	70°C	90°C
0	1.410	1.410	1.410
5	1.140	1.120	1.024
10	0.928	0.885	0.733
15	0.756	0.659	0.517
20	0.619	0.492	0.340
25	0.515	0.385	0.233
30	0.424	0.297	0.168
35	0.360	0.230	0.134
40	0.304	0.200	
45	0.264	0.172	
50	0.229	0.152	
55	0.210	0.138	
60	0.188	0.127	
65	0.169		
70	0.159		
75	0.147		
80	0.135		

Table C.6 Dry basis moisture content data for microwave assisted spouted bed drying at 624 W and different air temperatures.

Time (min)	50°C	70°C
0	1.410	1.410
5	0.976	0.949
10	0.647	0.578
15	0.405	0.302
20	0.254	0.180
25	0.185	0.112
30	0.148	
35	0.120	

Determination of Equilibrium Moisture Content

The equilibrium moisture content X_e in equation C.1 was evaluated from the sorption isotherm equation for wheat. Several sorption models have been proposed for correlation of equilibrium moisture content (X) with RH. Among them, the Guggenheim–Anderson–Boer (GAB) model covers the largest RH range of practical interest in a wide variety of food and agricultural products (Turhan et al, 2003). The GAB model is given in the following form:

$$X_e = \frac{X_M C \kappa a_w}{(1-\kappa a_w)(1-\kappa a_w + C \kappa a_{w)}} \qquad \text{C.1}$$

where, X_M is monolayer moisture content, a_w is water activity = RH/100, and C and are equation constants given as:

$$C = C_0 \exp\left[\frac{\alpha_c}{RT}\right]$$

$$k = k_0 \exp\left[\frac{\alpha_k}{RT}\right] \qquad \text{C.2}$$

Turhan et al. (2003) investigated the effect of temperature on sorption isotherms of bulgur. In order to obtain the equilibrium moisture for experimental conditions, the values of C, k, α_c and α_k were related in Turhan et al. study to temperature by the following equations:

$$C = 1 \times 10^{-4} \exp\left[\frac{32439}{RT}\right]$$

$$k = 0.46 \exp\left[\frac{1355}{RT}\right]$$

$$X_M (\%d.b.) = 9.7 \qquad \text{C.3}$$

The equilibrium moisture X_e values at the three spouted bed air conditions, were then estimated from equation C.3.

Table C.7 Calculated equilibrium moisture, X_e

Temperature(^{o}C)	C	k	RH(%)	X_e(kg/kg)
50	17.53	0.76	5.8	0.0454
70	8.671	0.74	2.2	0.0123
90	4.636	0.72	1.1	0.0035

*The RH of air was determined from the psychrometric chart based on the room air condition of 20^{o}C and 30% relative humidity (Table C.8)

Air Humidity

Table C.8 Psychrometric data for the air at the enviroment of experiment

Dry bulb temperature (^{o}C)	Wet bulb temperature (^{o}C)	% Relative humidity	Humidity (kg water vapor/kg air)
20	15	30	0.008

APPENDIX D

TABLE OF STATISTICAL TEST

D.1 Bulk Density

Table D.1.1 Anova Table for the effect of different drying conditions on bulk density

ANOVA Results					
Source of Variation	DF	SS	MS	F	P
Drying Conditions	7	33862	4837	24.11	0.000
Error	8	1605	201		
Total	15	35466			

Table D.1.2 Result of Tukey's test for the effect of different drying conditions on bulk density

Tukey Simultaneous Tests

All Pairwise Comparisons among Levels of Drying Condition

Drying Condition = MWSB-50C-288W subtracted from:

Drying Condition	Lower	Center	Upper
MWSB-50C-624W	-117.00	-60.92	-4.83
MWSB-70C-288W	-98.25	-42.17	13.92
MWSB-70C-624W	-205.31	-149.22	-93.14
MWSB-90C-288W	-189.53	-133.44	-7736
SB-50C	-104.42	-48.33	7.75
SB-70C	-106.14	-50.06	6.03
SB-90C	-128.61	-72.53	-16.44

Table D.1.2 cont'd

Drying Condition = MWSB-50C-624W subtracted from:			
MWSB-70C-288W	-37.33	18.75	74.83
MWSB-70C-624W	-144.39	-88.31	-32.22
MWSB-90C-288W	-128.61	-72.53	-16.44
SB-50C	-43.50	12.58	68.67
SB-70C	-45.22	10.86	66.94
SB-90C	-67.69	-11.61	44.47
Drying Condition = MWSB-70C-288W subtracted from:			
MWSB-70C-624W	-163.14	-107.06	-50.97
MWSB-90C-288W	-147.36	-91.28	-35.19
SB-50C	-62.25	-6.17	49.92
SB-70C	-63.97	-7.89	48.19
SB-90C	-86.44	-30.36	25.72
Drying Condition = MWSB-70C-624W subtracted from:			
MWSB-90C-288W	-40.31	15.78	71.86
SB-50C	44.81	100.89	156.97
SB-70C	43.08	99.17	155.25
SB-90C	20.61	76.69	132.78
Drying Condition = MWSB-90C-288W subtracted from:			
SB-50C	29.03	85.11	141.19
SB-70C	27.31	83.39	139.47
SB-90C	4.83	60.92	117.00
Drying Condition = SB-50C subtracted from:			
SB-70C	-57.81	-1.72	54.36
SB-90C	-80.28	-24.19	31.89
Drying Condition = SB-70C subtracted from:			
SB-90C	-78.56	-22.47	33.61

D.2 Apparent Density

Table D.2.1 Anova Table for the effect of different drying conditions on apparent density

ANOVA Results					
Source of Variation	DF	SS	MS	F	P
Drying Conditions	7	86169	12310	16.82	0.000
Error	8	5856	732		
Total	15	92025			

Table D.2.2 Result of Tukey's test for the effect of different drying conditions on apparent density

Tukey Simultaneous Tests

All Pairwise Comparisons among Levels of Drying Condition

Drying Condition = MWSB-50C-288W subtracted from:			
Drying Condition	Lower	Center	Upper
MWSB-50C-624W	-210.76	-103.63	3.50
MWSB-70C-288W	-122.81	-15.68	91.45
MWSB-70C-624W	-289.48	-182.35	-75.21
MWSB-90C-288W	-290.07	-182.94	-75,81
SB-50C	-120.43	-13.30	93.83
SB-70C	-104.51	2.62	109.75
SB-90C	-161.30	-54.17	52.96
Drying Condition = MWSB-50C-624W subtracted from:			
MWSB-70C-288W	-19.18	87.95	195.08
MWSB-70C-624W	-185.85	-78.72	28.41
MWSB-90C-288W	-186.44	-79.31	27.82
SB-50C	-16.80	90.33	197.46
SB-70C	-0.88	106.25	213.38

Table D.2.2 cont'd

SB-90C	-57.67	49.46	156.59
Drying Condition = MWSB-70C-288W subtracted from:			
MWSB-70C-624W	-273.80	-166.67	-59.54
MWSB-90C-288W	-274.39	-167.26	-60.13
SB-50C	-104.75	2.38	109.51
SB-70C	-88.83	18.30	125.43
SB-90C	-145.62	-38.49	68.64
Drying Condition = MWSB-70C-624W subtracted from:			
MWSB-90C-288W	-107.73	-0.60	106.54
SB-50C	61.92	169.05	276.18
SB-70C	77.84	184.97	292.10
SB-90C	21.04	128.17	235.31
Drying Condition = MWSB-90C-288W subtracted from:			
SB-50C	62.51	169.64	276.77
SB-70C	78.43	185.56	292.69
SB-90C	21.64	128.77	235.90
Drying Condition = SB-50C subtracted from:			
SB-70C	-91.21	15.92	123.05
SB-90C	-148.00	-40.87	66.26
Drying Condition = SB-70C subtracted from:			
SB-90C	-163.92	-56.79	50.34

D.3 Bulk Porosity

Table D.3.1 Anova Table for the effect of different drying conditions on bulk porosity

ANOVA Results					
Source of Variation	DF	SS	MS	F	P
Drying Conditions	7	0.0042781	0.0006112	17.09	0.000
Error	8	0.0002861	0.0000358		
Total	15	0.0045642			

Table D.3.2 Result of Tukey's test for the effect of different drying conditions on bulk porosity

Tukey Simultaneous Tests

All Pairwise Comparisons among Levels of Drying Condition

Drying Condition = MWSB-50C-288W subtracted from:			
Drying Condition	Lower	Center	Upper
MWSB-50C-624W	-0.023371	0.000308	0.023988
MWSB-70C-288W	0.006512	0.030192	0.053872
MWSB-70C-624W	0.015499	0.039178	0.062858
MWSB-90C-288W	-0.000243	0.023437	0.047116
SB-50C	0.012867	0.036547	0.060226
SB-70C	0.021767	0.045447	0.069126
SB-90C	0.013171	0.036851	0.060530
Drying Condition = MWSB-50C-624W subtracted from:			
MWSB-70C-288W	0.006204	0.029884	0.053564
MWSB-70C-624W	0.015190	0.038870	0062550
MWSB-90C-288W	-0.000551	0.023128	0.046808
SB-50C	0.012559	0.036238	0.059918
SB-70C	0.021459	0.045138	0.068818
SB-90C	0.012863	0.036542	0.060222

Table D.3.2 cont'd

Drying Condition = MWSB-70C-288W subtracted from:			
MWSB-70C-624W	-0.014693	0.008986	0.032666
MWSB-90C-288W	-0.030435	-0.006755	0.016924
SB-50C	-0.017325	0.006355	0.030034
SB-70C	-0.008425	0.015255	0.038934
SB-90C	-0.017021	0.006659	0.030338
Drying Condition = MWSB-70C-624W subtracted from:			
MWSB-90C-288W	-0.039422	-0.015742	0.007938
SB-50C	-0.026312	-0.002632	0.021048
SB-70C	-0.017412	0.006268	0.029948
SB-90C	-0.026007	-0.002328	0.021352
Drying Condition = MWSB-90C-288W subtracted from:			
SB-50C	-0.010570	0.013110	0.036790
SB-70C	-0.001670	0.022010	0.045690
SB-90C	-0.010266	0.013414	0.037094
Drying Condition = SB-50C subtracted from:			
SB-70C	-0.014780	0.008900	0.032580
SB-90C	-0.023376	0.000304	0.023984
Drying Condition = SB-70C subtracted from:			
SB-90C	-0.032276	-0.008596	0.015084

D.4 Pore Size Characteristics

Table D.4.1 Anova Table for the effect of different drying conditions on interior kernel porosity

ANOVA Results					
Source of Variation	DF	SS	MS	F	P
Drying Conditions	8	95.41	11.93	5.93	0.008
Error	9	18.09	2.01		
Total	17	113.50			

Table D.4.2 Result of Tukey's test for the effect of different drying conditions on interior kernel porosity

Tukey Simultaneous Tests

All Pairwise Comparisons among Levels of Drying Condition

Drying Condition = MWSB-50C-288W subtracted from:			
Drying Condition	Lower	Center	Upper
MWSB-50C-624W	-5.012	0.601	6.215
MWSB-70C-288W	-3.942	1.672	7.285
MWSB-70C-624W	-3.706	1.908	7.521
MWSB-90C-288W	-0.626	4.987	10.601
RAW	-8.179	-2.566	3.048
SB-50C	-7.325	-1.712	3.902
SB-70C	-6.935	-1.321	4.292
SB-90C	-7.845	-2.231	3.382
Drying Condition = MWSB-50C-624W subtracted from:			
MWSB-70C-288W	-4.543	1.070	6.684
MWSB-70C-624W	-4.307	1.306	6.920
MWSB-90C-288W	-1.228	4.386	9.999
RAW	-8.781	-3.167	2.446
SB-50C	-7.927	-2.313	3.300

Table D.4.2 cont'd

SB-70C	-7.536	-1.923	3.691
SB-90C	-8.446	-2.833	2.781
Drying Condition = MWSB-70C-288W subtracted from:			
MWSB-70C-624W	-5.377	0.236	5.850
MWSB-90C-288W	-2.298	3.316	8.929
RAW	-9.851	-4.237	1.376
SB-50C	-8.997	-3.383	2.230
SB-70C	-8.606	-2.993	2.621
SB-90C	-9.516	-3.903	1.711
Drying Condition = MWSB-70C-624W subtracted from:			
MWSB-90C-288W	-2.534	3.079	8.693
RAW	-10.087	-4.474	1.140
SB-50C	-9.233	-3.620	1.994
SB-70C	-8.843	-3.229	2.384
SB-90C	-9.753	-4.139	1.474
Drying Condition = MWSB-90C-288W subtracted from:			
RAW	-13.166	-7.553	-1.939
SB-50C	-12.312	-6.699	-1.085
SB-70C	-11.922	-6.308	-0.695
SB-90C	-12.832	-7.218	-1.605
Drying Condition = RAW subtracted from:			
SB-50C	-4.760	0.854	6.468
SB-70C	-4.369	1.245	6.858
SB-90C	-5.279	0.334	5.948
Drying Condition = SB-50C subtracted from:			
SB-70C	-5.223	0.390	6.004
SB-90C	-6.133	-0.520	5.094
Drying Condition = SB-70C subtracted from:			
SB-90C	-6.524	-0.910	4.703

Table D.4.3 Anova Table for the effect of different drying conditions on total intruded volume

ANOVA Results					
Source of Variation	DF	SS	MS	F	P
Drying Conditions	8	15482	1935	9.87	0.001
Error	9	1765	196		
Total	17	17247			

Table D.4.4 Result of Tukey's test for the effect of different drying conditions on total intruded volume

Tukey Simultaneous Tests

All Pairwise Comparisons among Levels of Drying Condition

Drying Condition	Lower	Center	Upper
MWSB-50C-624W	-32.00	23.45	78.90
MWSB-70C-288W	-41.80	13.65	69.10
MWSB-70C-624W	-5.65	49.80	105.25
MWSB-90C-288W	9.90	65.35	120.80
RAW	-78.30	-22.85	32.60
SB-50C	-68.15	-12.70	42.75
SB-70C	-71.50	-16.05	39.40
SB-90C	-68.40	-12.95	42.50
Drying Condition = MWSB-50C-624W subtracted from:			
MWSB-70C-288W	-65.25	-9.80	45.65
MWSB-70C-624W	-29.10	26.35	81.80
MWSB-90C-288W	-13.55	41.90	97.35
RAW	-101.75	-46.30	9.15
SB-50C	-91.60	-36.15	19.30
SB-70C	-94.95	-39.50	15.95
SB-90C	-91.85	-36.40	19.05
Drying Condition = MWSB-70C-288W subtracted from:			

Table D.4.4 cont'd

MWSB-70C-624W	-19.30	36.15	91.60
MWSB-90C-288W	-3.75	51.70	107.15
RAW	-91.95	-36.50	18.95
SB-50C	-81.80	-26.35	29.10
SB-70C	-85.15	-29.70	25.75
SB-90C	-82.05	-26.60	28.85
Drying Condition = MWSB-70C-624W subtracted from:			
MWSB-90C-288W	-39.90	15.55	71.00
RAW	-128.10	-72.65	-17.20
SB-50C	-117.95	-62.50	-7.05
SB-70C	-121.30	-65.85	-10.40
SB-90C	-118.20	-62.75	-7.30
Drying Condition = MWSB-90C-288W subtracted from:			
RAW	-143.65	-88.20	-32.75
SB-50C	-133,.50	-78.05	-22.60
SB-70C	-136.85	-81.40	-25.95
SB-90C	-133.75	-78.30	-22.85
Drying Condition = RAW subtracted from:			
SB-50C	-45.30	10.15	65.60
SB-70C	-48.65	6.80	62.25
SB-90C	-45.55	9.90	65.35
Drying Condition = SB-50C subtracted from:			
SB-70C	-58.80	-3.35	52.10
SB-90C	-55.70	-0.25	55.20
Drying Condition = SB-70C subtracted from:			
SB-90C	-52.35	3.10	58.55

Table D.4.5 Anova Table for the effect of different drying conditions on pore surface area

ANOVA Results					
Source of Variation	DF	SS	MS	F	P
Drying Conditions	8	9.38	1.17	0.52	0.816
Error	9	20.34	2.26		
Total	17	29.72			

Table D.4.6 Result of Tukey's test for the effect of different drying conditions on pore surface area

Tukey Simultaneous Tests

All Pairwise Comparisons among Levels of Drying Condition

Drying Condition = MWSB-50C-288W subtracted from:			
Drying Condition	Lower	Center	Upper
MWSB-50C-624W	-4.686	1.267	7.219
MWSB-70C-288W	-6.404	-0.452	5.501
MWSB-70C-624W	-5.758	0.195	6.147
MWSB-90C-288W	-7.066	-1.113	4.839
RAW	-6.123	-0.171	5.782
SB-50C	-6.121	-0.169	5.784
SB-70C	-6.165	-0.213	5.740
SB-90C	-7.358	-1.405	4.547
Drying Condition1 = MWSB-50C-624W subtracted from:			
MWSB-70C-288W	-7.671	-1.719	4.234
MWSB-70C-624W	-7.025	-1.072	4.880
MWSB-90C-288W	-8.333	-2.380	3.572
RAW	-7.390	-1.438	4.515
SB-50C	-7.388	-1.435	4.517
SB-70C	-7.432	-1.480	4.473
SB-90C	-8.624	-2.672	3.281

Table D.4.6 cont'd

Drying Condition = MWSB-70C-288W subtracted from:			
MWSB-70C-624W	-5.306	0.647	6.599
MWSB-90C-288W	-6.614	-0.661	5.291
RAW	-5.671	0.281	6.234
SB-50C	-5.669	0.283	6.236
SB-70C	-5.713	0.239	6.192
SB-90C	-6.906	-0.953	4.999
Drying Condition = MWSB-70C-624W subtracted from:			
MWSB-90C-288W	-7.261	-1.308	4.644
RAW	-6.318	-0.365	5.587
SB-50C	-6.316	-0.363	5.589
SB-70C	-6.360	-0.407	5.545
SB-90C	-7.552	-1.600	4.353
Drying Condition = MWSB-90C-288W subtracted from:			
RAW	-5.010	0.943	6.895
SB-50C	-5.008	0.945	6.897
SB-70C	-5.052	0.901	6.853
SB-90C	-6.244	-0.292	5.661
Drying Condition = RAW subtracted from:			
SB-50C	-5.951	0.002	5.955
SB-70C	-5.995	-0.042	5.910
SB-90C	-7.187	-1.234	4.718
Drying Condition = SB-50C subtracted from:			
SB-70C	-5.997	-0.044	5.908
SB-90C	-7.189	-1.236	4.716
Drying Condition = SB-70C subtracted from:			
SB-90C	-7.145	-1.192	4.760

D.5 Dimensional Properties

Table D.5.1 Anova Table for the effect of different drying conditions on sphericity

ANOVA Results					
Source of Variation	DF	SS	MS	F	P
Drying Conditions	7	0.13659	0.01951	15.50	0.000
Error	152	0.19140	0.00126		
Total	159	0.32799			

Table D.5.2 Result of Tukey's test for the effect of different drying conditions on sphericity

Tukey Simultaneous Tests

All Pairwise Comparisons among Levels of Drying Condition

Drying Condition = MWSB-50C-288W subtracted from:			
Drying Condition	Lower	Center	Upper
MWSB-50C-624W	-0.00081	0.03371	0.06822
MWSB-70C-288W	-0.00160	0.03292	0.06744
MWSB-70C-624W	0.03832	0.07284	0.10736
MWSB-90C-288W	0.03097	0.06549	0.10001
SB-50C	-0.04037	-0.00585	0.02866
SB-70C	-0.04053	-0.00602	0.02850
SB-90C	-0.02451	0.01000	0.04452
Drying Condition = MWSB-50C-624W subtracted from:			
Drying Condition	Lower	Center	Upper
MWSB-70C-288W	-0.03530	-0.00079	0.03373
MWSB-70C-624W	0.00462	0.03913	0.07365
MWSB-90C-288W	-0.00273	0.03178	0.06630
SB-50C	-0.07407	-0.03956	-0.00504
SB-70C	-0.07424	-0.03972	-0.00521
SB-90C	-0.05822	-0.02370	0.01081

Table D.5.2 cont'd

Drying Condition = MWSB-70C-288W subtracted from:			
MWSB-70C-624W	0.00540	0.03992	0.07444
MWSB-90C-288W	-0.00195	0.03257	0.06709
SB-50C	-0.07329	-0.03877	-0.00426
SB-70C	-0.07346	-0.03894	-0.00442
SB-90C	-0.05743	-0.02292	0.01160
Drying Condition = MWSB-70C-624W subtracted from:			
MWSB-90C-288W	-0.04187	-0.00735	0.02717
SB-50C	-0.11321	-0.07869	-0.04418
SB-70C	-0.11337	-0.07886	-0.04434
SB-90C	-0.09735	-0.06284	-0.02832
Drying Condition = MWSB-90C-288W subtracted from:			
SB-50C	-0.10586	-0.07134	-0.03683
SB-70C	-0.10603	-0.07151	-0.03699
SB-90C	-0.09000	-0.05549	-0.02097
Drying Condition = SB-50C subtracted from:			
SB-70C	-0.03468	-0.00017	0.03435
SB-90C	-0.01866	0.01586	0.05037
Drying Condition = SB-70C subtracted from:			
SB-90C	-0.01849	0.01602	0.05054

Table D.5.3 Anova Table for the effect of different drying conditions on equivalent diameter of dried cooked wheat

ANOVA Results					
Source of Variation	DF	SS	MS	F	P
Drying Conditions	7	3.3689	0.4813	6.51	0.000
Error	152	11.2391	0.0739		
Total	159	14.6081			

Table D.5.4 Result of Tukey's test for the effect of different drying conditions on equivalent diameter of dried cooked wheat

Tukey Simultaneous Tests

All Pairwise Comparisons among Levels of Drying Condition

Drying Condition = MWSB-50C-288W subtracted from:			
Drying Condition	Lower	Center	Upper
MWSB-50C-624W	-0.0596	0.2049	0.4694
MWSB-70C-288W	-0.2718	-0.0073	0.2572
MWSB-70C-624W	0.0078	0.2723	0.5368
MWSB-90C-288W	0.1097	0.3742	0.6387
SB-50C	-0.1433	0.1212	0.3857
SB-70C	-0.3498	-0.0853	0.1792
SB-90C	-0.1067	0.1578	0.4223
Drying Condition = MWSB-50C-624W subtracted from:			
MWSB-70C-288W	-0.4767	-0.2122	0.0523
MWSB-70C-624W	-0.1971	0.0674	0.3319
MWSB-90C-288W	-0.0952	0.1693	0.4338
SB-50C	-0.3482	-0.0837	0.1808
SB-70C	-0.5547	-0.2902	-0.0257
SB-90C	-0.3116	-0.0471	0.2174
Drying Condition = MWSB-70C-288W subtracted from:			
MWSB-70C-624W	0.0151	0.2796	0.5441

Table D.5.4 cont'd

MWSB-90C-288W	0.1170	0.3815	0.6460
SB-50C	-0.1360	0.1285	0.3930
SB-70C	-0.3425	-0.0780	0.1865
SB-90C	-0.0994	0.1651	0.4296
Drying Condition = MWSB-70C-624W subtracted from:			
MWSB-90C-288W	-0.1626	0.1019	0.3664
SB-50C	-0.4156	-0.1511	0.1134
SB-70C	-0.6221	-0.3576	-0.0931
SB-90C	-0.3790	-0.1145	0.1500
Drying Condition = MWSB-90C-288W subtracted from:			
SB-50C	-0.5175	-0.2530	0.0115
SB-70C	-0.7240	-0.4595	-0.1950
SB-90C	-0.4809	-0.2164	0.0481
Drying Condition = SB-50C subtracted from:			
SB-70C	-0.4710	-0.2065	0.0580
SB-90C	-0.2279	0.0366	0.3011
Drying Condition = SB-70C subtracted from:			
SB-90C	-0.0214	0.2431	0.5076

Table D.5.5 Anova Table for the effect of different drying conditions on geometric diameter of dried cooked wheat

ANOVA Results					
Source of Variation	DF	SS	MS	F	P
Drying Conditions	7	3.2881	0.4697	6.49	0.000
Error	152	11.0016	0.0724		
Total	159	14.2898			

Table D.5.6 Result of Tukey's test for the effect of different drying conditions on geometric diameter of dried cooked wheat

Tukey Simultaneous Tests

All Pairwise Comparisons among Levels of Drying Condition

Drying Condition = MWSB-50C-288W subtracted from:			
Drying Condition	Lower	Center	Upper
MWSB-50C-624W	-0.0525	0.2092	0.4709
MWSB-70C-288W	-0.2701	-0.0085	0.2532
MWSB-70C-624W	0.0037	0.2654	0.5271
MWSB-90C-288W	0.1114	0.3731	0.6348
SB-50C	-0.1393	0.1224	0.3841
SB-70C	-0.3415	-0.0798	0.1819
SB-90C	-0.1083	0.1534	0.4150
Drying Condition = MWSB-50C-624W subtracted from:			
MWSB-70C-288W	-0.4793	-0.2176	0.0440
MWSB-70C-624W	-0.2055	0.0562	0.3179
MWSB-90C-288W	-0.0978	0.1639	0.4256
SB-50C	-0.3485	-0.0868	0.1749
SB-70C	-0.5507	-0.2890	-0.0273
SB-90C	-0.3175	-0.0558	0.2058
Drying Condition = MWSB-70C-288W subtracted from:			
MWSB-70C-624W	0.0122	0.2739	0.5356

Table D.5.6 cont'd

MWSB-90C-288W	0.1199	0.3816	0.6432
SB-50C	-0.1308	0.1309	0.3926
SB-70C	-0.3331	-0.0714	0.1903
SB-90C	-0.0999	0.1618	0.4235
Drying Condition = MWSB-70C-624W subtracted from:			
MWSB-90C-288W	-0.1540	0.1077	0.3694
SB-50C	-0.4047	-0.1430	0.1187
SB-70C	-0.6069	-0.3453	-0.0836
SB-90C	-0.3738	-0.1121	0.1496
Drying Condition = MWSB-90C-288W subtracted from:			
SB-50C	-0.5124	-0.2507	0.0110
SB-70C	-0.7146	-0.4529	-0.1912
SB-90C	-0.4814	-0.2197	0.0419
Drying Condition = SB-50C subtracted from:			
SB-70C	-0.4639	-0.2023	0.0594
SB-90C	-0.2308	0.0309	0.2926
Drying Condition = SB-70C subtracted from:			
SB-90C	-0.0285	0.2332	0.4949

Table D.5.7 Anova Table for the effect of different drying conditions on arithmetic diameter of dried cooked wheat

ANOVA Results					
Source of Variation	DF	SS	MS	F	P
Drying Conditions	7	2.3166	0.3309	4.16	0.000
Error	152	12.0852	0.0795		
Total	159	14.4018			

Table D.5.8 Result of Tukey's test for the effect of different drying conditions on arithmetic diameter of dried cooked wheat

Tukey Simultaneous Tests

All Pairwise Comparisons among Levels of Drying Condition

Drying Condition = MWSB-50C-288W subtracted from:			
Drying Condition	Lower	Center	Upper
MWSB-50C-624W	-0.0986	0.1757	0.4499
MWSB-70C-288W	-0.3221	-0.0478	0.2264
MWSB-70C-624W	-0.0959	0.1783	0.4526
MWSB-90C-288W	0.0222	0.2965	0.5708
SB-50C	-0.1153	0.1590	0.4333
SB-70C	-0.3366	-0.0623	0.2119
SB-90C	-0.1096	0.1647	0.4389
Drying Condition = MWSB-50C-624W subtracted from:			
MWSB-70C-288W	-0.4978	-0.2235	0.0508
MWSB-70C-624W	-0.2716	0.0027	0.2769
MWSB-90C-288W	-0.1534	0.1208	0.3951
SB-50C	-0.2909	-0.0167	0.2576
SB-70C	-0.5123	-0.2380	0.0363
SB-90C	-0.2853	-0.0110	0.2633
Drying Condition = MWSB-70C-288W subtracted from:			
MWSB-70C-624W	-0.0481	0.2262	0.5004

Table D.5.8 cont'd

MWSB-90C-288W	0.0701	0.3443	0.6186
SB-50C	-0.0674	0.2068	0.4811
SB-70C	-0.2888	-0.0145	0.2598
SB-90C	-0.0618	0.2125	0.4868
Drying Condition = MWSB-70C-624W subtracted from:			
MWSB-90C-288W	-0.1561	0.1182	0.3924
SB-50C	-0.2936	-0.0193	0.2549
SB-70C	-0.5149	-0.2407	0.0336
SB-90C	-0.2879	-0.0137	0.2606
Drying Condition = MWSB-90C-288W subtracted from:			
SB-50C	-0.4118	-0.1375	0.1368
SB-70C	-0.6331	-0.3588	-0.0846
SB-90C	-0.4061	-0.1318	0.1424
Drying Condition = SB-50C subtracted from:			
SB-70C	-0.4956	-0.2213	0.0529
SB-90C	-0.2686	0.0057	0.2799
Drying Condition = SB-70C subtracted from:			
SB-90C	-0.0473	0.2270	0.5013

D.6 Color

Table D.6.1 Anova Table for the effect of different drying conditions on L* value of dried cooked wheat

ANOVA Results					
Source of Variation	DF	SS	MS	F	P
Drying Conditions	7	88.012	12.573	23.52	0.000
Error	72	38.497	0.535		
Total	79	126.509			

Table D.6.2 Result of Tukey's test for the effect of different drying conditions on L* value of dried cooked wheat

Tukey Simultaneous Tests

All Pairwise Comparisons among Levels of Drying Condition

Drying Condition = MWSB-50C-288W subtracted from:			
Drying Condition	Lower	Center	Upper
MWSB-50C-624W	0.3780	1.4000	2.4220
MWSB-70C-288W	-0.1620	0.8600	1.8820
MWSB-70C-624W	0.9480	1.9700	2.9920
MWSB-90C-288W	1.7680	2.7900	3.8120
SB-50C	-0.1220	0.9000	1.9220
SB-70C	-1.0820	-0.0600	0.9620
SB-90C	-1.5720	-0.5500	0.4720
Drying Condition = MWSB-50C-624W subtracted from:			
MWSB-70C-288W	-1.5620	-0.5400	0.4820
MWSB-70C-624W	-0.4520	0.5700	1.5920
MWSB-90C-288W	0.3680	1.3900	2.4120
SB-50C	-1.5220	-0.5000	0.5220
SB-70C	-2.4820	-1.4600	-0.4380
SB-90C	-2.9720	-1.9500	-0.9280

Table D.6.2 cont'd

Drying Condition = MWSB-70C-288W subtracted from:			
MWSB-70C-624W	0.0880	1.1100	2.1320
MWSB-90C-288W	0.9080	1.9300	2.9520
SB-50C	-0.9820	0.0400	1.0620
SB-70C	-1.9420	-0.9200	0.1020
SB-90C	-2.4320	-1.4100	-0.3880
Drying Condition = MWSB-70C-624W subtracted from:			
MWSB-90C-288W	-0.2020	0.8200	1.8420
SB-50C	-2.0920	-1.0700	-0.0480
SB-70C	-3.0520	-2.0300	-1.0080
SB-90C	-3.5420	-2.5200	-1.4980
Drying Condition = MWSB-90C-288W subtracted from:			
SB-50C	-2.9120	-1.8900	-0.8680
SB-70C	-3.8720	-2.8500	-1.8280
SB-90C	-4.3620	-3.3400	-2.3180
Drying Condition = SB-50C subtracted from:			
SB-70C	-1.9820	-0.9600	0.0620
SB-90C	-2.4720	-1.4500	-0.4280
Drying Condition = SB-70C subtracted from:			
SB-90C	-1.5120	-0.4900	0.5320

Table D.6.3 Anova Table for the effect of different drying conditions on a* value of dried cooked wheat

ANOVA Results					
Source of Variation	DF	SS	MS	F	P
Drying Conditions	7	219.98	31.43	21.19	0.000
Error	72	106.79	1.48		
Total	79	326.77			

Table D.6.4 Result of Tukey's test for the effect of different drying conditions on a* value of dried cooked wheat

Tukey Simultaneous Tests

All Pairwise Comparisons among Levels of Drying Condition

Drying Condition = MWSB-50C-288W subtracted from:			
Drying Condition	Lower	Center	Upper
MWSB-50C-624W	-2.462	-0.760	0.942
MWSB-70C-288W	-2.012	-0.310	1.392
MWSB-70C-624W	1.618	3.320	5.022
MWSB-90C-288W	1.248	2.950	4.652
SB-50C	-1.312	0.390	2.092
SB-70C	-1.522	0.180	1.882
SB-90C	1.778	3.480	5.182
Drying Condition = MWSB-50C-624W subtracted from:			
MWSB-70C-288W	-1.252	0.450	2.152
MWSB-70C-624W	2.378	4.080	5.782
MWSB-90C-288W	2.008	3.710	5.412
SB-50C	-0.552	1.150	2.852
SB-70C	-0.762	0.940	2.642
SB-90C	2.538	4.240	5.942
Drying Condition = MWSB-70C-288W subtracted from:			
MWSB-70C-624W	1.928	3.630	5.332

Table D.6.4 cont'd

MWSB-90C-288W	1.558	3.260	4.962
SB-50C	-1.002	0.700	2.402
SB-70C	-1.212	0.490	2.192
SB-90C	2.088	3.790	5.492
Drying Condition = MWSB-70C-624W subtracted from:			
MWSB-90C-288W	-2.072	-0.370	1.332
SB-50C	-4.632	-2.930	-1.228
SB-70C	-4.842	-3.140	-1.438
SB-90C	-1.542	0.160	1.862
Drying Condition = MWSB-90C-288W subtracted from:			
SB-50C	-4.262	-2.560	-0.858
SB-70C	-4.472	-2.770	-1.068
SB-90C	-1.172	0.530	2.232
Drying Condition = SB-50C subtracted from:			
SB-70C	-1.912	-0.210	1.492
SB-90C	1.388	3.090	4.792
Drying Condition = SB-70C subtracted from:			
SB-90C	1.598	3.300	5.002

Table D.6.5 Anova Table for the effect of different drying conditions on b* value of dried cooked wheat

ANOVA Results					
Source of Variation	DF	SS	MS	F	P
Drying Conditions	7	36.769	5.253	9.58	0.000
Error	72	39.485	0.548		
Total	79	76.254			

Table D.6.6 Result of Tukey's test for the effect of different drying conditions on b* value of dried cooked wheat

Tukey Simultaneous Tests

All Pairwise Comparisons among Levels of Drying Condition

Drying Condition = MWSB-50C-288W subtracted from:			
Drying Condition	Lower	Center	Upper
MWSB-50C-624W	-0.4251	0.6100	1.6451
MWSB-70C-288W	-0.3051	0.7300	1.7651
MWSB-70C-624W	0.1949	1.2300	2.2651
MWSB-90C-288W	1.0349	2.0700	3.1051
SB-50C	-0.2251	0.8100	1.8451
SB-70C	-0.5051	0.5300	1.5651
SB-90C	-1.3251	-0.2900	0.7451
Drying Condition = MWSB-50C-624W subtracted from:			
MWSB-70C-288W	-0.9151	0.1200	1.1551
MWSB-70C-624W	-0.4151	0.6200	1.6551
MWSB-90C-288W	0.4249	1.4600	2.4951
SB-50C	-0.8351	0.2000	1.2351
SB-70C	-1.1151	-0.0800	0.9551
SB-90C	-1.9351	-0.9000	0.1351
Drying Condition = MWSB-70C-288W subtracted from:			
MWSB-70C-624W	-0.5351	0.5000	1.5351

Table D.6.6 cont'd

MWSB-90C-288W	0.3049	1.3400	2.3751
SB-50C	-0.9551	0.0800	1.1151
SB-70C	-1.2351	-0.2000	0.8351
SB-90C	-2.0551	-1.0200	0.0151
Drying Condition = MWSB-70C-624W subtracted from:			
MWSB-90C-288W	-0.1951	0.8400	1.8751
SB-50C	-1.4551	-0.4200	0.6151
SB-70C	-1.7351	-0.7000	0.3351
SB-90C	-2.5551	-1.5200	-0.4849
Drying Condition = MWSB-90C-288W subtracted from:			
SB-50C	-2.2951	-1.2600	-0.2249
SB-70C	-2.5751	-1.5400	-0.5049
SB-90C	-3.3951	-2.3600	-1.3249
Drying Condition = SB-50C subtracted from:			
SB-70C	-1.3151	-0.2800	0.7551
SB-90C	-2.1351	-1.1000	-0.0649
Drying Condition = SB-70C subtracted from:			
SB-90C	-1.8551	-0.8200	0.2151

D.7 Yield

Table D.7.1 Anova Table for the effect of different drying conditions on yield value of bulgur

ANOVA Results					
Source of Variation	DF	SS	MS	F	P
Drying Conditions	7	0.011626	0.001661	10.54	0.002
Error	8	0.001261	0.000158		
Total	15	0.012887			

Table D.7.2 Result of Tukey's test for the effect of different drying conditions on yield value of bulgur

Tukey Simultaneous Tests

All Pairwise Comparisons among Levels of Drying Condition

Drying Condition = MWSB-50C-288W subtracted from:			
Drying Condition	Lower	Center	Upper
MWSB-50C-624W	-0.11801	-0.06830	-0.01859
MWSB-70C-288W	-0.09696	-0.04725	0.00246
MWSB-70C-624W	-0.11881	-0.06910	-0.01939
MWSB-90C-288W	-0.11306	-0.06335	-0.01364
SB-50C	-0.04856	0.00115	0.05086
SB-70C	-0.07416	-0.02445	0.02526
SB-90C	-0.09551	-0.04580	0.00391
Drying Condition = MWSB-50C-624W subtracted from:			
MWSB-70C-288W	-0.02866	0.02105	0.07076
MWSB-70C-624W	-0.05051	-0.00080	0.04891
MWSB-90C-288W	-0.04476	0.00495	0.05466
SB-50C	0.01974	0.06945	0.11916
SB-70C	-0.00586	0.04385	0.09356
SB-90C	-0.02721	0.02250	0.07221

Table D.7.2 cont'd

Drying Condition = MWSB-70C-288W subtracted from:			
MWSB-70C-624W	-0.07156	-0.02185	0.02786
MWSB-90C-288W	-0.06581	-0.01610	0.03361
SB-50C	-0.00131	0.04840	0.09811
SB-70C	-0.02691	0.02280	0.07251
SB-90C	-0.04826	0.00145	0.05116
Drying Condition = MWSB-70C-624W subtracted from:			
MWSB-90C-288W	-0.04396	0.00575	0.05546
SB-50C	0.02054	0.07025	0.11996
SB-70C	-0.00506	0.04465	0.09436
SB-90C	-0.02641	0.02330	0.07301
Drying Condition = MWSB-90C-288W subtracted from:			
SB-50C	0.01479	0.06450	0.11421
SB-70C	-0.01081	0.03890	0.08861
SB-90C	-0.03216	0.01755	0.06726
Drying Condition = SB-50C subtracted from:			
SB-70C	-0.07531	-0.02560	0.02411
SB-90C	-0.09666	-0.04695	0.00276
Drying Condition = SB-70C subtracted from:			
SB-90C	-0.07106	-0.02135	0.02836

D.8 Water Adsorption Capacity

Table D.8.1 Anova Table for the effect of different drying conditions on water absorption value of bulgur

ANOVA Results					
Source of Variation	DF	SS	MS	F	P
Drying Conditions	7	0.39790	0.05684	23.09	0.000
Error	8	0.01969	0.00246		
Total	15	0.41760			

Table D.8.2 Result of Tukey's test for the effect of different drying conditions on water absorption value of bulgur

Tukey Simultaneous Tests

All Pairwise Comparisons among Levels of Drying Condition

Drying Condition = MWSB-50C-288W subtracted from:			
Drying Condition	Lower	Center	Upper
MWSB-50C-624W	-0.28372	-0.08724	0.10923
MWSB-70C-288W	-0.27027	-0.07380	0.12267
MWSB-70C-624W	-0.31524	-0.11877	0.07770
MWSB-90C-288W	-0.29728	-0.10081	0.09567
SB-50C	0.05400	0.25047	0.44694
SB-70C	0.12523	0.32170	0.51817
SB-90C	-0.14202	0.05445	0.25092
Drying Condition = MWSB-50C-624W subtracted from:			
MWSB-70C-288W	-0.18303	0.01344	0.20991
MWSB-70C-624W	-0.22800	-0.03153	0.16495
MWSB-90C-288W	-0.21004	-0.01357	0.18291
SB-50C	0.14124	0.33771	0.53419
SB-70C	0.21247	0.40894	0.60541
SB-90C	-0.05478	0.14169	0.33817

Table D.8.2 cont'd

Drying Condition = MWSB-70C-288W subtracted from:			
MWSB-70C-624W	-0.24144	-0.04497	0.15150
MWSB-90C-288W	-0.22348	-0.02701	0.16947
SB-50C	0.12780	0.32427	0.52074
SB-70C	0.19903	0.39550	0.59197
SB-90C	-0.06822	0.12825	0.32472
Drying Condition = MWSB-70C-624W subtracted from:			
MWSB-90C-288W	-0.17851	0.01796	0.21443
SB-50C	0.17277	0.36924	0.56571
SB-70C	0.24400	0.44047	0.63694
SB-90C	-0.02325	0.17322	0.36969
Drying Condition = MWSB-90C-288W subtracted from:			
SB-50C	0.15481	0.35128	0.54775
SB-70C	0.22603	0.42251	0.61898
SB-90C	-0.04121	0.15526	0.35173
Drying Condition = SB-50C subtracted from:			
SB-70C	-0.12524	0.07123	0.26770
SB-90C	-0.39249	-0.19602	0.00045
Drying Condition = SB-70C subtracted from:			
SB-90C	-0.46372	-0.26725	-0.07078

APPENDIX E

PICTURES OF DRIED COOKED WHEAT

Figure E.1 Picture of dried cooked wheat at 50^{o}C

Figure E.2 Picture of dried cooked wheat at 50^{o}C, 288 W

Figure E.3 Picture of dried cooked wheat at 50^{o}C, 624 W

Figure E.4 Picture of dried cooked wheat at 70^{o}C

Figure E.5 Picture of dried cooked wheat at 70^{o}C, 288 W

Figure E.6 Picture of dried cooked wheat at 70^{o}C, 624 W

Figure E.7 Picture of dried cooked wheat at 90^{o}C

Figure E.8 Picture of dried cooked wheat at 90^{o}C, 288 W