USAGE OF SOLAR-SPOUTED BED DRIER IN THE DRYING OF PARBOILED WHEAT, CORN AND PEA

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USAGE OF SOLAR-SPOUTED BED DRIER IN THE DRYING OF PARBOILED WHEAT, CORN AND PEA

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ABSTRACT

USAGE OF SOLAR-SPOUTED BED DRIER IN THE DRYING OF PARBOILED WHEAT, CORN AND PEA

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The main objective of this study was the application of solar energy for drying of parboiled wheat, corn and pea. Drying experiments were performed under open sun and also in the solar-spouted bed drier in which air heated by solar energy was used. The effects of these drying methods on drying rate and quality parameters were investigated for drying of parboiled wheat, corn and pea. The quality parameters evaluated were color, shrinkage, bulk density, apparent density, bulk and internal porosity, microstructure, pore size distribution, sphericity and rehydration ratio. For peas, ascorbic acid content was also measured.

In solar-spouted bed drying, drying rates and effective diffusivity values for all samples were determined to be higher and therefore drying time was significantly lower as compared to open sun drying. Effective diffusivities were in the range of 0.30×10^{-10} m^2/s - 0.65×10^{-10} m^2/s for open sun and 1.35×10^{-10} m^2/s - 3.65×10^{-10} m^2/s for solar-spouted bed drying of different samples. In general, better quality parameters for solar-spouted bed dried samples were observed such as less shrinkage, higher rehydration capacities, more homogenous pore size distribution and higher ascorbic acid retention.

Keywords: bulgur, corn, open sun drying, pea, spouted bed drying

ÖZ

HAŞLANMIŞ BUĞDAY, MISIR VE BEZELYENİN KURUTULMASINDA GÜNEŞ ENERJİLİ- FISKİYELİ YATAKLI KURUTUCUNUN KULLANILMASI

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Bu çalışmanın amacı, haşlanmış buğday, mısır ve bezelyenin kurutulmasında güneş enerjisinin kullanılmasıdır. Kurutma deneyleri hem güneşte sererek hem de güneş enerjisi ile ısıtılan havanın kullanıldığı güneş enerjili-fıskiyeli yataklı kurutucu ile gerçekleştirilmiştir. Kurutma yöntemlerinin kuruma hızı ve ürün kalitesi üzerindeki etkileri haşlanmış buğday, mısır ve bezelyenin kurutulmasında incelenmiştir. İncelenen kalite değerleri, renk, büzülme, yığın yoğunluk, görünen yoğunluk, yığın ve iç gözeneklilik, mikroyapı, gözeneklilik boyutu dağılımı ve su emme kapasitesidir. Ayrıca, bezelye için askorbik asit miktarları ölçülmüştür.

Bütün örnekler için, güneş enerjili-fıskiyeli yataklı kurutucuda kuruma hızı ve etkin yayınma katsayıları güneşte sererek kurutma işlemine göre daha yüksek ve bu nedenle kuruma süreleri önemli derecede daha az bulunmuştur. Farklı numunelerin kurutulmasında, etkin yayınma katsayıları

güneş altında kurutmada 0.30x10^{-10} m^2/s -0.65x10^{-10} m^2/s aralığında, güneş enerjili-fıskiyeli yataklı kurutucuda ise 1.35x10^{-10} m^2/s–3.65x10^{-10} m^2/s aralığında değişmiştir. Genel olarak, güneş enerjili-fıskiyeli yataklı kurutucuda kurutulan örneklerin kalite değerlerinin daha iyi olduğu gözlenmiştir. Bunlara, daha az büzüşme, daha fazla su emme kapasitesi, daha homojen gözenek dağılımı ve askorbik asitin daha yüksek oranda korunması örnek olarak verilebilir.

Anahtar sözcükler: bezelye, bulgur, fıskiyeli yataklı kurutma, güneş ile kurutma, mısır

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INTRODUCTION

1.1 Wheat

Wheat is one of the most important staple foods because of its nutritional and functional properties and also long storage time. It is among the first domesticated cereals. Due to being self fertilized, it has many varieties on a great plant area. Genetic analysis of wheat showed that it has originated from Karacadag Mountains in southeastern Turkey and dated to between 8800 and 8400 B.C.E. (Ozkan et.al., 2002).

In Turkey, wheat is cultivated nearly on 9.3 million hectares and its production is about 20 million tones in average. Nearly 35% of the agricultural lands in Turkey are used for the production of wheat (Konyali, 2008). Turkey is one of most important wheat producer in the world. According to the report of Turkish Grain Board, in 2008, annual wheat production was 17 million tones (http://www.tmo.gov.tr).

One of the important properties of the wheat is its wide usage areas. It is used in production of bread, pasta, crackers, cookies, cakes, breakfast cereals as it is well known. In addition, it is also used in beer, sugar, starch, bran, food thickeners, gluten and in bulgur production (Sattore and Slafer, 1999).

Wheat bulgur is an important food product prepared from wheat due to its physical, nutritional and dietary properties. It has a long shelf life, due to inactivation of enzymes and stopped respiration, resistance to mold and insect contamination. It contains great amounts of folic acid and dietary fibers. It can be classified in semi-ready foods group making its digestion easier (Bayram and Oner, 2007). Because of these important properties, production and consumption of bulgur is increasing. Bulgur production capacity of Turkey, with over 500 producing plants, is 1 million tones annually (Bayram, 2005).

For the production of wheat bulgur, generally, *Triticum* durum is used. This type of wheat has a light yellow color and contains more proteins as compared to other wheat types. Protein content of bulgur is about 12-15%. In addition, it is rich in vitamin B and minerals such as iron, manganese and phosphorous (Bayram et. al., 2004). Moreover, it has 18.3 g of dietary fibers in 100 g, which means that it is a good source of dietary fibers. This content is 3.5, 6.8, 1.1, 1.8 times higher than rice, wheat flour, barley, oat meal, respectively (Dreher, 2001).

The processing steps (Figure 1.1) of the wheat for bulgur production can be listed as cleaning from foreign materials, boiling to achieve complete gelatinization, drying to have a stable final product, dehulling to remove the hull, grinding to produce smaller granular particles and finally classification to get standard sized particles (Bayram and Oner, 2006).

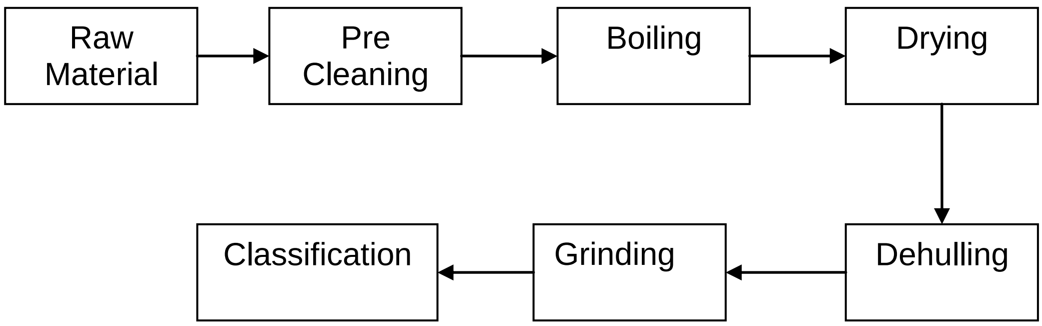

Figure 1.1 Flow diagram of bulgur production

Wheat is boiled in order to achieve complete starch gelatinization. Especially, for the bulgur production, cooking of the wheat is an important step since quality factors such as color, shape, size, develop at that cooking step. During cooking, getting complete gelatinization without deforming the wheat kernel is important, due to the fact that deformed wheat can cause problems during the following processes like drying, milling etc. Therefore, cooking time and temperature should be well adjusted for achieving complete gelatinization and not making the wheat so sticky which can be a problem during drying (Bayram, 2006).

Drying is another important step for the bulgur production since it affects the final quality of the product in terms of sensory and nutritional aspects. Bulgur is traditionally open sun dried, however commercially hot air dryers are used (Hayta, 2001).

1.2 Corn

Corn production has a great importance, especially due to its economical value. It contains high amounts of starch and additionally, products such as corn syrup, ethanol, oil and some chemicals can be made from corn (Hatamipour and Mowla, 2003).

For the origin of corn, there are several theories proposed that it is originated in Mesoamerica. It may be domesticated from the large group of grasses of *Zea* species in Mexica (Smith et. al, 2004). Today, corn in the world is cultivated widely in great amounts. In 2008, its production was 791 million tones having the first order in the category of grains. 40% of cultivation and production of corn are achieved by USA and 19% by China. In Turkey, production of corn has 5% ratio among grains after wheat and barley. In 2008, it was cultivated in 517000 hectares and 3.5 million tones of corn was produced (http://www.tmo.gov.tr).

Despite of its consumption as whole, corn is a good source of starch. Corn starch is used in many industrial products. In addition, corn starch can be hydrolyzed to get corn syrup, which is widely used as sweetener in the industry. Corn is also rich in oil and can be used for corn oil production. Moreover, corn ethanol is an alternative energy source due to increasing demand to energy. Because of these important usage areas, storage of corn is essential for further processing due to its high moisture content. Therefore, drying of corn is an important step before storage (Hatamipour and Mowla, 2003). Traditionally, corn is dried under open sun. However, during drying it may be contaminated due to environmental conditions and molds can grow. Therefore, uniform and rapid drying of corn should be provided for hygienic and high quality products by using hot air drying (Doymaz and Pala, 2003).

1.3 Pea

Pea is an important food product due to its high protein content. It is probably originated from Mediterranean and has been used by man since Stone ages. Pea was not used widely until Greek or Roman times but after that, it was introduced to the temperate regions of the world (Evans, 1975).

According to Food and Agriculture Organization of the United Nations, peas are in the second order of legumes produced in the world with its high yield. The production of pea in 2007 was 9.2 million tones. The highest production of pea was done in Canada. In Turkey, pea is mostly produced in Marmara and Middle Anatolia regions.

In terms of nutritional properties, peas contain 21.9 g of protein, 2.34 g of lipids, 10.4 g of fiber and 52.2 g of carbohydrates in 100 g sample (Costa et. al., 2006).

Freezing, canning and dehydration are the major processing technologies used for peas. Drying of peas provides effective and practical preservation in order to reduce the losses after harvest (Jadhav et. al., 2010). Dried peas can be used in the soups or meals as other legumes. It is used in some traditional meals in UK and North America. In addition it is mostly consumed in Asian countries (Costa et. al., 2006).

1.4 Drying

Drying is one of the food preservation methods depending on the principle of removing the moisture from the food. Microorganism growth and enzyme activity are prevented by reducing moisture content and quality losses are reduced. Therefore, dried food products can be stored for long periods of time.

There are several methods used for drying of foods which can be categorized according to the way of adding heat and remove water. In first category hot air is in direct content with food and water vapor is removed by this air. This principle is used for tray, tunnel, rotary, spouted bed or spray driers. In the second category, heat is applied indirectly by contacting with a metal wall or by radiation at low pressures as for the vacuum drying. In the last category, water is removed from frozen material by sublimation as in the case of freeze drying (Geankoplis, 2003).

1.4.1 Open Sun Drying

Drying of the food products has been an important preservation method. Open sun drying is one of the well known and easy ways of reducing the moisture content of the agricultural products since ancient times. It has been used to dry grains, vegetables, fruits and many other agricultural products (Togrul and Pehlivan, 2004)

For the open sun drying, products are heated up by direct solar radiation. Some part of the heat gets into the food resulting in the formation of vapour by increasing the temperature while some part provides the evaporation of water from the surface of the food. Moisture from the interior of the food diffuses towards the surface enriching the surface moisture and by that way moisture of the product reduces (Togrul, 2003). Rate of the drying for open sun drying is reported to be dependent on some external and internal parameters. External parameters are listed as solar radiation, ambient temperature, wind velocity and relative humidity; while internal parameters are initial moisture contents, type of crops, crop absorptivity and mass of product per unit exposed area etc. (Sodha et. al, 1985).

Open sun drying is advantageous in terms of its negligible cost and energy requirement. On the other hand, it has many disadvantageous like being a slow and labour intensive drying process. In addition, during drying products can be polluted from dust, dirt, insects, animals or microbial contamination and they are unprotected from environmental conditions like rain or storm. These factors, may lead important quality degradations in the products. In addition, some product losses due to insufficient or non uniform drying may be seen during storage (Sacilik et. al., 2006; Karathanos and Belessiotis, 1997; Tiris et. al, 1996). Moreover, due to direct exposing to sun light, discoloration of the food product occurs resulting quality losses (Sharma et. al, 2009).

In literature, there are many studies on open sun drying of food products. Lynch and Morey (1989) studied the open air drying of corn and reported that it had advantages as compared to high temperature drying in terms of quality but it made the drying period longer. Sobukola et. al. (2007) studied the thin layer drying characteristics of leafy vegetables using open sun drying method and it was observed that drying occurred only at falling rate period. Prasad (2009) investigate the effect of sun drying on herb and spices in terms of thermal behavior. Kumar and Tiwari (2007) dried onion flakes under open sun and greenhouse dryer. Drying continued for 33 h and it was reported that rate of drying was lower for open sun drying as compared to greenhouse drying.

1.4.2 Solar Drying

Hygienic and also low cost preservation of food products are important today due to depleting food supplies and increasing energy requirements. Solar drying can be used as a safer and more efficient method of preservation as compared to the traditional drying methods such as open sun or shade drying. It improves the quality of the final product and also reduces the product losses. In addition, it is efficient in terms of energy requirements as compared to other drying methods like tray drying since solar energy is free and renewable (Akpınar et. al, 2004; Togrul and Pehlivan, 2003).

Turkey has a great potential for usage of solar dryers because of the long sunshine duration. According to the measurements between the years of 1985 and 2006 made by General Directorate of Electrical Power Resources Survey and Development Administration, in Turkey average sunshine durations per day from January to December are 4.11, 5.22, 6.27, 7.46, 9.10, 10.81, 11.31, 10.70, 9.23, 6.87, 5.15, 3.75 hours, respectively (http://eie.gov.tr). In addition in Ankara, total sunshine durations are at similar values to average of Turkey. It has the highest value in July as 11.06 hours and the lowest value in December as 3.35 hours.

Solar dryers are available at different sizes and designs according to the amount and the kind of food to be dried. Leon et. al (2002) classifies the solar driers as forced and natural circulation dryers. Solar energy can be used for these dryers as direct or indirect irradiation, or as a mixed mode of these. Accordingly, solar dryer can be a box-type, cabinet or tunnel dryer. For direct solar drying, food is simply put under a transparent cover to direct sun light. The air under the cover becomes heated and product moisture decreases due to the heated environment. In the indirect type solar dryers, air is heated in a different part and product is not directly exposed to the sun light. Hot air provided in the collector part is used in the drying chamber (Sharma et. al., 2009).

There are numerous studies in literature about usage of solar dryers for drying of food products. El-Sebaii et. al (2002) dried green peas by using an indirect type natural convection solar dryer. It was reported that moisture content of 1 kg of green pea was reduced to 5% in 8-10 hours at 45.5-50.5ºC. Jadhav et. al (2010) used the solar cabinet dryer for drying of pretreated green peas. Quality parameters of the solar dried peas were found to be better than open sun drying and also fluidized bed drying. A forced convection solar drier was used to reduce the moisture content of paddy from 17% to 14% in Thailand. It took 1-4 days depending on the weather conditions (Soponronnarit, 1995). Elicin and Sacilik (2005) designed a solar tunnel dryer for dehydration of apples. Moisture content of apples was reduced from 82 to 11% in 32 and 28 hours for open sun and solar drying, respectively. Mohanraj and Chandrasekar (2008) used a forced convection solar dryer in order to produce copra (dried coconut) in India. Moisture content was reduced from about 52% to 8% in 82 hours. For drying of tomato slices, Rajkumar et. al. (2007) used vacuum assisted solar dryer and compared the method to open sun drying. Quality of products dried using solar dryer was found better in terms of color retention and rehydration ratio. Chen et. al. (2005) dried lemon slices using a closed type solar dryer. As compared to hot air drying at 60ºC, better quality lemon slices in terms of sensory parameters were obtained. In addition, some other studies on solar drying of fruits and vegetables exist in literature such as drying of potato (Akpinar et al., 2003), green pepper, green bean and squash (Yaldız and

Ertekin, 2001), apricot (Sarsılmaz et al., 2000; Togrul and Pehlivan, 2003), pistachio (Midilli, 2001), and green chilli (Hossain and Bala, 2002).

1.4.3 Spouted Bed Drying

The term spouted bed and spouting were aroused in 1954 by Gishler and Mathur at the National Research Council in Canada. Spouting method was firstly used for the drying of wheat. It could be applied without damaging the grains and could supply hotter air as compared to conventional wheat driers. Then, it was realized that the method could be used for other solid materials and it was improved using both air and water as spouting medium (Mathur and Epstein, 1974).

Spouted bed driers have several advantages. It introduces higher drying rates and therefore shorter drying times due to the continuous particle air contact. At lower drying temperatures, system can provide effective drying which is important for heat sensitive food products. It can also be used for other purposes than drying such as granulation and coating due to the moving of particles (Pallai et. al., 1995). However, the most important drawbacks of the spouted beds are the limitation of the size and bed height and also difficulty in the control of cyclic pattern (Chua and Chou, 2003).

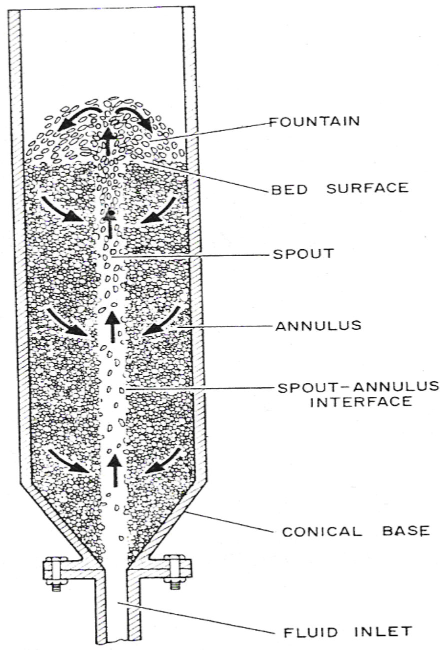

Figure 1.2 Schematic diagram of a spouted bed (Mathur and Epstein,1974)

In the spouted bed as shown in Figure 1.2, the central cavity formed during drying is called as a spout and the region around the spout where the product exists called as the annulus. In addition, the term fountain is used for the arch appears during the spouting at the top. Generally the bottom of the vessel is in the shape of a divergent cone in order to provide the recycling of the particles and to eliminate the dead zones (Mathur and Epstein,1974).

The drying air is introduced to the system from the nozzle located at the center of the conical base. The particles, by the interaction with the air at a certain flow rate that is adequate to provide spouting in the column, rise rapidly through the spout zone. At a certain height according to the air velocity, particles drop to the annulus part of the column. They move towards the bottom of the bed through annulus to spout again with the air supplied continuously from the inlet nozzle. During this recycling in the spouting bed, moisture is removed from the surface of the particles (Chua and Chou, 2003; Fayed and Otten, 1997).

Spouted bed driers have been used for drying of food products especially for granulated ones successfully like wheat, corn, oats and cereal seeds (Zahed and Epstein, 1993; Chua and Chou, 2003). For the drying of wheat, Zahed and Epstein (1992) considered usage of spouted bed. However, different than previous studies of spouted bed, it was assumed moisture content at the surface of the grain was not constant. Numerical analysis of the variation of grain temperature and moisture content with time was investigated. Jumah, et. al. (1996) had successful results for the drying of corn using spouted bed. In the study, intermittent drying was introduced to eliminate the slow drying characteristic of the corn and get high quality products with lower energy consumption. Nindo et. al. (2003) dried asparaguses using different drying methods such as tray, spouted bed, combined microwave and spouted bed , Refractance Window and freeze drying. As spouted bed was compared to tray drying, it was observed that at the same temperatures drying time was reduced sharply for spouted bed drying. Paddy drying experiments were also conducted using spouted bed drying (Madhiyanon et. al., 2001). Spouted bed was compared to fluidized bed drying. Higher yield of rice and also better products in terms of whiteness were obtained after spouted bed drying. Other than granulated particles, other foods like shrimps were also dried in spouted beds. For this purpose, Niamnuy et. al. (2007) designed jet spouting bed that was different from the classical beds with its cone angle. Spouted bed had the advantage of removing head, shell and tail of the shrimp during drying due to the moving. Drying was also achieved in shorter time as compared to conventional drying. In addition, spouted beds were used with combination of other drying methods like microwave drying in order to increase the efficiency of drying (Feng and Tang, 1999; Kahyaoglu et. al., 2010; Jumahand Raghavan, 2001). Kahyaoglu et. al. (2010), used the microwave assisted spouted bed dryer to dry the parboiled wheat. The method was compared with classical spouted bed drying and also different microwave powers were examined to evaluate its efficiency. Microwave assisted spouted bed was found to be preferable due to shortening drying time and acceptable final quality of products.

1.5 Objective of the Study

Wheat, corn and pea are important food products due to their low costs and high nutritional properties. They are widely produced and consumed in Turkey and in the world. They can be consumed not only as they are but also as products such as bulgur from wheat and starch from corn. In addition, they can be stored for long times when they are processed properly. For these purposes, one of the ways of preservation is the drying.

Drying is based on the principle of removing moisture from the food. Therefore, microbial growth is prevented and quality loss is slowed down. Open sun drying is one of the practiced methods since ancient times for traditional drying of several foods such as grape, apricot, rice, tomato etc. However, there is a risk of contamination from microorganisms, insects, dust etc. In addition, some quality loss is inevitable when food is dried under open sun. Spouted bed drying is the one, used especially for the drying of granular foods such as wheat, barley, coffee and larger foods like shrimp. In the spouted bed drying, hot air is provided by a heater. However, the solar heat which is abundant and free can be used to obtain hot air. Therefore, a combination of solar drying and spouted bed drying is used in this study in order to make the drying more efficient in terms of drying rate and quality of the final product. In literature, there is lack of study related to the combination of solar and spouted bed dryers.

The main objective of this study is to evaluate the effect of drying methods, which were solar-spouted bed and open sun drying, on the drying rates and also quality parameters of parboiled wheat, corn and pea. Color, shrinkage, bulk density, apparent density, bulk and internal porosity, microstructure, pore size distribution, sphericity and rehydration ratio; and also ascorbic acid content for pea were the quality parameters investigated.

CHAPTER 2

MATERIALS AND METHODS

2.1 Materials

Wheat (*Triticum durum)*, corn (*Zea mays*) and pea (*Pisum sativum*) purchased from the markets were used in the drying experiments.

2.2 Experimental Setup

Schematic diagram of solar spouted bed dryer experimental set up was shown in Figure 2.1. It consisted of three major parts; solar collector part of the solar dryer to get hot air, air blower to provide spouting, and spouting column for drying of samples.

In the system, a blower (TMM, KB-6, 2.2 kW, Ankara, Turkey) that can supply 250 m^3/h air at its maximum, was used to transport air into the spouting column. Ball valves were used to fix the air velocity. Three valves existed on the system; one for adjusting the air velocity entering spouting bed, one for flowing of the excess air back to solar collector and one for discharging air to outside if the valve for supplying air back to collector was not sufficient. Pitot tube (Testo 435-4, Lenzkirch, Germany) was used to adjust the spouting air velocity.

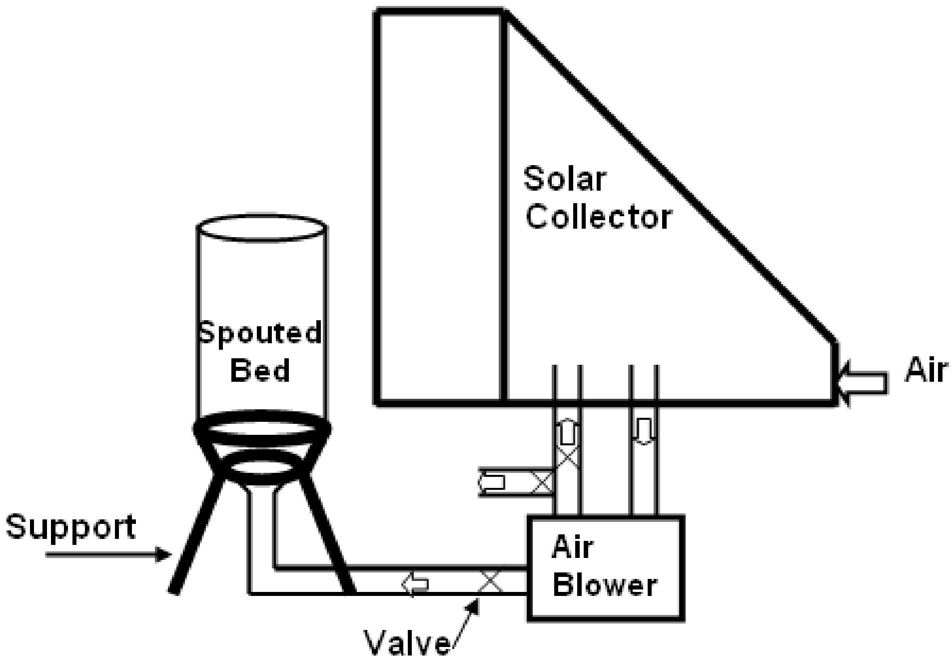

Figure 2.1 Schematic diagram of solar-spouted bed dryer

Hot air was provided in the solar collector part of solar dryer. Its dimensions are 1.80, 1.66 and 2.60 m in terms of width, height and length, respectively. It is positioned to south with 40º angle which is the most suitable for the conditions of solar irradiation in Ankara (Kose, 1997). It is covered by glass sheet and well isolated. The base is laid over with gravels to store energy and consequently to keep air temperature higher for longer time. In addition, they are blackened to absorb solar irradiation more. Temperature of the air used in the system was measured by NiCr-Ni thermocouples (Tetcis, TMO7-C-K130-10 tip, Ankara, Turkey). Temperature in solar collector, inlet and exit temperatures in spouted bed and outside temperature at shade and also under direct irradiation were recorded during the experiments.

The spouted bed column was made up of glass in order to observe the spouting visually during experiments. A schematic representation of the column was given in Figure 2.2. In the figure; D_c is column diameter, D_i is outer diameter of fluid inlet, H_m is maximum spoutable bed depth and α/2 is cone angle. Column diameter of the spouted bed was 15 cm and maximum spoutable bed depth was 100 cm. Cone angle, α/2, was chosen as 45º. Air was provided through the nozzle. The nozzle was located at the center of the bottom of the cone with a diameter of 2.54 cm. In addition, a screen was placed to the exit of the nozzle to prevent the particles falling down. Spouting column was placed on a support during the experiments.

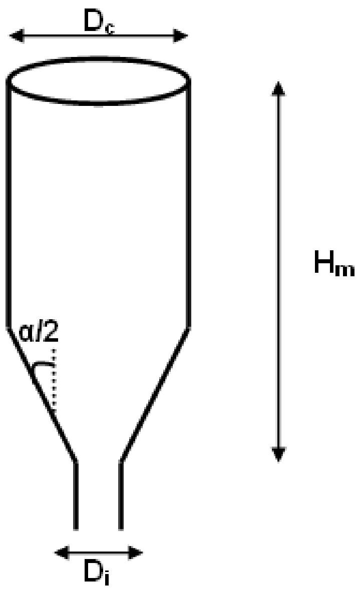

Figure 2.2 Schematic representation of spouted bed column

For the open sun drying experiments, samples were placed in a cage in order to minimize the environmental influences without interrupting the solar irradiation. Samples were put on a mesh and cage was positioned parallel to solar collector.

2.3 Minimum Spouting Air Velocity Determination

For the minimum spouting air velocity determination, a U-tube manometer to measure the pressure drop and a pitot tube (Testo 435-4, Lenzkirch, Germany) to measure the air velocity were used. U-tube manometer filled with water was placed to the inlet of the spouting column. By pitot tube, air velocity inside the column was measured. Flow rate of air was adjusted by the valves located at the exit of the air blower. The valve for supplying excess air back to solar collector was kept open while the one for outside discharge was kept closed. Flow was controlled with the valve that supplied air to the bed. Experiments for spouting velocity determination were done at early times of the day in order to reduce the moisture loss of the samples during measurements. For each experiment, 250 g of samples were loaded into the column. Firstly, flow rate of air was increased, and for each velocity value, pressure drop measured with U-tube manometer was recorded. At the same time, spouting in the column was observed. Flow rate was increased up to the constant pressure drop value was observed after spouting. Then, velocity was gradually decreased and again pressure drop was recorded. Each experiment was done in duplicate. From the plot of air velocity versus measured pressure drop, minimum spouting air velocity was determined.

2.4 Drying

2.4.1 Preparation of Materials

For wheat bulgur production, boiling is one of the most important processes before drying to achieve complete gelatinization. Wheat kernels were firstly cleaned from foreign materials manually. Then, they were cooked in water using wheat to water ratio of 1:5 by weight at 95ºC for 90 minutes (Kahyaoglu et. al., 2010). Corn was purchased from the local markets as fresh with its cob. Before the drying experiments, corn kernels were separated from the cob without damaging the wholeness. Pea was also purchased as fresh at its season from local markets. Pea grains were shelled before drying.

2.4.2 Open Sun Drying

For open sun drying experiments, samples were simply laid on a mesh under direct sun light. For each run, 250 g of samples were weighed with an electronic balance (AND EK-3000i, Tokyo, Japan). In order to avoid environmental influences, it was put in a cage placed parallel to solar collector. Weight change and outside temperature were recorded for every half hour. Open sun drying of wheat, corn and pea continued for 14, 20 and 18 hours, respectively. Experiments were repeated 3 or 4 times. Dried samples were stored in closed plastic bags to avoid the moisture content change for further analysis.

2.4.3 Solar-spouted Bed Drying

Solar-spouted bed drying experiment were carried out on the set up illustrated in Figure 2.1. The flow rate of the air was adjusted to the minimum spouting air velocity which changed according to the sample. Air blower was operated half an hour before the experiments to adjust steady temperature in spouting column. In addition, spouting column was placed on a support. When the steady conditions were provided, 250 g of sample was loaded into the spouting column. Weight change was measured for every half hour by loading out and loading in the samples again as fast as possible. Temperature at the inlet and exit of column as well as temperature of solar collector and surrounding were determined by NiCr- Ni thermocouples. Drying experiments took 5 hours. They replicated in 3 or 4 times. Dried samples were stored in closed plastic bags to avoid the moisture content change for further analysis. During drying solar irradiation was also measured using pyranometer (Kipp & Zonen, CM11, Delft, Holland) in units of W/m^2.

2.5 Measurement Methods

2.5.1 Moisture Content

Initial and final moisture contents of the samples were determined by using a moisture analyzer (OHAUS, MB45, Nanikon, Switzerland). About 10 g of samples were put into the sample holder and dried until the constant weight was obtained. Moisture content data was given in kg water/kg dry matter unit.

2.5.2 Color

The color of samples was determined by a color reader (Minolta, CR10, Osaka, Japan). The color values were expressed as CIE L^* (from light to dark), a* (from red to green), and b* (from yellow to blue).

2.5.3 Shrinkage

Dimensions of fresh and dried samples were used for initial and final apparent volume determination (Niamnuy et. al., 2007).
Shrinkage was expressed as follows:

$$S = \left[\frac{(V_0 - V_f)}{V_f} \right] \times 100 \qquad (2.1)$$

Where;
V_f ; apparent volume of the sample after drying (m^3)
V_o ; apparent volume of the fresh sample (m^3)

2.5.4 Bulk Density

In order to get the bulk density, a container with a known volume and weight, which were 20 ml and 24.9 g, respectively, was filled with sample. The container was tapped without compressing the sample and the excess was removed by sweeping the surface of the container with a ruler (Sahin and Sumnu, 2006). The weight of the sample with the container was measured by an electronic balance (OHAUS, Adventurer ARD110, Shanghai, China). Tapping and weighting procedure continued until an approximate constant value was reached. Then, bulk density was calculated by taking the ratio of the weight of sample and volume of the container in kg/m^3.

2.5.5 Apparent Density

The apparent density was determined by using Archimedes principle. A burette of 100 ml with a graduation of 1 ml was filled with certain amount of water. About 3 g of samples was immersed in to the water and the volume displaced by the samples was recorded. Then, the apparent density was calculated as the ratio between the sample weight and the displaced volume in kg/m^3.

2.5.6 Bulk Porosity

Bulk porosity was calculated using measured bulk and apparent densities (Sahin and Sumnu, 2006).

$$\varepsilon_{bulk} = 1 - \frac{\rho_{bulk}}{\rho_{app}} \qquad (2.2)$$

where ε_{bulk} is bulk porosity, ρ_{bulk} is bulk density and ρ_{app} is apparent density.

2.5.7 Internal porosity and pore size distribution

Before the experiment, all samples were freeze dried, not to damage the pores. For wheat and corn, porosity and pore size distribution were measured using mercury porosimeter (Poremaster 60, Quantachrome Corporation, Florida, USA). Measurements were done at its maximum pressure. For pea, low pressure, which is in the range of 0-50 psia, was used in mercury porosimeter experiments for determination of pore size distribution. For porosity determination of pea, a helium pycnometer (Ultrapycnometer 1000, Quantachrome Corporation, Florida, USA) was used.

2.5.8 Microstructural Analysis

For microstructural analysis, firstly samples were immersed into liquid nitrogen and cut into pieces not to damage microstructure and then freeze dried in order to reduce the moisture content without damaging the pores. It was necessary for the operation condition of the scanning electron microscope. Microstructural images were taken with scanning electron microscope (JSM-6400-NORAN, Tokyo, Japan). Different magnifications were used for each sample in order to get the best image. They were 300X, 500X and 250X for wheat, corn and pea, respectively.

2.5.9 Sphericity

For the dimension determination of the samples, a micrometer (Mitutoyo, CD-15D, Kanagawa, Japan) was used. Length (L), width (W) and thickness (T) were determined for 10 or more randomly selected wheat and corn kernels. From these dimensions, geometric mean (D_g), equivalent diameter (D_p), arithmetic diameter (D_a) in mm and also sphericity (Θ) were calculated for quality analysis (Mohsenin, 1986).

They are expressed as follows:

$$D_g = (LWT)^{\frac{1}{3}} \qquad (2.3)$$

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

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

$$\Theta = \frac{(LWT)^{\frac{1}{3}}}{L} \qquad (2.6)$$

2.5.10 Rehydration

Rehydration experiments were performed according to the method of Lewicki (1998). 10 g of dried samples were placed into a cloth and they were put in a beaker containing 250 ml distilled water. The beakers were kept at room temperature, nearly 20^{o}C, for 14 hours. Then, the samples were taken out and drained over a mesh for eliminating the superficial water and weighed. Rehydration capacity (RC) was defined as the ratio of the total weight after rehydration (W_f), to the dry weight of the sample (W_d) in grams:

$$\%RC = \left(\frac{W_f}{W_d} \right) \times 100 \qquad (2.7)$$

2.5.11 Ascorbic Acid Content

Experiments for ascorbic acid determination were performed for dried pea only. Ascorbic acid contents of the dried samples were determined by the 2,6-dichlorophenol indophenol visual titration method (AOAC, 2007). Before the titration of the sample, blank and ascorbic acid standard titrations were done for the final calculations. For the titration of the samples, they were ground to get a homogenous sample. 2 g of sample was mixed with 8 ml distilled water and 2 ml was taken for titration. Then, 5ml HPO_3 solution and 30 ml distilled water were added and it was titrated with 2,6-dichlorophenol indophenol solution. The volume used for the titration was noted to be used in the calculation. Calculation was done according to the following formula:

$$mgAA/\,mlsample = 2 \times \left[\frac{V_s - V_b}{V_{st} - V_b} \right] \quad (2.8)$$

where V_s is volume of 2,6-dichlorophenol indophenol solution used for titration of sample, V_b volume used for titration of blank and V_{st} is volume used titration of standard AA solution in ml. In addition, AA contents were given in units of mg AA/g sample by considering the grams of sample used at the beginning of the experiment.

2.5.12 Data Analysis

The effects of drying methods on the quality parameters such as color, bulk density, and rehydration ratio were determined by one way analysis of variance (ANOVA). For the comparison of the parameters Tukey's comparison test was used ($p< 0.05$). Statistics program Minitab (MINITAB English, version 15) was employed for all data analysis.

CHAPTER 3

RESULTS AND DISCUSSION

In this study, solar-spouted bed drying method was compared with open sun drying of wheat, corn and pea according to the drying rate and quality parameters. The quality parameters evaluated were color, shrinkage, bulk density, apparent density, bulk and internal porosity, microstructure, pore size distribution, sphericity and rehydration ratio. For peas only, ascorbic acid content was also measured. In addition, pictures of the samples after drying were taken and given in Appendix A.

3.1 Solar Irradiation and Temperature

Temperature as well as solar irradiation data during drying was illustrated in Figure 3.1.

As it can be seen from the plot, outside temperature changed between 25 and 32ºC while temperature of the collector part of the solar dryer changed between 42 and 74 ºC. In addition solar irradiation values ranged from 585 to 950 W/m^2. The highest value for solar irradiation was recorded at 13:00 while the highest temperature was at 15:00, but it was nearly constant after 13:00 despite the decrease in solar irradiation.

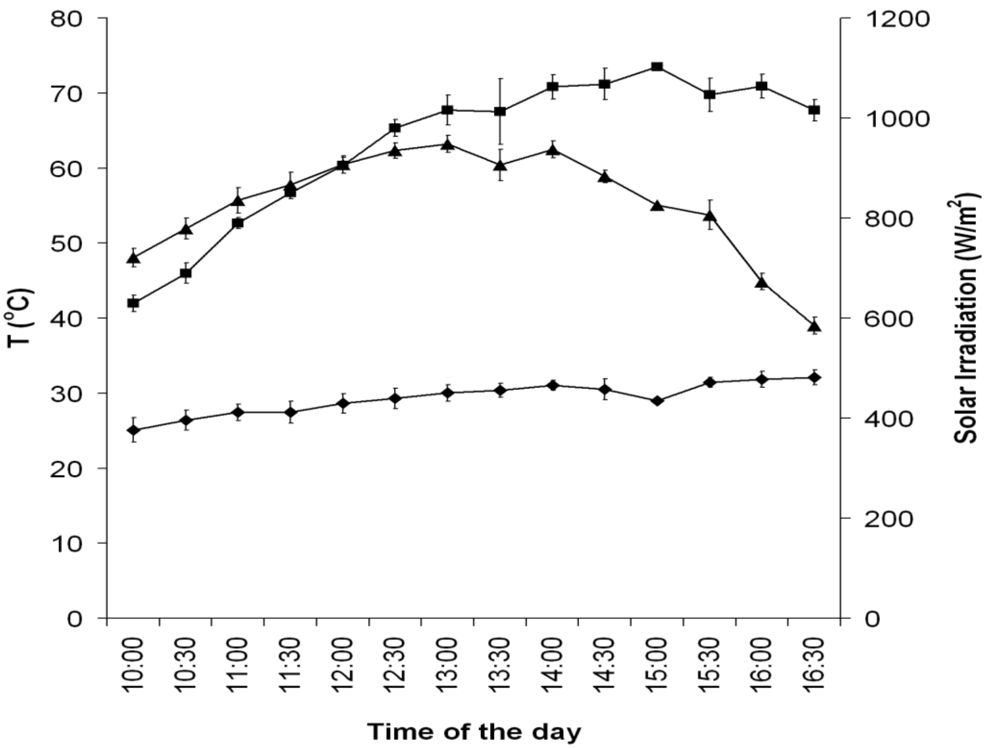

Figure 3.1 Variation of temperature and solar irradiation during the day
(■: collector air temperature; ♦:ambient air temperature; ▲: solar irradiation)

Although, outside temperature did not change so much, temperature in the collector part of the solar dryer varied accordingly solar irradiation. However, it did not drop drastically as solar irradiation at the end of the day. This is due to the gravels exiting on the base of the collector part; heat is deposited by the help of the gravels and temperature can be kept nearly constant for a certain period of time. In addition, air temperature in solar collector during solar-spouted bed drying experiments for all samples were almost the same.

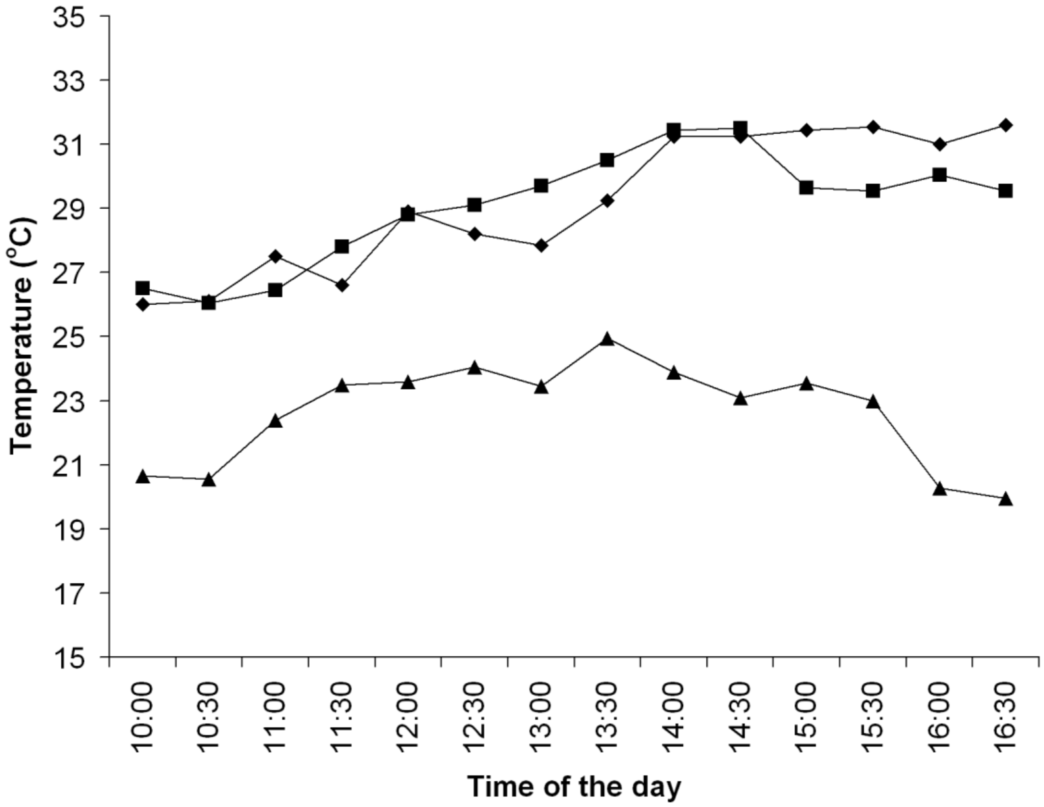

Figure 3.2 Variation of ambient temperature during drying of different samples (■: corn; ♦: wheat; ▲: pea)

Figure 3.2 illustrates the variation of ambient temperature during drying. Experiments for pea, wheat and corn were done in May, June and July, and average ambient temperatures were recorded as 25.1, 29.3, 28.7ºC, respectively.

In Figure 3.3, an average temperature at the inlet and exit of the spouting column was illustrated. During the experiments, average inlet and exit temperatures were recorded as 60.3 and 59.4 ºC. Average temperatures during drying experiments were given in Appendix B.1, B.2 and B.3 for parboiled wheat, corn and pea, respectively.

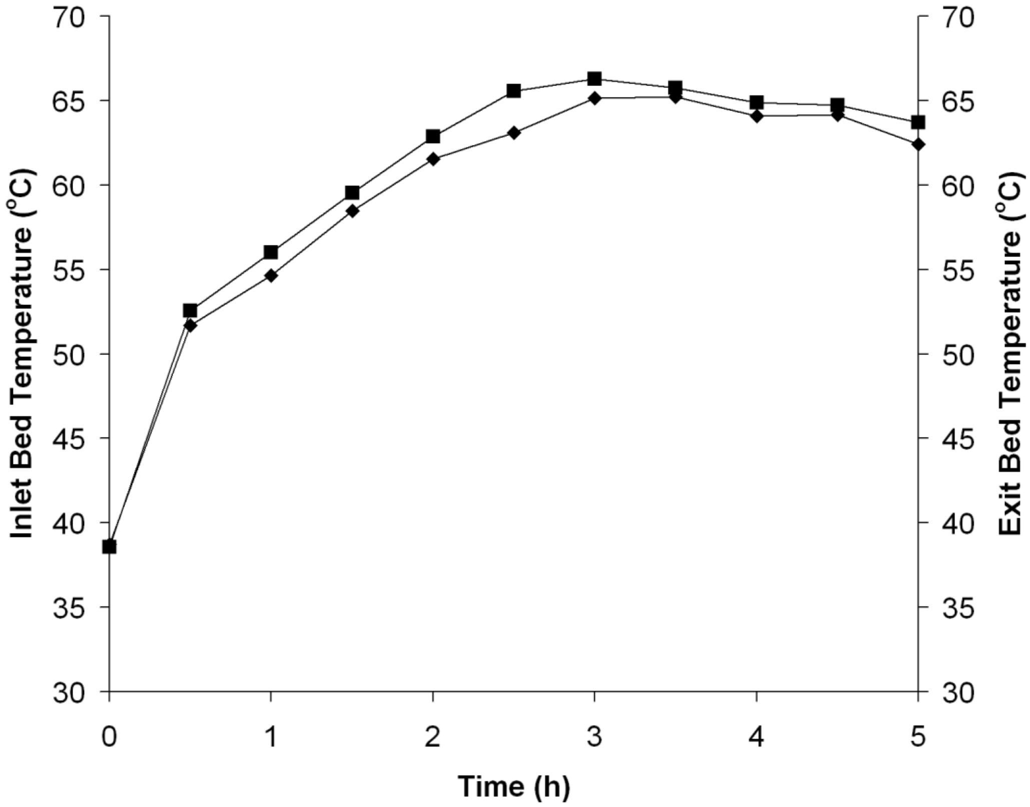

Figure 3.3 Variation of average inlet and exit temperature in spouting column (■: inlet bed temperature; ♦: exit bed temperature)

3.2 Drying of Parboiled Wheat

3.2.1 Minimum Spouting Air Velocity

In order to determine the minimum spouting air velocity, 250 g of parboiled wheat, which was the amount used for all experiments, was put into the spouted bed. Experiments were carried out at early times of the day; that is temperature of air was not more than 25ºC. Therefore, the change in determined spouting velocities was prevented by reducing the change in the moisture content of the samples during velocity experiments. In order to fix the minimum spouting velocity, pressure drop versus increasing and decreasing superficial air velocity curve was plotted (Figure 3.4). In addition, data for this plot are given in Appendix C.1 and C.2.

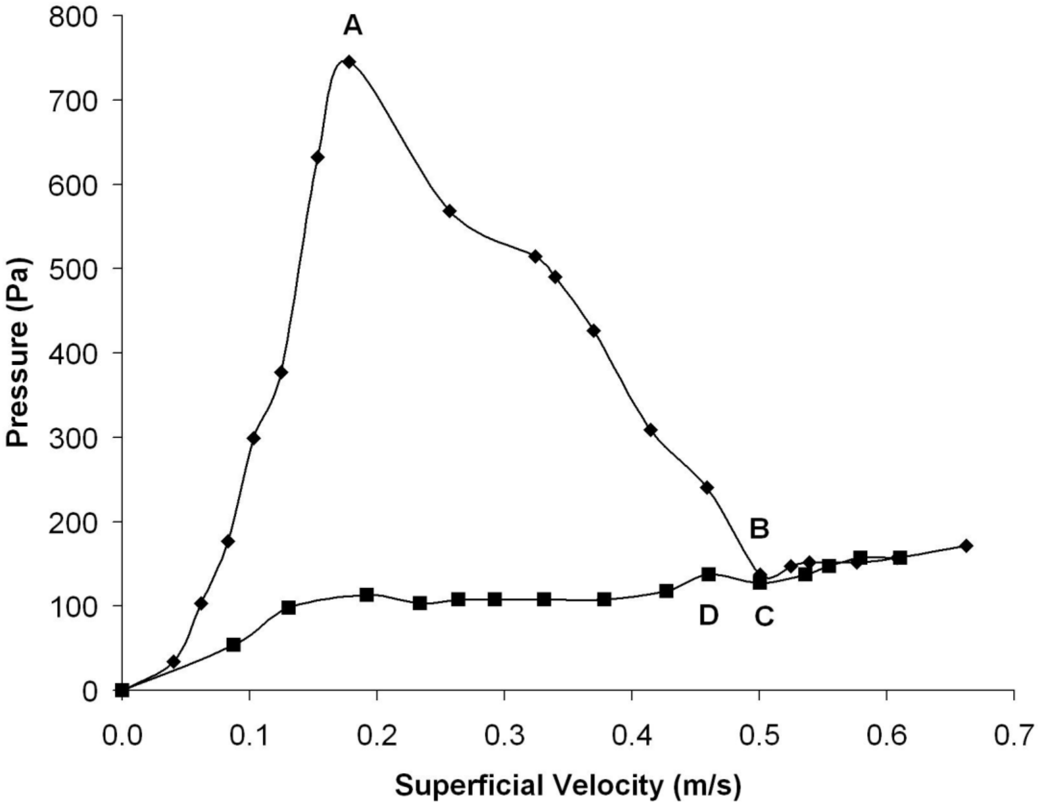

Figure 3.4 Pressure drop versus flow rate curve for minimum spouting velocity determination of parboiled wheat

A: maximum pressure drop; B: onset of spouting; C: minimum spouting point; D: collapse of spouting (♦: increasing flow; ■: decreasing flow)

As the flow rate of the air was increased, a linear increase in the pressure drop was observed up to point A (Figure 3.4). This increase was due to the wheat particles, which were compressed towards inside the bed by the flowing air, developing an arch and not letting the air at those velocities pass through them. After point A, the radius of the arch increases such that, air starts to pass through the wheat particles and pressure drop decreases gradually to point B. Point B is the point where spouting starts; after that increasing air velocity is not effective on pressure drop due to the fact that air can easily pass through the particles making them moving and circulating inside the bed. Minimum air velocity is determined by decreasing the air velocity after observing the spouting and constant pressure drop. Spouting is observed until point C after which there is a slight increase in the pressure drop. That increase, represented by point D, is the indication of the end of the spouting (Mathur and Epstein, 1974).

From the plot for superficial velocity versus pressure drop for wheat, point C, which is the minimum spouting point, was observed to be 0.5 m/s. Thus, spouting air velocity was chosen as 0.5 m/s, and used for drying of parboiled wheat experiments.

3.2.2 Drying Rate Curves

The effect of drying methods on drying rate was investigated. The weight data, taken during drying experiments and moisture content data, converted from the weight data were tabulated in Appendix B.4.

Figure 3.5, shows the variation of moisture content during drying of parboiled wheat for open sun and solar-spouted bed. When two drying methods were compared, it was obviously seen that moisture content decreased more rapidly for solar-spouted bed drying. This is most probably due to two reasons; higher temperatures of drying for solar-spouted bed and mobility of the particles in spouting column. In the study of the drying of asparagus with different drying methods, Nindo et. al. (2003) noted that, the decrease in the moisture content was higher for spouted bed drying of asparagus as compared to tray drying at the same temperatures, which showed the effect of mobility of the particles in spouted bed. For drying of asparagus, drying time was two times higher for the tray drying.

In addition to mobility of particles in spouted bed, temperature of air used for drying was higher. For open sun drying, temperature of air was in the range of 25 and 32ºC while it was in the range of 40 and 68ºC for solar-spouted bed drying. When the temperature difference between the heating medium and the food is higher, the rate of the heat transfer into the food becomes higher making the removal of the moisture easier (Potter and Hotchkiss, 1995).

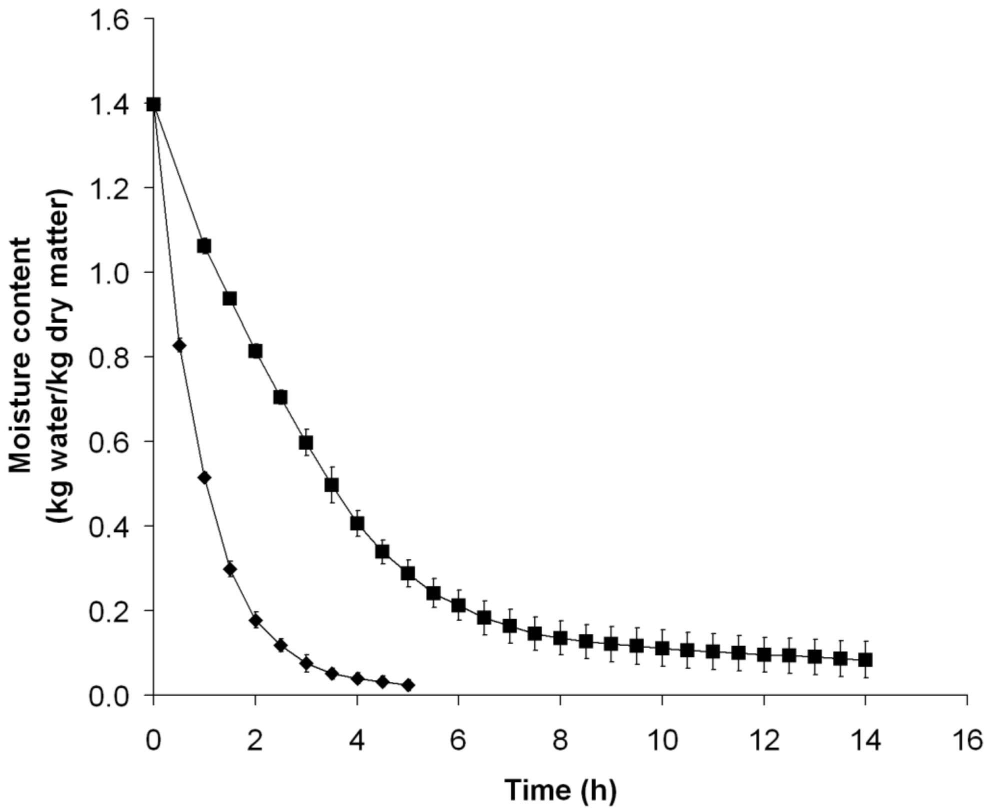

Figure 3.5 Drying curves for parboiled wheat
(■: open sun ♦: solar-spouted)

Thus, as temperature of the drying increases, drying time becomes shorter. In open sun drying, time for decreasing moisture contents of wheat to the same level was much higher as compared to solar-spouted bed drying. It took 5 hours for solar-spouted bed drying to reduce the moisture content of parboiled wheat to 7% while it was 14 hours for open sun drying.

The effect of drying methods on the rate of drying was illustrated in Figure 3.6 for open sun and in Figure 3.7 for solar-spouted bed drying. As can be seen from the figures drying rate for solar-spouted bed was about 3.5 times as high as open sun drying. As it was explained before, rate difference was due to the differences in temperatures of drying and also mobility of particles during spouting. In the study for asparagus, rate of drying was also examined and it was indicated that rate for spouted bed was nearly 2.5 times higher than that for tray drying (Nindo et. al., 2003).

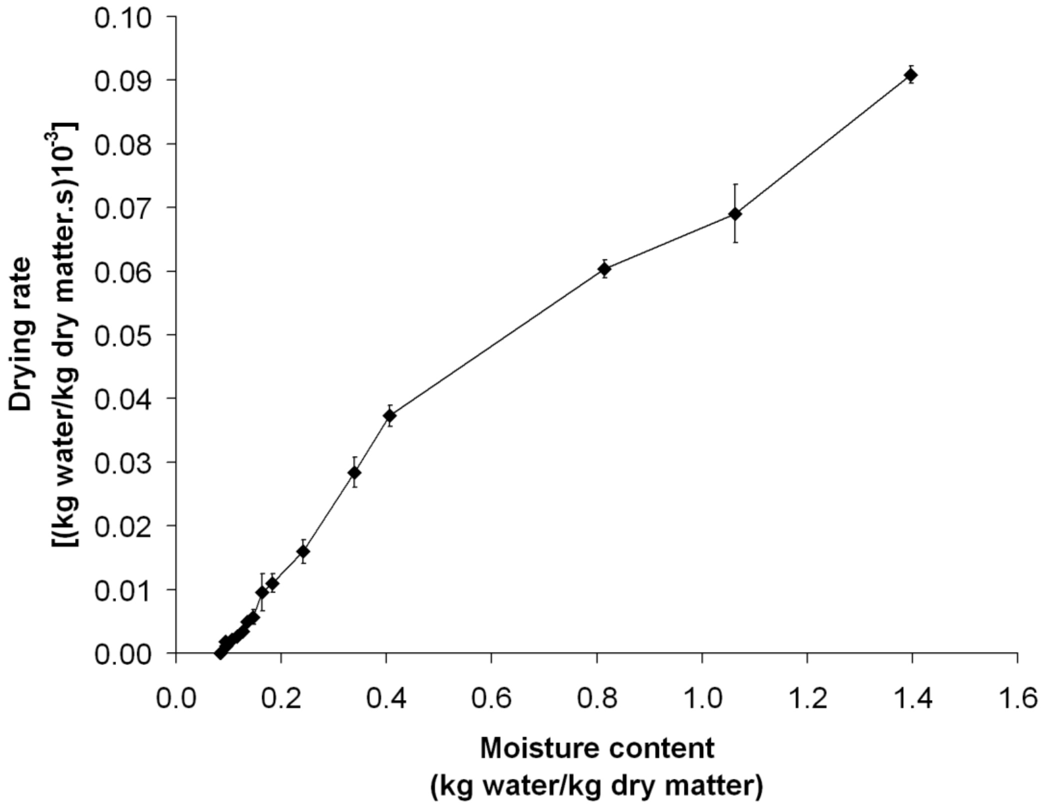

Figure 3.6 Drying rate curves of parboiled wheat for open sun drying

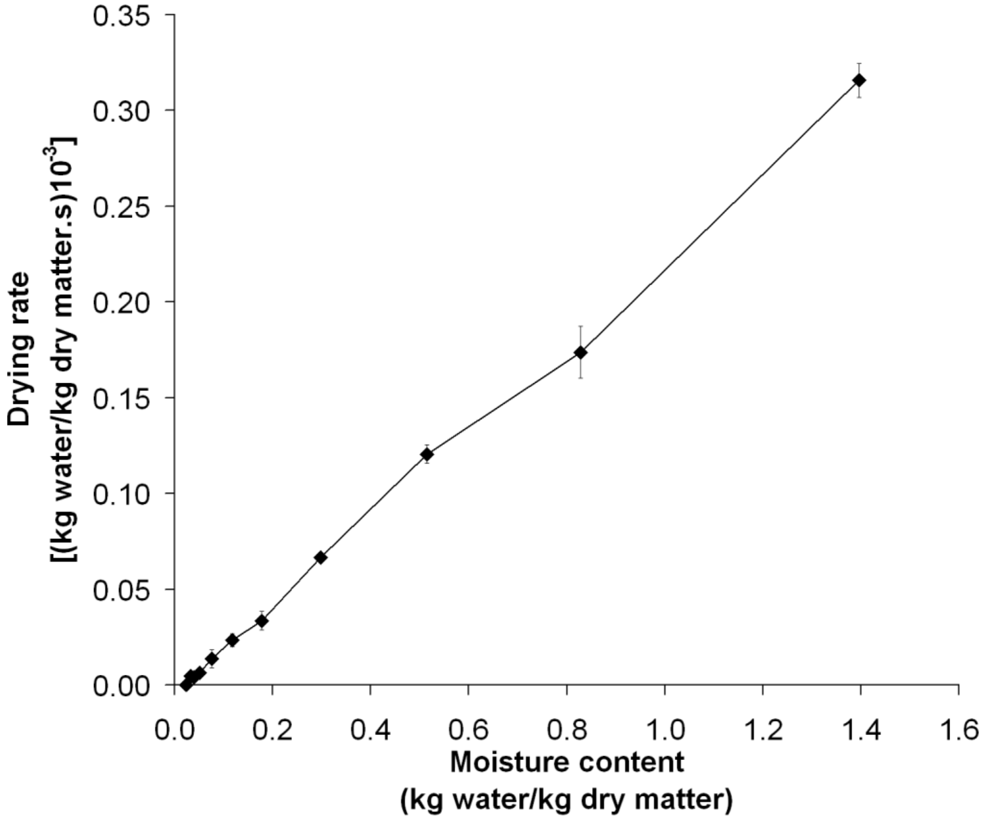

Figure 3.7 Drying rate curves of parboiled wheat for solar-spouted bed drying

In addition, during open sun and solar-spouted bed drying only falling rate period was observed, indicating the moisture diffusion was governing the drying process. Constant rate period occurs when the surface of the sample to be dried is very wet. When the falling rate period begins, water at the surface is no longer sufficient to act as a film of water. Sample surface is not wet enough for keeping constant rate and moisture content starts to decrease continuously (Geankoplis, 2003). In the study for drying of mint with solar dryer and under open sun, Akpinar (2010) also observed that drying occurred at falling rate period. This situation was explained by dry surface of mint during drying and moisture diffusion controlled mechanism of the drying. In addition, in the experiments for the spouted bed drying of parboiled wheat, only falling rate period was observed (Kahyaoglu et al., 2010).

3.2.3 Determination of Effective Diffusivity

For the drying process occurring only at falling rate period at which the moisture diffusion is the controlling mechanism, Fick's second law can be used to illustrate the drying:

$$\frac{\partial X}{\partial t} = \nabla(D_{eff} \nabla X) \qquad (3.1)$$

where X is the moisture content (kg water /kg dry matter), t (s) is the time and D_{eff} (m^2/s) is the effective diffusivity which includes effects of mechanism of moisture in liquid and vapour form.

By combining microscopic balance and drying at spherical coordinates Fick's law becomes (Simal et. al, 1996);

$$\frac{\partial X}{\partial t} = -D_{eff}\left(\frac{\partial^2 X}{\partial r^2} + \frac{2}{r}\frac{\partial X}{\partial r}\right) \qquad (3.2)$$

Fick's equation, by assuming negligible shrinkage and, constant temperature and diffusion coefficients becomes as follows:

$$\frac{X - X_e}{X_0 - X_e} = \frac{6}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{n^2}\exp\left[-\frac{n^2 D_{eff}\pi^2}{R^2}t\right] \qquad (3.3)$$

where X_e and X_0 is the equilibrium and initial moisture contents, respectively, and R is the radius of the particles.

For long drying times, series converges immediately and Equation (3.3) can be simplified to first term of the series (Doymaz and Pala, 2003):

$$\ln\left(\frac{X - X_e}{X_0 - X_e}\right) = \ln\left(\frac{6}{\pi^2}\right) - \frac{\pi^2 D_{eff}}{R^2} t \qquad (3.4)$$

In order to check the long drying time assumption, dimensionless Fourier number, $\frac{D_{eff} t}{R^2}$, should be checked whether it is greater than 0.1 or not.

Moisture content data were used to determine effective diffusivity (D_{eff}) values by using Equation (3.4). Equilibrium moisture content was assumed to be zero since it was relatively small compared to initial moisture content and moisture content at any time during drying (Doymaz and Pala, 2003). According to the equation, slope of logarithmic moisture ratio versus time curve gave the D_{eff} as it was shown in Figure 3.8 for parboiled wheat.

As it can be seen from the figure, for determination of D_{eff} there was more than one falling rate period for both drying methods. It was due to the fact that moisture content of parboiled wheat was as high as 60%. In the study of drying of gelatinized soft and durum wheat, also two falling rate periods were observed (Turhan et. al., 2001).

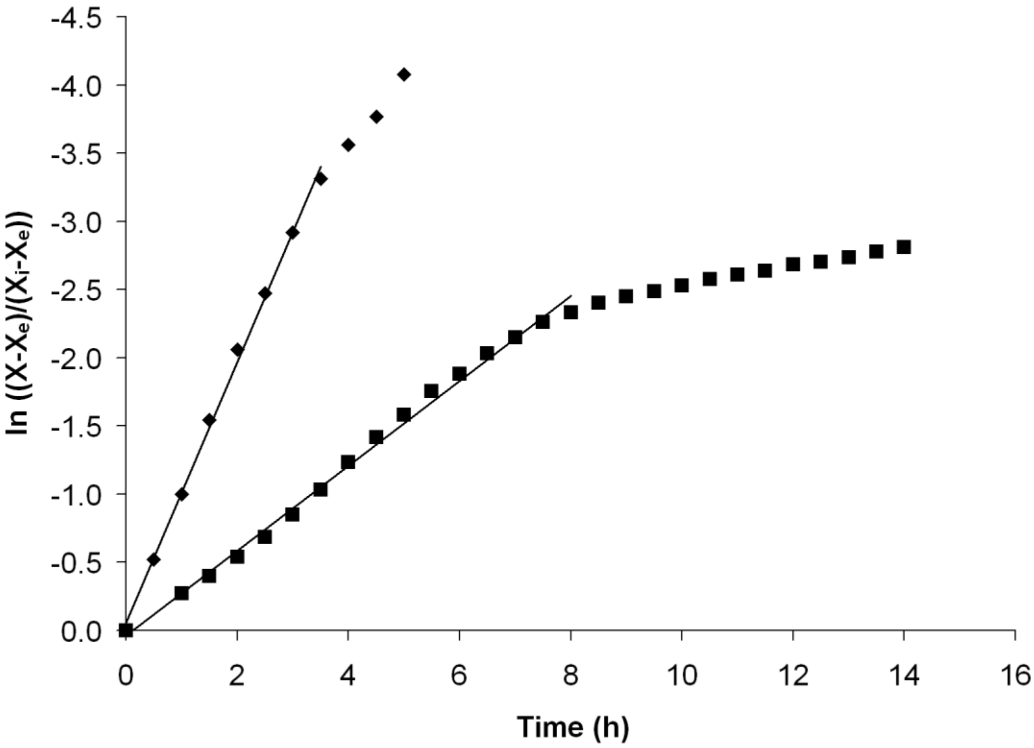

Figure 3.8 Dimensionless moisture content change with time for parboiled wheat (■: open sun ♦: solar-spouted)

For the effective diffusivity determination only first falling rate were considered in order to eliminate the effect of shrinkage. They were determined by linear regression of the curves and values were given in Table 3.1 for parboiled wheat. For D_{eff} analysis Fourier number was also considered in order to verify the long drying time assumption. For that it should be greater than 0.1, which fitted for both drying methods for parboiled wheat.

Table 3.1 Effective diffusivity values of parboiled wheat for the first falling rate period

Sample	**D_{eff}x10^{-10} (m^2/s)**	**r^2**	**Fo**
Open sun dried	0.44	0.9948	0.25
Solar-spouted dried	1.35	0.9975	0.34

Effective diffusivities were found as 0.44 and 1.35 x10^{-10} m^2/s for open sun and solar-spouted dried wheat, respectively. For the drying of food products, effective diffusivities were found to be in the range of 10^{-9} and 10^{-11} m^2/s (Madamba et. al., 1996). In addition, for drying of apricots (Mirzaee et. al, 2009) and apples (Meisami-asl et al, 2010) at different temperatures effective diffusivities were reported to be between 10^{-8} and 10^{-10} m^2/s. For the studies of apricot and apple, effect of temperature was also investigated. By keeping all other variables constant as temperature changed, it was observed that effective diffusivity was higher at higher drying temperatures.

Higher effective moisture diffusivity of parboiled wheat during drying in solar-spouted bed drier as compared to that during drying under open sun may be due to the higher temperature of drying and good contact of particles with hot air for solar-spouted bed.

By determining the effective diffusivity for two drying methods, equations relating moisture content and time can be written as follows:

$\ln\left(\frac{X}{X_0}\right) = 0.0370 - 0.3113t$; r^2=0.9948 for open sun drying of parboiled wheat

$\ln\left(\frac{X}{X_0}\right) = -0.0572 - 0.9551t$; r^2=0.9975 for solar-spouted bed drying of parboiled wheat

3.2.4 Quality Parameters of Parboiled Wheat After Drying

3.2.4.1 Color

Color of the dried and as well as parboiled wheat were investigated in terms of CIE L^*, a*, and b* color values. The effect of drying methods on color values for wheat was shown in Table 3.2. In addition, statistics for L*a*b* values in terms of ANOVA tables and Tukey's comparison test results were given in Appendix D.1.1-1.4.

Table 3.2 Color values of parboiled wheat samples dried using different methods

Sample	**L***	**a***	**b***
Parboiled	35.7 ± 1.93^a	12.0 ± 0.62^b	32.9 ± 0.07^a
Open sun dried	32.2 ± 1.75^a	15.1 ± 0.51^a	33.5 ± 1.29^a
Solar-spouted dried	35.3 ± 1.46^a	15.5 ± 0.99^a	35.6 ± 1.92^a

From the color analysis it was observed that, the change in L* and b* values with drying were not significant. However, a* value increased for both open sun and solar-spouted bed drying.

Non-enzymatic reactions or the Maillard reaction are important factors for the drying of foods with intermediate moisture contents (Marty-Audouin et al., 1999). Maillard reactions are generally found to be responsible for the change in color. However, in lower temperatures, the change can be related to the enzyme-linked glycosylation or proanthocyanidin (PA) oxidation. PA is responsible for brown or red-brown color on the coat of the mature seeds (Konopka et al., 2008). The increase in the a* value may be due to the Maillard reactions or enzyme linked glycosylation. In addition, exposing of sample to heat during drying may also responsible for the increase in a* value.

3.2.4.2 Shrinkage

Shrinkage percents of parboiled wheat was calculated using geometric mean diameter and given in Table 3.3. Statistical analysis in terms of ANOVA tables and Tukey's comparison results were given in Appendix D.2.1 and D.2.2.

Table 3.3 Shrinkage values of parboiled wheat samples dried using different methods

Sample	Shrinkage (%)
Open sun dried	34.79 ± 7.90[a]
Solar-spouted dried	21.13 ± 6.98[b]

From the shrinkage analysis, it was observed that, shrinkage was more for the open sun dried wheat samples. Statistically, drying methods found to be effective on shrinkage significantly.

Konopko et. al. (2008) observed that drying in spouted bed resulted in the shrinkage of the kernel. In the study of drying of carrots in fluidized bed, it was stated that shrinkage was inversely proportional to the drying rate (Hatamipour and Mowla, 2002). Therefore, higher drying rate of the solar-spouted bed drying resulted in less shrinkage of parboiled wheat particles.

3.2.4.3 Bulk Density

Bulk density values for the dried parboiled wheat were given in Table 3.4 according to different drying methods. Moreover, statistics for bulk density values in terms of ANOVA tables and Tukey's comparison test results were given in Appendix D.3.1 and D.3.2.

Table 3.4 Bulk density values of parboiled wheat samples dried using different methods

Sample	Bulk Density (kg/m^3)
Parboiled	630.0 ± 5.00^{ab}
Open sun dried	650.0 ± 8.66^{a}
Solar-spouted dried	591.0 ± 28.43^{b}

Bulk density of parboiled wheat dried under open sun was higher than that dried in solar-spouted bed drier. Statistically, it was observed that, drying methods were effective on bulk densities of the samples. Higher bulk density value for open sun dried wheat may be due to the lower drying temperature and lower drying rate. That resulted in higher percents of shrinkage for open sun dried samples (Table 3.3) and therefore higher bulk density values than that of solar-spouted bed dried ones.

3.2.4.4 Apparent Density

Apparent density values for the dried parboiled wheat dried using different methods were given in Table 3.5. Moreover, statistics for apparent density values in terms of ANOVA tables were given in Appendix D.4.1.

Table 3.5 Apparent density values of parboiled wheat samples dried using different methods

Sample	Apparent Density (kg/m^3)
Parboiled	1257.1 ± 219.90^{a}
Open sun dried	1158.7 ± 167.20^{a}
Solar-spouted dried	1000.0 ± 25.00^{a}

As it can be seen from Table 3.5 apparent densities were not different statistically. This indicates that during drying relative decrease in moisture content was balanced with the relative decrease in volume due to shrinkage. Although, not statistically different, lower apparent density of parboiled wheat dried in solar-spouted bed dryer may be due to the higher temperature of drying which caused less shrinkage.

3.2.4.5 Bulk and Internal Porosity

Internal porosity which is defined as the porosity due to the enclosed air space within particles was determined with mercury porosimeter and bulk porosity, which is defined as the porosity due to voids outside the boundary of particles when stacked as bulk, was calculated theoretically using bulk and apparent densities. In addition, bulk porosity change during drying experiments was shown in Figure 3.9.

Table 3.6 Internal and bulk porosity values of parboiled wheat samples dried using different methods

Sample	Internal Porosity	Bulk Porosity
Parboiled	0.16	0.49
Open sun dried	0.05	0.43
Solar-spouted dried	0.04	0.41

As it can be seen from the Table 3.6 and Figure 3.9, internal and bulk porosities decreased as parboiled wheat kernels dried with both open sun and solar-spouted bed drying. When two drying methods were compared, it was seen that internal and bulk porosity decreased more for solar-spouted bed. It may be due to the fact that, drying rate and drying temperature was greater for solar-spouted bed drying.

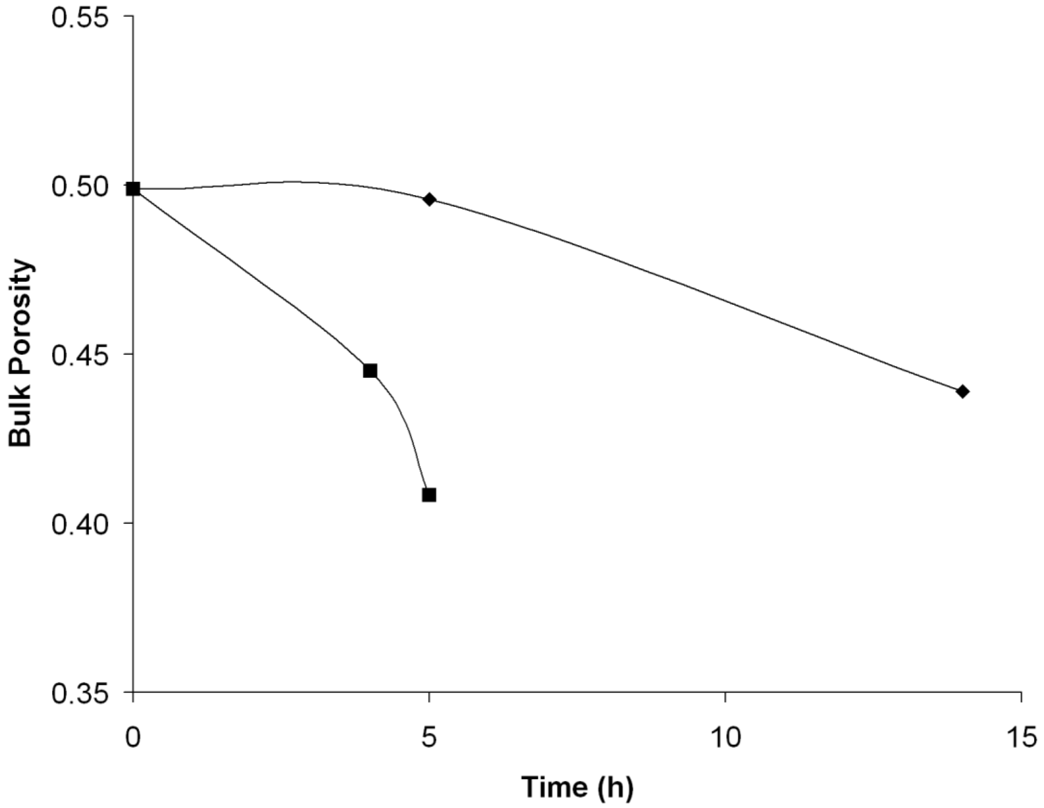

Figure 3.9 Variation of bulk porosity of parboiled wheat during drying
(♦: open sun ■: solar-spouted bed)

Formation of the pores during drying is categorized into two groups as one with an inversion point and another without an inversion point. For the formation with an inversion point, pores may collapse up to a critical point and further decrease in moisture content lead to formation of pores till the end of the drying. In addition opposite steps; first increase then decrease, for the pore formation with an inversion point can also be observed during drying. When the formation is considered without an inversion point, porosity may increase or decrease accordingly with moisture content (Rahman, 2003). In the study for drying of apples, porosity decreased with decreasing moisture content (Rahman et. al., 2005) while it increased for starch samples during drying (Marousis and Saravacos, 1990). In addition, for carrot and banana shrinkage rate was so high that lower porosity values were determined at the end of the drying (Mujumdar, 2000).

As it can be seen from the Figure 3.9, porosity change of wheat for both drying methods obeyed the theory for the formation of the pores without an inversion point and it decreased as moisture content decreased.

3.2.4.6 Microstructural Analysis

Scanning Electron Microscopy (SEM) images of parboiled wheat before drying, and after drying under open sun and with solar-spouted bed dryer were given in Figure 3.10. Images of the wheat samples taken interrupting the drying process nearly at half of drying period were also shown in order to illustrate the change in the microstructure during drying. The SEM images of all wheat samples were taken at X300 magnification.

When the image of the parboiled wheat was considered, it was observed that complete gelatinization occurred during boiling process before drying. Besides, structure was seen as smooth and some pores were observed. Srikaeo (2008) observed the complete gelatinization of starch molecules during cooking at 60ºC for 120 minutes. It was also indicated that, by heating wheat particles to 95ºC, starch granules disintegrated and melted resulting in a homogenous appearance (Bilbao-Sainz et. al., 2007) which was the case for cooking of wheat in this study.

As the wheat kernels continued to be dried, porosity of the kernels decreased for both drying methods (Figure 3.10). Porosities were observed to be higher in the intermediate products for both methods. The SEM images of open sun and solar-spouted bed dried wheat samples were similar which was in accordance with their similar porosity values (Table 3.6).

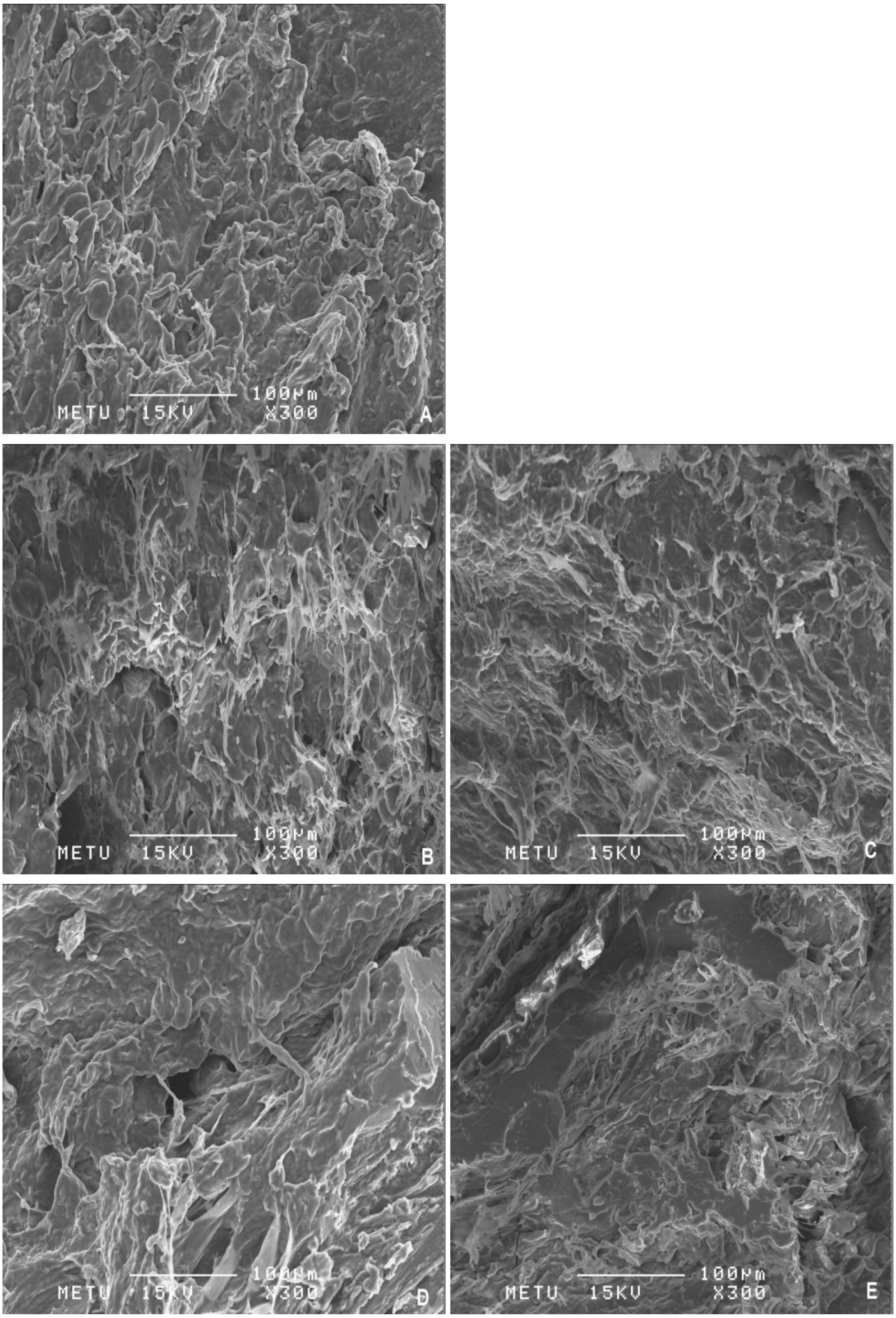

Figure 3.10 SEM images of parboiled wheat (**A**: parboiled, t=0; **B**: open sun dried, t=8h; **C**: open sun dried, t=14h; **D**: solar-spouted dried, t=2h; **E**: solar-spouted dried, t=5h)

3.2.4.7 Pore Size Distribution

The data obtained from mercury porosimeter experiments, were converted into graphs as cumulative intrusion (Figure 3.11 - 3.13), pore size distribution (Figure 3.14 - 3.16) and differential pore size distribution curves (Figure 3.17-3.19).

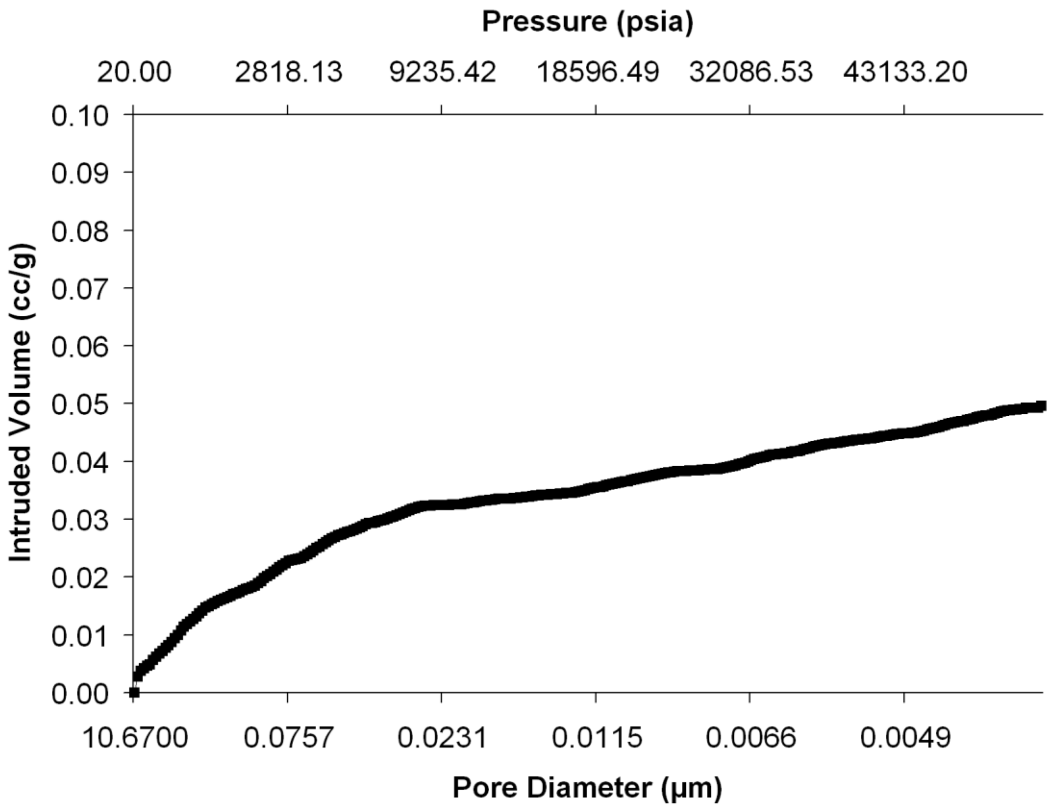

Figure 3.11 Cumulative intrusion curve for parboiled wheat

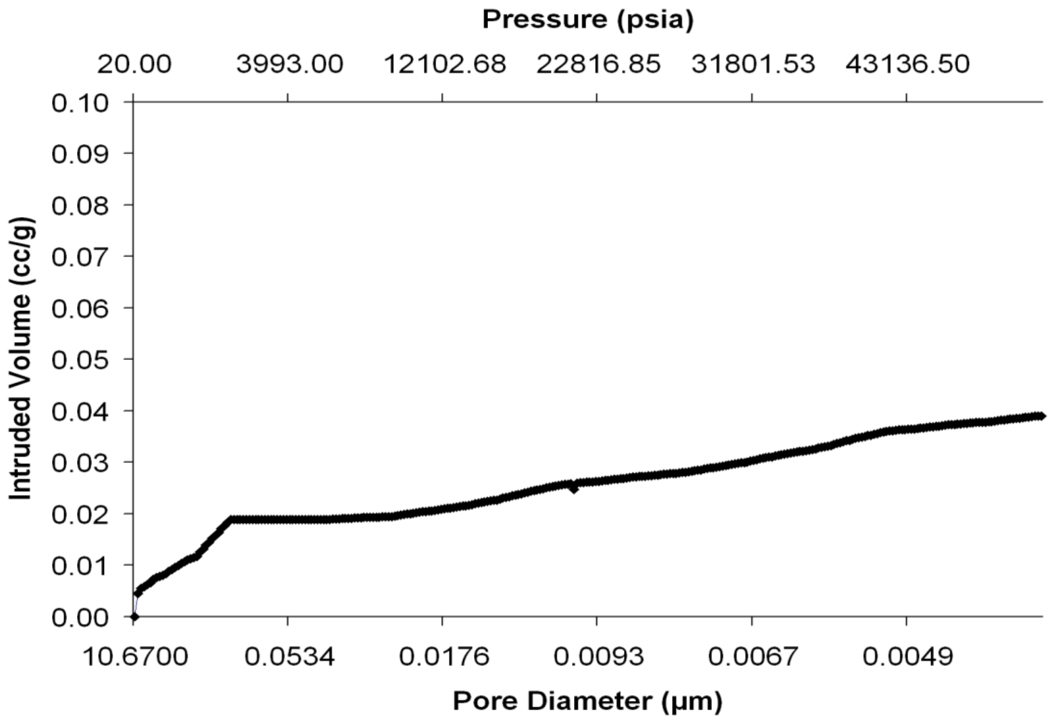

Figure 3.12 Cumulative intrusion curve for open sun dried parboiled wheat

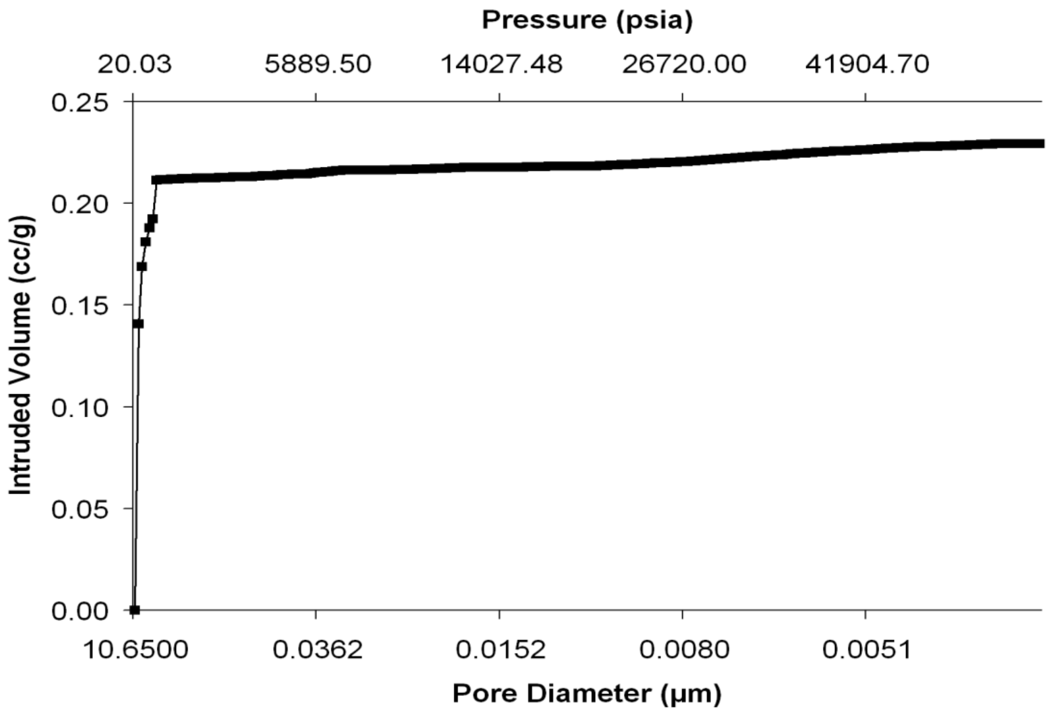

Figure 3.13 Cumulative intrusion curve for solar-spouted bed dried parboiled wheat

Cumulative intrusion curves were the plots of volume of the mercury intruded versus pore diameter. From the cumulative intrusion curve, total volume of mercury intruded, pore volume in any range, median pore diameter and also mode pore diameter can be determined. The pore diameter at the steepest slope gives the mode pore diameter. Pressure was also introduced in the plot. At the highest pressure and lower pore diameter value, internal porosity was obtained by porosimeter (Aligizaki, 2006). A gradient on the slope shows the decreasing pore size in the interior parts of the sample, a sharp rise indicates the same sized pores in large number and macro pores on the surface while a vertical line means absolutely the same sized pores (Rahman et. al, 2002).

In cumulative intrusion curve of dried wheat samples, a sharp increase was determined for solar-spouted dried samples (Figure 3.13). This indicated that, for solar-spouted bed, same sized pores were more and there was macro pores on the surface. This may be due to short drying time and therefore less collapse in the structure. For all samples, nearly a vertical line was observed. However, a gradient in slope existed in the curve for parboiled wheat indicating decrease of pore size towards the inside of the kernel. Vertical line indicates exactly same sized pores; therefore pores of solar-spouted bed dried wheat were more homogenously distributed. Pore size range for all samples was between 10.67-0.004 μm at pressure range of 20-55000 psia (Figure 3.11-3.13). However, threshold pore sizes, that were the pore diameter where the vertical line was observed, changed for the samples and were 0.015, 0.010 and 0.400 μm for parboiled, open sun dried and solar-spouted bed dried wheat, respectively. In addition, mode pore diameters for open sun and solar-spouted dried samples, that can be determined at the steepest slope, were 0.1078 and 0.6189 μm, respectively.

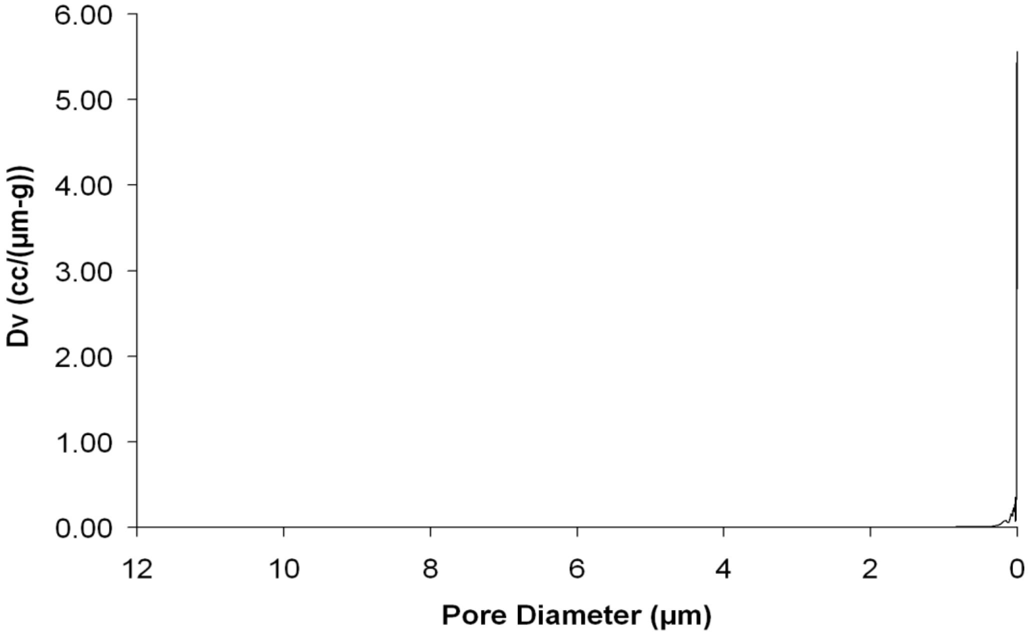

Figure 3.14 Pore size distribution curve for parboiled wheat

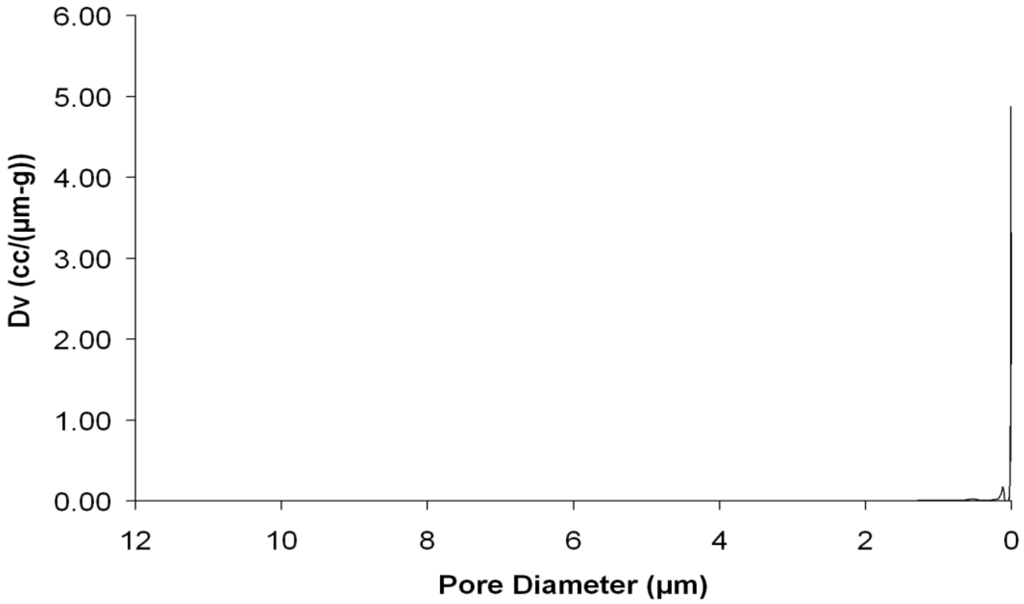

Figure 3.15 Pore size distribution curve for open sun dried parboiled wheat

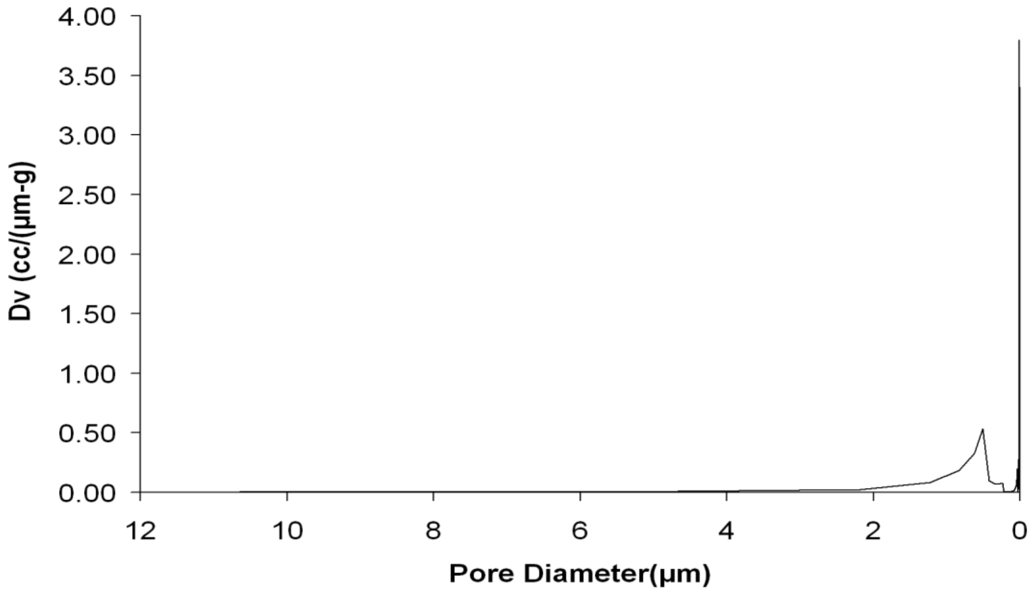

Figure 3.16 Pore size distribution curve for solar-spouted bed dried parboiled wheat

Pore size distribution was calculated using the pore radius and volume by assuming cylindrical pores. Pore size distribution is defined as;

$$D_V = \left(\frac{P}{r}\right) \cdot \left(\frac{dV}{dP}\right)$$

where D_v is the pore size distribution function (cc/g-µm), P is the pressure applied and r is the radius of pores while $\frac{dV}{dP}$ is the first derivative of pressure versus intruded mercury volume data. Pore size distribution curves are considered in terms of number, size and shape of the peaks. Sharp peaks are the indication of the pores mostly exists at that size range while wider peaks shows larger pores are followed by smaller sized ones. The height of the peak and the number of the pores at that size is analogous (Rahman et. al, 2005). Furthermore, a higher height indicates more pores at that pore size (Rahman et. al, 2002).

When the pore size distribution curves were considered for wheat, one sharp peak was observed for all samples (Figure 3.14-3.16). However, the height of the peak and the diameter changed according to the sample. For parboiled wheat, sharp peak was observed at the pore size of 0.0043 μm while height was 5.488 in terms of the unit of D_v. They were 0.0054 and 4.787; 0.0049 and 3.797; for open sun and solar-spouted dried wheat, respectively. That showed that larger sized pores in large number formed during the drying under open sun. This was also observed when the porosity values were discussed considering two drying methods (Table 3.6). In addition, a small peak was observed for pore size distribution curve of solar-spouted bed dried wheat. Since it was not as sharp as the other one, it was not considered for pore size distribution analysis.

The differential pore size distribution curve was obtained using the $\frac{dV}{d(\log D)}$ and pore diameter data. This plot showed the pore size distribution of the samples. From the figure for parboiled wheat it can be seen that, pore size varied in a great range. For the open sun dried wheat kernels it was mostly between the ranges of 0.04 and 0.002 μm while it was in a lower range for solar-spouted wheat; that was between 0.01 and 0.001 μm (Figure 3.18-3.19).

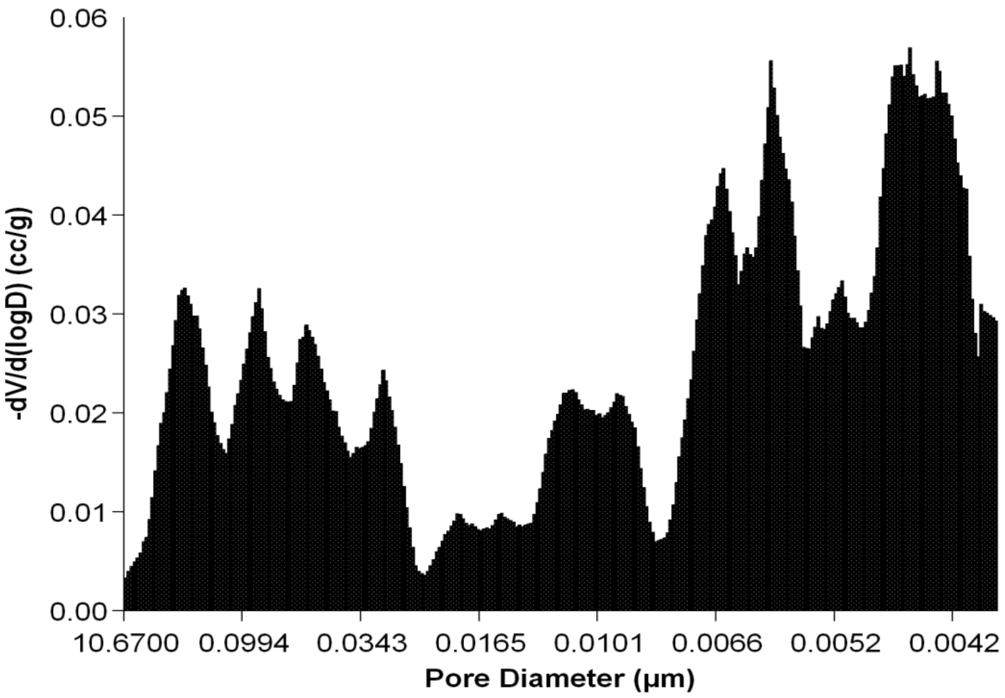

Figure 3.17 Differential pore size distribution curve for parboiled wheat

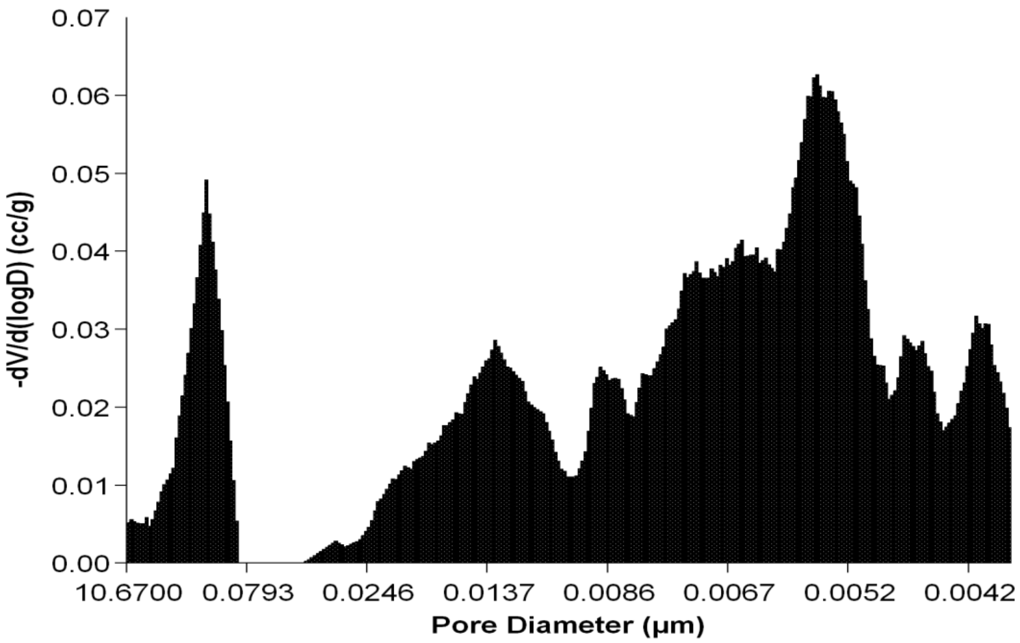

Figure 3.18 Differential pore size distribution curve for open sun dried parboiled wheat

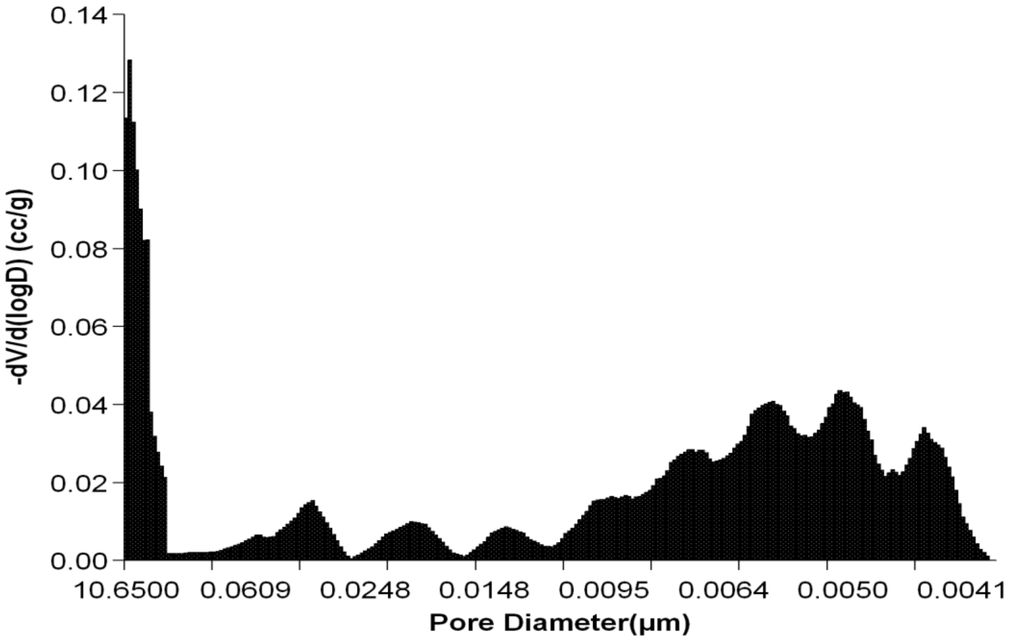

Figure 3.19 Differential pore size distribution curve for solar-spouted bed dried parboiled wheat

3.2.4.8 Sphericity

Geometric mean, equivalent diameter and arithmetic diameter as well as sphericity values for wheat were shown in Table 3.7. Statistical analysis in terms of ANOVA tables and Tukey's comparison results were given in Appendix D.5.1-5.6.

Table 3.7 Sphericity values of parboiled wheat samples dried using different methods

Sample	Geometric mean (mm)	Equivalent dia. (mm)	Arithmetic dia. (mm)	Sphericity
Parboiled	4.49±0.338[b]	4.52±0.335[b]	4.77±0.382[a]	0.61±0.038[a]
Open sun dried	4.03±0.236[a]	4.07±0.243[a]	4.34±0.254[a]	0.64±0.038[a]
Solar-spouted dried	4.11±0.247[ab]	4.14±0.244[ab]	4.41±0.256[a]	0.61±0.030[a]

Statistical analysis showed that the change in the sphericity and also in arithmetic diameter were not different while it was found that drying method was significantly effective on the change in geometric mean and equivalent diameter. Devahastin et. al. (1999) measured the geometric and equivalent diameter as well as sphericity of rewetted and dried wheat. While geometric mean and equivalent diameters decreased, sphericity was found to increase. Sphericity values of wheat samples were in the range of 0.61-0.64. They were close to the values reported by Devahastin et. al. (1999) which were 0.616 and 0.675 for rewetted and dried wheat, respectively. Moreover, it was emphasized that drying methods significantly affected barley kernel dimensions, especially length (Konopka et. al., 2008).

3.2.4.9 Rehydration

Rehydration values for open sun and solar-spouted bed drying of parboiled wheat was determined in terms of rehydration capacity (RC) as percents. The values of RC for two drying methods were tabulated in Table 3.8.

Table 3.8 Rehydration capacity values for parboiled wheat dried using different methods

Sample	**Rehydration capacity (%)**
Open sun dried	195.33 ± 2.080
Solar-spouted dried	201.00 ± 4.000

As can be seen from the table, rehydration capacity for the solar spouted bed dried wheat was higher than the one for open sun dried. In the study on the bulgur quality affected by drying methods, Hayta (2001) indicated that water absorption of solar dried pilav bulgur was significantly higher than the one for open sun dried.

Since the drying temperature therefore the drying rate was higher for solar-spouted bed drying as compared to open sun drying, less shrinkage was observed for solar-spouted dried wheat, resulting in a higher degree of rehydration.

3.3 Drying of Corn

3.3.1 Minimum Spouting Air Velocity

In Figure 3.20 the change in the pressure drop with increasing and decreasing air flow rate was illustrated. Variation of pressure drop with increasing and decreasing air velocity was tabulated in Appendix C.3 and C.4.

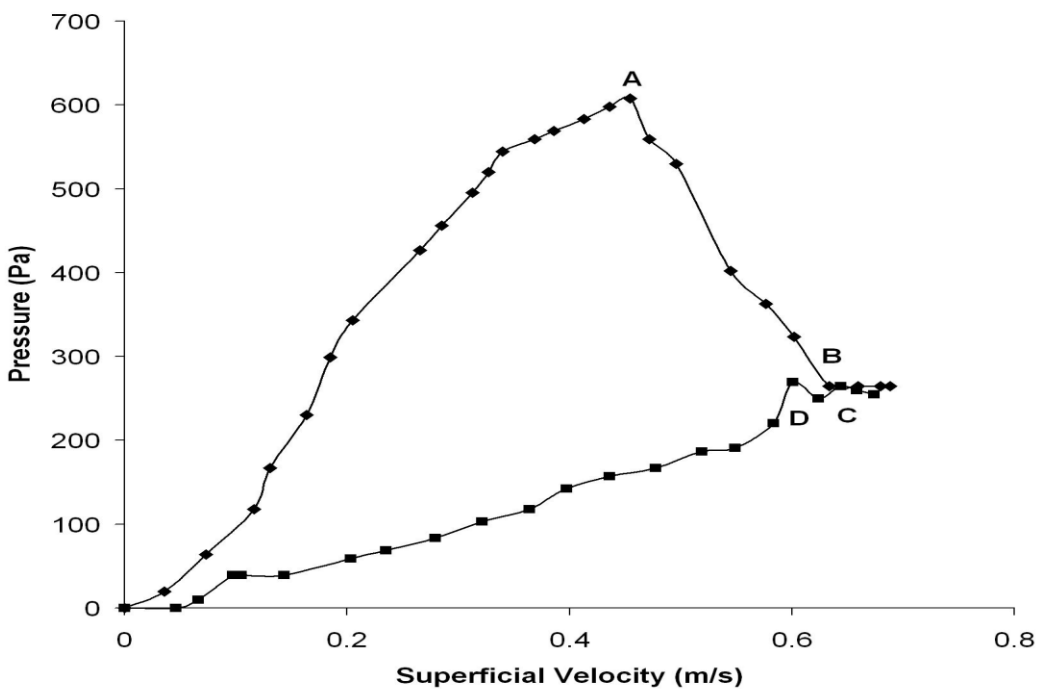

Figure 3.20 Pressure drop versus flow rate curve for minimum spouting velocity determination of corn

A: maximum pressure drop; B: onset of spouting; C: minimum spouting point; D: collapse of spouting (♦: increasing flow ; ■: decreasing flow)

As it was explained for the minimum spouting air velocity determination for wheat, a similar trend was also observed for corn.

From the plot for superficial velocity versus pressure drop for corn, point C, which is the minimum spouting point, was observed to be approximately 0.62 m/s. Therefore, spouting air velocity was chosen as 0.62 m/s for drying of corn.

3.3.2 Drying Rate Curves

Variation of moisture content during drying for corn can be seen in Figure 3.21. Also drying rate curves for both open sun drying and solar-spouted bed drying were given in Figure 3.22 and Figure 3.23, respectively. The weight data recorded during drying experiments and moisture content data calculated using weight data were tabulated in Appendix B.5.

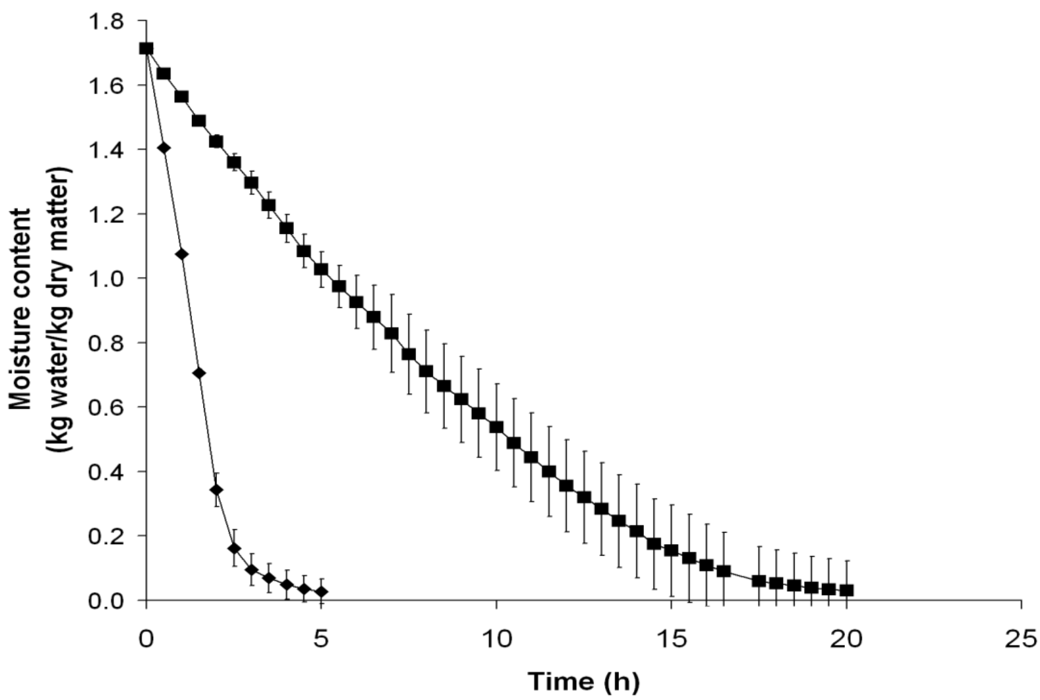

Figure 3.21 Drying curves for corn (■: open sun ♦: solar-spouted)

From Figure 3.21 it can be seen that more rapid decrease in moisture content occurred for solar-spouted bed. If the drying rates were compared, higher drying rate can be observed in solar-spouted bed drying as compared to open sun drying. This situation can be explained by the temperature difference between two drying methods and moving of particles during solar-spouted bed drying.

The higher the temperature difference between drying medium and food, the higher the rate of heat transfer (Potter and Hotchkiss, 1995). Temperature of drying air varied between 25-32 ºC for open sun while it was in the range of 40-68 ºC for solar-spouted bed (Figure 3.1). Therefore, as in the case of solar-spouted bed drying of parboiled wheat, higher temperature makes drying period shorter. It took 5 hours for solar-spouted bed drying of corn while it took 20 hours for open sun drying to decrease moisture content to 8% In the study of drying of asparagus with spouted bed and tray dryer, effect of mobility of particles on drying were seen. Although the air temperature was the same, removal of moisture was more rapid in spouted bed drying of asparagus because of the mobility of the particles. Drying rate was found to be 2.5 times higher than that in tray drying (Nindo et. al., 2003).

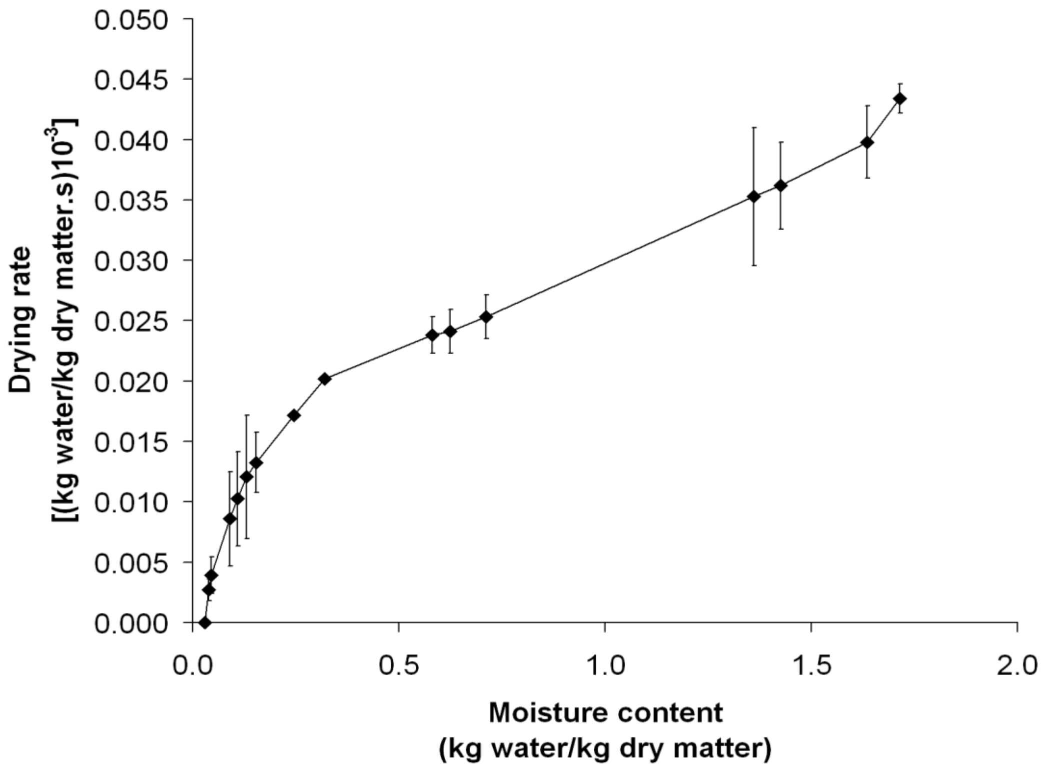

Figure 3.22 Drying rate curve of corn for open sun drying

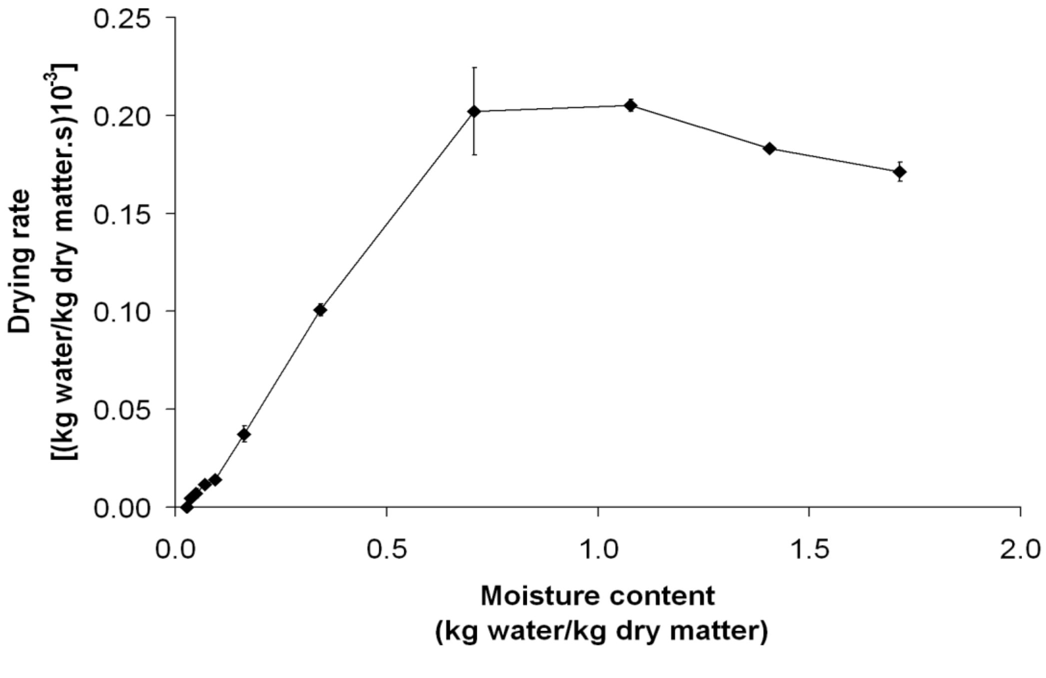

Figure 3.23 Drying rate curve of corn for solar-spouted bed drying

In addition, during open sun drying only falling rate period was observed, indicating the moisture diffusion was governing the drying process (Figure 3.22). However, when drying with solar-spouted bed was considered, a slight increase at the beginning and then a constant rate period was observed (Figure3.23). Constant rate period occurs when the surface of the sample to be dried is very wet. When the falling rate period begins, water at the surface is no longer sufficient to act as a film of water, sample surface is not wet enough for keeping constant rate and moisture content starts to decrease continuously (Geankoplis, 2003). At the beginning of the process, corn particles were stuck on the sides of the spouting column and good spouting could not be obtained. Air passed through the central cavity and recycling of particles can not be achieved. That situation continued for about one hour and it was tried to be prevented by interfering the corn particles when they were stuck on the sides. However, passing of the hot air among particles and not cycling them, led the surface of the corn particles to be wet. The slight increase and then a constant rate period in the drying rate curve may be related to the irregular spouting at the beginning of drying.

3.3.3 Determination of Effective Diffusivity

Using Equation (3.4) and moisture content data for drying of corn, effective diffusivity (D_{eff}) values were determined. Equilibrium moisture content was assumed to be zero (Doymaz and Pala, 2003) and from logarithmic moisture ratio versus time graph, diffusivity values were determined.

As for the case of drying of wheat, there were more than one falling rate periods for drying of corn. It was related with the high initial moisture content of corn samples which was about 70%.

In order to eliminate the effect of shrinkage, only first falling rate period was considered for the determination of effective diffusivity. Linear regression of dimensionless moisture ratio and time gave D_{eff} values which were tabulated in Table 3.9. In order to check the long drying time assumption Fourier numbers were also illustrated.

Table 3.9 Effective diffusivity values of corn for the first falling rate period

Sample	**D_{eff}x10^{-10} (m^2/s)**	**r^2**	**Fo**
Open sun dried	0.30	0.9949	0.11
Solar-spouted dried	3.65	0.9950	0.21

Effective diffusivities were found as 0.30 x10^{-10} and 3.65 x10^{-10} m^2/s for open sun and solar-spouted dried corn, respectively. Doymaz and Pala (2003) in their study for the thin layer drying characteristics of corn were also investigated effective diffusivity and found values in the range of 10^{-10} and 10^{-11} m^2/s. In addition, effect of drying temperature was also analyzed and it was observed that, D_{eff} value increased as drying temperature increased. The drying of corn with solar-spouted bed was also resulted in higher effective diffusivity value due to the higher drying temperatures.

By determining the effective diffusivity for two drying methods, equations relating moisture content and time can be written as follows:

$\ln\left(\frac{X}{X_0}\right) = 0.0399 - 0.1134t$; r^2=0.9949 for open sun drying of corn

$\ln\left(\frac{X}{X_0}\right) = 1.1151 - 1.3566t$; r^2=0.9950 for solar-spouted bed drying of corn

3.3.4 Quality Parameters of Corn After Drying

3.3.4.1 Color

Color of the fresh and dried corn were investigated in terms of CIE L^*, a* and b* color values. The effect of drying methods on color values for corn was shown in Table 3.10. In addition, statistics for L*a*b* values in terms of ANOVA tables and Tukey's comparison results were given in Appendix D.1.5-1.9.

Table 3.10 Color values of corn dried using different methods

Sample	**L***	**a***	**b***
Fresh	43.8 ± 3.02^{a}	14.5 ± 1.70^{a}	39.8 ± 3.00^{a}
Open sun dried	49.3 ± 3.70^{ab}	16.9 ± 1.26^{ab}	38.5 ± 1.60^{a}
Solar-spouted dried	52.6 ± 1.11^{b}	17.8 ± 0.29^{b}	33.5 ± 4.13^{a}

From the color analysis, it was observed that L* and a* values increased while b* value decreased after drying. The L* and a* color values of fresh corn and corn dried using solar-spouted bed were found to be significantly different while the change in b* value was not significant.

L* and a* values of corn dried in solar dryer were higher than that of corn dried under direct sunlight. However, these values were not statistically significant. Higher L* value indicates lighter samples. Therefore, solar-spouted dried corn was lighter when compared with open sun dried ones. The darkness in the color for the open sun drying was due to the direct exposing of the sample surface to the solar radiation for the long period of drying time. Sacilik et. al. (2006) also found that for the drying experiments of tomatoes, the ones that were dried with a solar dryer had more red color and brighter when compared with open sun dried ones.

3.3.4.2 Shrinkage

Shrinkage percents of the dried corn samples calculated from the dimensions were illustrated in Table 3.11. Statistical analysis of shrinkage of corn samples dried using different drying methods were also given in Appendix D.2.3 and D.2.4.

Table 3.11 Shrinkage values of corn samples dried using different methods

Sample	**Shrinkage (%)**
Open sun dried	23.87 ± 3.64^{a}
Solar-spouted dried	15.42 ± 4.38^{b}

Shrinkage analysis showed that, corn particles dried under open sun had significantly higher shrinkage percent when compared to solar-spouted dried ones. This can also be seen from the pictures of corn samples dried under different conditions (Appendix A.2).

Hatamipour and Mowla (2003), in their study for drying of maize and green peas related the shrinkage to moisture content and stated that shrinkage increased with decreasing moisture content. Since the moisture contents of open sun and solar-spouted bed dried corns were the same, difference in shrinkage values of corn particles may be related to the difference in rates of drying as in the case of drying of parboiled wheat. Solar-spouted bed drying method which had a higher drying rate than open sun drying resulted in lower shrinkage value.

3.3.4.3 Bulk Density

Bulk density values for the corn were given in Table 3.12 regarding the drying methods. In addition, statistics for bulk density values in terms of ANOVA tables and Tukey's comparison test results were given in Appendix D.3.3 and D.3.4.

Table 3.12 Bulk density values of corn samples dried using different methods

Sample	**Bulk density (kg/m^3)**
Fresh	575.0 ± 0.00^{a}
Open sun dried	475.0 ± 42.43^{b}
Solar-spouted dried	555.0 ± 25.98^{a}

Bulk density analysis of corn showed that, drying under open sun resulted in significantly lower bulk density as compared to drying with solar-spouted bed. Bulk densities of fresh and solar-spouted dried corn were found to be similar showing a better quality for solar-spouted bed dried corn. Similar bulk density values of fresh corn and corn dried in solar-spouted bed dryer can be explained by drying temperature. Higher temperature used in solar-spouted bed drying resulted in higher drying rate and in consequence less shrinkage (Table 3.11).

3.3.4.4 Apparent Density

Apparent density values of the fresh corn and corn dried under different conditions were given in Table 3.13. In addition, statistics for apparent density values in terms of ANOVA tables were given in Appendix D.4.2.

Table 3.13 Apparent density values of corn samples dried using different methods

Sample	**Apparent density (kg/m^3)**
Fresh	904.7 ± 82.60^a
Open sun dried	952.6 ± 21.40^a
Solar-spouted dried	941.6 ± 74.90^a

As it was shown in the Table 3.13, apparent density values for corn after drying increased for both open sun and solar-spouted bed drying methods. However, the difference between apparent density values was found to be not statistically significantly different.

Similarly, in the study for structural properties of vegetables during air drying, it was observed that, as the moisture content of the corn decreased, its apparent density increased (Boukouvalas et. al., 2010). Karababa (2006) also observed the relation between the moisture content and apparent density, and indicated that apparent density increased with decreasing moisture content. In addition, it was emphasized that drying method was significantly effective on apparent density, which can be higher or lower when compared with the initial value, due to the shrinkage or the development of pores, respectively (Vadivambal and Jayas, 2007). Therefore increase in apparent density values for corn in this study can be related to the shrinkage. When dimensions of the dried corn particles were compared with the one for fresh corn, they decreased for both open sun and solar-spouted bed dried corn. Therefore as shrinkage increased for both drying methods, apparent density increased. In addition, apparent density of solar-spouted bed dried corn increased less than open sun dried corn, which can also be explained by more shrinkage in open sun dried corn.

3.3.4.5 Bulk and Internal Porosity

Internal porosity values that were determined with mercury porosimeter and also bulk porosity values calculated theoretically using bulk and apparent densities were given in Table 3.14.

Table 3.14 Internal and bulk porosity values of corn samples dried using different methods

Sample	Internal Porosity	Bulk Porosity
Fresh	0.09	0.36
Open sun dried	0.24	0.50
Solar-spouted dried	0.15	0.41

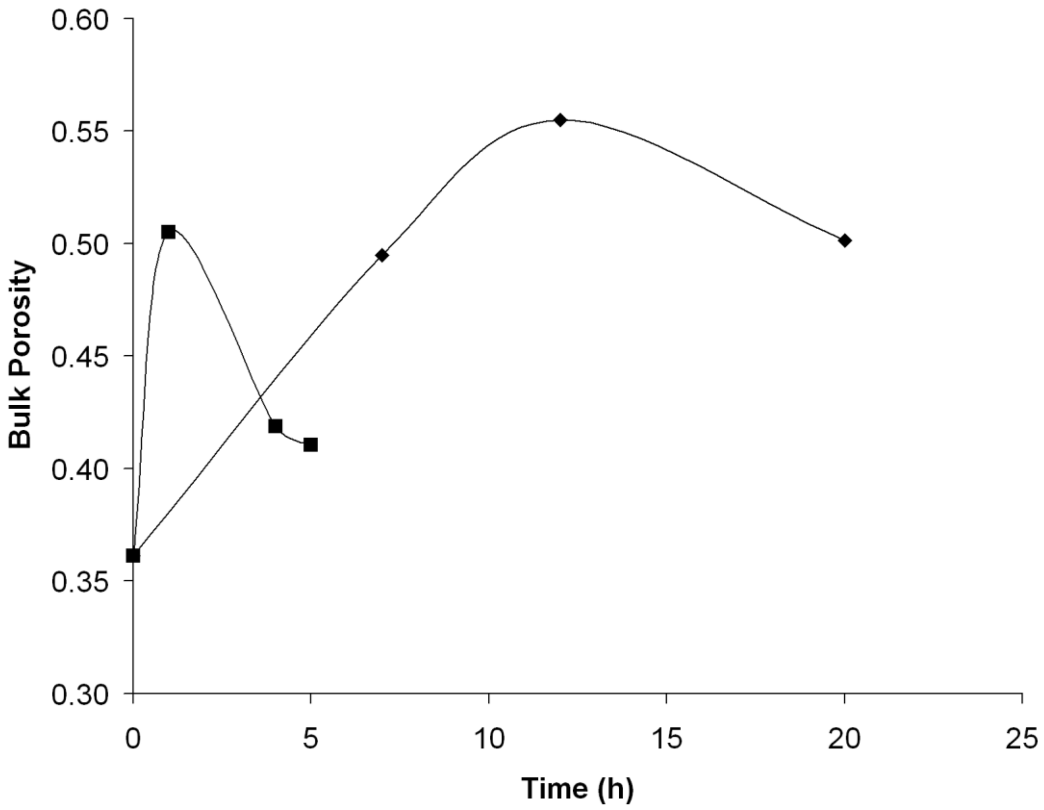

Figure 3.24 Variation of bulk porosity of corn during drying
(♦: open sun ■: solar-spouted bed)

As it is obviously seen from the table, internal and bulk porosities increased as corn particles dried in both open sun and solar-spouted bed drying. When two drying methods were compared, this increase was more for open sun drying. This may be due to the longer drying time of open sun drying.

As it was discussed before for the parboiled wheat, formation of the pores during drying is categorized into two groups as one with an inversion point and another without an inversion point. Increase or decrease in the porosity can be observed accordingly with moisture content (Rahman, 2003).

As it can be seen from the Figure 3.24, porosity change of corn for both drying methods was consistent with the theory for the formation of the pores with an inversion point; it firstly increased at a critical point and then decreased. The difference of porosities between the open sun and solar-spouted bed dried corn may be explained by the difference in the drying rate of two methods. That is, after the inversion point which was near values for both methods, porosity decrease was more rapid for solar-spouted bed due to higher drying rate.

3.3.4.6 Microstructural Analysis

Scanning Electron Microscopy (SEM) images of corn particles before drying, and after drying under open sun and with solar-spouted bed dryer was given in Figure 3.25. Images of the corn samples taken interrupting the drying process nearly at half were also shown in order to illustrate the change in the microstructure during drying. The SEM images of all corn samples were taken at X500 magnification.

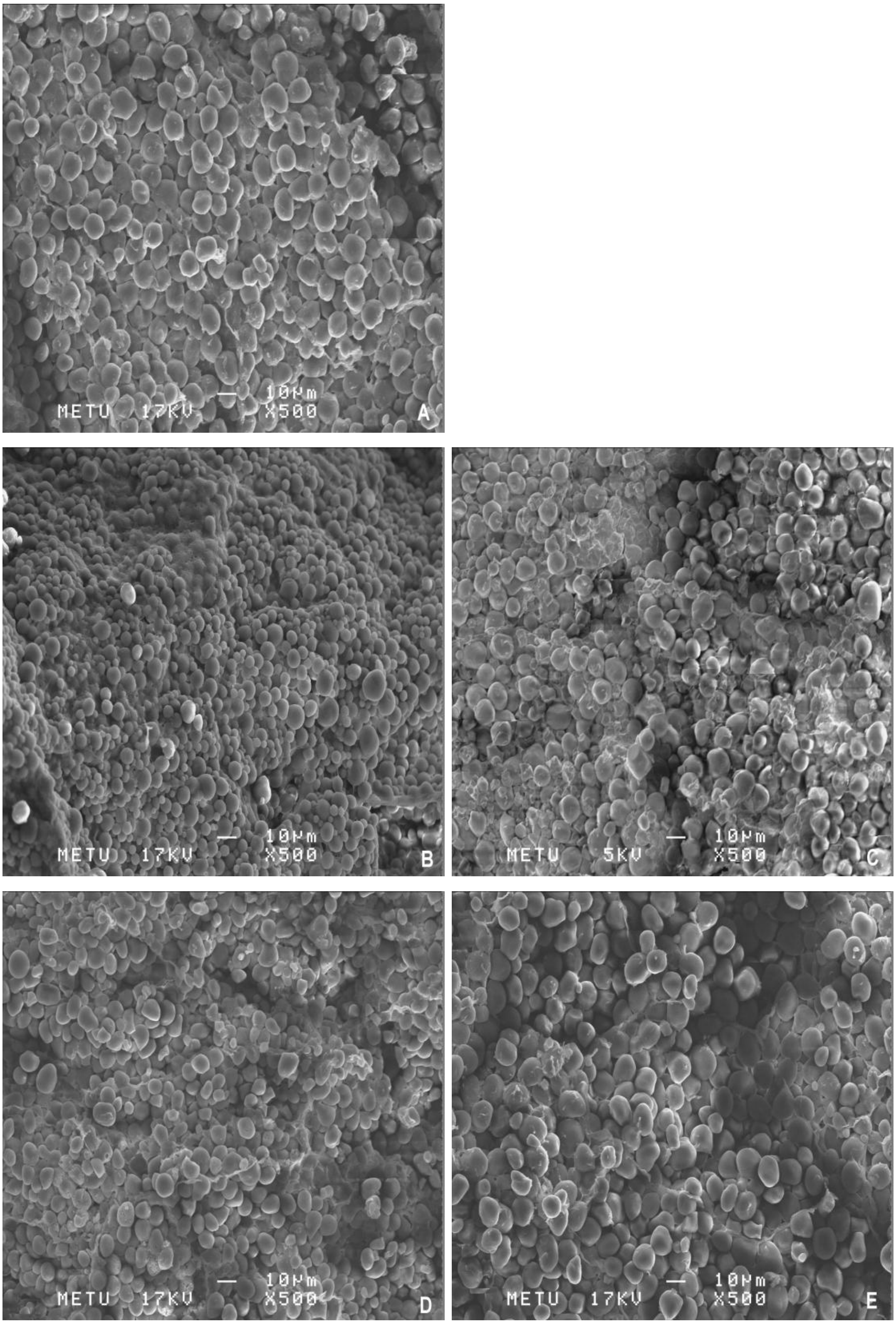

Figure 3.25 SEM images of corn (**A**: fresh, t=0; **B**: open sun dried, t=8h; **C**: open sun dried, t=14h; **D**: solar-spouted dried, t=2h; **E**: solar-spouted dried, t=5h)

When the image of the fresh corn was considered, starch granules that were well integrated can easily be observed. Corn is a good source of starch. Kernels contain about 70-72% starch in dry basis (Smith et. al.,2004).

Ratnayake and Jackson (2006) in their study on gelatinization of corn starch observed that during the heating of corn in water, starch granules were not disintegrated up to 50ºC. In addition, disruption of starch molecules observed at around 70ºC. Since, the drying temperatures do not exceed 32ºC for open sun drying and air used for drying in the solar-spouted bed drying were around 60ºC, starch molecules remained intact as can be seen in all SEM images for corn (Figure 3.25).

Furthermore, in the study of Altay and Gunasekaran (2006), the images of corn starch dried at 20 and 100°C and waxy corn starch dried at 70 and 100°C were observed and important morphological changes were not reported except the wrinkled surfaces of the starch granules due to shrinkage. For all images after drying, starch granules seemed to keep their structure (Figure 3.25, C). Starch granules of solar-spouted bed dried corn seemed more likely to the ones of the fresh corn. Porosity change can not be clearly observed for the intermediate product of open sun drying. It seemed more like the fresh corn and it may be due to moisture content of the sample which was still high. In general for both drying methods, porosity was observed to increase when compared with SEM image of fresh corn. However, it was not so clear due to the high starch content of the corn particles.

3.3.4.7 Pore Size Distribution

Using the data obtained from mercury porosimeter experiments cumulative intrusion, pore size distribution and differential pore size distribution curves were prepared (Figure 3.26-3.34).

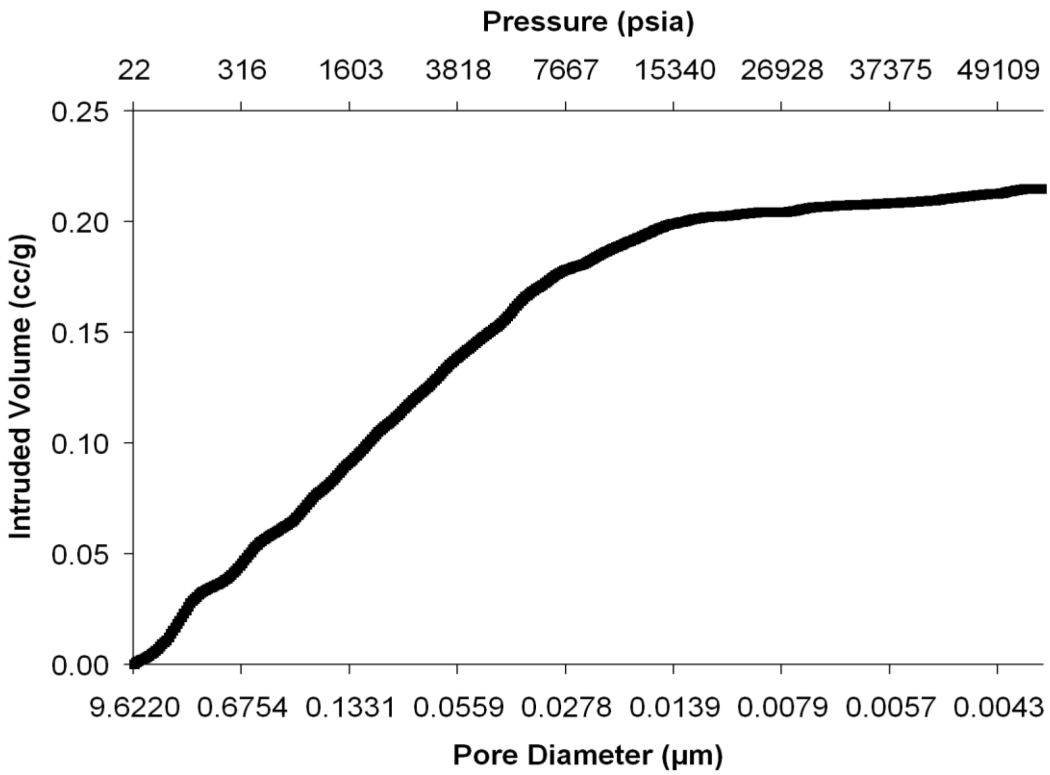

Figure 3.26 Cumulative intrusion curve for fresh corn

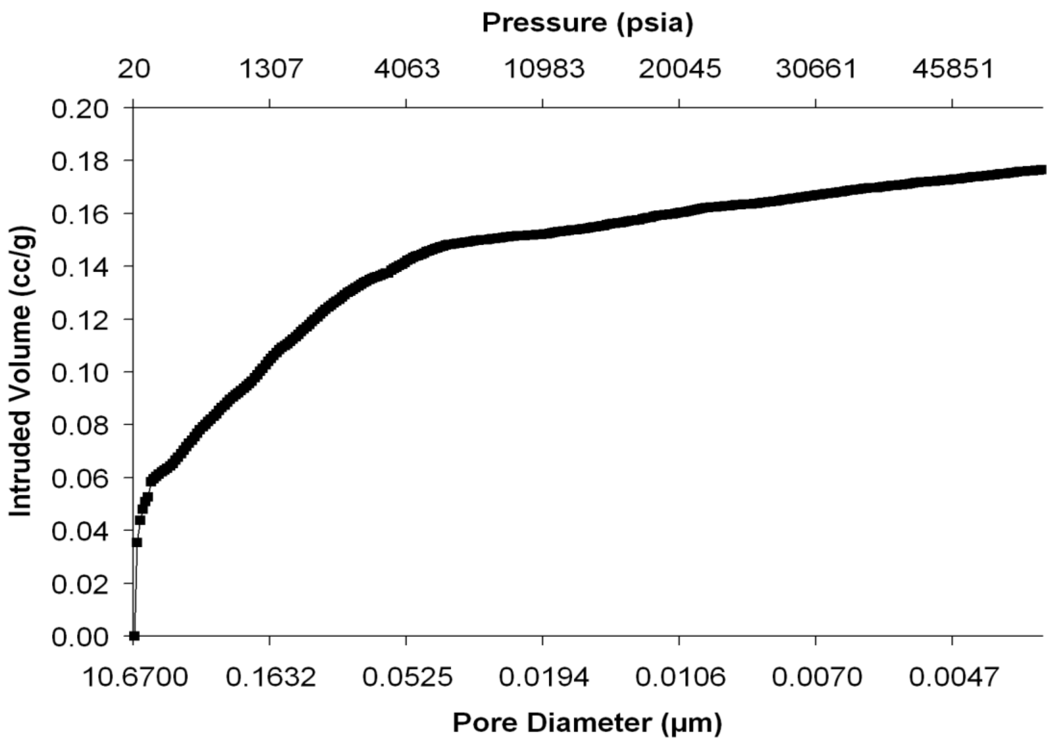

Figure 3.27 Cumulative intrusion curve for open sun dried corn

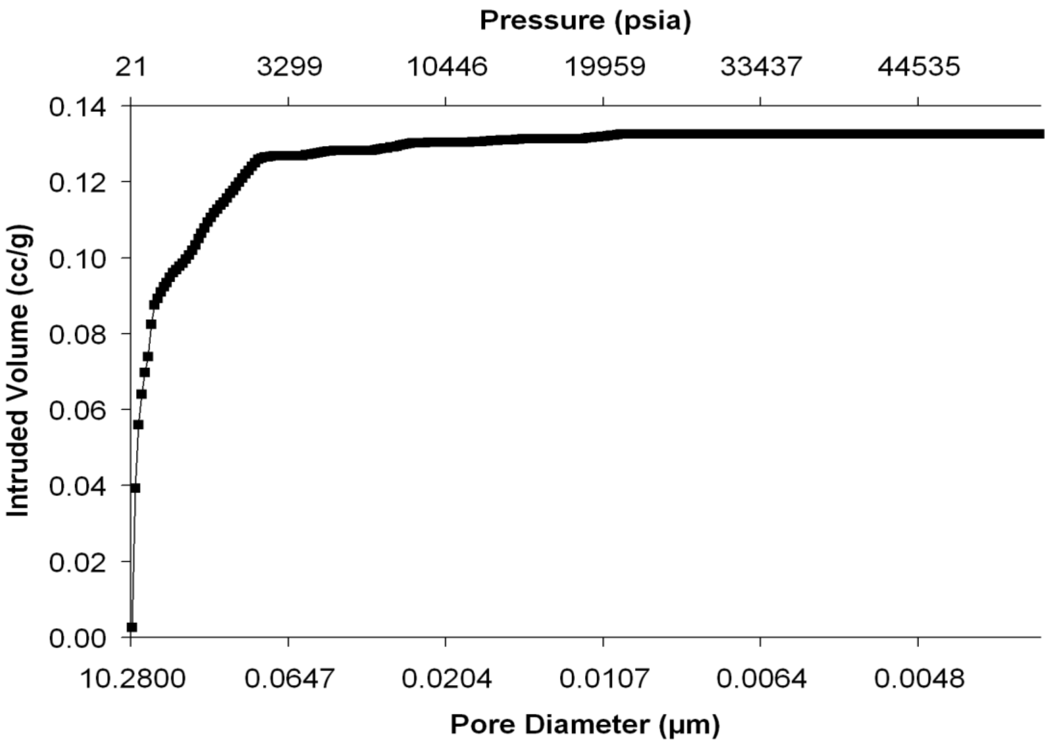

Figure 3.28 Cumulative intrusion curve for solar-spouted bed dried corn

Cumulative intrusion curves are the plots of volume of the mercury intruded versus pore diameter. As it was explained before for parboiled wheat, cumulative intrusion curve gives information for total volume of mercury intruded, pore volume in any range, median pore diameter and also mode pore diameter.

For the corn samples dried using different methods, a sharp increase was determined with different slopes and in different range of pore size (Figure 3.26-28). Sharp increase was steeper for solar spouted bed indicating more same sized pores and more macro pores on the surface. This may be due to shorter drying time of solar-spouted bed drying and therefore less collapse in the structure. For all samples, nearly a vertical line was observed. However, a gradient in slope exists in the curve for fresh corn indicating pore size decreased towards the inside of the kernel (Figure 3.26). Vertical line indicates exactly same sized pores; therefore pores of solar-spouted bed dried corn were more homogenously distributed. Pore size range for all samples was between 10.67-0.004 μm at pressure range of 20-55000 psia. However, threshold pore sizes, that was the pore diameter where the vertical line was observed, changes for the samples and were 0.01, 0.03 and 0.08 μm for fresh, open sun dried and solar-spouted bed dried corn, respectively. In addition, mode pore diameters that can be determined at the steepest slope were 2.2340 and 1.4960 μm, for open sun and solar-spouted dried samples, respectively.

Pore size distribution was calculated using the pore radius and volume by assuming cylindrical pores. Pore size distribution is defined as;

$$D_V = \left(\frac{P}{r}\right) \cdot \left(\frac{dV}{dP}\right)$$

where D_v is the pore size distribution function (cc/g-μm), P is the pressure applied and r is the radius of pores while $\frac{dV}{dP}$ is the first derivative of pressure versus intruded mercury volume data. Pore size distribution curves gives information about the pores mostly at which sizes exist and also height of the peaks indicates the number of the pores are more or less.

When the pore size distribution curves were considered for corn, one sharp peak was observed for all samples (Figure 3.29-3.31). However, the height of the peak and the diameter at which the peak was observed changed according to the sample. For fresh corn, sharp peak was observed at the pore size of 0.0042 μm while height is 8.228 in terms of the unit of D_V. They were 0.0042 and 5.470; 0.0107 and 0.636 for open sun and solar-spouted dried corn, respectively. This showed that smaller sized but much large number of pores formed during the drying under open sun. This was also observed when the porosity values and SEM images were discussed considering two drying methods (Figure 3.25).

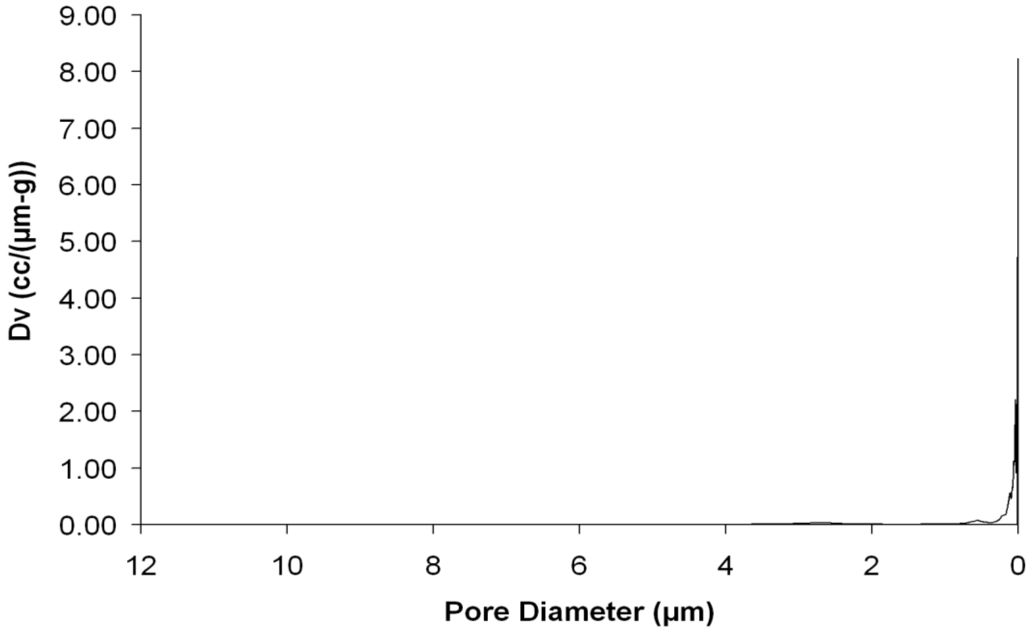

Figure 3.29 Pore size distribution curve for fresh corn

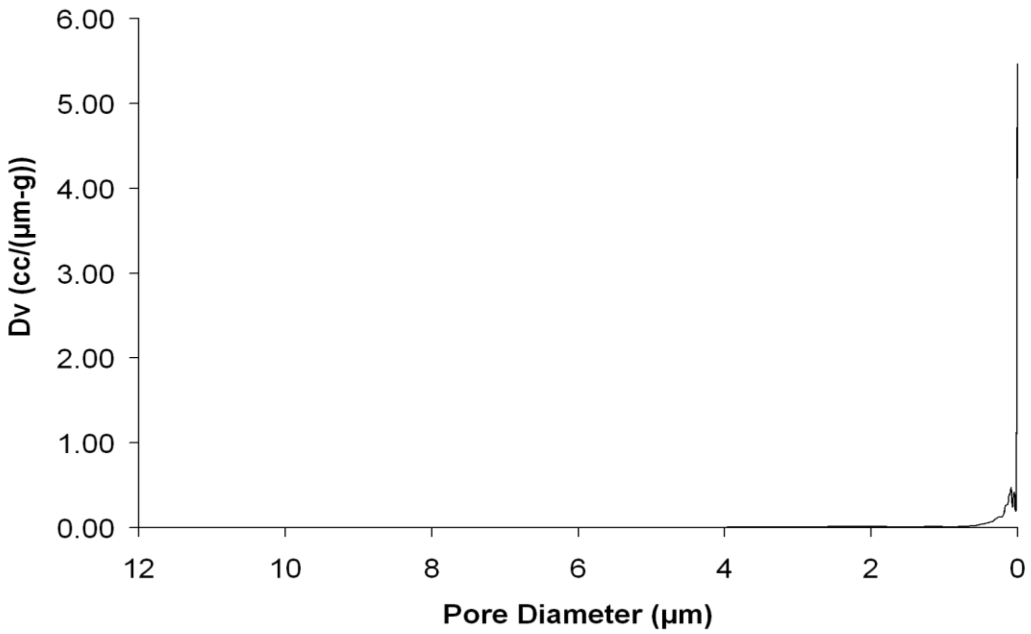

Figure 3.30 Pore size distribution curve for open sun dried corn

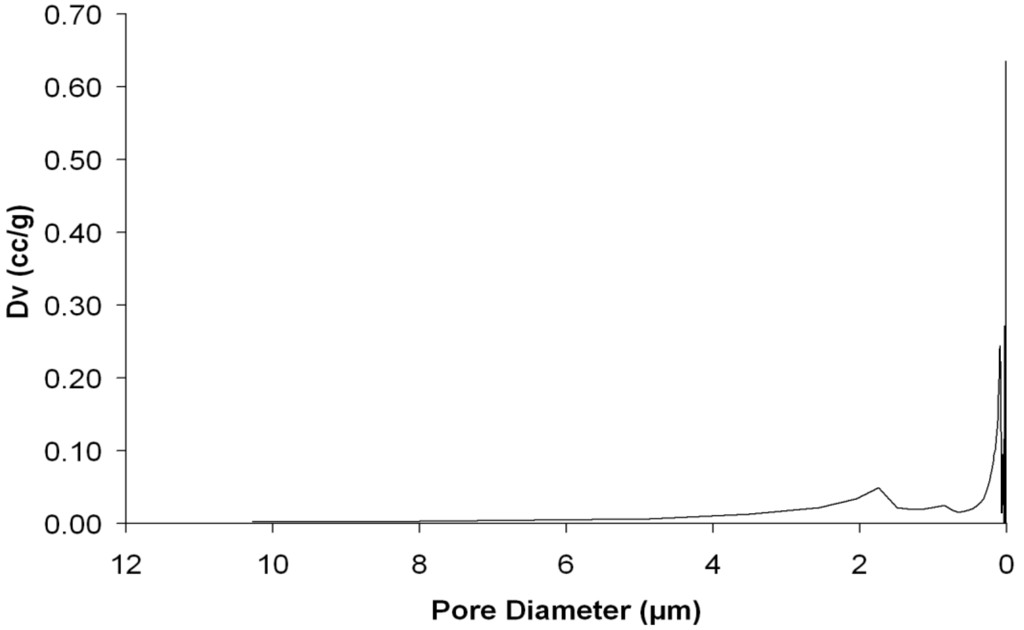

Figure 3.31 Pore size distribution curve for solar-spouted bed dried corn

The differential pore size distribution curve was obtained using the $\frac{dV}{d(\log D)}$ and pore diameter data. This plot shows the pore size distribution of the samples. From the figure for fresh corn, it can be seen that, pore size varied in a great range (Figure 3.32). For the open sun dried corn particles, it was distributed in a large range as for the fresh corn. However distribution of smaller sized pores increased (Figure 3.33). For solar-spouted dried corn particles, pores were distributed more in the larger size range as 10.28 to 0.06 µm (Figure 3.34).

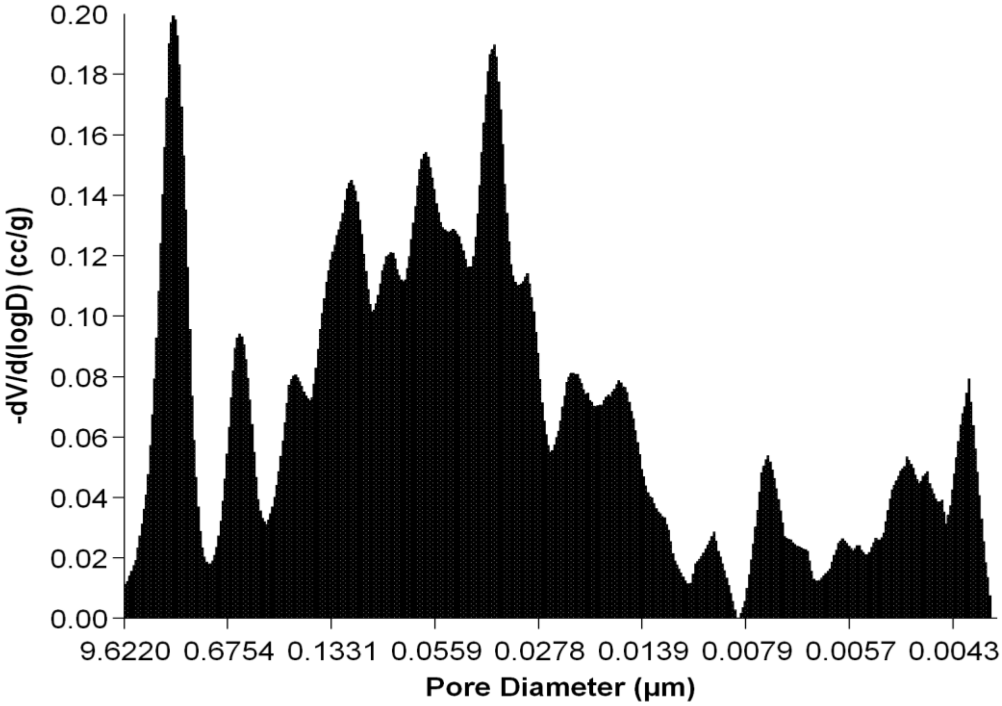

Figure 3.32 Differential pore size distribution curve for fresh corn

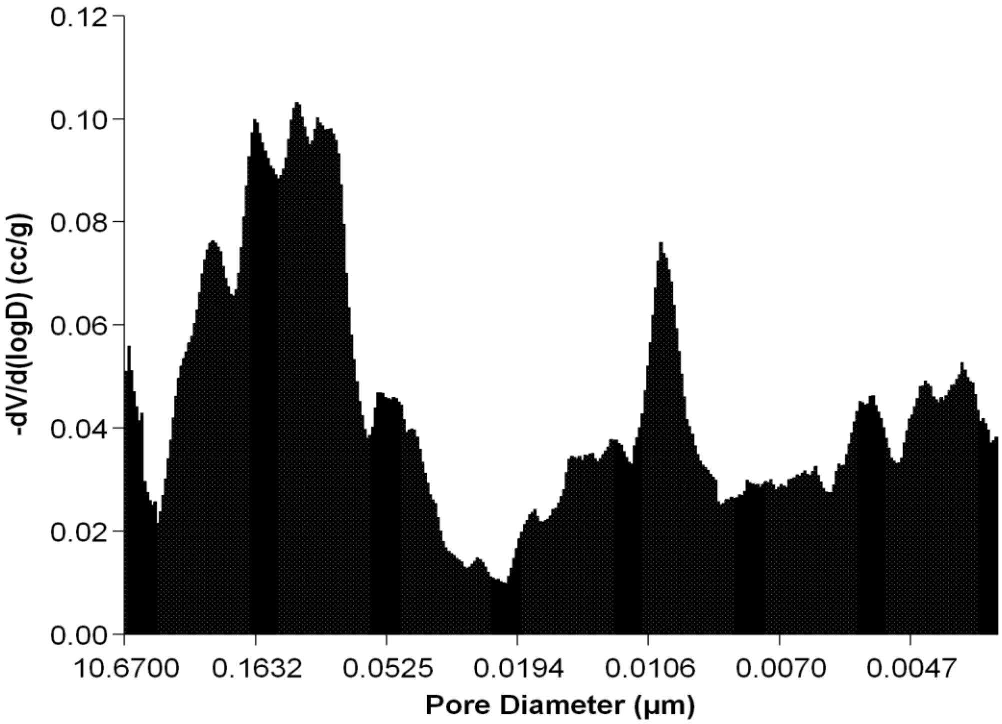

Figure 3.33 Differential pore size distribution curve for open sun dried corn

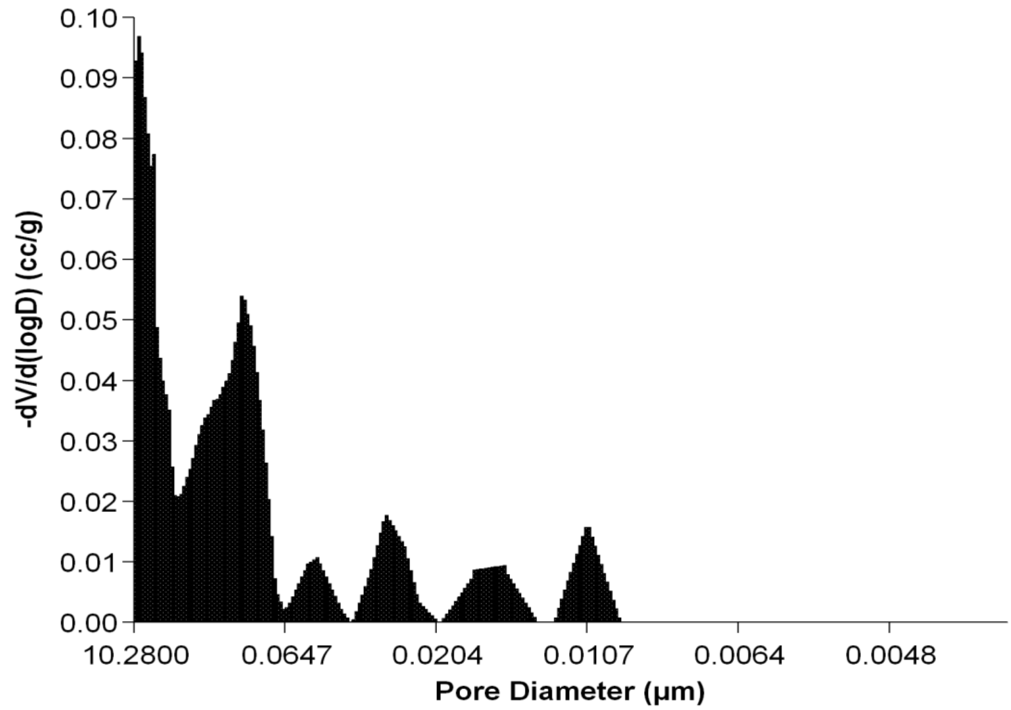

Figure 3.34 Differential pore size distribution curve for solar-spouted bed dried corn

3.3.4.8 Sphericity

Geometric mean, equivalent diameter and arithmetic diameter as well as sphericity values for corn were given in Table 3.15. Statistical analysis in terms of ANOVA tables and Tukey's comparison results were given in Appendix D.5.7-5.13

Table 3.15 Sphericity values of corn samples dried using different methods

Sample	Geometric mean (mm)	Equivalent dia.(mm)	Arithmetic dia.(mm)	Sphericity
Fresh	6.18±0.205[a]	6.50±0.290[a]	6.57±0.292[a]	0.77±0.032[a]
Open sun dried	5.48±0.265[b]	5.83±0.266[b]	5.92±0.248[b]	0.74±0.042[a]
Solar-spouted dried	5.66±0.182[b]	6.03±0.114[b]	6.10±0.128[b]	0.75±0.014[a]

As it can be seen from Table 3.15 the effect of drying on geometric mean, equivalent diameter and arithmetic diameter was concluded to be significant. However, they were found to be not significantly different for open sun and solar-spouted bed drying. The sphericity values obtained were close to the value reported for yellow dent corn by Kalwar et. al. (1991) which was 0.707.

3.3.4.9 Rehydration

Rehydration capacities (RC) for open sun and solar-spouted bed drying of corn were tabulated in Table 3.16.

Table 3.16 Rehydration capacity values of corn samples dried using different methods

Sample	Rehydration capacity (%)
Open sun dried	181.33 ± 21.390
Solar-spouted dried	214.67 ± 17.010

As it can be observed from the table, rehydration capacity for the solar spouted bed dried corn was higher than the one for open sun dried.

In literature, it was found that as temperature of drying increases rehydration ratio for asparagus also increased. It was explained by the fact that as temperature of the drying increased, rate of the drying also increased and resulted in less shrinkage (Jokic at al., 2009). Similarly, it was indicated that the shrimps dried at higher temperatures in jet spouted bed had higher degree of rehydration due to less shrinkage and therefore due to the increased surface area of the samples (Niamnuy et al., 2007).

Drying temperature was higher for solar-spouted bed drying and also it made the drying rate higher as compared to open sun drying. Therefore, less shrinkage regarding the dimension changes was observed for solar-spouted dried corn (Table 3.11). Since the shrinkage was less for solar-spouted bed dried corn, it had higher rehydration capacity.

3.4 Drying of Pea

3.4.1 Minimum Spouting Air Velocity

Figure 3.35, shows the pressure change with increasing and also decreasing air velocity. Pressure drop and superficial air velocity data were given in Appendix C.5 and C.6. As it was explained before for minimum spouting air velocity determination for wheat and corn, points of onset of spouting (point B), minimum spouting (point C) and also collapse of spouting (point D) were observed from the plot.

From the plot of superficial velocity versus pressure drop for pea, point C, which is the minimum spouting point, was observed to be nearly 0.60 m/s. That is; minimum spouting air velocity was chosen as 0.60 m/s and used for all solar-spouted bed experiments of pea.

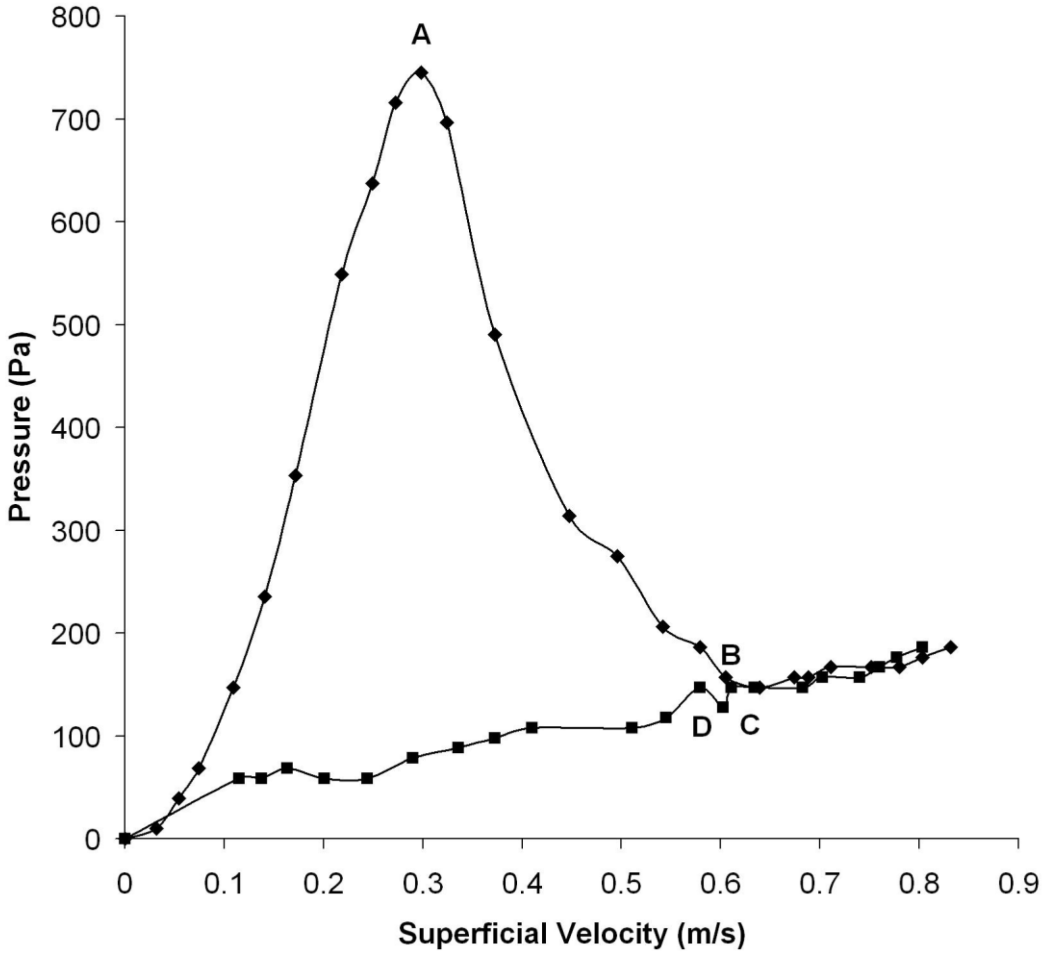

Figure 3.35 Pressure drop versus flow rate curve for minimum spouting velocity determination of pea

A: maximum pressure drop; B: onset of spouting; C: minimum spouting point; D: collapse of spouting (♦: increasing flow; ■: decreasing flow)

3.4.2 Drying Rate Curves

Figure 3.36 shows the variation of moisture content during the drying for open sun and solar-spouted bed drying of pea. When two drying methods were compared, it was observed that moisture content decreased more rapidly for solar-spouted bed drying. This was similar to the drying of corn and parboiled wheat which was explained by higher temperature of drying and also by the mobility of the particles in spouted bed. Time for decreasing moisture contents of pea to the same level was much higher for open sun drying. It took 5 hours for solar-spouted bed drying while it was 18 hours for open sun drying.

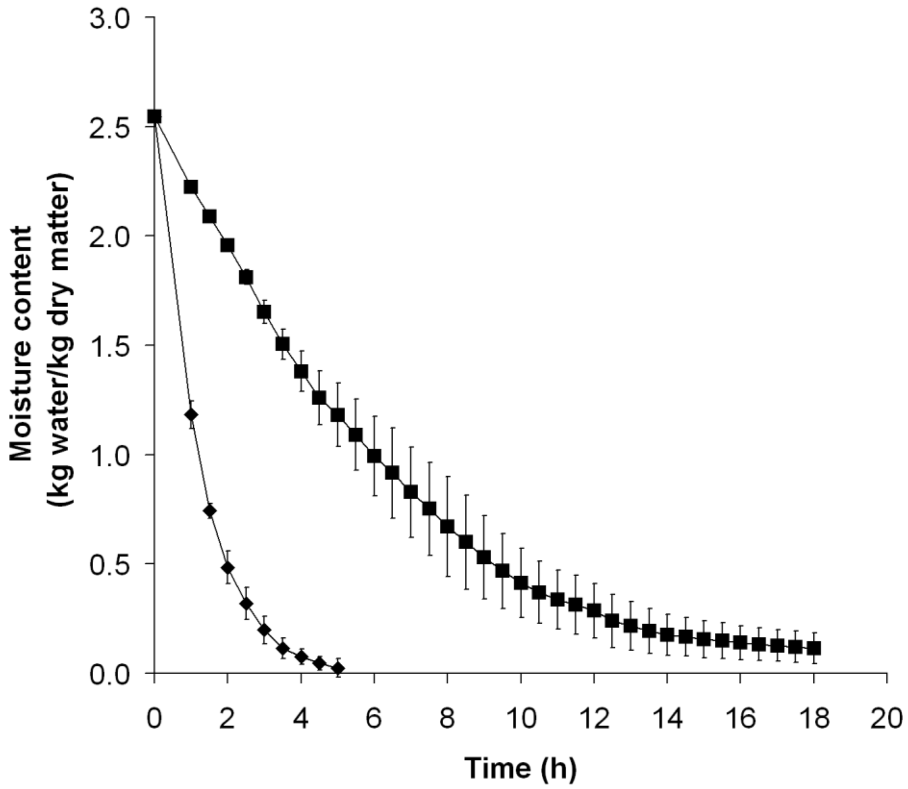

Figure 3.36 Drying curves for pea

(■: open sun ♦: solar-spouted)

The weight data taken during drying experiments and moisture content calculated from weight data were tabulated in Appendix B.6.

The effect of drying methods on the rate of drying was illustrated in Figure 3.37 and 3.38 for open sun and solar-spouted bed drying, respectively. As can be seen from the figures drying rate for solar-spouted bed was high as nearly 3.5-4 times as open sun drying. Rate difference was due to higher temperature of drying and also mobility of particles during spouting as explained before. Furthermore, during both drying methods only falling rate period was observed, indicating that the mechanism in drying was moisture diffusion controlled. Constant rate period occurs due to the wet surface of the sample to be dried. At the falling rate period, sample surface is not wet enough for keeping constant rate and moisture content starts to decrease continuously (Geankoplis, 2003). In the study of drying of green peas using a hot air dryer at different temperatures, Simal et. al. (1996) also did not observed a constant rate drying period. In addition, Akpinar and Bicer (2008) during drying of green pepper under open sun and using solar dryer observed only falling rate.

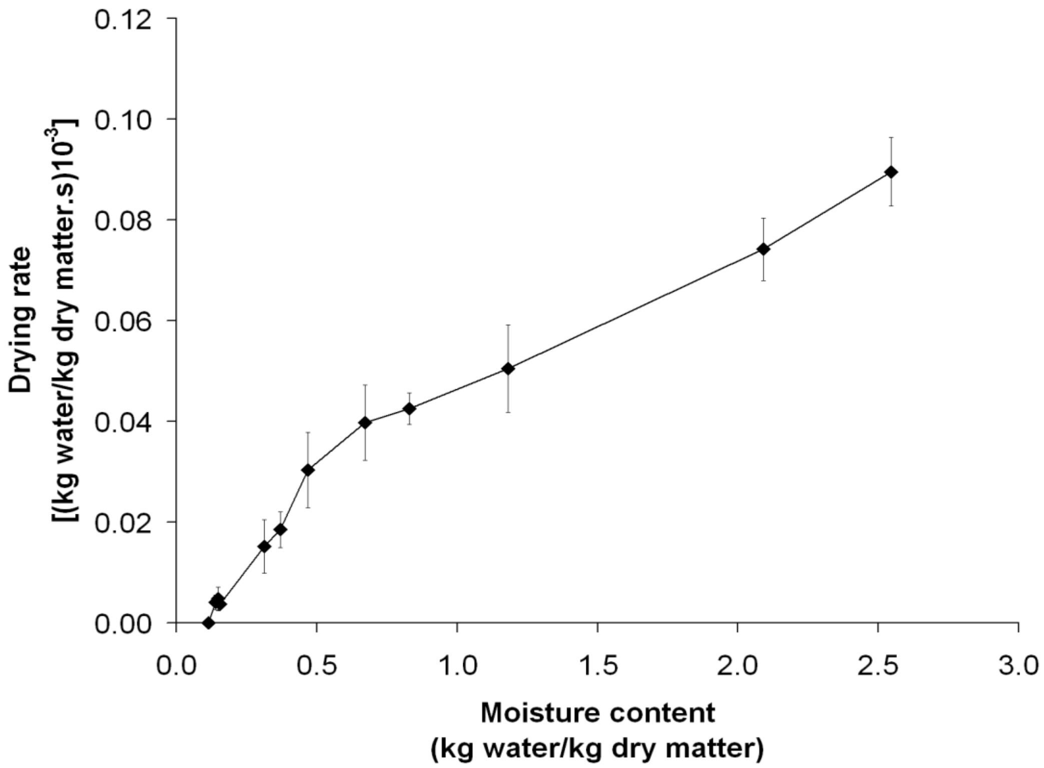

Figure 3.37 Drying rate curve of pea for open sun drying

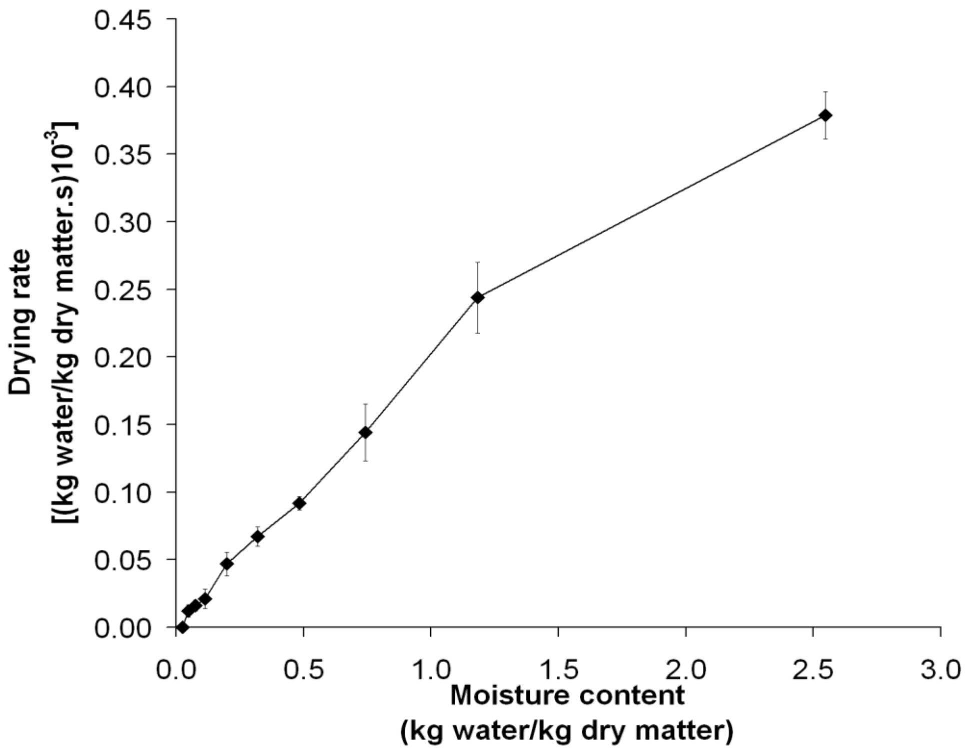

Figure 3.38 Drying rate curve of pea for solar-spouted bed drying

3.4.3 Determination of Effective Diffusivity

Effective diffusivity (D_{eff}) values for pea were determined by using Equation (3.4) and moisture content data. From the plot of dimensionless moisture ratio versus time for pea that was shown in Figure 3.39, D_{eff} values were determined by linear regression. Equilibrium moisture content was taken as zero (Doymaz and Pala, 2003).

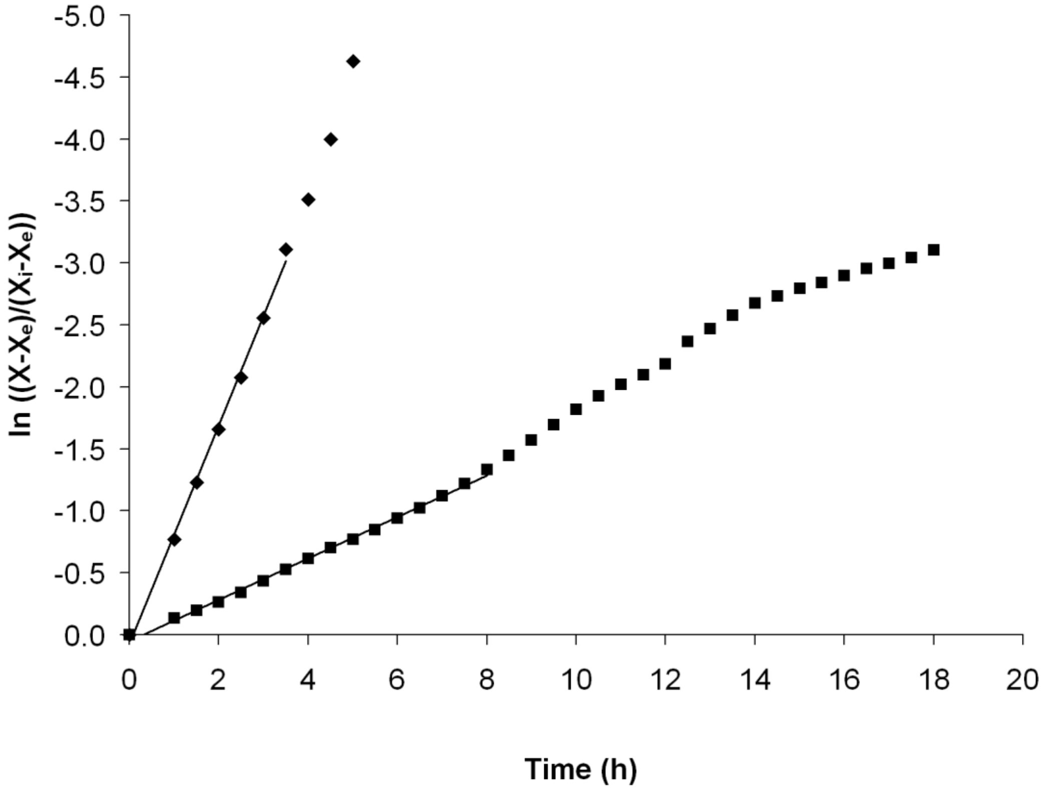

Figure 3.39 Dimensionless moisture content change with time for pea (■: open sun ♦: solar-spouted)

As described for wheat and corn, more than one falling rate periods was also observed for the drying of pea. Simal et al. (1996) also observed more than one falling rate period while drying of green peas.

Effective diffusivity values as well as Fourier number in order the check the long drying time assumption were given in Table 3.17.

Table 3.17 Effective diffusivity values of pea for the first falling rate period

Sample	D_{eff}x10^{-10} (m^2/s)	r^2	Fo
Open sun dried	0.65	0.9968	0.14
Solar-spouted dried	3.45	0.9969	0.31

Effective diffusivities were found as 0.65 and 3.45 x 10^{-10} m^2/s for open sun and solar-spouted dried pea, respectively. Madamba et. al., (1996) observed the effective diffusivities for the drying of food products and found to be in the range of 10^{-9} and 10^{-11} m^2/s. In addition, Jadhav et. al. (2010) determined the effective diffusivities for drying of green pea using different methods in the range of 0.41 x 10^{-10} and 3.03 x 10^{-10} m^2/s which were approximate values found for this study.

By determining the effective diffusivity for two drying methods, equations relating moisture content and time can be written as follows:

$\ln\left(\frac{X}{X_0}\right) = 0.0511 - 0.1671t$; r^2=0.9968 for open sun drying of pea

$\ln\left(\frac{X}{X_0}\right) = 0.0734 - 0.8826t$; r^2=0.9969 for solar-spouted bed drying of pea

3.4.4 Quality Parameters of Pea After Drying

3.4.4.1 Color

Color of fresh and dried peas were investigated in terms of CIE L^* , a*, and b* color values. The effect of drying methods on color values for pea was shown in Table 3.18. In addition, statistics for L*a*b* values in terms of ANOVA tables and Tukey's comparison results were given in Appendix D.1.10-1.14.

Table 3.18 Color values of pea dried using different methods

Sample	L*	a*	b*
Fresh	36.1 ± 3.29^a	1.3 ± 0.30^b	33.3 ± 1.53^a
Open sun dried	35.5 ± 0.69^a	5.4 ± 0.73^a	26.8 ± 0.48^b
Solar-spouted dried	35.9 ± 0.73^a	4.3 ± 0.55^a	27.2 ± 1.74^b

From the color analysis it was observed that b* value decreased while a* value increased significantly during drying. However, for different drying methods, these values were not different statistically.

Vadivambal and Jayas (2007), in their study a* and b* values of heat treated peas could either decrease or increase according to the heat treatment. According to a* values, it can also be said that, the one with the lowest a* value is the most green one that was obtained for fresh pea. Increase of a* values (Table 3.18) after drying of peas in this study may be due to the exposing of the samples to heat during drying and also direct exposing of open sun dried peas to sun light.

3.4.4.2 Shrinkage

For the shrinkage analysis of pea, which can be considered as a sphere, diameter of the pea particles was measured and converted into shrinkage values by using the diameters. Results were given in Table 3.19. Statistical analysis in terms of ANOVA tables and Tukey's comparison results were given in Appendix D.2.5 and D.2.6.

Table 3.19 Diameter and shrinkage values of pea for different drying methods

Sample	Diameter (mm)	Shrinkage (%)
Fresh	7.45 ± 0.47^{a}	
Open sun dried	5.82 ± 0.71^{c}	50.24 ± 16.16^{a}
Solar-spouted dried	6.53 ± 0.43^{b}	31.90 ± 11.29^{b}

Decline in diameters of peas for both drying methods can be clearly seen from Table 3.19. Besides, decrease was more for open sun dried pea. Statistically, drying was found to be effective on diameter and also values were significantly different from each other. From the diameter data, volumes of the pea particles were calculated and they were converted to shrinkage data. Since it was related to diameter, shrinkage in open sun dried pea samples was determined to be higher. As for the case of diameters, shrinkage of the peas dried by two methods was significantly different. From the pictures of dried pea samples in Appendix A.3 difference in the dimensions can also be clearly identified. The difference in the shrinkage for two drying methods was probably due to the rate of drying which was higher for solar-spouted bed drying. In the study of drying of carrots in fluidized bed, it was stated that shrinkage was inversely proportional with the drying rate (Hatamipour and Mowla, 2002). In addition, more shrinkage in open sun dried peas resulted in higher apparent densities (Table 3.21).

3.4.4.3 Bulk Density

Bulk density values for the fresh pea and pea dried using different methods were given in Table 3.20. In addition, statistical data for bulk density values in terms of ANOVA tables and Tukey's comparison test results were given in Appendix D.3.5 and D.3.6.

Table 3.20 Bulk density values of pea samples dried using different methods

Sample	**Bulk density (kg/m^3)**
Fresh	385.0 ± 0.00^{b}
Open sun dried	610.0 ± 13.23^{a}
Solar-spouted dried	407.5 ± 17.08^{b}

Bulk density analysis of pea showed that, for both open sun and solar-spouted bed dried pea, bulk density increased when compared with their initial values. Statistically, bulk density of fresh and solar-spouted bed dried pea particles were found to be similar showing a better quality for solar-spouted bed dried pea. By drying under open sun, due to the lower drying rate, more shrinkage was observed. Therefore, bulk density of open sun dried peas was higher than that of solar-spouted dried ones due to the considerable difference in the shrinkage percents (Table 3.19) of the samples.

3.4.4.4 Apparent Density

Apparent density values for the pea were given in Table 3.21 considering the drying methods. In addition, statistical data for apparent density values in terms of ANOVA tables and Tukey's comparison test results were given in Appendix D.4.3 and D.4.4.

Table 3.21 Apparent density values of pea sample dried using different methods

Sample	Apparent density (kg/m^3)
Fresh	750.0 ± 0.00^b
Open sun dried	1023.8 ± 41.20^a
Solar-spouted dried	754.8 ± 9.60^b

As illustrated in the table for apparent densities, the values increased significantly during open sun drying. Statistically, the apparent density values of peas dried in open sun and solar-spouted bed were found to be significantly different. The apparent density value for solar-spouted bed dried pea was similar to the one of fresh pea indicating the change was not significant during drying in terms of apparent density. In addition, apparent density of solar-spouted bed dried pea was less than open sun dried, which was also consisted with shrinkage data (Table 3.19).

It was emphasized that drying method was significantly effective on apparent density that can be higher or lower when compared with the initial value, due to the shrinkage or the development of pores, respectively (Vadivambal and Jayas, 2007). Increase in apparent density values for pea during drying can be related to the shrinkage.

3.4.4.5 Bulk and Internal Porosity

Internal and bulk porosity values of pea for different drying methods were given in Table 3.22.

As it can be seen from the table, internal and bulk porosities decreased as pea particles dried with both open sun and solar-spouted bed. When two drying methods were compared, it was seen that decrease in internal and bulk porosity was less for solar-spouted bed drying. This may be due to higher drying rate and temperature for solar-spouted bed. The difference of porosities between the open sun and solar-spouted bed dried pea may be explained by the shrinkage of the samples during drying. Shrinkage was more for open sun dried pea resulting lower porosity values (Table 3.19).

Table 3.22 Internal and bulk porosity values of pea samples dried using different methods

Sample	Internal Porosity	Bulk Porosity
Fresh	0.46	0.49
Open sun dried	0.24	0.40
Solar-spouted dried	0.32	0.46

3.4.4.6 Microstructural Analysis

Scanning Electron Microscopy (SEM) images of pea particles before and after drying under open sun and with solar-spouted bed dryer were given in Figure 3.40. Images of the pea particles taken interrupting the drying process nearly at half, were also shown in order to illustrate the change in the microstructure during drying. The SEM images of all pea samples were taken at X250 magnification.

When the image for the fresh pea was observed, bigger pores and higher porosity of the sample can easily be seen. When the images of intermediate and final products were compared first decrease and then increase was observed clearly for both drying methods. In the image of the final product of pea dried under open sun less and smaller pores were observed while they seem more and bigger for solar-spouted bed dried pea. Higher porosity values of solar-spouted dried pea than open sun dried ones (Table 3.22) explain the difference in the images for final products.

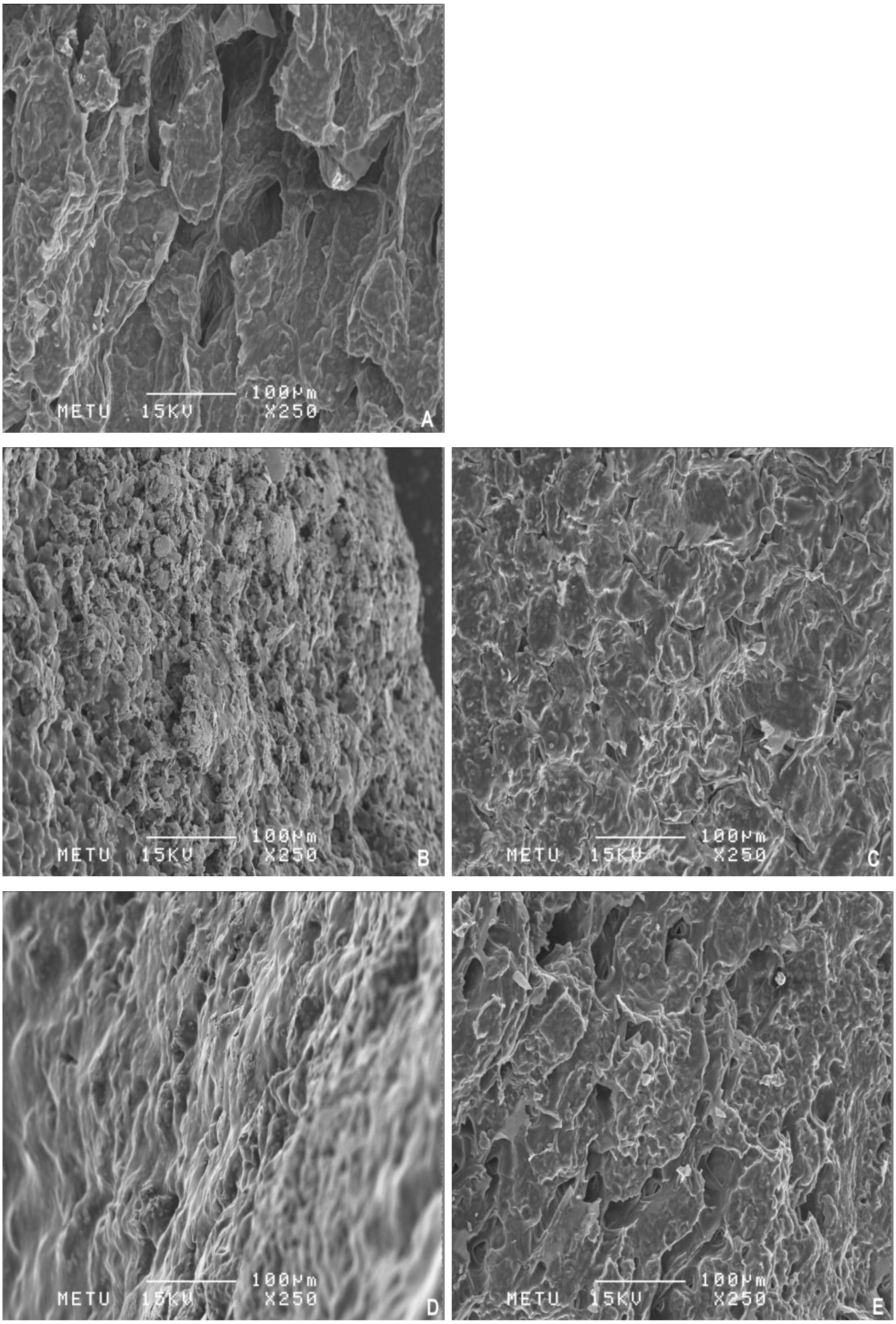

Figure 3.40 SEM images of pea (**A**: fresh, t=0; **B**: open sun dried, t=8h; **C**: open sun dried, t=14h; **D**: solar-spouted dried, t=2h; **E**: solar-spouted dried, t=5h)

3.4.4.7 Pore Size Distribution

The data obtained from mercury porosimeter experiments, were converted into cumulative intrusion, pore size distribution and differential pore size distribution curves (Figure 3.41-3.49).

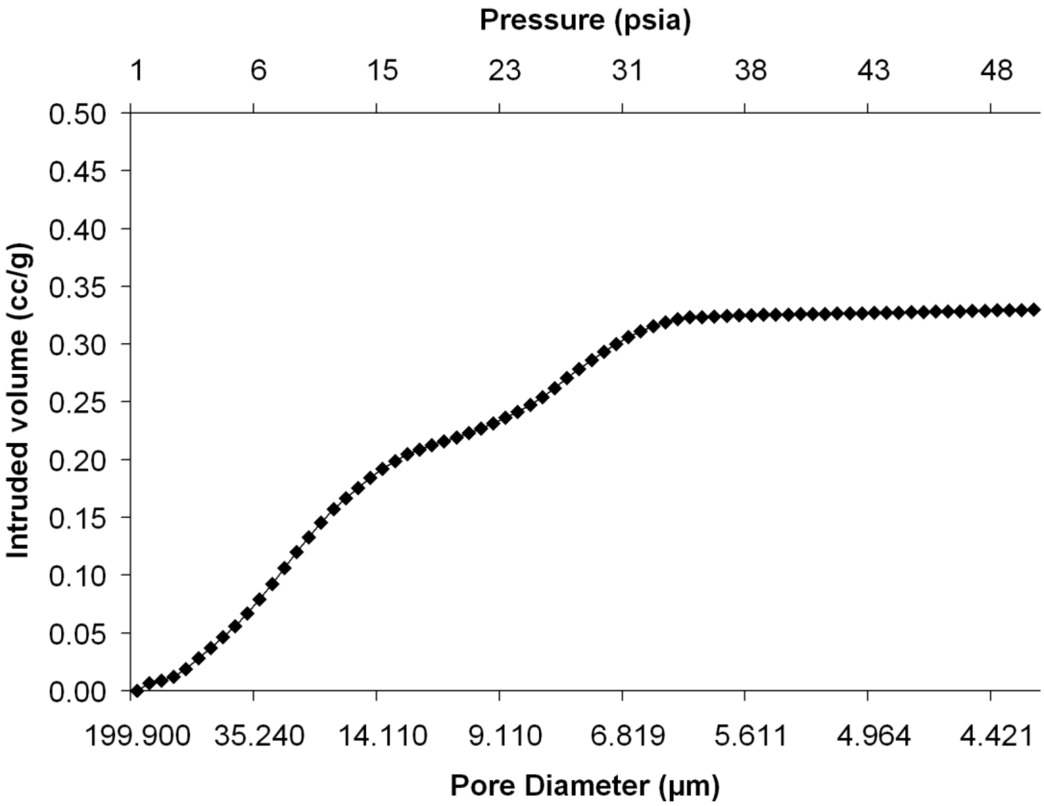

Figure 3.41 Cumulative intrusion curve for fresh pea

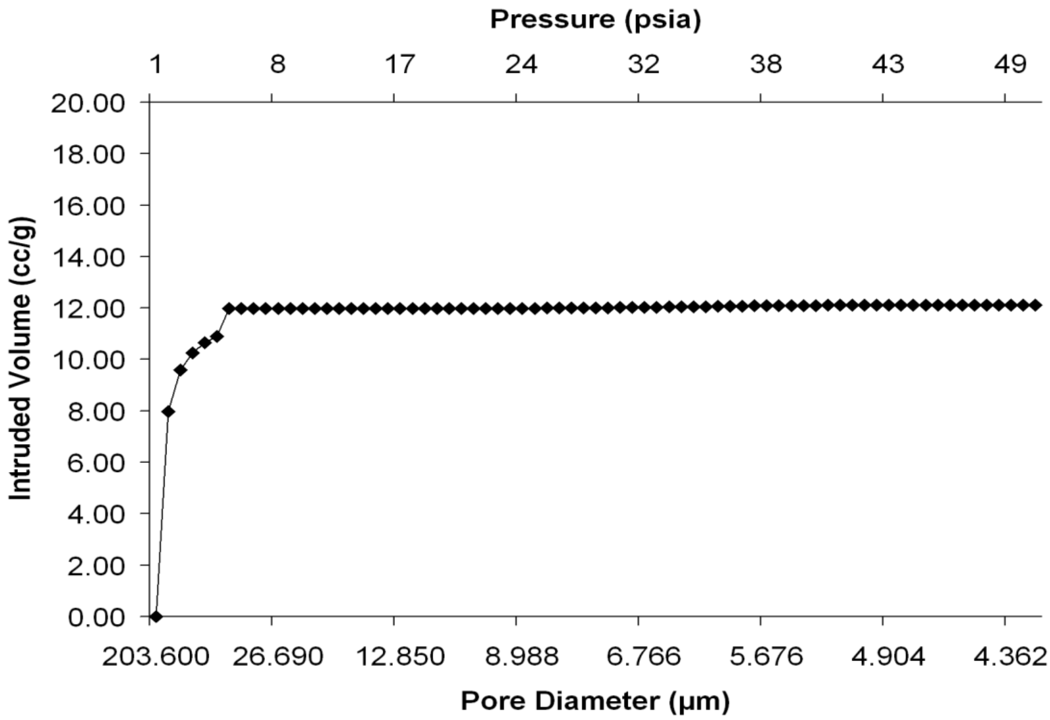

Figure 3.42 Cumulative intrusion curve for open sun dried pea

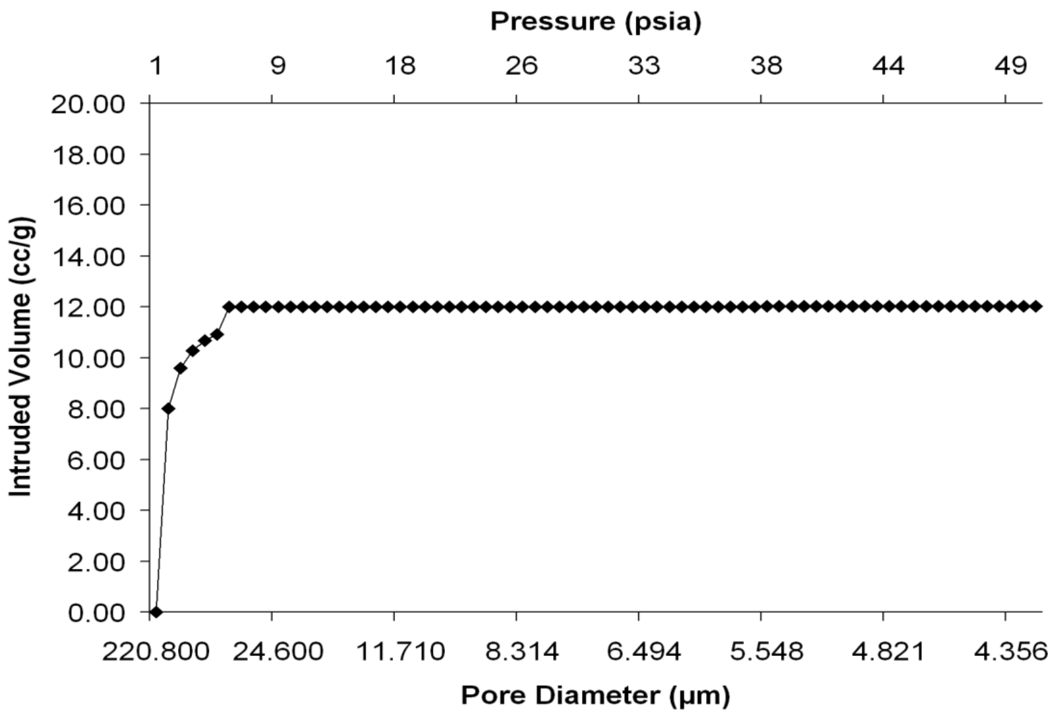

Figure 3.43 Cumulative intrusion curve for solar-spouted bed dried pea

For the dried pea samples with both drying methods, a sharp increase was determined with different slopes and in different range of pore size (Figure 3.42 and 3.43. For all samples, a vertical line was observed. However, a gradient in slope exists in the curve for fresh pea (Figure 3.41) indicating decrease in pore size towards the inside of the kernel. Vertical line indicates exactly same sized pores; therefore pores of solar-spouted bed dried pea were more homogenously distributed. Pore size range was 199.90- 4.29 μm for fresh pea, 203.60-4.28 μm for open sun dried pea and 220.8-4.27 μm for solar-spouted bed dried pea at pressure range of 1-50 psia. However, threshold pore sizes, that was the pore diameter where the vertical line was observed, changes for the samples and were 6.11, 45.77 and 43.32 μm for fresh, open sun dried and solar-spouted bed dried pea, respectively. Moreover, mode pore diameters for open sun and solar-spouted dried samples, that can be determined at the steepest slope, were 45.77 and 43.32 μm, respectively.

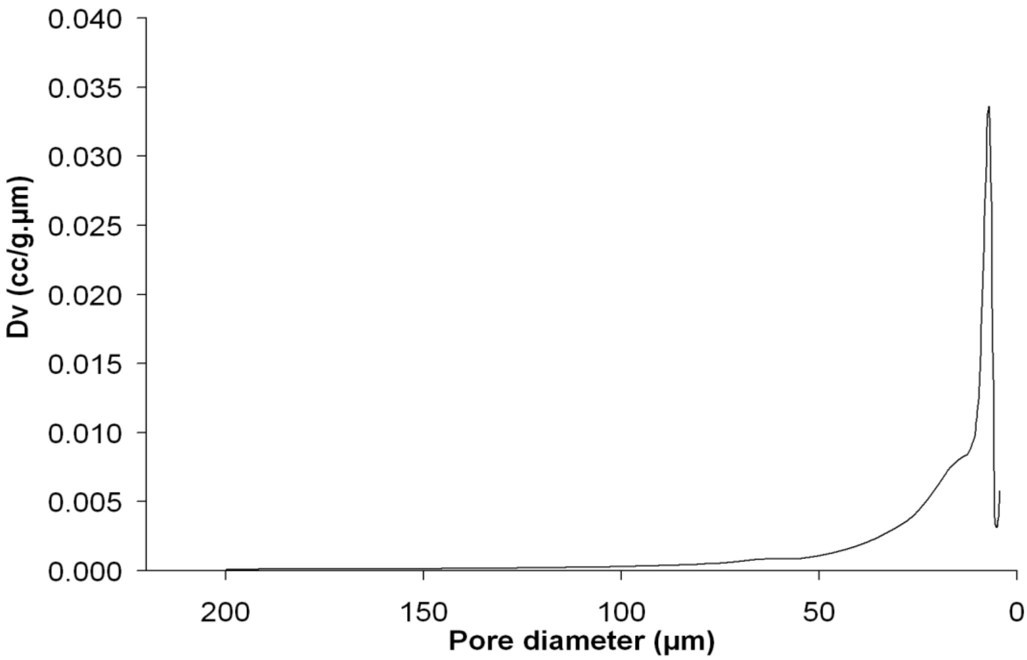

Figure 3.44 Pore size distribution curve for fresh pea

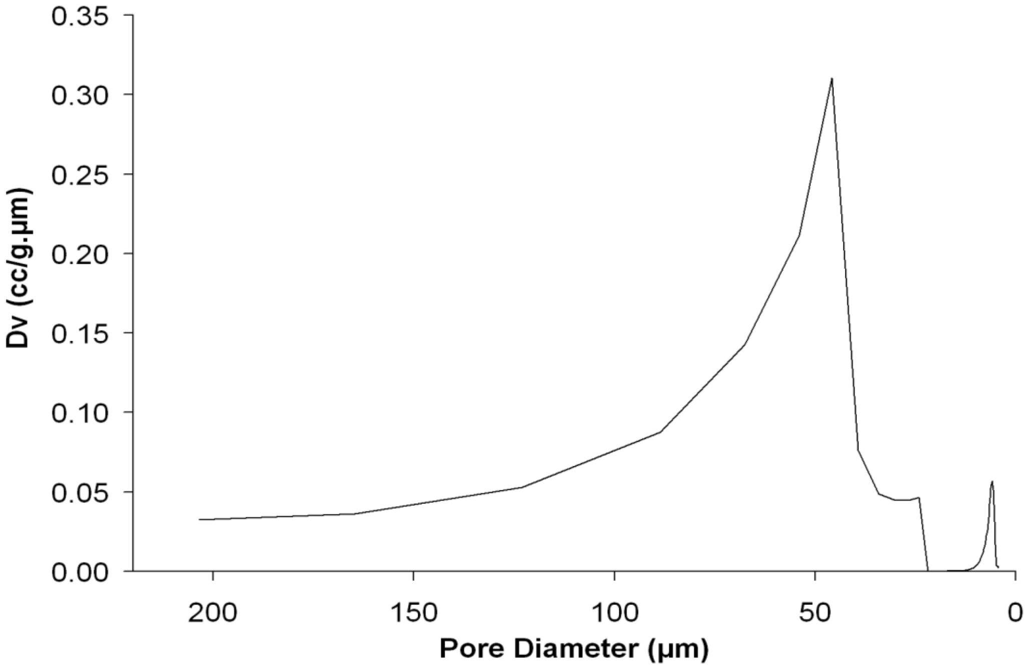

Figure 3.45 Pore size distribution curve for open sun dried pea

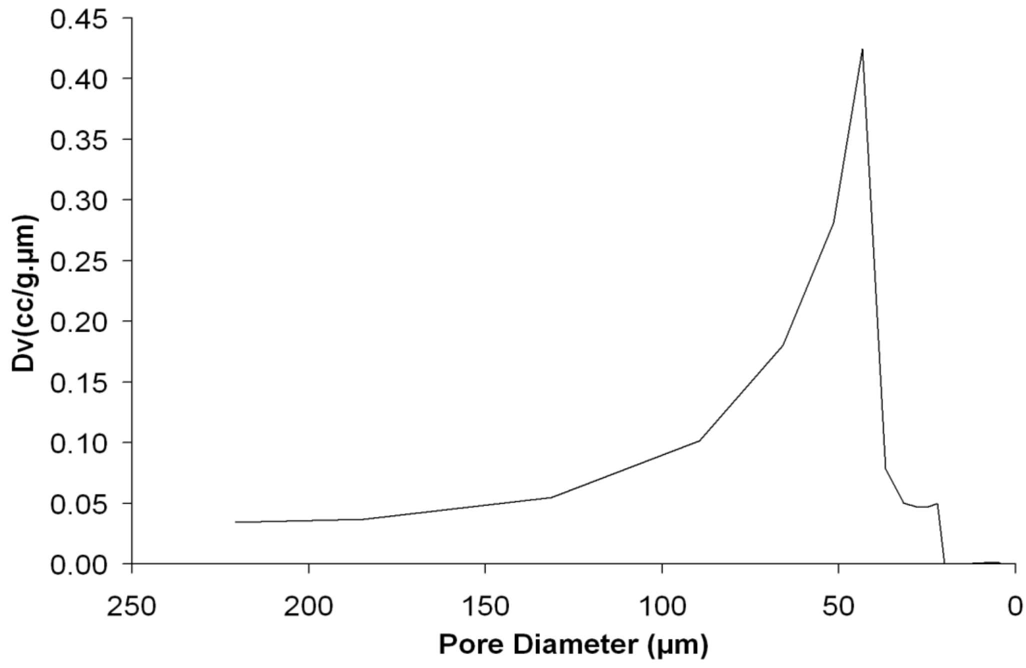

Figure 3.46 Pore size distribution curve for solar-spouted bed dried pea

As it was indicated for wheat and corn, pore size distribution curves are considered in terms of number, size and shape of the peaks. Sharp peaks is the indication of the pores mostly exist at that size range while wider peaks shows larger pores are followed by smaller sized ones (Rahman et. al, 2005).

When the pore size distribution curves were considered for pea, a wider peak as compared to the peaks observed in dried parboiled wheat and corn was observed for all samples indicating larger pores existed and they were followed by smaller sized pores (Figure 3.44-3.46). However, the height of the peak and the diameter at which the peak was observed changed according to the sample. For fresh pea, peak was observed at the pore size of 6.99 μm while height is 0.032 in terms of the unit of D_v. They were 45.77 and 0.31; 43.32 and 0.42 for open sun and solar-spouted dried pea, respectively. This showed that larger sized pores in small number formed during the drying under open sun. This result was parallel with the porosity values (Table 3.22) and SEM images (Figure 3.40) of the peas dried under open sun.

The differential pore size distribution curve shows the pore size distribution of the samples. From the Figure 3.47 for fresh pea it can be seen that, pore size changed in a great range as 199.9 to 5 μm. For the open sun dried and solar-spouted dried pea particles it was distributed in the larger pore size side of the graph. For open sun dried pea it was between 203.6 and 24 μm and for solar-spouted bed it was between 220.8 and 22 μm (Figure 3.48 and 3.49). In addition, a very small part of the pores were distributed in the range of 8 and 5 μm for open sun dried pea.

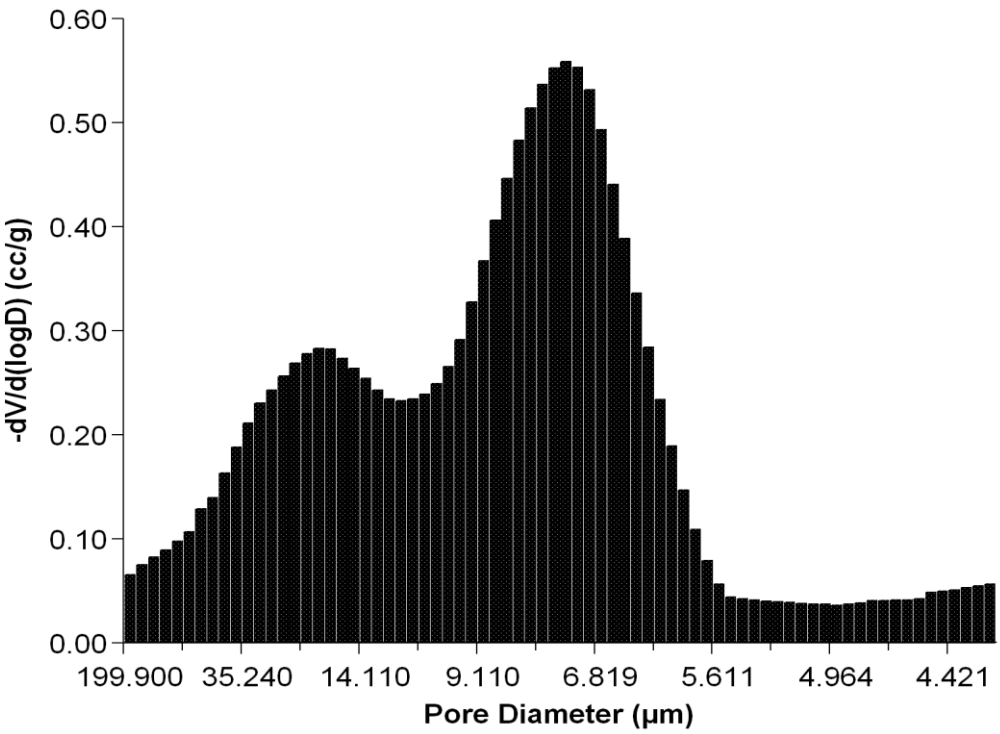

Figure 3.47 Differential pore size distribution curve for fresh pea

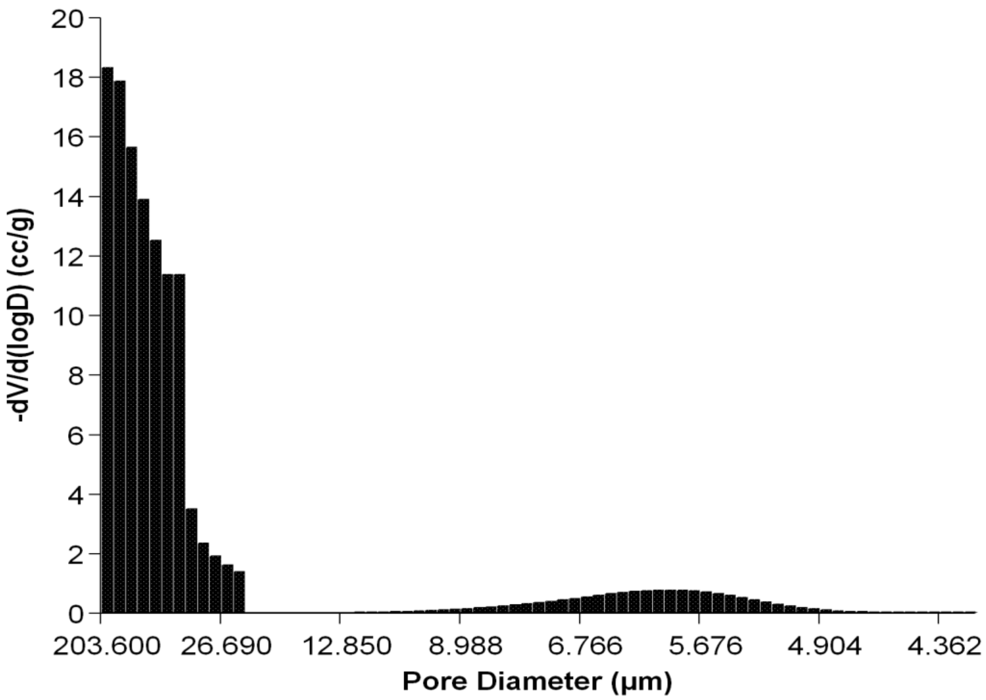

Figure 3.48 Differential pore size distribution curve for open sun dried pea

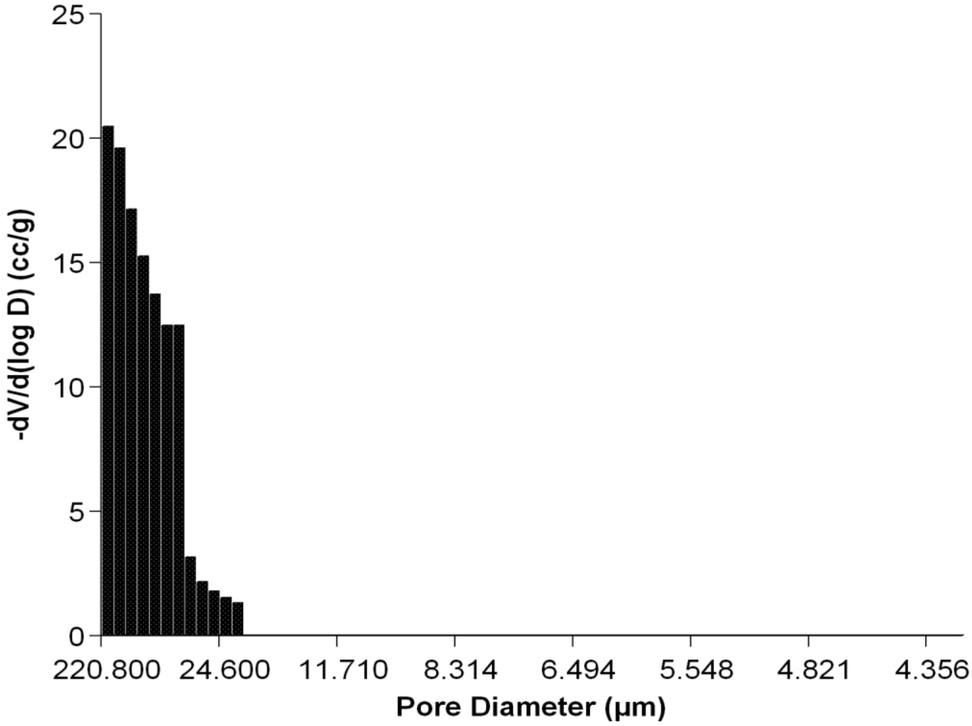

Figure 3.49 Differential pore size distribution curve for solar-spouted bed dried pea

3.4.4.8 Rehydration

Rehydration capacity (RC) for open sun and solar-spouted bed dried pea were given in Table 3.23.

Table 3.23 Rehydration capacity values of pea samples dried using different methods

Sample	**Rehydration capacity (%)**
Open sun dried	290.0 ± 4.00
Solar-spouted dried	306.5 ± 22.83

Similar to the results obtained for wheat and corn, rehydration capacity for the solar spouted bed dried pea was higher than the one for open sun dried.

Jadhav et al. (2010) observed that, open sun dried peas had the lowest rehydration ratio when compared with other drying methods, that were solar cabinet, fluidized bed and freeze drying. It was related to the highest shrinkage rate of the open sun dried peas.

As discussed before for wheat and corn, since the drying temperature and so drying rate was higher for solar-spouted bed as compared with open sun drying, less shrinkage was observed for solar-spouted dried pea (Table 3.19). That resulted in a higher degree of rehydration.

3.4.4.9 Ascorbic Acid

Ascorbic acid contents of both open sun and solar-spouted bed dried peas were shown in Table 3.24 and ANOVA tables with comparison test results were given in Appendix D.6.1 and D.6.2.

Table 3.24 Ascorbic acid (AA) contents of pea samples dried using different methods

Sample	mg AA/g sample
Open sun dried	0.05 ± 0.016^a
Solar-spouted dried	0.21 ± 0.102^b

Peas are good source of vitamin C and the amount is changing according to varieties. Fresh peas of most varieties contain 25 mg/ 100 g or more ascorbic acid. Vitamin C is highly sensitive to air, heat and light. Great amounts can easily be lost by processing with heat and exposure to light (Arthey and Denis, 1991).

Ascorbic acid contents of peas dried under open sun and using solar spouted bed were significantly different. The amount for the solar-spouted bed dried peas were significantly higher than that of the open sun dried ones showing better quality in terms of ascorbic acid. That is, ascorbic acid of fresh pea was conserved much during drying in solar-spouted bed. Although in solar-spouted bed, peas were exposed to air at higher temperature, loss was less due to shorter drying time and therefore less exposing to air.

CHAPTER 4

CONCLUSION AND RECOMMENDATIONS

For drying of parboiled wheat, corn and pea, drying rates and effective diffusivities were observed to be much higher for drying in solar-spouted bed drier as compared to open sun drying. Therefore, drying time was lower for solar-spouted bed drying to reduce the moisture content to the same level. In addition, only falling rate period was observed in all drying experiments.

For all samples, more shrinkage was observed for open sun dried ones as compared to the ones dried in solar-spouted bed dryer. In addition, cumulative intrusion curves showed that pores were more homogenous for solar-spouted bed dried samples. The visual observations of SEM images were in accordance with the internal porosity results obtained from mercury porosimeter. Moreover, rehydration capacities were higher for solar-spouted bed dried samples.

For parboiled wheat, drying method only affected a* value and it increased for both drying methods. Additionally, it was found that bulk density was also affected by drying method. Bulk and internal porosity of parboiled wheat decreased after drying in both methods. According to pore size distribution curves, larger pores in large number were observed in open sun dried parboiled wheat.

For corn, L* and a* values increased during drying. Method of drying affected the bulk density of samples while it did not change the apparent density. Furthermore, bulk and internal porosities increased for both methods which were more for open sun drying. Pore size distribution curves also showed that pores were small sized but more in number for samples dried under open sun. For the dimensional changes, drying methods were found to be effective on geometric mean, equivalent and arithmetic diameters; however it did not affect sphericity.

For pea, a* value decreased while b* value increased after drying. Apparent and bulk densities tended to increase for open sun drying. Both after open sun and solar-spouted bed drying, bulk and internal porosities decreased and this decrease was more for open sun drying. In addition, pore size distribution curve for open sun dried pea showed the existence of less but larger pores. Finally, ascorbic acid of pea was preserved more when solar-spouted bed drying was used.

Solar-spouted bed drier can be recommended for drying of parboiled wheat, corn and pea since drying time was significantly reduced and higher quality products were obtained.

For the future studies, in order to make the solar-spouted bed more energy efficient, the electricity used to operate the blower can be achieved using solar panels and therefore system becomes self-sufficient. In addition, other particulated products suitable for spouted bed can be dried in solar-spouted bed dryer and the products can be evaluated in terms of their nutritional properties.

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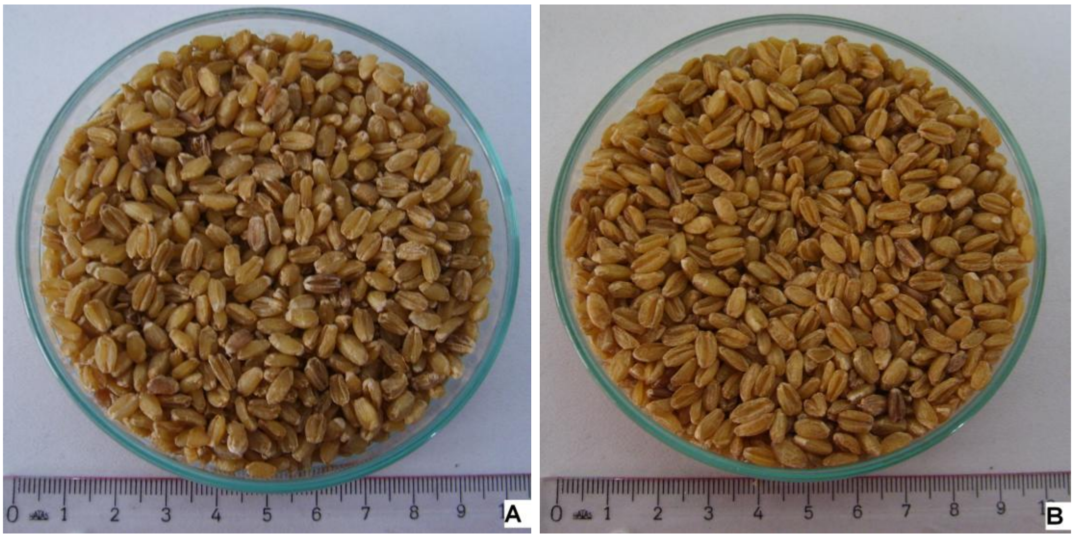
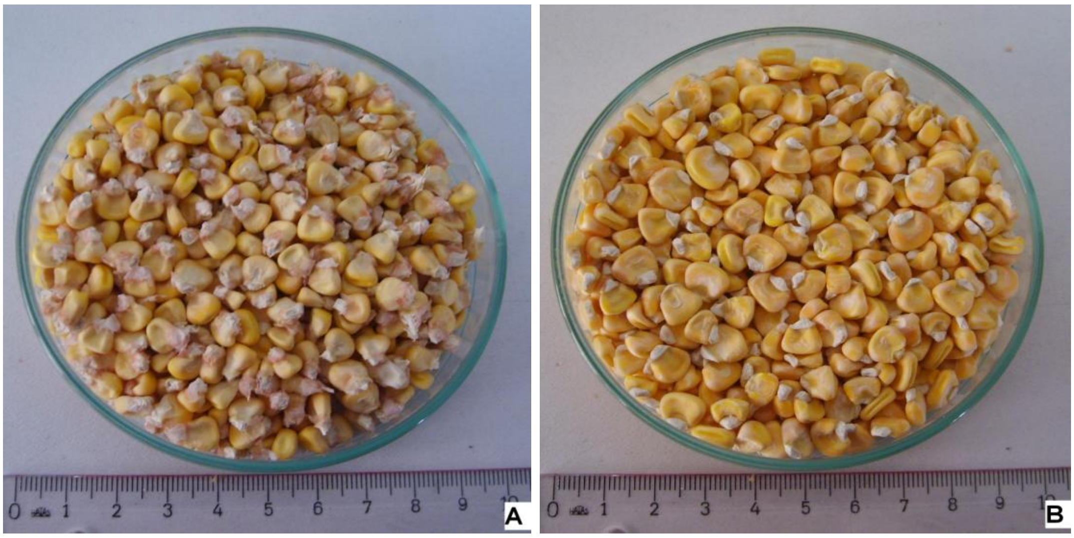
APPENDIX A

Pictures of Dried Products

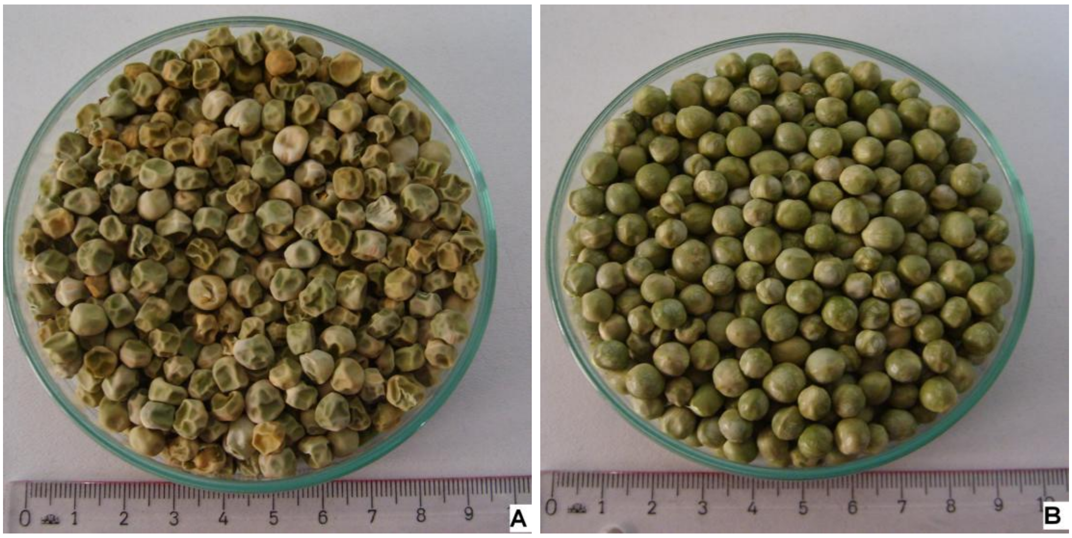
A.1 Pictures of parboiled wheat (A: open sun, B: solar-spouted bed dried)



A.2 Pictures of corn (A: open sun, B: solar-spouted bed dried)



A.3 Pictures of pea (A: open sun, B: solar-spouted bed dried)



APPENDIX B

Data for Drying Experiments

Table B.1 Average temperatures during drying of parboiled wheat

	Temperature (°C)			
Time (h)	**Ambient**	**Collector**	**Bed Inlet**	**Bed Exit**
0.0	26.0	46.3	40.2	41.2
0.5	26.1	53.0	51.3	50.3
1.0	27.5	57.0	55.4	53.3
1.5	26.6	60.7	59.7	58.6
2.0	28.9	63.2	62.1	61.3
2.5	28.2	66.7	65.1	62.3
3.0	28.2	69.4	66.9	66.5
3.5	29.9	71.7	66.9	67.7
4.0	31.3	69.4	64.8	64.6
4.5	31.3	69.5	65.3	65.8
5.0	31.5	69.0	65.2	64.4
5.5	31.6			
6.0	31.0			
6.5	31.6			
7.0	28.0			
7.5	26.1			
8.0	27.1			
8.5	26.3			
9.0	27.3			
9.5	27.6			
10.0	29.1			
10.5	30.8			

Table B.1 cont'd.

11.0	32.2
11.5	31.0
12.0	30.4
12.5	31.3
13.0	31.7
13.5	31.2
14.0	30.6

Table B.2 Average temperatures during drying of corn

	Temperature (°C)			
Time (h)	Ambient	Collector	Bed Inlet	Bed Exit
0.0	26.5	47.9	42.3	43.1
0.5	26.1	54.4	56.3	55.9
1.0	26.5	57.0	58.1	58.2
1.5	27.8	61.5	60.9	59.4
2.0	28.8	65.3	64.9	62.9
2.5	29.1	68.6	68.8	67.0
3.0	29.7	68.3	67.9	66.6
3.5	30.5	66.6	66.3	64.2
4.0	31.5	66.1	66.3	65.2
4.5	31.5	62.5	63.6	63.0
5.0	29.7	60.6	62.6	62.6
5.5	29.6			
6.0	30.1			
6.5	29.6			
7.0	25.8			
7.5	24.6			
8.0	25.6			

Table B.2 cont'd.

8.5	26.9
9.0	26.3
9.5	26.5
10.0	26.7
10.5	27.9
11.0	29.3
11.5	29.1
12.0	29.3
12.5	31.1
13.0	31.1
13.5	30.7
14.0	30.9
14.5	30.1
15.0	27.1
15.5	28.2
16.0	26.8
16.5	28.1
17.5	29.2
18.0	30.8
18.5	30.9
19.0	30.2
19.5	30.0
20.0	29.1

Table B.3 Average temperatures during drying of pea

	Temperature (°C)			
Time (h)	**Ambient**	**Collector**	**Bed Inlet**	**Bed Exit**
0.0	20.7	40.0	35.3	34.6
1.0	20.6	50.7	52.5	52.0
1.5	22.4	54.9	56.2	55.4
2.0	23.5	58.0	58.6	58.3
2.5	23.6	63.1	62.8	61.4
3.0	24.1	66.4	64.7	62.6
3.5	23.5	67.2	65.5	63.7
4.0	25.0	68.1	65.1	63.8
4.5	23.9	68.2	65.4	64.1
5.0	23.1	67.5	64.9	63.1
5.5	23.6			
6.0	23.0			
6.5	20.3			
7.0	20.0			
7.5	21.1			
8.0	21.9			
8.5	23.3			
9.0	23.5			
10.0	22.6			
10.5	24.0			
11.0	24.9			
11.5	24.5			
12.0	24.0			
12.5	25.9			
13.0	27.4			
13.5	27.9			
14.0	28.4			
14.5	29.1			

Table B.3 cont'd.

15.0	28.1
15.5	30.1
16.0	29.5
16.5	29.1
17.0	31.8
17.5	32.1
18.0	32.3

Table B.4 Weight and dry basis moisture content (MC in kg water/kg dry matter) data for parboiled wheat

	Open Sun Drying		**Solar-spouted Bed Drying**	
Time (h)	**Weight (g)**	**MC**	**Weight (g)**	**MC**
0.0	250.0	1.396	250.0	1.396
0.5	232.5	1.229	187.4	0.796
1.0	211.3	1.025	159.6	0.530
1.5	200.0	0.917	138.8	0.330
2.0	186.5	0.788	126.8	0.215
2.5	175.6	0.683	119.2	0.143
3.0	164.7	0.579	116.4	0.116
3.5	158.1	0.515	112.2	0.075
4.0	146.2	0.401	111.0	0.064
4.5	139.6	0.338	110.1	0.055
5.0	134.9	0.293	109.1	0.046
5.5	131.1	0.257		
6.0	127.7	0.224		
6.5	124.6	0.194		
7.0	122.0	0.169		
7.5	119.1	0.142		

Table B.4 cont'd.

8.0	117.6	0.127
8.5	116.4	0.116
9.0	115.7	0.109
9.5	115.1	0.103
10.0	114.5	0.097
10.5	113.9	0.092
11.0	113.3	0.086
11.5	113.0	0.083
12.0	112.6	0.079
12.5	112.5	0.078
13.0	112.3	0.076
13.5	112.0	0.074
14.0	110.9	0.063

Table B.5 Weight and dry basis moisture content (MC in kg water/kg dry matter) data for corn

	Open Sun Drying		**Solar-spouted Bed Drying**	
Time (h)	**Weight (g)**	**MC**	**Weight (g)**	**MC**
0.0	250.0	1.714	250.0	1.714
0.5	242.8	1.635	221.6	1.405
1.0	236.2	1.564	191.3	1.076
1.5	229.4	1.489	157.3	0.707
2.0	223.4	1.425	123.8	0.343
2.5	217.4	1.360	107.1	0.162
3.0	211.6	1.296	100.9	0.095
3.5	205.2	1.227	98.5	0.069
4.0	198.5	1.155	96.6	0.049
4.5	192.1	1.085	95.5	0.036
5.0	186.8	1.027	94.7	0.028

Table B.5 cont'd.

5.5	181.9	0.974
6.0	177.5	0.926
6.5	173.1	0.879
7.0	168.5	0.829
7.5	162.6	0.764
8.0	157.6	0.711
8.5	153.4	0.665
9.0	149.6	0.624
9.5	145.6	0.580
10.0	141.7	0.538
10.5	137.2	0.489
11.0	133.0	0.444
11.5	129.0	0.400
12.0	125.0	0.356
12.5	121.6	0.320
13.0	118.3	0.284
13.5	114.8	0.246
14.0	112.0	0.215
14.5	108.3	0.175
15.0	106.4	0.154
15.5	104.2	0.130
16.0	102.2	0.109
16.5	100.5	0.090
17.5	97.6	0.059
18.0	97.0	0.052
18.5	96.4	0.046
19.0	95.7	0.039
19.5	95.3	0.034
20.0	94.9	0.030

Table B.6 Weight and dry basis moisture content (MC in kg water/kg dry matter) data for pea

	Open Sun Drying		Solar-spouted Bed Drying	
Time (h)	Weight (g)	MC	Weight (g)	MC
0.0	250.0	2.546	250.0	2.546
1.0	231.5	2.284	153.9	1.182
1.5	223.1	2.165	122.9	0.743
2.0	213.9	2.034	104.6	0.484
2.5	201.4	1.857	93.0	0.319
3.0	189.3	1.685	84.5	0.198
3.5	178.6	1.533	78.5	0.113
4.0	167.4	1.374	75.9	0.076
4.5	156.3	1.217	73.8	0.047
5.0	150.9	1.140	72.3	0.025
5.5	144.7	1.052		
6.0	133.4	0.892		
6.5	128.4	0.821		
7.0	121.8	0.728		
7.5	115.1	0.633		
8.0	107.8	0.529		
8.5	102.3	0.451		
9.0	99.4	0.410		
10.0	92.7	0.315		
10.5	90.7	0.287		
11.0	88.8	0.260		
11.5	87.0	0.234		
12.0	85.5	0.213		
12.5	81.6	0.157		
13.0	78.4	0.112		
13.5	77.4	0.098		
14.0	76.9	0.091		

Table B.6 cont'd.

14.5	76.5	0.085
15.0	76.0	0.078
15.5	75.8	0.075
16.0	75.5	0.071
16.5	75.1	0.065
17.0	74.9	0.062
17.5	74.7	0.060
18.0	74.3	0.054

APPENDIX C

Data for Minimum Spouting Air Velocity Determination

Table C.1 Pressure drop in the spouting bed with increasing air velocity for parboiled wheat

Superficial Air velocity (m/s)	Pressure Drop (Pa)
0.00	0.00
0.04	34.32
0.06	102.97
0.08	176.52
0.10	299.10
0.12	377.56
0.15	632.53
0.18	745.31
0.26	568.79
0.32	514.85
0.34	490.33
0.37	426.59
0.41	308.91
0.46	240.26
0.50	137.29
0.52	147.10
0.54	152.00
0.58	152.00
0.61	156.91

Table C.2 Pressure drop in the spouting bed with decreasing air velocity for parboiled wheat

Superficial Air velocity (m/s)	Pressure Drop (Pa)
0.61	156.91
0.58	156.91
0.55	147.10
0.54	137.29
0.50	127.49
0.46	137.29
0.43	117.68
0.38	107.87
0.33	107.87
0.29	107.87
0.26	107.87
0.23	102.97
0.19	112.78
0.13	98.07
0.09	53.94
0.00	0.00

Table C.3 Pressure drop in the spouting bed with increasing air velocity for corn

Superficial Air velocity (m/s)	Pressure Drop (Pa)
0.00	0.00
0.04	19.61
0.07	63.74
0.12	117.68
0.13	166.71
0.16	230.46
0.18	299.10
0.21	343.23
0.27	426.59
0.29	456.01
0.31	495.24
0.33	519.75
0.34	544.27
0.37	558.98
0.39	568.79
0.41	583.50
0.44	598.21
0.45	608.01
0.47	558.98
0.50	529.56
0.54	402.07
0.58	362.85
0.60	323.62
0.63	264.78
0.66	264.78
0.68	264.78
0.69	264.78

Table C.4 Pressure drop in the spouting bed with decreasing air velocity for corn

Superficial Air velocity (m/s)	Pressure Drop (Pa)
0.69	264.78
0.62	250.07
0.60	269.68
0.58	220.65
0.55	191.23
0.52	186.33
0.48	166.71
0.44	156.91
0.40	142.20
0.36	117.68
0.32	102.97
0.28	83.36
0.24	68.65
0.20	58.84
0.14	39.23
0.10	39.23
0.10	39.23
0.07	9.81
0.00	0.00

Table C.5 Pressure drop in the spouting bed with increasing air velocity for pea

Superficial Air velocity (m/s)	Pressure Drop (Pa)
0.00	0.00
0.04	14.71
0.06	49.03
0.08	78.45
0.11	152.00
0.14	225.55
0.16	304.01
0.19	446.20
0.22	519.75
0.24	583.50
0.26	622.72
0.28	622.72
0.32	578.59
0.37	529.56
0.41	436.40
0.45	357.94
0.49	333.43
0.52	304.01
0.56	250.07
0.59	245.17
0.62	230.46
0.64	220.65
0.66	235.36
0.71	259.88
0.73	259.88
0.75	264.78
0.78	294.20

Table C.6 Pressure drop in the spouting bed with decreasing air velocity for pea

Superficial Air velocity (m/s)	Pressure Drop (Pa)
0.78	294.20
0.71	279.49
0.69	269.68
0.65	264.78
0.62	250.07
0.61	230.46
0.59	230.46
0.57	210.84
0.54	201.04
0.48	191.23
0.46	186.33
0.43	176.52
0.39	166.71
0.35	152.00
0.32	156.91
0.28	142.20
0.24	107.87
0.21	93.16
0.16	98.07
0.11	78.45
0.09	39.23
0.07	9.81
0.00	0.00

APPENDIX D

Statistical Tests

D.1 Color

Table D.1.1 ANOVA table for the effect of drying methods on L* value of parboiled wheat

Source	DF	SS	MS	F	P
Drying Methods	2	21.61	10.80	3.64	0.092
Error	6	17.83	2.97		
Total	8	39.44			

Table D.1.2 ANOVA table for the effect of drying methods on a* value of parboiled wheat

Source	DF	SS	MS	F	P
Drying Methods	2	21.523	10.762	19.88	0.002
Error	6	3.247	0.541		
Total	8	24.771			

Table D.1.3 Tukey's Test results for the effect of drying methods on a* value of parboiled wheat

Pair wise comparisons for drying methods

Drying Methods	Lower	Center	Upper
Parboiled subtracted from:			
Open sun	1.2121	3.0556	4.8990
Solar-spouted	1.6233	3.4667	5.3101
Open sun subtracted from:			
Solar-spouted	-1.4323	0.4111	2.2545

Table D.1.4 ANOVA table for the effect of drying methods on b* value of parboiled wheat

Source	DF	SS	MS	F	P
Drying Methods	2	10.59	5.30	2.48	0.179
Error	5	10.68	2.14		
Total	7	21.28			

Table D.1.5 ANOVA table for the effect of drying methods on L* value of corn

Source	DF	SS	MS	F	P
Drying Methods	2	120.67	60.33	7.53	0.023
Error	6	48.10	8.02		
Total	8	168.76			

Table D.1.6 Tukey's Test results for the effect of drying methods on L* value of corn

Pair wise comparisons for drying methods

Drying Methods	Lower	Center	Upper
Fresh subtracted from:			
Open sun	-1.550	5.544	12.639
Solar-spouted	1.783	8.878	15.972
Open sun subtracted from:			
Solar-spouted	-3.761	3.333	10.428

Table D.1.7 ANOVA table for the effect of drying methods on a* value of corn

Source	DF	SS	MS	F	P
Drying Methods	2	17.18	8.59	5.64	0.042
Error	6	9.14	1.52		
Total	8	26.33			

Table D.1.8 Tukey's Test results for the effect of drying methods on a* value of corn

Pair wise comparisons for drying methods

Drying Methods	Lower	Center	Upper
Fresh subtracted from:			
Open sun	-0.693	2.400	5.493
Solar-spouted	0.173	3.267	6.360
Open sun subtracted from:			
Solar-spouted	-2.227	0.867	3.960

Table D.1.9 ANOVA table for the effect of drying methods on b* value of corn

Source	DF	SS	MS	F	P
Drying Methods	2	39.94	19.97	2.09	0.205
Error	6	57.31	9.55		
Total	8	97.25			

Table D.1.10 ANOVA table for the effect of drying methods on L* value of pea

Source	DF	SS	MS	F	P
Drying Methods	2	0.73	0.36	0.11	0.901
Error	7	24.17	3.45		
Total	9	24.90			

Table D.1.11 ANOVA table for the effect of drying methods on a* value of pea

Source	DF	SS	MS	F	P
Drying Methods	2	27.868	13.934	45.12	0.000
Error	7	2.162	0.309		
Total	9	30.029			

Table D.1.12 Tukey's Test results for the effect of drying methods on a* value of pea

Pair wise comparisons for drying methods

Drying Methods	Lower	Center	Upper
Fresh subtracted from:			
Open sun	2.8066	4.1444	5.482
Solar-spouted	1.7569	3.0083	4.2598
Open sun subtracted from:			
Solar-spouted	-2.3876	-1.1361	0.1153

Table D.1.13 ANOVA table for the effect of drying methods on b* value of pea

Source	DF	SS	MS	F	P
Drying Methods	2	84.09	42.05	20.61	0.001
Error	7	14.28	2.04		
Total	9	98.38			

Table D.1.14 Tukey's Test results for the effect of drying methods on b* value of pea

Pair wise comparisons for drying methods

Drying Methods	Lower	Center	Upper
Fresh subtracted from:			
Open sun	-9.972	-6.533	-3.094
Solar-spouted	-9.375	-6.158	-2.941
Open sun subtracted from:			
Solar-spouted	-2.842	0.375	3.592

D.2 Shrinkage

Table D.2.1 ANOVA table for the effect of drying methods on shrinkage of parboiled wheat

Source	DF	SS	MS	F	P
Drying Methods	1	158.8	158.8	9.55	0.018
Error	7	116.4	16.6		
Total	8	275.3			

Table D.2.2 Tukey's Test results for the effect of drying methods on shrinkage of parboiled wheat

Pair wise comparisons for drying methods

Drying Methods	Lower	Center	Upper
Open sun subtracted from:			
Solar-spouted	-14.924	-8.455	-1.985

Table D.2.3 ANOVA table for the effect of drying methods on shrinkage of corn

Source	DF	SS	MS	F	P
Drying Methods	1	414.6	414.6	7.60	0.028
Error	7	381.8	54.5		
Total	8	796.3			

Table D.2.4 Tukey's Test results for the effect of drying methods on shrinkage of corn

Pair wise comparisons for drying methods

Drying Methods	Lower	Center	Upper
Open sun subtracted from:			
Spouted	-25.373	-13.659	-1.945

Table D.2.5 ANOVA table for the effect of drying methods on shrinkage of pea

Source	DF	SS	MS	F	P
Drying Methods	1	1767	1767	7.67	0.010
Error	26	5990	230		
Total	27	7757			

Table D.2.6 Tukey's Test results for the effect of drying methods on shrinkage of pea

Pair wise comparisons for drying methods

Drying Methods	Lower	Center	Upper
Open sun subtracted from:			
Solar-spouted	-31.96	-18.35	-4.73

D.3 Bulk Density

Table D.3.1 ANOVA table for the effect of drying methods on bulk density of parboiled wheat

Source	DF	SS	MS	F	P
Drying Methods	2	5272	2636	8.95	0,016
Error	6	1767	294		
Total	8	7039			

Table D.3.2 Tukey's Test results for the effect of drying methods on bulk density of parboiled wheat

Pair wise comparisons for drying methods

Drying Methods	Lower	Center	Upper
Open sun subtracted from:			
Parboiled	-63.00	-20.00	23.00
Solar-spouted	-101.33	-58.33	-15.34
Parboiled subtracted from:			
Solar-spouted	-81.33	-38.33	4.66

Table D.3.3 ANOVA table for the effect of drying methods on bulk density of corn

Source	DF	SS	MS	F	P
Drying Methods	2	12750	6375	10.12	0.017
Error	5	3150	630		
Total	7	15900			

Table D.3.4 Tukey's Test results for the effect of drying methods on bulk density of corn

Pair wise comparisons for drying methods

Drying Methods	Lower	Center	Upper
Open sun subtracted from:			
Fresh	25.47	100.00	174.53
Solar-spouted	5.47	80.00	154.53
Fresh subtracted from:			
Solar-spouted	-86.66	-20.00	46.66

Table D.3.5 ANOVA table for the effect of drying methods on bulk density of pea

Source	DF	SS	MS	F	P
Drying Methods	2	88875	44438	217.65	0.000
Error	6	1225	204		
Total	8	90100			

Table D.3.6 Tukey's Test results for the effect of drying methods on bulk density of pea

Pair wise comparisons for drying methods

Drying Methods	Lower	Center	Upper
Open sun subtracted from:			
Fresh	-265.03	-225.00	-184.97
Solar-spouted	-235.99	-202.50	-169.01
Fresh subtracted from:			
Solar-spouted	-15.47	22.50	60.47

D.4 Apparent Density

Table D.4.1 ANOVA table for the effect of drying methods on apparent density of parboiled wheat

Source	DF	SS	MS	F	P
Drying Methods	2	100996	50498	1.98	0.218
Error	6	152679	25446		
Total	8	253675			

Table D.4.2 ANOVA table for the effect of drying methods on apparent density of corn

Source	DF	SS	MS	F	P
Drying Methods	2	3352	1676	0.33	0.733
Error	5	25317	5063		
Total	7	28669			

Table D.4.3 ANOVA table for the effect of drying methods on apparent density of pea

Source	DF	SS	MS	F	P
Drying Methods	2	146484	73242	119.46	0.000
Error	6	3679	613		
Total	8	150163			

Table D.4.4 Tukey's Test results for the effect of drying methods on apparent density of pea

Pair wise comparisons for drying methods

Drying Methods	Lower	Center	Upper
Open sun subtracted from:			
Fresh	-343.18	-273.81	-204.44
Solar-spouted	-327.04	-269.00	-210.96
Fresh subtracted from:			
Solar-spouted	-61.00	4.81	70.62

C.5 Dimensional Properties

Table D.5.1 ANOVA table for the effect of drying methods on geometric mean diameter of parboiled wheat

Source	DF	SS	MS	F	P
Drying Methods	2	0.7312	0.3656	4.74	0.025
Error	15	1.1559	0.0771		
Total	17	1.8871			

Table D.5.2 Tukey's Test results for the effect of drying methods on geometric mean diameter of parboiled wheat

Pair wise comparisons for drying methods

Drying Methods	Lower	Center	Upper
Open sun subtracted from:			
Parboiled	0.0444	0.4603	0.8762
Solar-spouted	-0.3404	0.0755	0.4914
Parboiled subtracted from:			
Solar-spouted	-0.8007	-0.3848	0.0311

Table D.5.3 ANOVA table for the effect of drying methods on equivalent diameter of parboiled wheat

Source	DF	SS	MS	F	P
Drying Methods	2	0.7190	0.3595	4.67	0.026
Error	15	1.1540	0.0769		
Total	17	1.8729			

Table D.5.4 Tukey's Test results for the effect of drying methods on equivalent diameter of parboiled wheat

Pair wise comparisons for drying methods

Drying Methods	Lower	Center	Upper
Open sun subtracted from:			
Parboiled	0.0387	0.4542	0.8698
Solar-spouted	-0.3465	0.0690	0.4846
Parboiled subtracted from:			
Solar-spouted	-0.8008	-0.3852	0.0304

Table D.5.5 ANOVA table for the effect of drying methods on aritmetric diameter of parboiled wheat

Source	DF	SS	MS	F	P
Drying Methods	2	0.6542	0.3271	3.56	0.054
Error	15	1.3798	0.0920		
Total	17	2.0341			

Table D.5.6 ANOVA table for the effect of drying methods on sphericity of parboiled wheat

Source	DF	SS	MS	F	P
Drying Methods	2	0.00283	0.00141	1.11	0.355
Error	15	0.01912	0.00127		
Total	17	0.02195			

Table D.5.7 ANOVA table for the effect of drying methods on geometric mean diameter of corn

Source	DF	SS	MS	F	P
Drying Methods	2	1.4001	0.7001	14.34	0.000
Error	14	0.6836	0.0488		
Total	16	2.0838			

Table D.5.8 Tukey's Test results for the effect of drying methods on geometric mean diameter of corn

Pair wise comparisons for drying methods

Drying Methods	Lower	Center	Upper
Open sun subtracted from:			
Fresh	0.3481	0.6982	1.0482
Solar-spouted	-0.1515	0.1823	0.5161
Fresh subtracted from:			
Solar-spouted	-0.8659	-0.5158	-0.1657

Table D.5.9 ANOVA table for the effect of drying methods on equivalent diameter of corn

Source	DF	SS	MS	F	P
Drying Methods	2	1.2780	0.6390	11.83	0.001
Error	14	0.7562	0.0540		
Total	16	2.0342			

Table D.5.10 Tukey's Test results for the effect of drying methods on equivalent diameter of corn

Pair wise comparisons for drying methods

Drying Methods	Lower	Center	Upper
Open sun subtracted from:			
Fresh	0.3043	0.6725	1.0407
Solar-spouted	-0.1527	0.1984	0.5494
Fresh subtracted from:			
Solar-spouted	-0.8423	-0.4741	-0.1059

Table D.5.11 ANOVA table for the effect of drying methods on arithmetic diameter of corn

Source	DF	SS	MS	F	P
Drying Methods	2	1.2281	0.6140	11.75	0.001
Error	14	0.7315	0.0523		
Total	16	1.9596			

Table D.5.12 Tukey's Test results for the effect of drying methods on arithmetic diameter of corn

Pair wise comparisons for drying methods

Drying Methods	Lower	Center	Upper
Open sun subtracted from:			
Fresh	0.2955	0.6577	1.0198
Solar-spouted	-0.1581	0.1872	0.5325
Fresh subtracted from:			
Solar-spouted	-0.8326	-0.4704	-0.1083

Table D.5.13 ANOVA table for the effect of drying methods on sphericity of corn

Source	DF	SS	MS	F	P
Drying Methods	2	0.002604	0.001302	1.32	0.298
Error	14	0.013810	0.000986		
Total	16	0.016414			

D.6 Ascorbic Acid

Table D.6.1 ANOVA table for the effect of drying methods on ascorbic acid content of pea

Source	DF	SS	MS	F	P
Drying Methods	1	0.05797	0.05797	8.76	0.018
Error	8	0.05297	0.00662		
Total	9	0.11094			

Table D.6.2 Tukey's Test results for the effect of drying methods on ascorbic acid content of pea

Pair wise comparisons for drying methods

Drying Methods	Lower	Center	Upper
Open sun subtracted from:			
Solar-spouted	0.03430	0.15542	0.27654