FLUIDIZED BED, MICROWAVE AND MICROWAVE ASSISTED FLUIDIZED BED DRYING OF MACARONI BEADS

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ABSTRACT

FLUIDIZED BED, MICROWAVE AND MICROWAVE ASSISTED FLUIDIZED BED DRYING OF MACARONI BEADS

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This study is aimed to compare the fluidized bed and microwave drying with microwave assisted fluidized bed drying. For this purpose, macaroni beads (2.4±0.08 mm diameter) were dried from about 20% to 12% moisture content in a fluidized bed of 7.6 cm diameter, in a domestic microwave oven with a power of 609 W and in the fluidized bed placed in the microwave oven conditions. In the experiments with the fluidized bed three air temperatures; 50, 60 and 70°C at an air velocity of 2.3 m/s and in those with the microwave oven two power levels; 50% and 100% were used.

The drying curves indicated that the drying rate increased with the air temperature and microwave power in each drying method. Microwave assisted fluidized bed drying reduced the drying time by about 50% and 11% on the average

compared with the fluidized bed and microwave drying, respectively. Therefore, it was concluded that the drying time was reduced more by the effect of microwave energy than the fluidization.

The effective diffusivities in the fluidized bed and microwave assisted fluidized bed drying were found to be in the order of 4.125×10^{-11} and 8.772×10^{-11} m^2/s on the average, respectively. The effective diffusivities for the fluidized bed drying were fitted to an Arrhenius type of equation and the magnitude of the activation energy was found to be in the order of 12595 kJ/kg mol.

Keywords: Drying, microwave assisted fluidized bed drying, macaroni beads, effective diffusivity

ÖZ

MAKARNA BONCUKLARININ AKIŞKAN YATAK, MİKRODALGA VE MİKRODALGA YARDIMLI AKIŞKAN YATAKTA KURUTULMASI

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Temmuz 2003, 74 sayfa

Bu çalışmanın amacı akışkan yatakta ve mikrodalga kurutma ile mikrodalga yardımlı akışkan yatakta kurutma arasında bir karşılaştırmaya yöneliktir. Boncuk makarna taneleri (2.4±0.08 mm çap) yaklaşık %20 nem içeriğinden %12'ye düşürülünceye kadar çapı 7.6 cm olan bir akışkan yatakta, 609 W gücünde ev tipi bir mikrodalga fırında ve bu mikrodalga fırının içine yerleştirilen akışkan yatakta üç değişik koşulda kurutulmuştur. Akışkan yataklı deneylerde 50, 60 ve 70°C olmak üzere üç hava sıcaklığı ve 2.3 m/s hava hızı, mikrodalga fırında da %50 ve %100 güç düzeyleri uygulanmıştır.

Kuruma eğrileri karşılaştırılmış ve kurumanın herbir kurutma yönteminde mikrodalga gücü ve hava sıcaklığının artırılmasıyla hızlandığı görülmüştür.

Mikrodalga yardımlı akışkan yatakta kurutma, akışkan yatakta ve mikrodalga kurutmayla karşılaştırıldığında kuruma süresini ortalama olarak sırasıyla %50 ve %11 oranında kısaltmıştır. Bu sebeple kuruma hızında mikrodalga enerjisinin akışkanlaştırmaya göre daha etkili olduğu sonucuna varılmıştır.

Kuruma hızlarından akışkan yatakta ve mikrodalga yardımlı akışkan yatakta kurutmadaki etkin yayınma katsayılarının ortalama olarak sırasıyla 4.125×10^{-11} ve 8.772×10^{-11} m^2/s düzeyinde olduğu bulunmuştur. Akışkan yataklı kurutmadaki etkin yayınma katsayıları Arrhenius tipi bir denklemle açıklanabilmiş ve etkinlik enerjisinin 12595 kJ/kg mol düzeyinde olduğu saptanmıştır.

Anahtar sözcükler: Kurutma, Mikrodalga yardımlı akışkan yatakta kurutma, Boncuk makarna, Etkin yayınma katsayısı.

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INTRODUCTION

1.1 Drying

Drying refers commonly to the removal of water from substances by applying heat. However, the removal of other liquids such as organic solvents is also referred to as drying. In addition, there are various methods other than thermal drying such as mechanical means of removing of liquids. Therefore, general definition may be the removal of volatile substances from a mixture that yields a solid product. Commonly, the principal volatile substance is water (Keey, 1972; Treybal, 1981; Geankoplis, 1993).

The reasons for drying are almost as diverse as the dried materials. Sometimes drying is carried out for economic reasons or to ease handling. Moisture content of many materials should be decreased to a prescribed value before being sold. Foods are dried generally for preservation purposes (Keey, 1972).

Drying is by far the oldest and the most widely used method of preserving foods (Khraisheh et al., 1997). Water activity of a food is lowered resulting in the prevention of the growth of the spoilage causing microorganisms and minimized enzymatic activity (Karel et al., 1975). Packaging requirements and weight of the product are reduced. Drying of foods is complex since it is difficult to establish phenomenological characteristics and appropriate process model and characteristics for optimization and scale up (Reyes et al., 2002).

Broadly, drying methods can be subdivided by mode of operation, whether continuous or batchwise. Another type of drying methods classification can be based on the method of supplying the heat.

There are four methods of heating: convective, conductive, radiative and dielectric. Most thermal dryers embody convective heating. The heat is supplied by the direct contact of the drying substance with the hot gas which is generally air. An example of a convective dryer is a fluidized bed dryer. If the material to be dried is very thin or very wet, then conductive heating may be employed where the drying material is contacted with hot surfaces. Electromagnetic radiation whose wavelengths range from those of solar radiation to those of microwaves may be used for drying purposes where the radiation within this waveband penetrates into the exposed material. In dielectric heating, energy is dissipated within a moist, dielectric material placed in an electric field which is very rapidly oscillating. Heat is internally generated throughout the whole material. One example of dielectric drying is microwave drying (Keey, 1972).

1.2 Fluidization

1.2.1 The Phenomenon of Fluidization

Fluidization is the process by which the solid particles are transformed into a fluid like state through contact with a gas or liquid stream (Kunii and Levenspiel, 1991).

When a fluid is passed upward through a bed of solid particles, fluid percolates through voids between the stationary particles at low flow rates. By gradually increasing the superficial fluid velocity, u_0, particles move apart and a few are seen to vibrate, this is a fixed bed. Further increasing the flow rate, at a specific velocity, the particles will be suspended in the fluid to give rise to a fluidized bed. At the same time, the fluid will be resisted in its motion during its travel through the bed support and particles resulting in a pressure drop across the bed. When this pressure drop is sufficient to support the weight of the particles and fluid in the bed, the bed is referred to as an incipiently fluidized bed or a bed at minimum fluidization. The specific velocity of the fluid corresponding to this condition is termed as the 'minimum fluidization velocity' and designated as u_{mf} (Kunii and Levenspiel, 1991).

If the flow rate of fluid is continuously increased above minimum fluidization velocity, one of two things will happen; either the average distance between the particles will become greater as a result of the bed expansion and bubbles do not form, or the excess fluid will pass through the bed in the form of bubbles giving rise to a two-phase system. These two types were referred to as 'particulate' and, 'aggregative' or 'bubbling' fluidized bed, respectively. If the fluid velocity exceeds the terminal velocity of the solids, pneumatic transport of solids commences (Richardson, 1971).

1.2.2 Pressure Drop - Velocity Relationship

The pressure drop in the bed, Δp_b, will rise as the superficial fluid velocity is increased at the initial stage. As long as the bed behaves as a packed bed, the pressure drop is approximately proportional to the gas velocity. When the pressure drop becomes equal to the buoyant weight per area of the particles, Δp_{eq}, any further increase in velocity must result in slight upward movement of the particles resulting in a decrease in the resistance to fluid flow. The voidage of the bed will increase and in an idealized system, the pressure drop will remain constant at Δp_{eq}. When the particles become physically separated from one another and free to move within the fluid, the minimum fluidization condition will be achieved. The pressure drop over the bed then on remains about constant as the fluid velocity is increased. If the fluid velocity is progressively reduced, the pressure remains constant till to the point of 'incipient fluidization'. If the velocity is further reduced, the pressure drop will decrease. However, the bed voidage will remain approximately at the value ε_{mf}

corresponding to a bed at the point of incipient fluidization. Therefore, lower pressure drop values will be observed as shown in Figure 1.1 (Richardson, 1971; Kunii and Levenspiel, 1991).

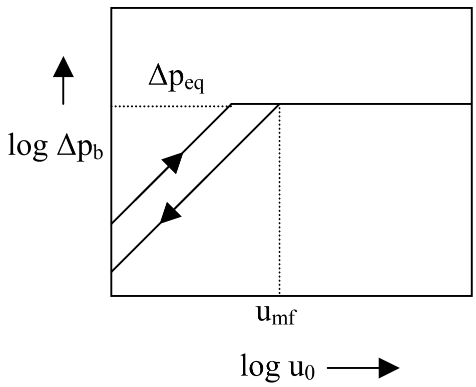

Figure 1.1 Pressure drop - velocity relationship for an ideal bed.
increasing air velocity   decreasing air velocity

However, the ideal case virtually cannot be achieved in practice due to arching, forces between the particles, etc. This necessitates an extra force to overcome these forces and in the actual case there is a maximum point for the pressure drop as in Figure 1.2 (Esin, 1978).

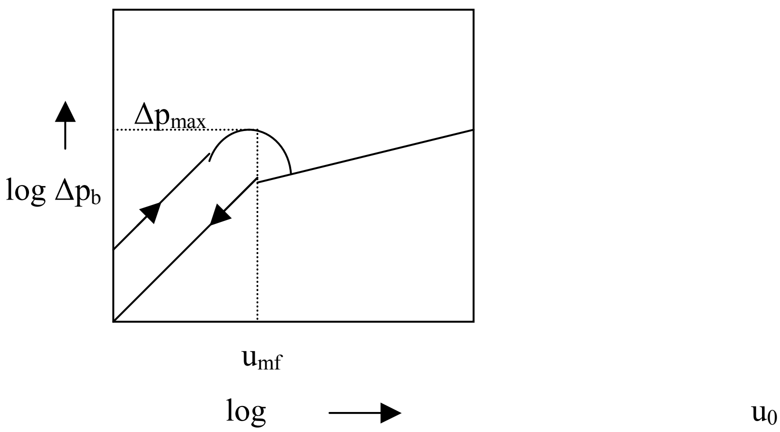

Figure 1.2 Pressure drop - velocity relationship for an actual bed.
increasing air velocity   decreasing air velocity

1.2.3 Fluidized Bed Drying

Due to the fact that the heat and mass transfer coefficients are much higher than those in conventional hot air drying, drying rates in fluidized beds are higher resulting in shorter drying times (Wang and Chen, 2000; Tatemoto et al., 2001). Therefore, fluidized bed dryers are widely used in food, chemical, metallurgical and pharmaceutical industries (Mujumdar and Devahastin, 2000).

Fluidized bed drying is a kind of convective drying in which the following mechanism is observed:

There is a very thin film of liquid covering the surface of a solid which is initially very wet. This film is generally assumed as entirely unbound moisture. Evaporation will take place from the surface when this material is exposed to relatively dry air. The rate of the evaporation is independent of the solid. Since evaporation of moisture absorbs latent heat, the liquid surface will come to, and remain at, an equilibrium temperature where the rate of the heat flow from the surroundings to the surface exactly equals the rate of heat absorption. If the solid is porous, most of the water evaporated is supplied from the interior of the solid. This period of drying is known as the constant-rate period. This period continues as long as the delivery of the liquid to the surface is as rapidly as it evaporates there (Treybal, 1981; Geankoplis, 1993). During this period water removal is limited to heat available for vaporization and capacity of the air to absorb the moisture. Hence the rate of drying is mainly affected by air flow rate, inlet temperature and humidity (Hlinak and Saleki-Gerhardt, 2000).

When the average moisture content of the solid has reached a value X_c, the critical moisture content, the surface film of moisture has been so reduced. Further drying causes dry spots to appear on the surface; these spots occupy larger portions of the exposed surface as drying proceeds. Ultimately, the original surface film of liquid will have entirely evaporated. This is the first part of the falling-rate period, the period of unsaturated surface drying. Since the mechanism of evaporation during this period is the same as that in the constant-rate period, the effects of such variables as temperature, humidity and velocity of the gas are the same as for constant-rate drying (Treybal, 1981).

On further drying, the plane of evaporation recedes from the surface. Heat for the evaporation is transferred to the zone of vaporization through the solid. Vaporized water moves through the solid into the air stream (Geankoplis, 1993). In this period, the controlling step is the rate at which moisture can move through the solid, as a result of concentration gradients existing between the deeper parts and the surface. The rate of internal movement of the moisture decreases as the moisture content of the solid is lowered by drying. Finally, the moisture content of the solid falls to the equilibrium value X^* and drying stops. This is the second part of the falling-rate period and known as the internal diffusion-controlling step (Treybal, 1981). In the falling rate period, the drying rate depends mainly on the physical characteristics of the solid to be dried and main process of drying takes place in the falling rate period (Hlinak and Saleki-Gerhardt, 2000; Elbert et al., 2001).

One of the theories for porous media transport is the work of Luikov. Temperature (T), moisture content (M) and gas pressure (P) were selected as primary variables and the equations were (Ni, 1997):

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

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

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

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

In these equations, the contributions of two distinct variables on the transport of the third variable are presented. In Eq. 1.2, it can be seen that the mass transfer is determined not only by the differences in the concentration of matter, but also by thermal and momentum diffusion. The effect of thermal diffusion on the mass transport is known as the Soret effect. Luikov's equations can be simplified depending on the drying method. In convective drying, for most practical cases, the effects of thermal and momentum diffusion are often ignored since their influences are very small (Keey, 1972). Therefore, Eq. 1.2 reduces to:

$$\frac{\partial M}{\partial t} = K_{22} \nabla^2 M \tag{1.4}$$

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

$$\frac{\partial M}{\partial t} = \nabla \left(D_{eff} \nabla M \right) \tag{1.5}$$

where D_{eff} (m^2/s) is the effective diffusivity that includes the effects of all possible mechanisms of transport of moisture in both liquid and vapor form. The solution of Eq. 1.5 for a sphere under the conditions of constant moisture diffusivity and neglecting the shrinkage results in (Crank, 1975):

$$\frac{X_t - X^*}{X_0 - X^*} = \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp\left(-n^2 \frac{\pi^2 D_{eff} t}{r^2} \right) \tag{1.6}$$

where, X_t is the moisture content at time t, X^* is the equilibrium moisture content, X_0 is the initial moisture content, r (m) is the radius of the particle and the group $D_{eff}t/r^2$ is the dimensionless Fourier number for the mass transfer. When Fourier number is greater than about 0.1, the terms higher than the first can be disregarded and taking the natural logarithm of both sides condenses the relation into the form:

$$\ln\left(\frac{X_t - X^*}{X_0 - X^*} \right) = \ln\left(\frac{6}{\pi^2} \right) - \frac{\pi^2 D_{eff}}{r^2} t \tag{1.7}$$

The effective diffusivities of some materials follow an Arrhenius type of equation as:

$$D_{eff} = D_0 \exp\left(\frac{-E_a}{RT}\right) \quad 1.8$$

where E_a is the activation energy (kJ/kg mol), T is temperature (K), R is the gas law constant (kJ/kg mol K) and D_0 is a constant.

Eq. 1.8 can be rearranged into the form of:

$$\ln(D_{eff}) = \ln(D_0) - \frac{E_a}{RT} \quad 1.9$$

1.3 Microwave Heating

1.3.1 Microwaves

Microwaves are high frequency, electromagnetic waves which are composed of electric and magnetic fields. The frequency range of microwaves is from 300 MHz to 300 GHz (Khraisheh et al., 1997). Microwaves are produced by the alternating electrical field generated between the two plates that are oppositely charged. The microwave oven frequency, *f*, is fixed at 2450 MHz for consumer ovens, although 915 MHz may also be used for microwave processing. The wavelength the microwave oven frequency of 2450 MHz is 12.8 cm (Buffler, 1993).

1.3.2 Mechanism of Microwave Heating

There are two mechanisms responsible for the heating of the foods by the microwaves:

Dipolar rotation:

The water molecules are composed of two hydrogen atoms attached to the oxygen atom. The hydrogen atoms each consist of a positive charge, and the oxygen atom consists of two negative charges. The physically separated charges are called dipole. If these water molecules are placed in a region of an oscillating electrical field, they will experience a torque or rotational force attempting to orient them in the direction of the field (Buffler, 1993).

Before the microwave electrical field is applied, all the water molecules in the food are thermally agitated in a random fashion corresponding to the initial temperature of the sample. When the field is applied, the molecules attempt to orient themselves in the initial field direction and collide randomly with their neighbors. When the field reverses, they attempt to reverse direction and further collisions occur. Hence, the electric field provides energy for water molecules to rotate into alignment (Khraisheh et al., 1997). This mechanism is known as dipolar rotation and is the basic phenomenon for heating of the foods at microwave frequencies (Schiffmann, 1987).

Ionic interaction:

Any charged particle found in the oven experiences a force alternating in the three orthogonal directions (top to bottom, side to side and front to back) at 2.45 billion times per second. The net force due to the three fields will be in some arbitrary direction in space, depending on the amplitude of the three individual forces. The net force will first accelerate the particle in one direction and then in opposite, with particles of opposite charges being accelerated in opposite directions.

If the accelerating particle collides with an adjacent particle, it will impact kinetic energy to it and set it into more agitated motion than it previously had and the temperature of the particle increases. As the second, more agitated, particle interacts with its neighbors, it transfers agitation or heat with them, until all neighboring particles have had their temperature increased. By this mechanism, energy from the oscillating microwave electric field in the microwave oven cavity is imparted to charged particles in terms of physical agitation. This increased energy of agitation, or heat, is then transferred to other parts of the material. This mechanism of heating is known as ionic interaction and very effective on the food materials containing high amounts of dissolved salts (Buffler, 1993).

1.3.3 Microwave Drying

There are several foods such as pasta and potato chips that have been dried successfully by microwave drying (Buffler, 1993). Pasta products are generally dried to a moisture level of 13% (Dablon and Oehler, 1983). Unfortunately, the diffusion rate through the partially dried pasta is low, presenting a very long falling-rate region. The only way to speed the process is to increase the ambient drying temperature. This procedure “case-hardens” or cracks the outside, creating an unacceptable product. Microwave drying prevents case hardening due to its mechanism (Decareau, 1986; Schiffmann, 1986). Another advantage of microwave drying is that selective heating of the water component is achieved because of the substantially higher dielectric activity of water as compared to most solid components (Ahmad et al., 2001). However, it has the disadvantage of non-homogenous distribution in the processing cavity, creating problems of non-uniform heating (Drouzas et al., 1999).

The microwave energy is introduced into the conventional system at about 20% moisture content in the industrial applications and this is strategic. At this moisture content, microwave penetration depth is not seriously affected by the moisture content. Furthermore, the drying seems to be approaching in the second falling rate period where conventional systems perform poorly. Microwaves accelerate moisture movement within the product to the surface (Owusu-Ansah, 1991).

Generally, microwave drying of foods at moisture contents higher than 20% is not comparatively economical. Conventional heating methods more effectively remove water than microwaves at high moisture contents. This is due to the fact that although water has high dielectric constant and can absorb microwaves easily, it also has a very high specific heat. Hence considerable amount of microwave energy would be supplied to raise the temperature for dehydration significantly if the bulk water is high, which may cause partial heating of material as well (Owusu-Ansah, 1991).

The mechanism of microwave drying is completely different from the conventional drying methods. As the temperature inside the material approach the boiling point of water, pressure development becomes significant. This pushes moisture from inside toward the surface leading to Darcy's flow. Generally, it results in a much higher surface moisture level than due to the diffusion alone. The air in the oven cavity being colder than the inner parts of the particle reduces the moisture removal capacity of the surface and aids in the moisture buildup near the surface. In a very wet material, large enough pressures are developed that lead to 'pumping out' of water at the surface. This can lead to a much higher rate of moisture loss (Ni, 1997). Pressure gradient is the major effect on the moisture transport in the microwave drying.

As a result of the preceding discussion, in microwave drying, Luikov's equation given in Eq. 1.2 reduces to:

$$\frac{\partial M}{\partial t} = K_{23} \nabla^2 P \qquad 1.10$$

In some studies microwave drying was studied by the effective diffusivity model (Shivhare, 1991; Yaşar, 1999). However, the internal absorption of heat and internal evaporation are often significant in microwave heating (Ni, 1997). Therefore, application of effective diffusivity model in the microwave drying is limited in the literature. However, this approach might be utilized for the comparison of the mechanism of microwave drying with other conventional drying methods.

1. 4 Microwave Assisted Fluidized Bed Drying

Fluidized bed and microwave drying compensate some of the drawbacks of each other. Combination of two methods can give rise to several desired results; the uniformity of the temperature among the particles can be provided by well mixing due to fluidization (Feng and Tang, 1998) and the drying times can be reduced by the utilization of microwave energy (Jumah and Raghavan, 2001; Wang et al., 2002).

At the first stage of the microwave assisted fluidized bed drying, liquid water transports from the interior to the exterior of the particle by Darcy's flow. As the temperature inside the material approaches to the boiling of water, pressure development occurs pushing the moisture toward the surface. As the time proceeds, the liquid water supply cannot maintain the evaporation rate at the surface. Afterwards, the water starts to evaporate inside the particle. Darcy's flow and the vapor diffusion are the major mechanisms for the moisture transport in the particle. As the drying progresses, the moisture content near the surface decreases below critical moisture content. Darcy's flow disappears so that liquid water has to be evaporated and then transported to the particle surface by vapor diffusion (Chen et al., 2001).

In the microwave assisted fluidized bed drying, the effects of both moisture and pressure gradients are observed. Therefore, Luikov's equation given in Eq. 1.2 reduces to:

$$\frac{\partial M}{\partial t} = K_{22}\nabla^2 M + K_{23}\nabla^2 P \qquad 1.11$$

The first term in Eq. 1.11 can be neglected at the early stage whereas the second term can be neglected at the final stage of drying. However, neither of them can be neglected at the middle stage.

1.5 Objectives of the Study

Drying is one of the most significant steps in the processing of many foods. In this study, the effects of different drying methods on drying time were investigated. One of these methods is the microwave assisted fluidized bed drying. The studies on microwave assisted fluidized bed drying of various types of products are limited in the literature.

Drying is the critical step in the macaroni production since some disorders such as cracks may occur unless the conditions are carefully controlled. The risk of this problem can be reduced by microwave assisted fluidized bed drying. Macaroni beads are appropriate for both fluidized bed and microwave drying. Therefore, the main objective of this study is to compare the fluidized bed, microwave and microwave assisted fluidized bed drying of macaroni beads.

For this purpose, the experimental drying rates for these methods at different conditions were compared and the effects of air temperature and microwave power level on drying time were investigated. In addition, the effective diffusivities were calculated and effective diffusivities for the fluidized drying were fitted to an Arrhenius type of equation.

CHAPTER 2

MATERIALS AND METHODS

2.1 Macaroni Beads

Macaroni beads (Nuh'un Ankara Makarnası, Turkey) were obtained from a local market. Their average diameter was 2.4 ± 0.08 mm.

2.2 Dry Weight Determination

20 g of macaroni beads were weighed in a balance (Scaltec, SP051, Germany) and scattered in a glass plate in a way that they do not contact each other. The plate was placed in lab oven (Dedeoğlu, TS-5050, Turkey) adjusted to 100°C. The weight was measured until a constant value was attained.

2.3 Superficial Air Velocity Determination

The superficial air velocity of the bed to be used in the experiments was determined by the aid of the system constructed (Figure 2.1). Column of the fluidized bed was glass with an inner diameter of 73 mm, outer diameter of 77 mm and height of 176 mm. The distributor plate, 2.5 mm thick, was made of teflon and had 1.5 mm diameter holes on it. The distributor was fixed to the bottom of the column. The column was connected to an air fan by plastic pipe. An open-end U-tube manometer containing water was connected between the fluidized bed and air fan close to the entrance of the fluidized bed to measure the pressure drop in the bed. A ball valve was connected to the exit of the air fan to adjust the air flow rate entering the bed after a 90° side vent piece.

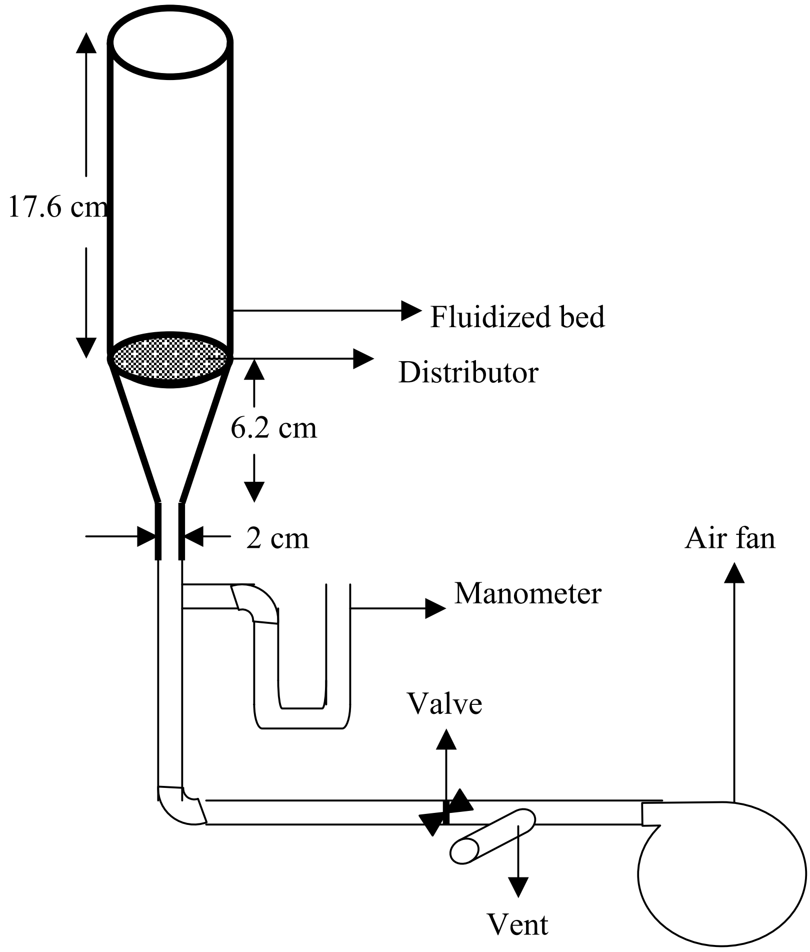

Figure 2.1 Apparatus for the determination of superficial air velocity.

225 g of macaroni beads were weighed by a balance (Scaltec, SP051, Germany) and placed into the column to form the bed. The air fan was turned on and the valve was gradually opened with stepwise increments up to an air velocity of 2.1 m/s. The air velocities at the exit of the fluidized bed were measured by an anamometer (Turbo Meter, Davis Instruments, U.S.A.) and for each valve setting the corresponding pressure drop values were read from the manometer. These values were recorded. Then, the procedure was reversed by gradually closing the valve and

reading the pressure. The data of air velocity versus pressure drop were used to prepare the log (Δp_b) vs log (u_0) plot for determination of the superficial air velocity used in the experiments.

2.4 Rehydration

A glass jar, 13 cm outer diameter and 14.5 cm height was filled with distilled water to a height of 3 cm from the bottom. 200 g of macaroni beads containing about 12% moisture content were weighed and put into a perforated metal cup, 7.3 cm outer diameter, 7.2 cm height, and was hanged to the lid of the jar. The lid was closed tightly with the cup in the jar avoiding direct contact of the macaroni beads with the water. This system is shown in Figure 2.2.

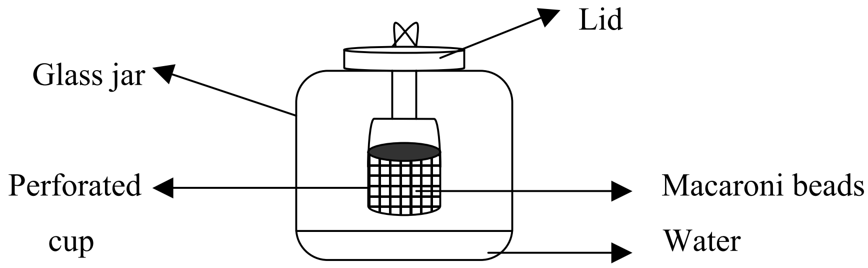

Figure 2.2 Rehydration apparatus.

The jar with its contents was replaced into an incubator (NÜVE EN 400, Turkey) at 60°C and kept there for 45 hours for the moisture content to increase to about 20%. For each experimental run the same procedure was followed for the macaroni beads.

2.5 Relative Humidity Determination

The dry bulb and wet bulb temperatures of the air were measured with the aid of a psychrometer (Cole-Parmer, W.3312-40, U.S.A.). The humidity of the air was determined with the aid of a psychrometric chart. The relative humidity of the air was assumed to be the same for each experiment.

2.6 Drying

2.6.1 Fluidized Bed Drying

The system shown in Figure 2.3 was used for the fluidized bed drying experiments. An electrical heater was installed between the fluidized bed and air fan to heat the air entering the fluidized bed. A potentiometer was connected on the line to the heater to adjust the temperature of the air. The temperature of the air was measured at the inlet of the fluidized bed by a thermometer (Labortherm-N, GDR).

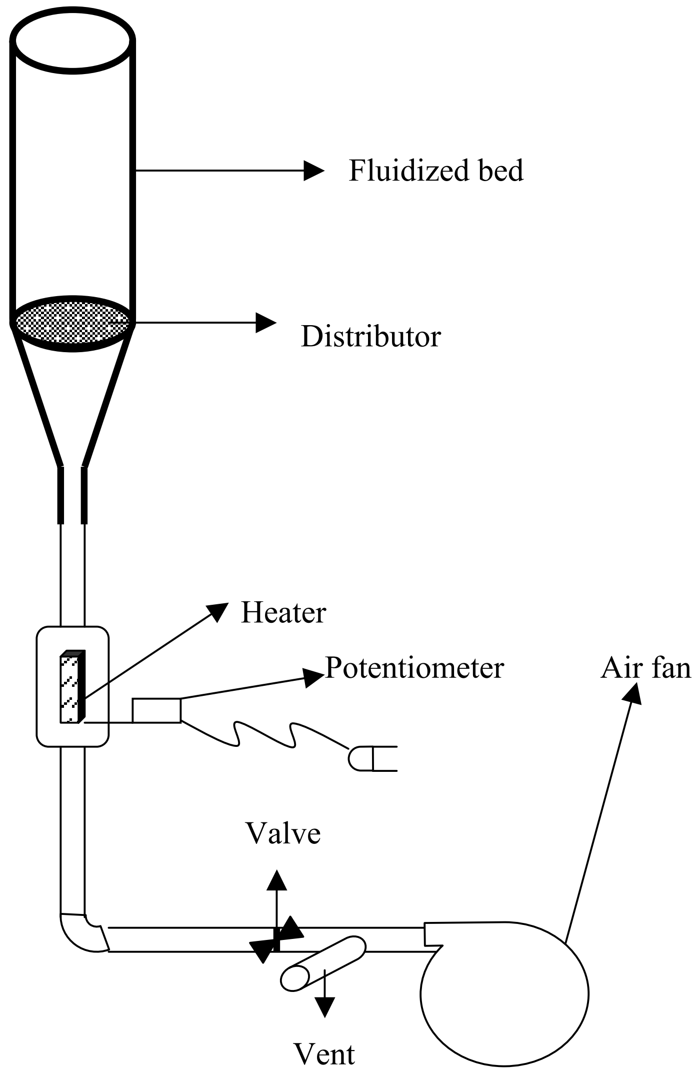

Figure 2.3 Fluidized bed drying apparatus.

The fan was switched on and velocity of the air at the outlet of the fluidized bed was adjusted to 2.3 m/s. The heater was put on using the potentiometer and the air was brought to the desired temperature. Sufficient time was allowed to heat-up the system. Then, quickly the fan was closed and rehydrated macaroni beads were placed in the fluidized bed and the air fan was switched on. The weight data was taken in one minute intervals by removing the beads from the bed and then replacing them until the moisture content of the macaroni beads was reduced below 11.8%. This procedure was followed for the air temperatures of 50, 60 and 70°C.

2.6.2 Microwave Drying

A domestic microwave oven (White-Westing House Type: SJ Model: KM 90 VP-63103, U.S.A.) with a frequency 2450 MHz was used throughout the experiments. A hole, 24 mm diameter was drilled at the floor of the microwave oven for the stem of the column to protrude through the hole and out from the bottom. By this means the fluidized bed was installed into the oven cavity for the microwave assisted fluidized bed drying experiments. The hole was closed by a bung. The power of the microwave oven was found by the 2-Liter Test whose procedure is given in Appendix C and the results are given in Appendix C Table C.1.

For the microwave drying experiments, the rehydrated macaroni beads were weighed and 10% of them were scattered on a petri dish (115 mm diameter) in a way that they do not contact each other. Then, the petri dish was placed at the center of a wide borosilicate glass plate (395 mm x 350 mm). Other portion of the macaroni beads were scattered around the petri dish in a way that at all the particles were nearly separated from each other. Afterwards, the plate was placed into the microwave oven. This system is shown in Figure 2.4. The microwave oven was started and weight of the petri dish and its contents was measured until the moisture content of the macaroni beads in it decreased below 11.8%. The experiments were performed at 50% and 100% microwave power levels.

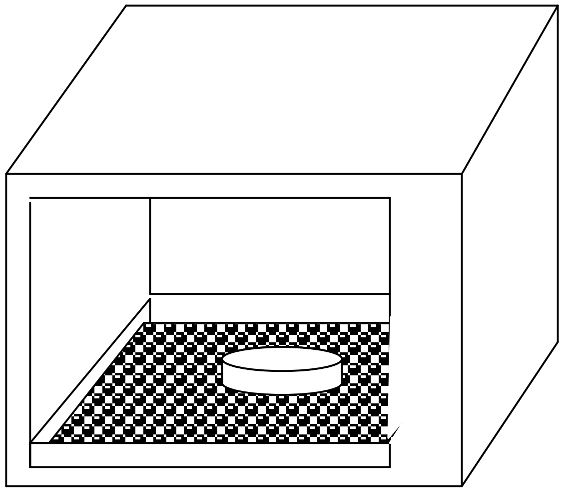

Figure 2.4 Microwave drying apparatus.

2.6.3 Microwave Assisted Fluidized Bed Drying

The system shown in Figure 2.5 was used for the microwave assisted fluidized bed drying experiments. The fluidized bed was placed into the microwave oven as described above. The other parts of the system were the same as the ones in the fluidized bed drying.

Velocity of the air at the exit of the fluidized bed was adjusted to 2.3 m/s using the valve. The heater was adjusted to obtain the desired air temperature. Sufficient time was allowed to heat-up the system and then the fan was switched off. The rehydrated macaroni beads were placed in the fluidized bed quickly and the air fan and microwave oven was turned on. The weight data was taken in one minute intervals until the moisture content of the macaroni beads reduced below 11.8%.

The experiments were performed at 50, 60 and 70°C air temperatures and at two microwave power levels; 50% and 100%.

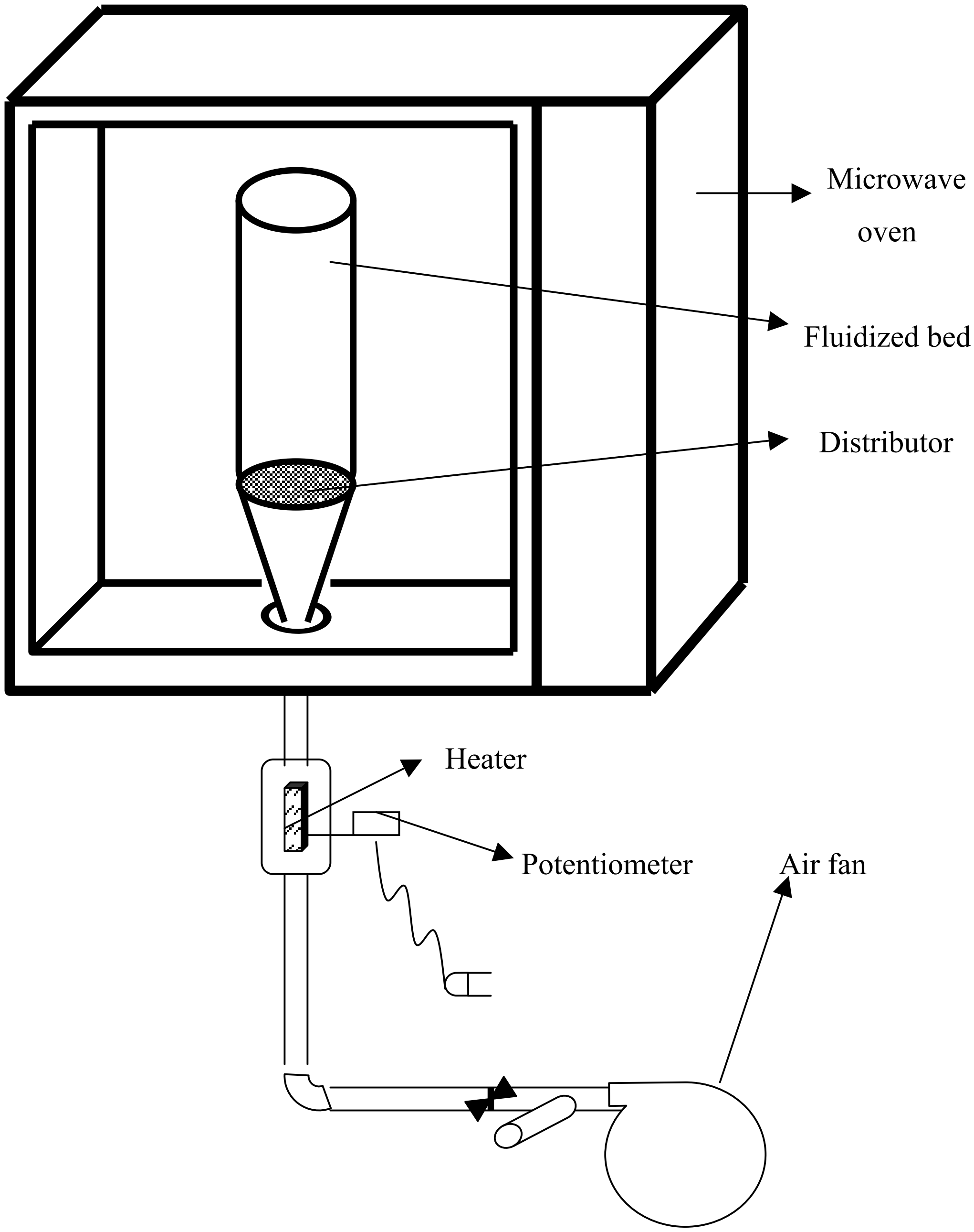

Figure 2.5 Microwave assisted fluidized bed drying apparatus.

CHAPTER 3

RESULTS AND DISCUSSION

Drying is the critical step in the processing of pasta products since some cracks or streaks may occur on the surface unless the conditions are carefully controlled. This is due to the fact that a case hardening occurs as a result of the rapid drying on the surface by conventional methods. Microwave assisted fluidized bed drying which combines the advantages of fluidized bed and microwave drying may overcome this problem. Therefore, macaroni beads which are quite spherical and appropriate for both fluidized bed and microwave drying were used as the samples throughout the experiments.

3.1 Superficial Air Velocity Determination

The weight of the rehydrated macaroni beads used in the experiments was nearly 225 g. The height of the fixed bed and the diameter of the bed were nearly equal at this amount of macaroni beads and therefore the effect of geometry on drying was minimized. The amount of macaroni beads used in the superficial air velocity determination experiment was selected as 225 g since the minimum fluidization velocity at this amount would be greater than the minimum fluidization velocity with the dried samples (200 g). Hence it was ensured that the superficial air velocity was always greater than the minimum fluidization velocity.

The separation point of the two curves one of which is for the increasing and the other for the decreasing superficial air velocity would give a greater value than the minimum fluidization velocity. Referring to the data given in Appendix B Tables B.1 and B.2, Figure 3.1 was plotted and used for the determination of the superficial air velocity that was used in the experiments.

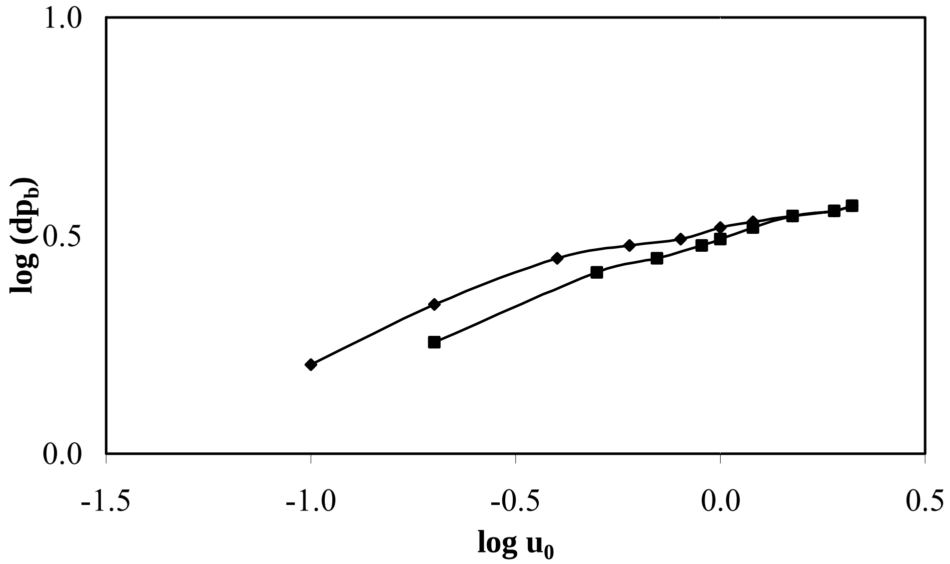

Figure 3.1 Variation of the pressure drop with the superficial air velocity in the fluidized bed.
(♦)increasing superficial air velocity (■)decreasing superficial air velocity

The separation point corresponds to a superficial air velocity of nearly 1.5 m/s. In the experiments, to ensure the bed was in the bubbling fluidization region, a superficial air velocity of 2.3 m/s, which corresponds to about 1.5 times the minimum fluidization velocity, was used. As the velocity is increased, greater degree of mixing together with the bed expansion is achieved. However, for the experimental bed, the overall height was limited with the microwave oven's cavity. At the superficial air velocities above 2.3 m/s there was the chance that some beads might be discharged from the bed. Therefore, a superficial air velocity of 2.3 m/s was appropriate for the experiments.

3.2 Fluidized Bed Drying

Macaroni beads are generally dried at nearly 60°C in conventional drying (Dablon and Oehler, 1983). Upon establishing the operational parameters of the fluidized bed the air temperatures of 50, 60 and 70°C were selected since 60°C is in between them.

The weight data taken in the fluidized bed experiments are given in Appendix D Table D.3.1. This data were converted into the moisture content in the dry basis data given in Appendix D Table D.4.1 using Table A.1 in Appendix A. The data in Appendix D Table D.4.1 were used in plotting the curves in Figure 3.2 where the effect of air temperature on fluidized bed drying can be observed.

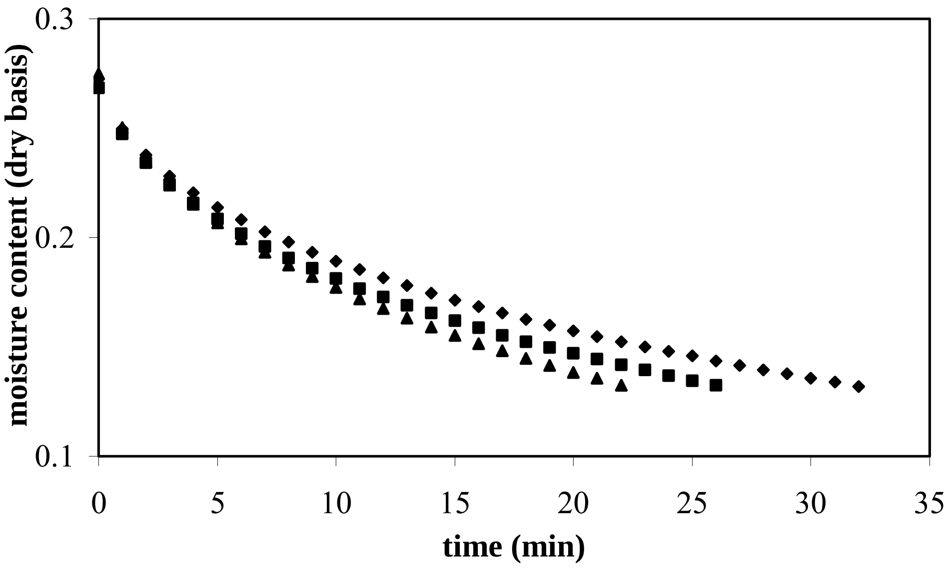

Figure 3.2 Fluidized bed drying curves at different temperatures.
(♦)50°C temperature (■)60°C temperature (▲)70°C temperature

As the temperature increased, the drying time decreased. The temperature of the particles could not exceed the air temperature in the fluidized bed drying since it was the only energy source. The evaporation rate and the effective diffusivity increased with the increasing air temperature resulting in a higher drying rate.

3.3 Microwave Drying

The power of the microwave oven was determined by the 2-Liter test given in Appendix C as 609 W. In the fluidized bed drying, it is assumed that the particles are physically separated from each other and to obtain such a condition in the microwave drying experiments, the macaroni beads were scattered on a large plate in a way that the contact of particles were minimized. The weight of the particles in the petri dish placed at the center was measured to minimize the effects of the geometry since the fluidized bed was placed at the center of the microwave oven cavity. The other portion of the rehydrated macaroni beads was placed around the petri dish, otherwise the power absorption of the particles would change resulting in errors.

The drying data obtained in microwave drying of macaroni beads are given in Appendix D Table D.3.2 and were converted into the moisture content in the dry basis which are given in Appendix D Table D.4.2 using Table A.1 in Appendix A. The data in Appendix D Table D.4.2 were used in plotting the curves in Figure 3.3 where the effect of microwave power level on microwave drying can be observed.

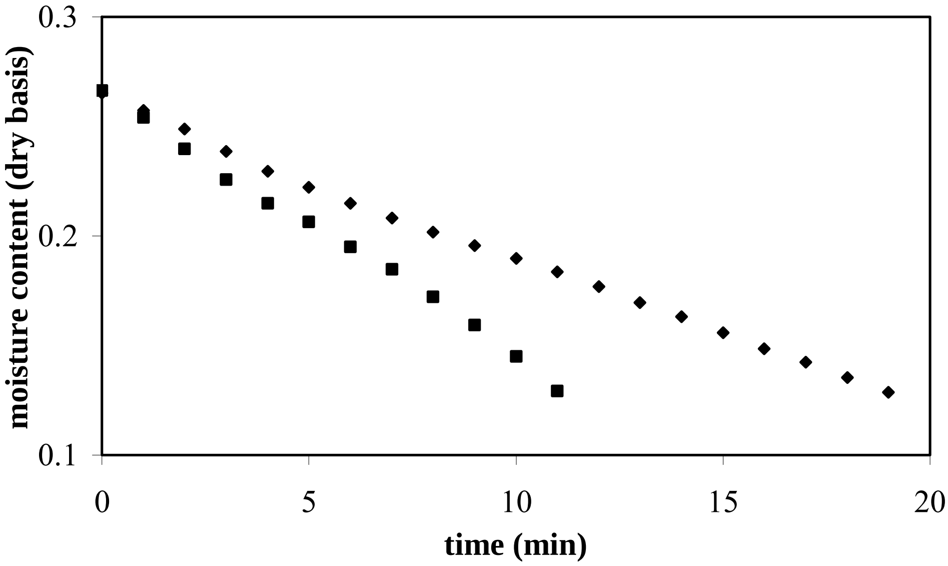

Figure 3.3 Microwave drying curves at different power levels.
(♦)50% power level (■)100% power level

In Figure 3.3, it can be observed that the variations are different from those of in the fluidized bed drying. Primarily, when the microwave power increased, the drying time decreased. This was expected since with higher microwave power more energy was supplied to the particles and higher internal temperatures were obtained. This in turn caused the vapor pressure to increase resulting in an increased driving force for mass transfer and hence the drying rate.

Another point is that these results represent the average moisture content of the particles which were not mixed. Because of the non-uniform energy distribution within the microwave cavity, it is impossible to claim that each particle had the same average moisture content. On the other hand, in the fluidized bed and microwave assisted fluidized bed drying it can be assumed that each particle had the same average moisture content since well mixing was provided.

3.4 Microwave Assisted Fluidized Bed Drying

The data taken in the microwave assisted fluidized drying are given in Appendix D Tables D.3.3 and D.3.4. This data were converted into moisture content in dry basis data given in Appendix D Tables D.4.3 and D.4.4 using Table A.2 in Appendix A and Figures 3.4, 3.5, 3.6, 3.7, 3.8, 3.9, 3.10, 3.11, 3.12, 3.13 and 3.14 were plotted.

Figures 3.4, 3.5 and 3.6 show the comparison of fluidized bed and microwave assisted fluidized bed drying whereas Figures 3.7 and 3.8 show the comparison of microwave only and microwave assisted fluidized bed drying. Figures 3.9, 3.10, 3.11, 3.12, 3.13 and 3.14 show the comparison of fluidized bed, microwave and microwave assisted fluidized bed drying.

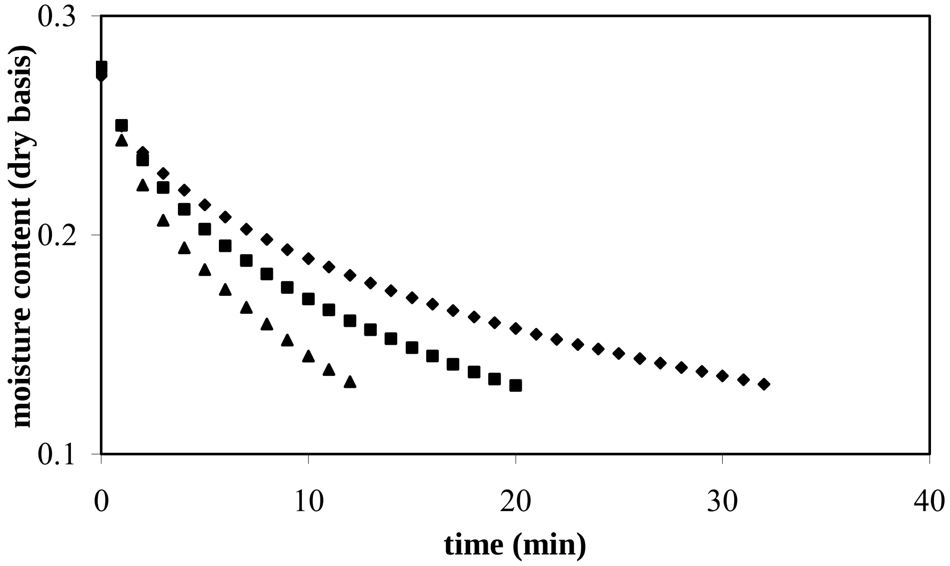

Figure 3.4 Drying curves for fluidized bed and microwave assisted fluidized bed drying at 50°C temperature.

(♦)fluidized bed only (■)50% power level (▲)100% power level

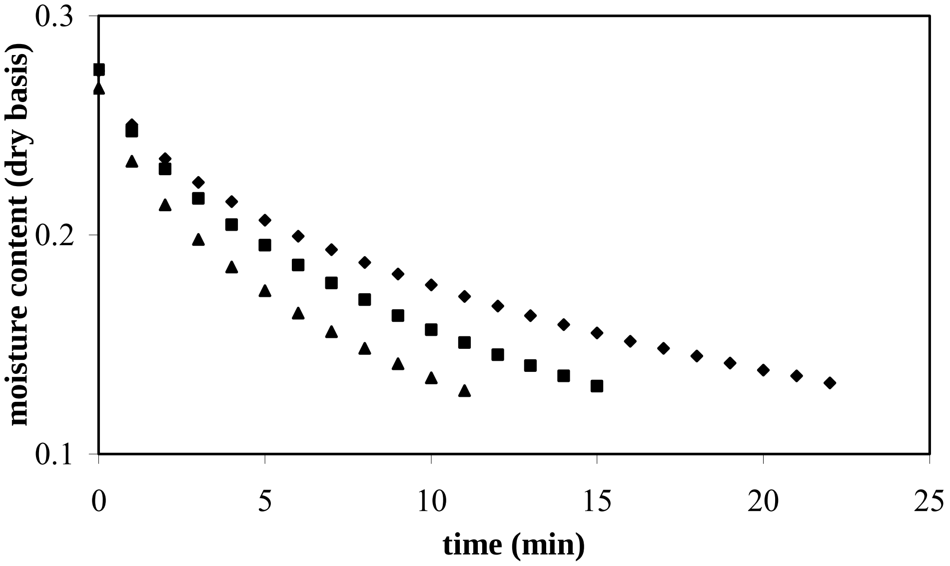

Figure 3.5 Drying curves for fluidized bed and microwave assisted fluidized bed drying at 60°C temperature.

(♦)fluidized bed only (■)50% power level (▲)100% power level

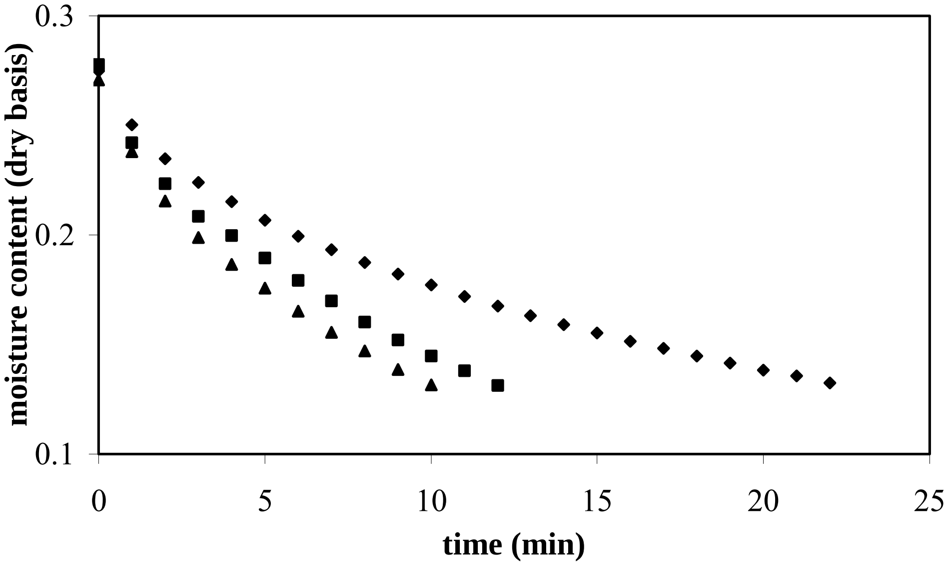

Figure 3.6 Drying curves for fluidized bed and microwave assisted fluidized bed drying at 70°C temperature.

(♦)fluidized bed only (■)50% power level (▲)100% power level

Figures 3.3, 3.4 and 3.5 clearly indicate the positive effect of the microwave energy and its power on the reduction of the drying time. As it was mentioned, the contribution was mostly due to the elevated internal temperature of the particles resulting in a greater vapor pressure hence the driving force. In addition, it was observed that the drying rate curves for the fluidized bed and microwave assisted fluidized bed drying highly resembled each other.

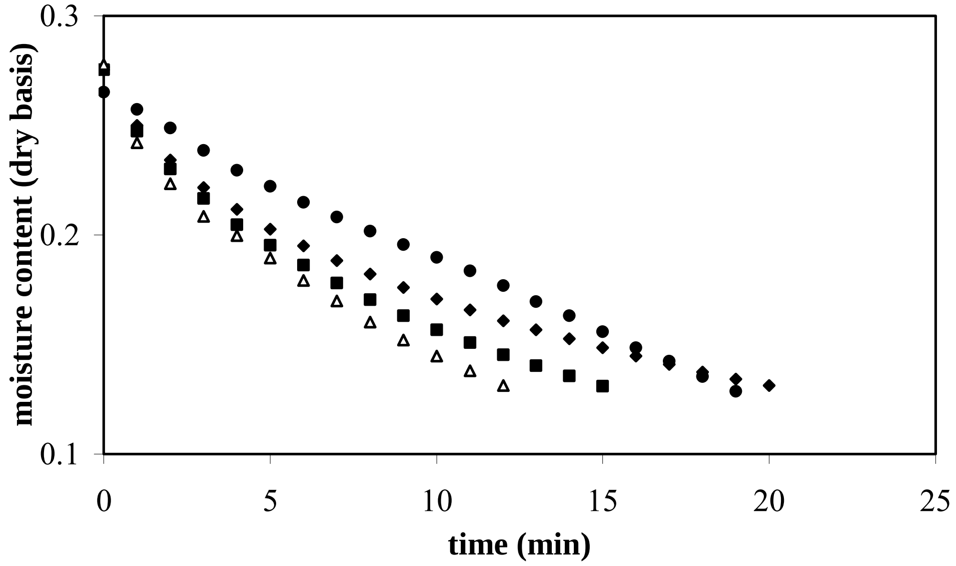

Figure 3.7 Drying curves for microwave and microwave assisted fluidized bed drying at 50% power level.

(♦)50°C temperature (■)60°C temperature (Δ)70°C temperature (●)microwave only

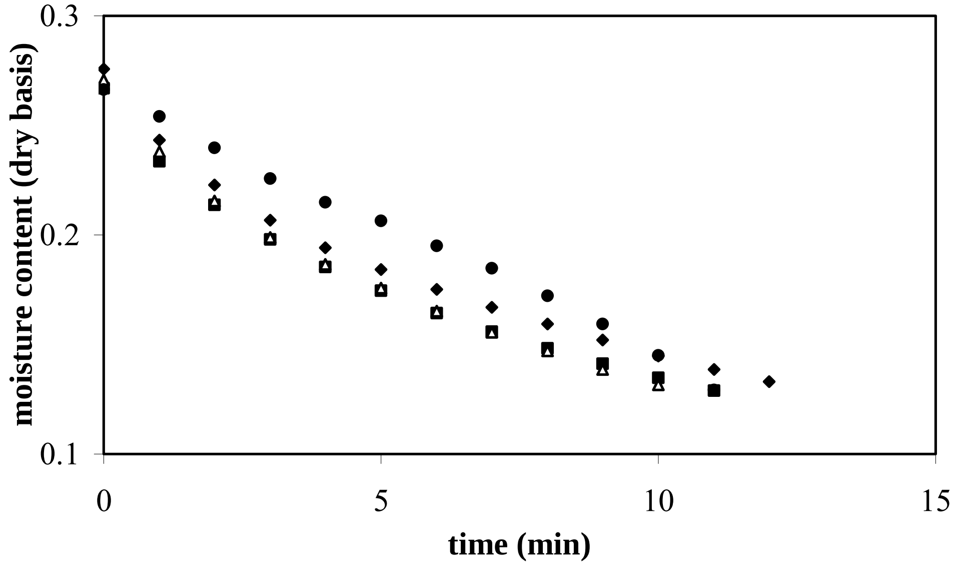

Figure 3.8 Drying curves for microwave and microwave assisted fluidized bed drying at 100% power level.

(♦)50°C temperature (■)60°C temperature (Δ)70°C temperature (●) microwave only

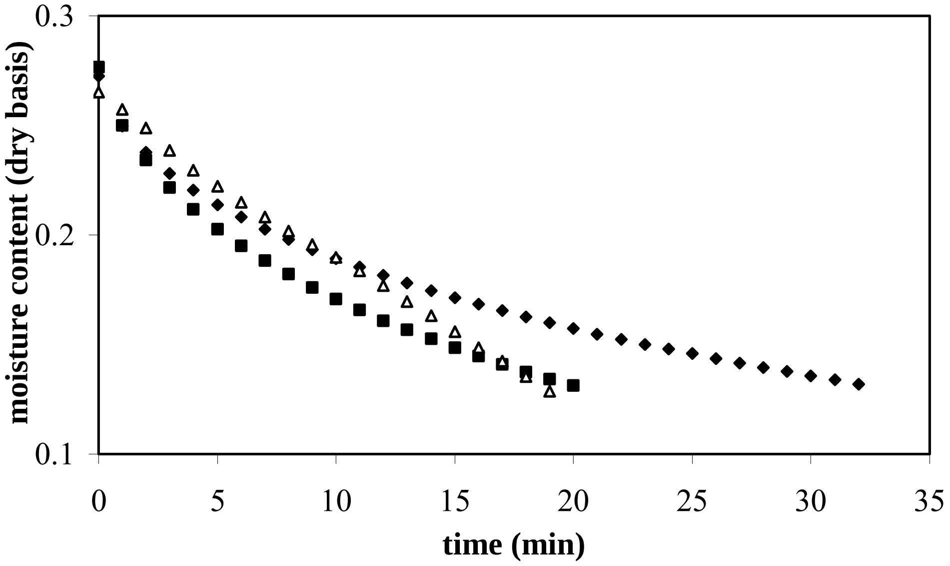

Figure 3.9 Drying curves for 50°C temperature and 50% power level.
(♦)50°C temperature fluidized bed only (Δ)50% power level microwave only (■)50°C and 50% microwave assisted fluidized bed drying

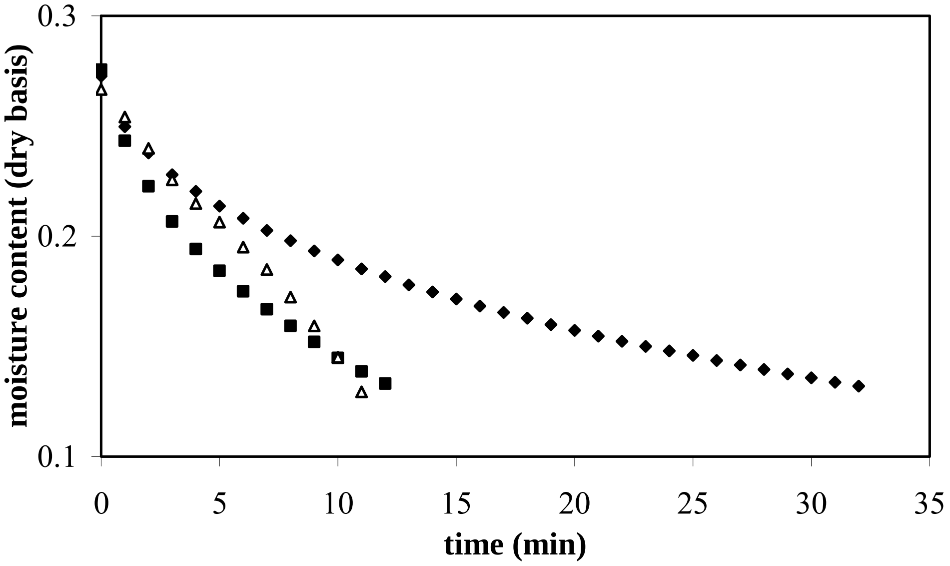

Figure 3.10 Drying curves for 50°C temperature and 100% power level.
(♦)50°C temperature fluidized bed only (Δ)100% power level microwave only (■)50°C and 100% microwave assisted fluidized bed drying

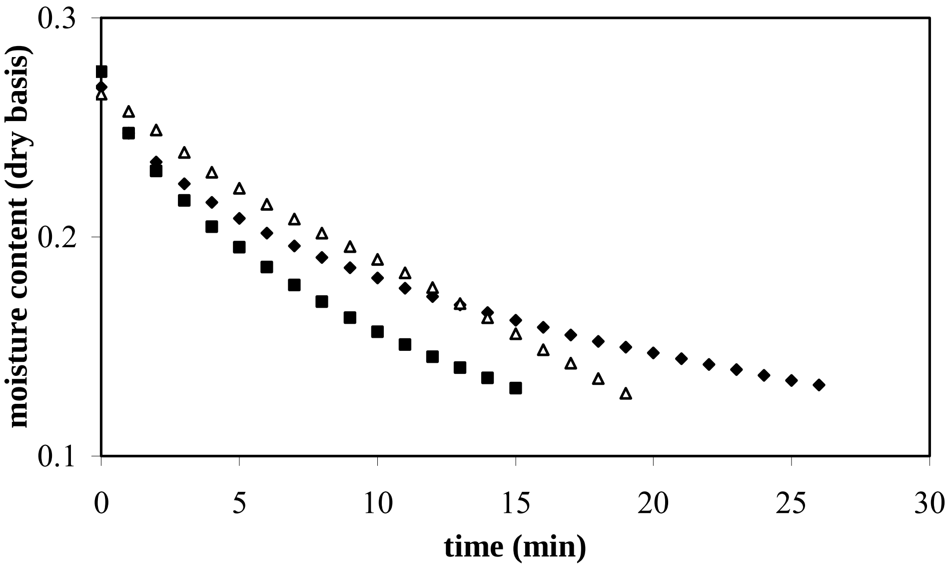

Figure 3.11 Drying curves for 60°C temperature and 50% power level.
(♦)60°C temperature fluidized bed only (Δ)50% power level microwave only (■)60°C and 50% microwave assisted fluidized bed drying

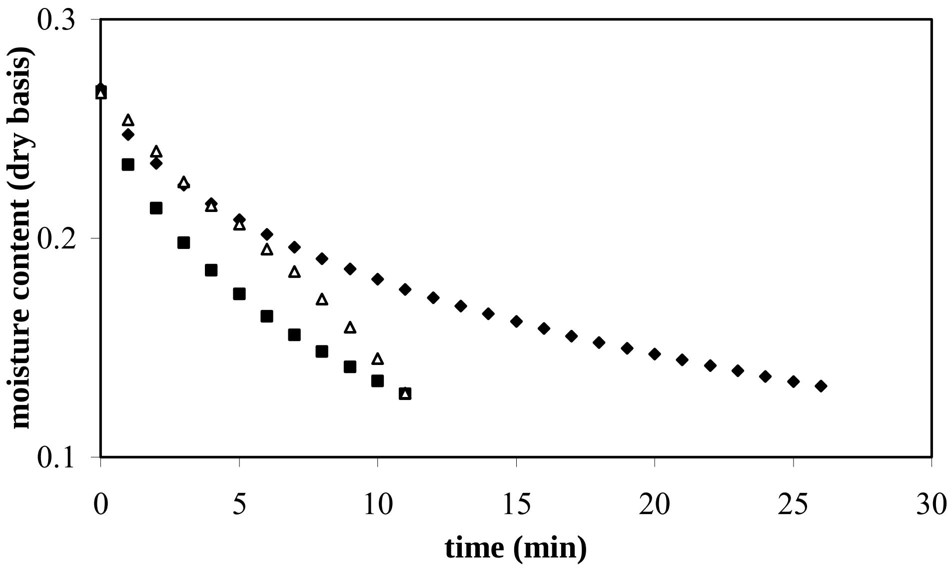

Figure 3.12 Drying curves for 60°C temperature and 100% power level.
(♦)60°C temperature fluidized bed only (Δ)100% power level microwave only (■)60°C and 100% microwave assisted fluidized bed drying

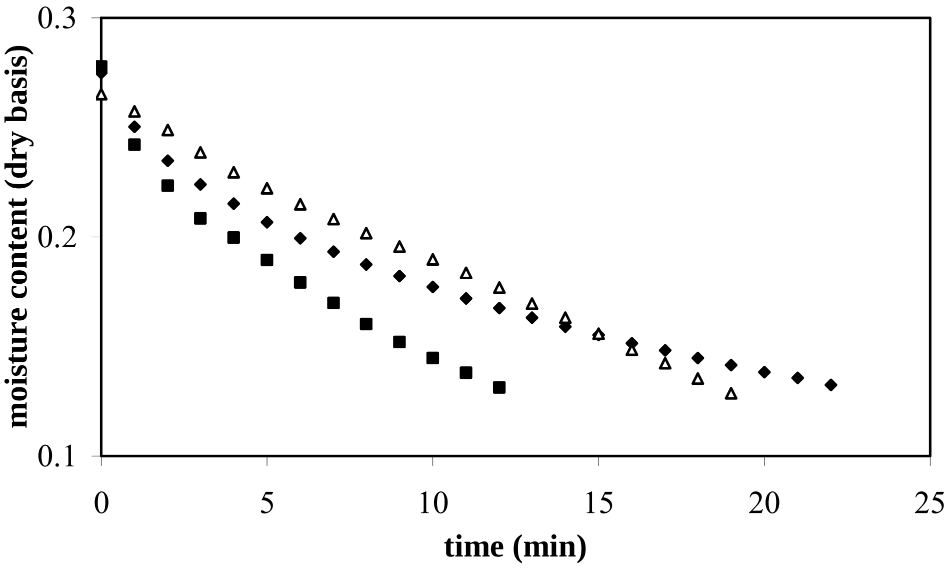

Figure 3.13 Drying curves for 70°C temperature and 50% power level.
(♦)70°C temperature fluidized bed only (Δ)50% power level microwave only (■)70°C and 50% microwave assisted fluidized bed drying

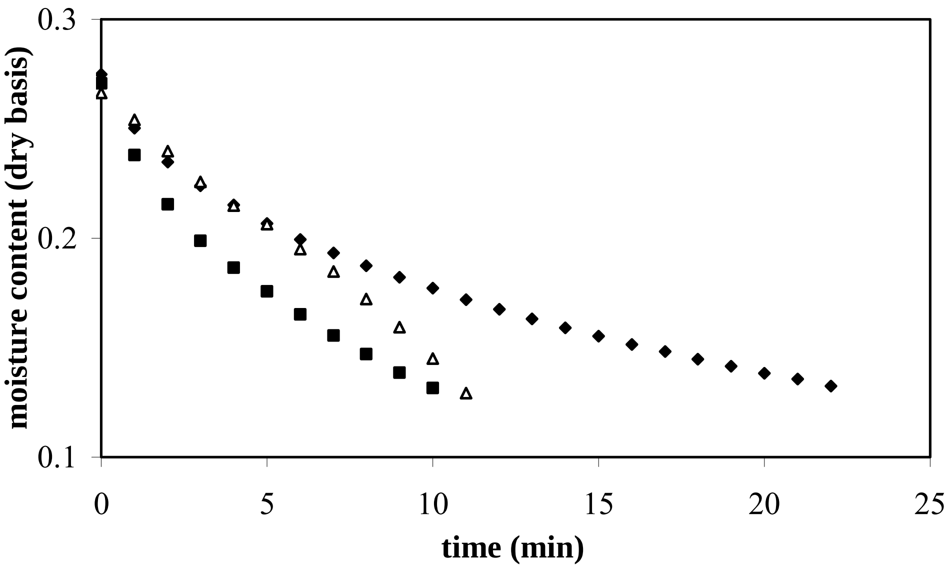

Figure 3.14 Drying curves for 70°C temperature and 100% power level.
(♦)70°C temperature fluidized bed only (Δ)100% power level microwave only (■)70°C and 100% microwave assisted fluidized bed drying

Figures 3.7 and 3.8 reflected a similar positive contribution of the air temperature on the drying in the microwave assisted fluidized bed drying.

In Figures 3.9, 3.10, 3.11, 3.12, 3.13 and 3.14, it can be seen that the drying time in microwave drying at 50% power level was shorter than that of the microwave assisted fluidized bed drying at 50°C air temperature and 50% power level. An identical behavior was valid also for the microwave drying at 100% power level and the microwave assisted fluidized bed drying at 50°C air temperature and 100% power level. This can be due to a number of factors. The non-uniform energy distribution within the oven cavity might cause overdried particles at some locations and decreased the average value in the microwave drying. Further, the cooling might affect the vapor pressure in the reverse manner and caused the driving force to decrease. However, it is quite impossible to determine the partial contribution of these or some other effects on the behavior.

Table 3.1 Drying times for different drying conditions.

	No fluidization	**50°C air temperature**	**60°C air temperature**	**70°C air temperature**
No microwave energy		32 min	26 min	22 min
50% microwave power level	19 min	20 min	15 min	12 min
100% microwave power level	11 min	12 min	11 min	10 min

The magnitude of contribution of fluidization or microwave energy on the microwave assisted fluidized bed drying can be decided from the time reduction using the Table 3.1. It can be seen that the drying time was reduced more by the effect of microwave energy than the fluidization. For instance, when the microwave assisted fluidized bed drying at 60°C air temperature and 50% power level was compared with the fluidized bed drying at 60°C air temperature and microwave drying at 50% power level, the drying times were reduced nearly 42% and 21%, respectively. Therefore, it can be concluded that the magnitude of the contribution of microwave energy on microwave assisted fluidized bed drying was more than the fluidization.

In accordance with the discussions above, the shortest drying time among all the drying conditions studied was obtained in the microwave assisted fluidized bed drying at 70°C air temperature and 100% microwave power level.

3.5 Effective Diffusivities

The relative humidity of the air was found referring to the data given in Appendix D Table D.1. The humidity of the air was not changed and the relative humidity of the air used in the experiments was found with the aid of a psychrometric chart. The relative humidity and the corresponding equilibrium moisture contents are given in Appendix D Table D.2. The moisture contents given in Appendix D Tables D.4.1, D.4.2 and D.4.3 and the equilibrium moisture contents given in Appendix D Table D.2 were treated according to Eq. 1.7. In microwave assisted fluidized bed drying, the particles contacted with air resulting in a temperature decrease and the temperature within the particles could not be measured. Therefore, equilibrium moisture contents at 50, 60 and 70°C were used to compare microwave assisted fluidized bed and fluidized bed drying. The results are given in Appendix D Tables D.5.1, D.5.2 and D.5.3 and were used to plot the curves in Figures 3.15, 3.16 and 3.17. The linear portions of these curves were fitted to linear equations given in Appendix D Table D.6 by regression analysis.

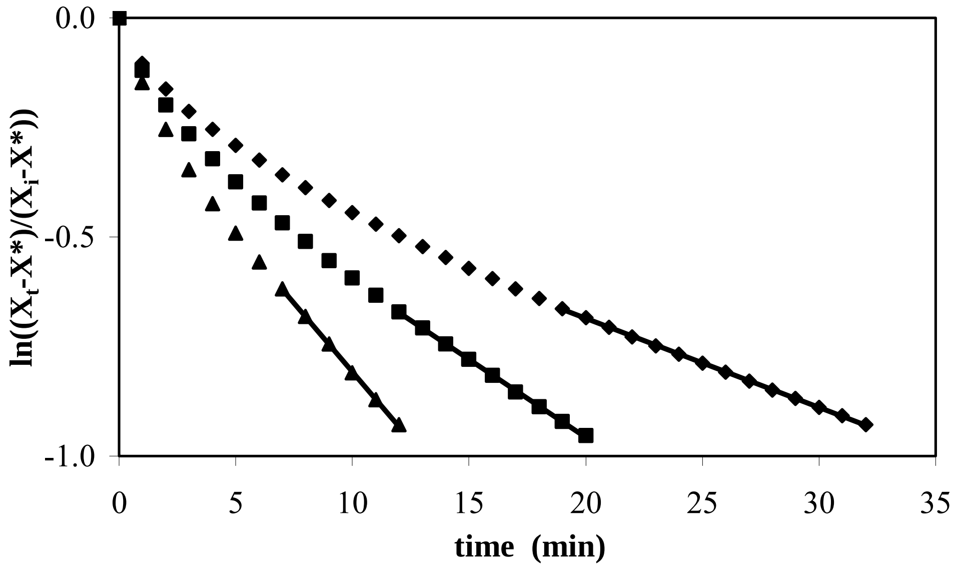

Figure 3.15 Variation of dimensionless moisture content with time for the fluidized bed and microwave assisted fluidized bed drying at 50°C temperature.
(♦)fluidized bed only (■)50% power level (▲)100% power level

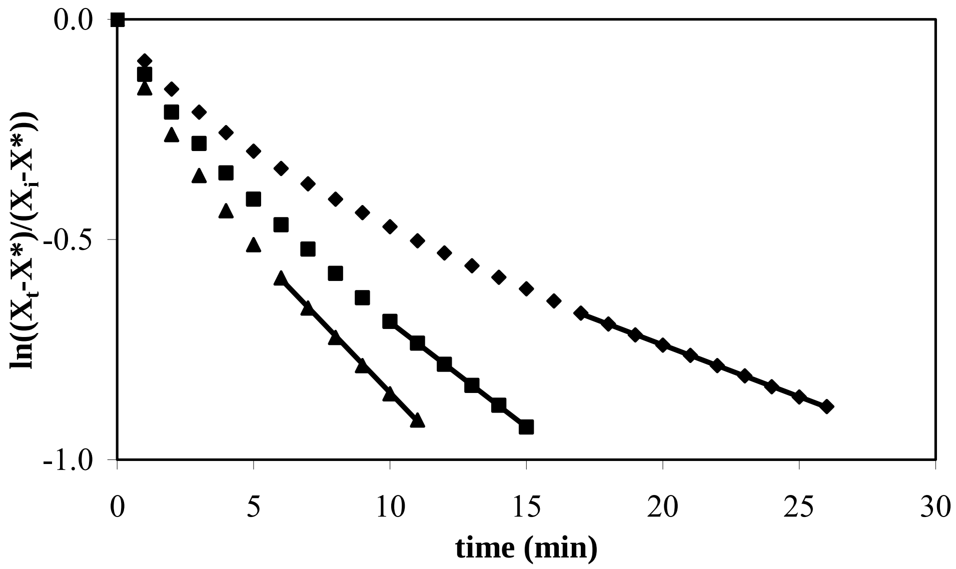

Figure 3.16 Variation of dimensionless moisture content with time for the fluidized bed and microwave assisted fluidized bed drying at 60°C temperature.
(♦)fluidized bed only (■)50% power level (▲)100% power level

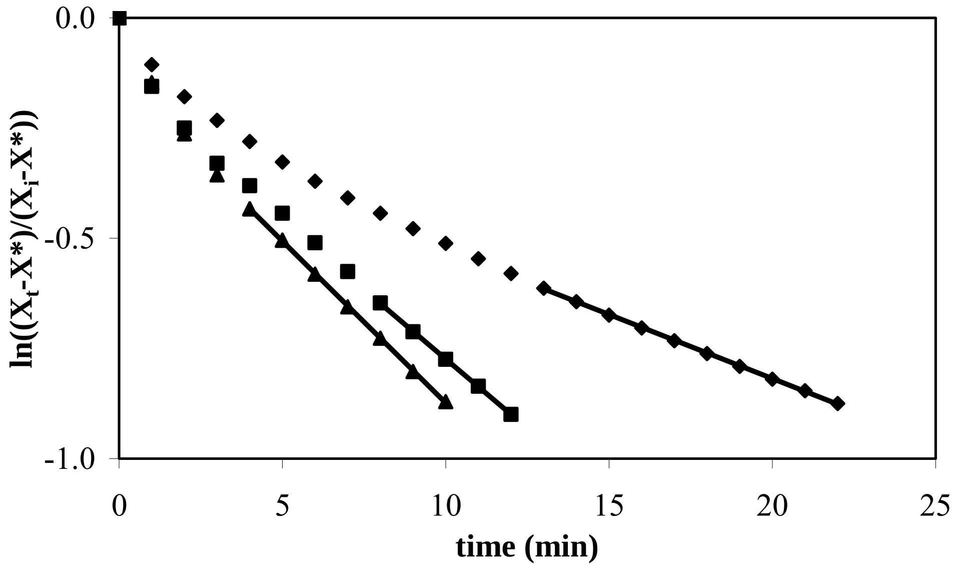

Figure 3.17 Variation of dimensionless moisture content with time for the fluidized bed and microwave assisted fluidized bed drying at 70°C temperature.
(♦)fluidized bed only (■)50% power level (▲)100% power level

It can be seen from Figures 3.9, 3.10 and 3.11 that the curves for the microwave assisted fluidized bed resemble those for the fluidized bed drying.

The slopes of the lines in the Figures 3.15, 3.10, 3.16 and 3.17 were used to calculate the effective diffusivities using the Eq. 1.7. The results were tabulated in Table 3.2.

Table 3.2 Effective diffusivities for approach 1.

Drying Condition	**Effective diffusivity x 10^{11} (m^2/s)**
Fluidized bed drying 50°C temperature	4.936
Microwave assisted fluidized bed drying 50°C temperature 50% power level	8.633
Microwave assisted fluidized bed drying 50°C temperature 100% power level	15.198
Fluidized bed drying 60°C temperature	5.763
Microwave assisted fluidized bed drying 60°C temperature 50% power level	11.624
Microwave assisted fluidized bed drying 60°C temperature 100% power level	15.709
Fluidized bed drying 70 °C temperature	7.076
Microwave assisted fluidized bed drying 70°C temperature 50% power level	15.295
Microwave assisted fluidized bed drying 70°C temperature 100% power level	17.824

For this approach to be applicable, it should be checked that the Fourier number is greater than 0.1. Fourier number data for the last minute for each application are given in Table 3.2.

Table 3.3 Fourier numbers for approach 1.

Drying Condition	Fourier number
Fluidized bed drying 50°C temperature	0.066
Microwave assisted fluidized bed drying 50°C temperature 50% power level	0.072
Microwave assisted fluidized bed drying 50°C temperature 100% power level	0.076
Fluidized bed drying 60°C temperature	0.062
Microwave assisted fluidized bed drying 60°C temperature 50% power level	0.073
Microwave assisted fluidized bed drying 60°C temperature 100% power level	0.072
Fluidized bed drying 70 °C temperature	0.065
Microwave assisted fluidized bed drying 70°C temperature 50% power level	0.076
Microwave assisted fluidized bed drying 70°C temperature 100% power level	0.074

The Fourier numbers were found to be smaller than 0.1, therefore, another approach was developed. The first ten terms of the right hand side of the Eq. 1.6 were taken into account and starting from the final time, the effective diffusivities at each time were calculated by means of Mathcad program. The average effective diffusivities were calculated from $t=t_{final}$ to t=t. In addition, the percent deviations of each effective diffusivity from the average value were calculated. The last average effective diffusivity at which percent deviation was smaller or equal to 5% was taken to be the effective diffusivity for those drying conditions. All of the relevant data are given in Appendix D Tables D.7.1, D.7.2, D.7.3, D.7.4, D.7.6, D.7.7, D.7.8 and D.7.9.

Table 3.4 Effective diffusivities for approach 2.

Drying Condition	**Effective diffusivity x 10^{11} (m^2/s)**
Fluidized bed drying 50°C temperature	3.596
Microwave assisted fluidized bed drying 50°C temperature 50% power level	5.986
Microwave assisted fluidized bed drying 50°C temperature 100% power level	9.597
Fluidized bed drying 60°C temperature	4.051
Microwave assisted fluidized bed drying 60°C temperature 50% power level	7.556
Microwave assisted fluidized bed drying 60°C temperature 100% power level	10.168
Fluidized bed drying 70°C temperature	4.728
Microwave assisted fluidized bed drying 70°C temperature 50% power level	8.977
Microwave assisted fluidized bed drying 70°C temperature 100% power level	10.348

In fluidized bed and microwave assisted fluidized bed drying, one can see the increase in effective diffusivities with the air temperature and microwave power level in Table 3.2. These are in conjunction with the discussions above. As a means of comparison, the effective diffusivities of water in dehydrated and gelatinized starch are in the order of $10^{-10} - 10^{-9}$ m^2/s and $10^{-11} - 10^{-10}$ m^2/s, respectively (Uzman and Şahbaz, 2000). In addition, the effective diffusivity of water in ethanol is in the order of 10^{-9} m^2/s (Geankoplis, 1993).

3.6 Effect of Temperature

The temperatures and the corresponding effective diffusivities for fluidized bed drying given in Table 3.4 were treated with the Eq. 1.9 and the Arrhenius plot is given in Figure 3.18 below. A linear regression analysis was performed and the equation is given in Appendix D Table D.8. The effective diffusivities for microwave assisted fluidized bed drying could also have been included to this plot if it were possible to measure the temperatures.

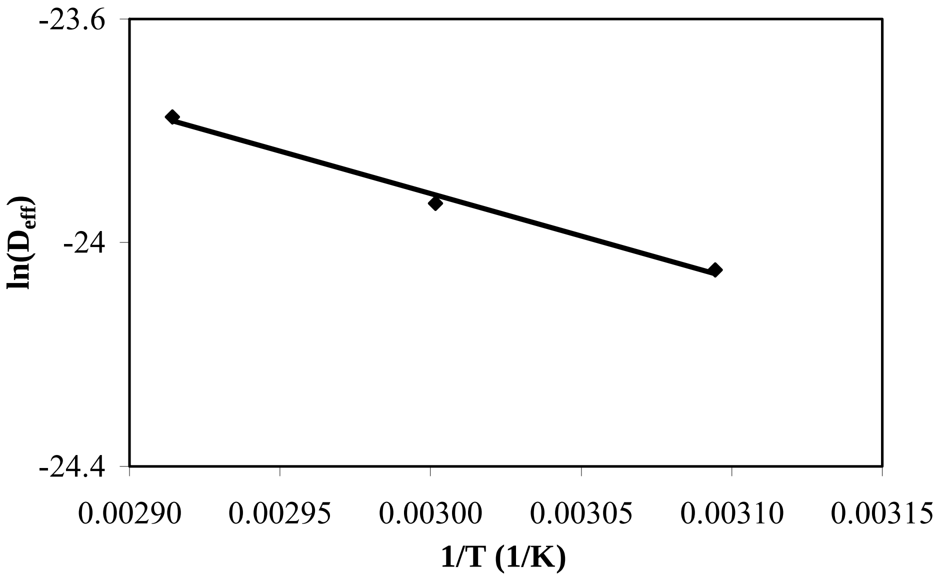

Figure 3.18 Arrhenius plot for the fluidized bed drying.

D_0 and the activation energy were found from the intercept and slope of the line as 3.88 x 10^{-9} m^2/s and 12595.71 kJ/kg mol, respectively. This activation energy was about 5.5 times smaller than the value of 68938.46 kJ/kg mol calculated for tray drying of macaroni balls by Adar (1989). The difference may be due to the drying method, size and structural differences among the particles and it reflects the advantage of fluidized bed drying over tray drying whenever the application is possible. The activation energies related to the mass transfer by diffusion mechanism in foods are generally close to the range of 15 – 40 kJ/mol (Lenz, 2003). The activation energy found in this study is close to this range.

CHAPTER 4

CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions

In the light of the experimental results and the prevailing discussions the following conclusions can be reached. The drying time in the fluidized bed drying can be reduced by about 17% as the temperature of the air was increased by 10°C on the average. On the same basis the drying time in microwave drying can be decreased by about 42% as the microwave power was increased by 50%. These two independent effects can be used to reduce the drying time appreciably in the microwave assisted fluidized bed drying.

Microwave assisted fluidized bed drying reduced the drying time by about 50% and 11% on the average compared with the fluidized bed and microwave drying, respectively. On the basis of these results, it can be concluded that the microwave energy is more dominant on affecting the drying rate than fluidization. With regard to this fact the fluidization is useful to render equal drying rates for the individual particles as well as rapid removal of the internal moisture transferred to the surface of the particles.

The effective moisture diffusivities in the fluidized bed and microwave assisted fluidized bed drying were calculated. The average effective diffusivity found in the microwave assisted fluidized bed was found to become higher as the air temperature and the microwave power level were increased. Further, the effective diffusivities in the fluidized bed drying can be explained by an Arrhenius type of relation which indicates an activation energy in the order of 12595 kJ/kg mol.

4.2 Recommendations

The studies on the microwave assisted fluidized bed drying are limited in the literature. For the future studies, it can be recommended that not only the drying of several types of particulate foods but also the drying of other materials such as powders should be studied in terms of the drying rates and effective diffusivities. The studies on these materials can be improved by modeling the drying via measuring the temperature and pressure. The effect of microwave assisted fluidized bed drying on the texture of macaroni beads and other several types of foods can be studied. Furthermore, economic analysis can be performed to optimize the drying conditions.

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APPENDIX A

DRY WEIGHT DETERMINATION

Table A.1 Final weight of macaroni beads at 100°C.

Replicate	Weight (g)
1	175.92
2	177.01
3	176.27
Average	**176.40**

APPENDIX B

SUPERFICIAL AIR VELOCITY DETERMINATION

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

Superficial air velocity, u_0 (m/s)	**Pressure drop, Δp_b (cm H_2O)**	**log (u_0)**	**log (Δp_b)**
0.1	1.6	-1.00000	0.20412
0.2	2.2	-0.69897	0.34242
0.4	2.8	-0.39794	0.44716
0.6	3.0	-0.22185	0.47712
0.8	3.1	-0.09691	0.49136
1.0	3.3	0.00000	0.51851
1.2	3.4	0.07918	0.53148
1.5	3.5	0.17609	0.54407
1.9	3.6	0.27875	0.55630
2.1	3.7	0.32222	0.56820

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

Superficial air velocity, u_0 (m/s)	**Pressure drop, Δp_b (cm H_2O)**	**log (u_0)**	**log (Δp_b)**
2.1	3.7	0.32222	0.56820
1.9	3.6	0.27875	0.55630
1.5	3.5	0.17609	0.54407
1.2	3.3	0.07918	0.51851
1.0	3.1	0.00000	0.49136
0.9	3.0	-0.04576	0.47712
0.7	2.8	-0.15490	0.44716
0.5	2.6	-0.30103	0.41497
0.2	1.8	-0.69897	0.25527

APPENDIX C

POWER MEASUREMENT TEST PROCEDURE-IMPI 2-LITER TEST

Operate the oven at its rated line voltage with oven set on high with a load of 2000 ± 5 g placed in two 1-L beakers. The beakers should initially be at room ambient temperature. Initial water temperature should be 20^0C ± 2^0C, measured after water is placed in beakers and before placing in the microwave oven. The beakers are placed in the center of the oven, side by side in the width dimension of the cavity, and touching each other. The oven is turned on for 2 min and 2 s. The beakers are removed from the oven, and the final temperatures are measured and recorded.

The power is calculated from the following formula:

$$P(W) = 70 \times \left(\frac{\Delta T_1(°C) + \Delta T_2(°C)}{2} \right) \qquad \text{C.1}$$

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

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

Note: The oven should be pre-warmed by heating 2L of water for 5 minutes, then wiping the shelf with a cold wet rag.

The water in each vessel should be well stirred by plastic or wooden spoon before measuring the starting and final temperatures. The temperature should be measured with a thermometer with 0.1°C resolution (Buffler, 1993).

Table C.1 Power measurement test data.

Replicate		**T_1 (°C)**	**T_2 (°C)**	**Power (W)**	**% dev**
1	T_i	20.6	20.6	616	1.1
	T_f	29.3	29.5		
	ΔT	8.7	8.9		
2	T_i	21.2	21	616	1.1
	T_f	29.7	30.1		
	ΔT	8.5	9.1		
3	T_i	21.1	21.3	595	3
	T_f	29.5	29.9		
	ΔT	8.4	8		
Average P (W)				**609**	

APPENDIX D

DRYING EXPERIMENTS

D.1 Psychrometric Data

Table D.1 Psychrometric data for the air at the surroundings.

Dry bulb temperature (°C)	**Wet bulb temperature (°C)**	**% Relative humidity**	**Humidity (kg water vapor/kg dry air)**
22.8	14	40	0.008

D.2 Equilibrium Moisture Contents

Dinçer (1991) found out that:

Table D.2 Equilibrium moisture content of macaroni at different temperatures.

Temperature (°C)	**% Relative humidity**	**Equilibrium moisture content (db)**
50	7.5	0.040
60	4.5	0.036
70	2.5	0.031

D.3 Weight Data

Table D.3.1 Weight data for fluidized bed drying at different air temperatures.

time (min)	50°C air temperature	60°C air temperature	70°C air temperature
0	224.49	223.76	224.87
1	220.46	220.06	220.54
2	218.33	217.74	217.84
3	216.62	215.97	215.93
4	215.27	214.45	214.36
5	214.11	213.17	212.87
6	213.10	211.98	211.56
7	212.13	210.96	210.47
8	211.30	210.02	209.47
9	210.49	209.18	208.52
10	209.78	208.36	207.65
11	209.09	207.56	206.75
12	208.43	206.86	205.95
13	207.80	206.19	205.16
14	207.20	205.57	204.46
15	206.64	204.98	203.78
16	206.09	204.40	203.14
17	205.58	203.81	202.53
18	205.10	203.29	201.95
19	204.60	202.79	201.36
20	204.15	202.33	200.82
21	203.70	201.86	200.31
22	203.28	201.42	199.79
23	202.88	200.99	
24	202.50	200.56	
25	202.12	200.15	
26	201.74	199.76	
27	201.36		
28	201.01		
29	200.67		
30	200.33		
31	200.01		
32	199.68		

Table D.3.2 Weight data for microwave drying at different power levels.

time (min)	50% microwave power	100% microwave power
0	223.20	223.40
1	221.80	221.20
2	220.30	218.70
3	218.50	216.20
4	216.90	214.30
5	215.60	212.80
6	214.30	210.80
7	213.10	209.00
8	212.00	206.80
9	210.90	204.50
10	209.90	202.00
11	208.80	199.20
12	207.60	
13	206.30	
14	205.20	
15	203.90	
16	202.60	
17	201.50	
18	200.30	
19	199.10	

Table D.3.3 Weight data for microwave assisted fluidized bed drying at 50% power level and different air temperatures.

time (min)	50°C air temperature	60°C air temperature	70°C air temperature
0	225.21	224.99	225.41
1	220.48	220.03	219.13
2	217.70	216.97	215.79
3	215.49	214.60	213.17
4	213.73	212.53	211.62
5	212.16	210.83	209.80
6	210.82	209.24	208.00
7	209.61	207.80	206.36
8	208.53	206.46	204.67
9	207.45	205.19	203.22
10	206.52	204.03	201.93
11	205.62	203.00	200.74
12	204.79	202.04	199.58
13	204.03	201.15	
14	203.30	200.32	
15	202.60	199.49	
16	201.91		
17	201.24		
18	200.64		
19	200.07		
20	199.55		

Table D.3.4 Weight data for microwave assisted fluidized bed drying at 100% power level and different air temperatures.

time (min)	50°C air temperature	60°C air temperature	70°C air temperature
0	225.03	223.49	224.18
1	219.31	217.63	218.39
2	215.68	214.11	214.40
3	212.85	211.33	211.49
4	210.66	209.12	209.31
5	208.91	207.19	207.42
6	207.28	205.40	205.54
7	205.85	203.91	203.84
8	204.49	202.53	202.32
9	203.20	201.30	200.84
10	201.94	200.16	199.59
11	200.85	199.16	
12	199.88		

D.4 Moisture Content Data

Table D.4.1 Moisture content (dry basis) data for fluidized bed drying at different air temperatures.

time (min)	**50°C air temperature**	**60°C air temperature**	**70°C air temperature**
0	0.27262	0.26848	0.27477
1	0.24977	0.24751	0.25023
2	0.23770	0.23435	0.23492
3	0.22800	0.22432	0.22409
4	0.22035	0.21570	0.21519
5	0.21378	0.20845	0.20675
6	0.20805	0.20170	0.19932
7	0.20255	0.19592	0.19314
8	0.19785	0.19059	0.18747
9	0.19325	0.18583	0.18209
10	0.18923	0.18118	0.17715
11	0.18532	0.17664	0.17205
12	0.18158	0.17268	0.16752
13	0.17800	0.16888	0.16304
14	0.17460	0.16536	0.15907
15	0.17143	0.16202	0.15522
16	0.16831	0.15873	0.15159
17	0.16542	0.15539	0.14813
18	0.16270	0.15244	0.14484
19	0.15986	0.14960	0.14150
20	0.15731	0.14700	0.13844
21	0.15476	0.14433	0.13554
22	0.15238	0.14184	0.13260
23	0.15011	0.13940	
24	0.14796	0.13696	
25	0.14580	0.13464	
26	0.14365	0.13243	
27	0.14150		
28	0.13951		
29	0.13759		
30	0.13566		
31	0.13384		
32	0.13197		

Table D.4.2 Moisture content (dry basis) data for microwave drying at different power levels.

time (min)	50% microwave power	100% microwave power
0	0.26531	0.26644
1	0.25737	0.25397
2	0.24887	0.23980
3	0.23866	0.22562
4	0.22959	0.21485
5	0.22222	0.20635
6	0.21485	0.19501
7	0.20805	0.18481
8	0.20181	0.17234
9	0.19558	0.15930
10	0.18991	0.14512
11	0.18367	0.12925
12	0.17687	
13	0.16950	
14	0.16327	
15	0.15590	
16	0.14853	
17	0.14229	
18	0.13549	
19	0.12868	

Table D.4.3 Moisture content (dry basis) data for microwave assisted fluidized bed drying at 50% power level and different air temperatures.

time (min)	50°C air temperature	60°C air temperature	70°C air temperature
0	0.27670	0.27545	0.27783
1	0.24989	0.24734	0.24223
2	0.23413	0.22999	0.22330
3	0.22160	0.21655	0.20845
4	0.21162	0.20482	0.19966
5	0.20272	0.19518	0.18934
6	0.19512	0.18617	0.17914
7	0.18827	0.17800	0.16984
8	0.18214	0.17041	0.16026
9	0.17602	0.16321	0.15204
10	0.17075	0.15663	0.14473
11	0.16565	0.15079	0.13798
12	0.16094	0.14535	0.13141
13	0.15663	0.14031	
14	0.15249	0.13560	
15	0.14853	0.13090	
16	0.14461		
17	0.14082		
18	0.13741		
19	0.13418		
20	0.13124		

Table D.4.4 Moisture content (dry basis) data for microwave assisted fluidized bed drying at 100% power level and different air temperatures.

time (min)	50°C air temperature	60°C air temperature	70°C air temperature
0	0.27568	0.26695	0.27086
1	0.24325	0.23373	0.23804
2	0.22268	0.21378	0.21542
3	0.20663	0.19802	0.19892
4	0.19422	0.18549	0.18656
5	0.18430	0.17455	0.17585
6	0.17506	0.16440	0.16519
7	0.16695	0.15595	0.15556
8	0.15924	0.14813	0.14694
9	0.15193	0.14116	0.13855
10	0.14478	0.13469	0.13146
11	0.13861	0.12902	
12	0.13311		

D.5 Dimensionless Moisture Content Data

Table D.5.1 $\ln((X_t-X^*)/(X_i-X^*))$ data for fluidized bed drying at different air temperatures.

time (min)	50°C air temperature	60°C air temperature	70°C air temperature
0	0.00000	0.00000	0.00000
1	-0.11964	-0.10993	-0.12135
2	-0.18917	-0.18558	-0.20524
3	-0.24871	-0.24741	-0.26913
4	-0.29836	-0.30374	-0.32490
5	-0.34308	-0.35377	-0.38086
6	-0.38372	-0.40263	-0.43280
7	-0.42436	-0.44651	-0.47816
8	-0.46051	-0.48872	-0.52167
9	-0.49709	-0.52802	-0.56484
10	-0.53029	-0.56792	-0.60608
11	-0.56364	-0.60845	-0.65060
12	-0.59663	-0.64531	-0.69192
13	-0.62916	-0.68192	-0.73446
14	-0.66116	-0.71703	-0.77374
15	-0.69198	-0.75162	-0.81343
16	-0.72320	-0.78684	-0.85228
17	-0.75305	-0.82398	-0.89076
18	-0.78198	-0.85790	-0.92879
19	-0.81304	-0.89164	-0.96901
20	-0.84183	-0.92372	-1.00729
21	-0.87149	-0.95759	-1.04485
22	-0.89998	-0.99038	-1.08465
23	-0.92789	-1.02350	
24	-0.95515	-1.05775	
25	-0.98317	-1.09153	
26	-1.01200	-1.12477	
27	-1.04168		
28	-1.06983		
29	-1.09795		
30	-1.12688		
31	-1.15490		
32	-1.18464		

Table D.5.2 $\ln((X_t-X^*)/(X_i-X^*))$ data for microwave assisted fluidized bed drying at 50% power level and different air temperatures.

time (min)	50°C air temperature	60°C air temperature	70°C air temperature
0	0.00000	0.00000	0.00000
1	-0.13894	-0.14488	-0.17843
2	-0.23063	-0.24602	-0.28813
3	-0.31003	-0.33205	-0.38349
4	-0.37811	-0.41376	-0.44451
5	-0.44302	-0.48625	-0.52125
6	-0.50196	-0.55917	-0.60343
7	-0.55834	-0.63013	-0.68468
8	-0.61149	-0.70102	-0.77594
9	-0.66764	-0.77318	-0.86148
10	-0.71864	-0.84398	-0.94427
11	-0.77061	-0.91134	-1.02724
12	-0.82106	-0.97849	-1.11533
13	-0.86959	-1.04506	
14	-0.91854	-1.11139	
15	-0.96784	-1.18245	
16	-1.01893		
17	-1.07118		
18	-1.12040		
19	-1.16952		
20	-1.21654		

Table D.5.3 $\ln((X_t\text{-}X^*)/(X_i\text{-}X^*))$ data for microwave assisted fluidized bed drying at 100% power level and different air temperatures.

time (min)	50°C air temperature	60°C air temperature	70°C air temperature
0	0.00000	0.00000	0.00000
1	-0.17156	-0.18169	-0.16919
2	-0.29801	-0.30916	-0.30507
3	-0.40903	-0.42275	-0.41728
4	-0.50429	-0.52326	-0.51044
5	-0.58752	-0.62014	-0.59890
6	-0.67182	-0.71925	-0.69540
7	-0.75213	-0.80997	-0.79149
8	-0.83499	-0.90202	-0.88599
9	-0.92049	-0.99189	-0.98747
10	-1.01171	-1.08307	-1.08202
11	-1.09795	-1.17053	
12	-1.18150		

D.6 Effective Diffusivity Calculations for First Approach

Table D.6 Equations for the linear portions of the variation of dimensionless moisture content with time curves.

$$y = ax + b$$

Drying Condition	**a**	**b**	**Correlation Coefficient**
Fluidized bed drying 50°C temperature	-0.0203	-0.2798	0.9998
Microwave assisted fluidized bed drying 50°C temperature 50% power level	-0.0355	- 0.2470	0.9996
Microwave assisted fluidized bed drying 50°C temperature 100% power level	-0.0625	-0.1825	0.9996
Fluidized bed drying 60°C temperature	-0.0237	-0.2651	0.9999
Microwave assisted fluidized bed drying 60°C temperature 50% power level	-0.0478	-0.2089	0.9999
Microwave assisted fluidized bed drying 60°C temperature 100% power level	-0.0646	-0.2028	0.9994
Fluidized bed drying 70°C temperature	-0.0291	-0.2375	0.9998
Microwave assisted fluidized bed drying 70°C temperature 50% power level	-0.0629	-0.1453	0.9999
Microwave assisted fluidized bed drying 70°C temperature 100% power level	-0.0733	-0.1399	0.9998

D.7 Effective Diffusivity Calculations for Second Approach

Table D.7.1 Effective diffusivity data for fluidized bed drying at 50°C air temperature.

time (min)	Effective diffusivity x 10^{11} (m^2/s)	Average effective diffusivity x 10^{11} from t=32 min to t=t (m^2/s)	% Deviation
32	3.712	3.712	0.0
31	3.699	3.706	0.2
30	3.692	3.701	0.2
29	3.681	3.696	0.4
28	3.674	3.692	0.5
27	3.665	3.687	0.6
26	3.649	3.682	0.9
25	3.636	3.676	1.1
24	3.627	3.671	1.2
23	3.624	3.666	1.1
22	3.616	3.661	1.2
21	3.606	3.657	1.4
20	3.589	3.652	1.7
19	3.578	3.646	1.9
18	3.551	3.640	2.4
17	3.540	3.634	2.6
16	3.525	3.627	2.8
15	3.499	3.620	3.3
14	3.479	3.613	3.7
13	3.451	3.605	4.3
12	3.420	**3.596**	4.9
11	3.389	3.586	5.5
10	3.359	3.577	6.1
9	3.338	3.567	6.4
8	3.286	3.555	7.6
7	3.252	3.544	8.2
6	3.170	3.530	10.2
5	3.107	3.515	11.6
4	3.010	3.497	13.9
3	2.864	3.476	17.6
2	2.566	3.447	25.6
1	2.129	3.406	37.5
Standard deviation	0.348×10^{-11}		

Table D.7.2 Effective diffusivity data for fluidized bed drying at 60°C air temperature.

time (min)	Effective diffusivity x 10^{11} (m^2/s)	Average effective diffusivity x 10^{11} from t=26 min to t=t (m^2/s)	% Deviation
26	4.193	4.193	0.0
25	4.179	4.186	0.2
24	4.162	4.178	0.4
23	4.140	4.169	0.7
22	4.123	4.159	0.9
21	4.109	4.151	1.0
20	4.087	4.142	1.3
19	4.077	4.134	1.4
18	4.056	4.125	1.7
17	4.033	4.116	2.0
16	3.986	4.104	2.9
15	3.952	4.091	3.4
14	3.926	4.079	3.7
13	3.895	4.066	4.2
12	3.853	**4.051**	4.9
11	3.812	4.036	5.6
10	3.733	4.019	7.1
9	3.663	3.999	8.4
8	3.605	3.978	9.4
7	3.518	3.955	11.1
6	3.417	3.929	13.0
5	3.249	3.899	16.7
4	3.076	3.863	20.4
3	2.802	3.819	26.6
2	2.417	3.763	35.8
1	1.439	3.673	60.8
Standard deviation	0.629×10^{-11}		

Table D.7.3 Effective diffusivity data for fluidized bed drying at 70°C air temperature.

time (min)	**Effective diffusivity x 10^{11} (m^2/s)**	**Average effective diffusivity x 10^{11} from t=22 min to t=t (m^2/s)**	**% Deviation**
22	4.912	4.912	0.0
21	4.874	4.893	0.4
20	4.849	4.878	0.6
19	4.818	4.863	0.9
18	4.771	4.845	1.5
17	4.739	4.827	1.8
16	4.702	4.809	2.2
15	4.662	4.791	2.7
14	4.614	4.771	3.3
13	4.570	4.751	3.8
12	4.493	**4.728**	5.0
11	4.428	4.703	5.8
10	4.327	4.674	7.4
9	4.267	4.645	8.1
8	4.189	4.614	9.2
7	4.115	4.583	10.2
6	4.029	4.551	11.5
5	3.848	4.512	14.7
4	3.606	4.464	19.2
3	3.397	4.411	23.0
2	3.050	4.346	29.8
1	1.974	4.238	53.4
Standard deviation	0.698×10^{-11}		

Table D.7.4 Effective diffusivity data for microwave assisted fluidized bed drying at 50°C air temperature and 50% power level.

time (min)	**Effective diffusivity x 10^{11} (m^2/s)**	**Average effective diffusivity x 10^{11} from t=20 min to t=t (m^2/s)**	**% Deviation**
20	6.202	6.202	0.0
19	6.184	6.193	0.1
18	6.145	6.177	0.5
17	6.101	6.158	0.9
16	6.028	6.132	1.7
15	5.957	6.103	2.4
14	5.900	6.074	2.9
13	5.843	6.045	3.3
12	5.788	6.016	3.8
11	5.711	**5.986**	4.6
10	5.616	5.952	5.6
9	5.533	5.917	6.5
8	5.379	5.876	8.5
7	5.271	5.833	9.6
6	5.122	5.785	11.5
5	4.940	5.733	13.8
4	4.657	5.669	17.9
3	4.329	5.595	22.6
2	3.741	5.497	31.9
1	2.669	5.356	50.2
Standard deviation	0.893×10^{-11}		

Table D.7.5 Effective diffusivity data for microwave assisted fluidized bed drying at 50°C air temperature and 100% power level.

time (min)	**Effective diffusivity x 10^{11} (m^2/s)**	**Average effective diffusivity x 10^{11} from t=12 min to t=t (m^2/s)**	**% Deviation**
12	9.912	9.912	0.0
11	9.753	9.833	0.8
10	9.529	9.731	2.1
9	9.192	**9.597**	4.2
8	8.900	9.457	5.9
7	8.621	9.318	7.5
6	8.372	9.183	8.8
5	8.034	9.039	11.1
4	7.733	8.894	13.1
3	7.138	8.718	18.1
2	6.029	8.474	28.9
1	4.190	8.117	48.4
Standard deviation	$1.604x10^{-11}$		

Table D.7.6 Effective diffusivity data for microwave assisted fluidized bed drying at 60°C air temperature and 50% power level.

time (min)	**Effective diffusivity x 10^{11} (m^2/s)**	**Average effective diffusivity x 10^{11} from t=15 min to t=t (m^2/s)**	**% Deviation**
15	7.886	7.886	0.0
14	7.747	7.817	0.9
13	7.636	7.756	1.6
12	7.510	7.695	2.4
11	7.363	7.628	3.5
10	7.196	**7.556**	4.8
9	6.966	7.472	6.8
8	6.692	7.375	9.3
7	6.417	7.268	11.7
6	6.121	7.153	14.4
5	5.776	7.028	17.8
4	5.433	6.895	21.2
3	4.875	6.740	27.7
2	4.198	6.558	36.0
1	2.910	6.315	53.9
Standard deviation	1.400×10^{-11}		

Table D.7.7 Effective diffusivity data for microwave assisted fluidized bed drying at 60°C air temperature and 100% power level.

time (min)	**Effective diffusivity x 10^{11} (m^2/s)**	**Average effective diffusivity x 10^{11} from t=11 min to t=t (m^2/s)**	**% Deviation**
11	10.450	10.450	0.0
10	10.310	10.380	0.7
9	10.080	10.280	1.9
8	9.831	**10.168**	3.3
7	9.513	10.037	5.2
6	9.183	9.895	7.2
5	8.636	9.715	11.1
4	8.095	9.512	14.9
3	7.435	9.281	19.9
2	6.340	8.987	29.5
1	4.622	8.590	46.2
Standard deviation	1.752×10^{-11}		

Table D.7.8 Effective diffusivity data for microwave assisted fluidized bed drying at 70°C air temperature and 50% power level.

time (min)	**Effective diffusivity x 10^{11} (m^2/s)**	**Average effective diffusivity x 10^{11} from t=12 min to t=t (m^2/s)**	**% Deviation**
12	9.413	9.413	0.0
11	9.116	9.265	1.6
10	8.843	9.124	3.1
9	8.536	**8.977**	4.9
8	8.145	8.811	7.6
7	7.601	8.609	11.7
6	7.186	8.406	14.5
5	6.719	8.195	18.0
4	6.359	7.991	20.4
3	6.517	7.844	16.9
2	5.803	7.658	24.2
1	4.649	7.407	37.2
Standard deviation	1.398×10^{-11}		

Table D.7.9 Effective diffusivity data for microwave assisted fluidized bed drying at 70°C air temperature and 100% power level.

time (min)	**Effective diffusivity x 10^{11} (m^2/s)**	**Average effective diffusivity x 10^{11} from t=10 min to t=t (m^2/s)**	**% Deviation**
10	10.710	10.710	0.0
9	10.400	10.555	1.5
8	9.933	**10.348**	4.0
7	9.516	10.140	6.2
6	9.013	9.914	9.1
5	8.439	9.669	12.7
4	8.030	9.434	14.9
3	7.516	9.195	18.3
2	6.395	8.884	28.0
1	4.138	8.409	50.8
Standard deviation	1.908×10^{-11}		

D.8 Effect of Temperature

Table D.8 Constants for the equation of the Arrhenius plot.

$$y = ax + b$$

Drying Condition	a	b	Correlation Coefficient
Fluidized bed drying	-1515	-19.367	0.9916