EVALUATION OF HIGH PRESSURE PRETREATMENT FOR ENHANCING THE DRYING RATE OF SELECTED FRUITS AND VEGETABLES

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

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

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ABSTRACT

EVALUATION OF HIGH PRESSURE PRETREATMENT FOR ENHANCING THE DRYING RATE OF SELECTED FRUITS AND VEGETABLES

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Drying is a process of moisture removal due to simultaneous heat and mass transfer. High hydrostatic pressure (HHP) processing subjects liquid and solid foods, with or without packaging, to pressures between 100 and 800 MPa. The application of HHP affects cell wall structures, leaving the cells more permeable, facilitating the diffusion and providing higher drying rates.

In this study, two variety of apples, i.e. Amasya and red delicious, green beans and carrots were pretreated with HHP at different pressure-time-temperature combinations (100 – 300 MPa for 5 – 45 min at 20 and 35°C) prior to drying. Hot air drying experiments were carried at different temperatures (27, 45, 65, and 85°C) and air velocity of 0.4 and 0.8 m/s. To obtain the drying data, samples were subjected to hot air drying under constant external conditions. The applicability of 14 kinetic models selected from the literature for the drying of fruits and vegetables was determined by appropriate statistical analyses procedures.

Improving the drying conditions by increasing the drying temperature generally masked the effect of HHP pretreatment on drying rate. Only for green beans, HHP treatments at 20°C decreased the drying rate. Generally pressures of HHP pretreatment higher than 100 MPa caused cell permeabilization resulted in higher drying rates for apples and carrots. Among the 14 models, modified Page model for apples, and modified Page and two term exponential models for green beans and carrots were found to best explain the drying behaviors.

Keywords: Drying, High Hydrostatic Pressure, Modeling, Fruit, Vegetable

ÖZ

YÜKSEK BASINÇ ÖN İŞLEMİNİN SEÇİLMİŞ MEYVE VE SEBZELERİN KURUTMA HIZLARI ÜZERİNE ETKİSİNİN BELİRLENMESİ

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Kurutma işlemi, eşzamanlı ısı ve kütle transferleri sonucu oluşan su kaybıdır. Yüksek hidrostatik basınç (YHB) işlemi 100 ve 800 MPa basınç aralığında, paketli veya paketsiz haldeki sıvı ve katı gıdalara ugulanabilir. YHB uygulaması hücre duvarının yapısını etkileyerek hücrelerin geçirgenliğini arttırır; ve böylece difüzyonu kolaylaştırarak yüksek kurutma hızları sağlar.

Bu çalışmada, iki tür elma, Amasya ve kırmızı elma, yeşil fasülye ve havuç çeşitli basınç-zaman-sıcaklık kombinasyonlarında (100 – 300 MPa, 5 – 45 dak. süreyle ve 20 ve 35°C sıcaklıklarında) uygulanan YHB ön işleminden sonra kurutulmuştur. Kurutma deneyleri, çeşitli sıcaklıklarda (27, 45, 65 ve 85°C) ve 0.4 ve 0.8 m/s hava hızlarında gerçekleştirilmiştir. Kurutma verilerini elde etmek için, numuneler sabit dış etkenler altında sıcak havayla kurutulmuşlardır. Meyve ve sebzelerin kurutma davranışlarını incelemek için, literatürden seçilen 14 kinetik modelin uygulanabilirliği uygun istatistiksel analiz yöntemleri kullanılarak belirlenmiştir

Kurutma sıcaklığının arttırılarak kurutma koşullarının iyileştirilmesi, YHB ön işleminin kurutma hızı üzerindeki etkisini maskelemiştir. Sadece, 20°C’ de uygulanan YHB ön işlemlerinden sonra kurutulan taze fasülyelerde kurutma hızlarının azaldığı gözlenmiştir. Genel olarak, 100 MPa üzerindeki YHB ön işlemi hücre geçirgenliğini arttırarak, elma ve havuçların kurutma hızlarını arrtırmıştır. Seçilen 14 model arasında, elmalar için modifiye Page modelinin, yeşil fasülye ve havuç için ise modifiye Page ve iki terim üstel modellerinin kurutma davranışlarını açıklamada en uygunları oldukları belirlenmiştir.

Anahtar Kelimeler: Kurutma, Yüksek Hidrostatik Basınç, Modelleme, Meyve, Sebze

To my family,
and also to Aysu

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INTRODUCTION

1.1 Drying

Fruits and vegetables are regarded as highly perishable due to their high moisture content. Different processes such as freezing, modified atmosphere storage, canning and drying are used to preserve these types of food. Drying is one of the oldest forms of food preservation techniques and has always been of great importance for the food industry. It is a process of moisture removal due to simultaneous heat and mass transfer. This operation is an energy intensive operation of some industrial significance. In most industrialized countries, the energy used in drying accounts for 7–15% of the industrial energy, often with relatively low thermal efficiencies ranging from 25% to 50% (Chua et al., 2001; Dincer, 1998). A greater understanding of the drying process is important if drying efficiency is to be increased while maintaining product quality.

In many agricultural countries, large quantities of food products are dried to improve shelf life, reduce packing costs, lower shipping weights, retain good appearance and original flavor and maintain nutritional value. In this regard, the goals of drying process research in the food industry may be classified in three groups: (a) economic considerations, (b) environmental concerns and (c) product quality aspects. Though the primary objective of food drying is preservation, depending on the drying mechanisms, the raw material may end up a completely different material with significant variation in product quality (Gunhan et al., 2005; Chou and Chua, 2001). In some instances the dried (or partially rehydrated) product has it own characteristic flavor and may be thought of as an independent product and different from original. Such an example is the prune. The prune occupies a small niche market, mainly for the middle-aged and over, because of its laxative effect (Sabarez et al., 1997).

Many kinds of fresh fruits and vegetables can be dried such as apples, berries, cherries, peaches, apricots, pears, peas, corn, peppers, zucchini, okra, onions, and green beans. Dried fruits are used for snacks, cookies, granula recipes and breakfast cereal. Dried vegetables are used for stews, casseroles, soups, sauces and gravies. Moreover, according to the Turkish tradition, some of the vegetables are dried in summer times and consumed in winter months.

Several methods can be used for drying purposes: solar, hot-air, freeze, osmotic, spray drying, impregnation vacuum, microwave, radio frequency, infrared etc. (Vega et al., 2006). The drying processes differ primarily by the type of drying method used and the selection of the optimal method is determined by quality requirements, raw material characteristics, and economic factors. In general, dried fruits and vegetables undergo the following process steps: pre-drying treatments, such as size selection, washing, peeling, cutting, color preservation and blanching; drying using natural or artificial methods; and post-dehydration treatments, such as sweating, inspection, and packaging.

Conventional air-drying is the most frequently used operation in food industry. Dried products are characterized by low porosity and high apparent density. Significant color changes occur during air -drying, and most frequently the dried product has low sorption capacity. Microwave drying is an alternative drying method that has recently been used. Applying microwave energy under vacuum combines advantages of both vacuum drying and microwave drying as far as improved energy efficiency and product quality are concerned. Vacuum dried materials are characterized by higher porosity, depending on level of vacuum and less deterioration of color and volatile aroma. Osmotic dehydration minimizes the heat effects on color and flavor, prevents enzymatic browning, increasing in this way the retention of nutrients during subsequent convective drying. Osmotic dehydration greatly affects apparent density and porosity. Freeze drying is one of the most sophisticated dehydration methods. It provides dried products of porous structure and little or no shrinkage, superior taste and aroma retention, better rehydration properties, compared to products of alternative drying processes. However, its advantages are directly weighed against its corresponding high treatment cost (UNISDO, 2004).

Moreover, infrared-assisted microwave drying is a new technology and it combines the time-saving advantages of microwave drying with surface moisture removal advantages of infrared drying (Tireki et al., 2006).

Sun drying is one of the most commonly used methods to dry fruits and vegetables. Natural sun drying is practiced widely in the World and also Turkey and advantages of this process are its simplicity and small capital investment. However, this drying technique has some disadvantages like the slowness of the process, the exposure to environmental contamination by dirt and dust, infestation by insects, rodents and other animals, and the hand labor requirement. Therefore, to improve the quality of the final product, the drying process should be undertaken in closed equipments, which are far more rapid, providing uniformity and hygiene, and they are inevitable for industrial food drying processes.

Drying of fruits and vegetables demands special attention, as these are considered important sources of vitamins and minerals essential for mankind. Dried fruits and vegetables have gained commercial importance and their growth on a commercial scale has become an important sector of the agricultural industry. Losses of fruits and vegetables in developing countries are estimated to be about 30–40% of production (Jayaraman and Gupta, 1995). The need to reduce post-harvest losses is of vital importance for these countries.

Fruits and vegetables have certain morphological features quite distinct from other natural materials that greatly influence their behavior during drying and preservation. They are generally characterized by high initial moisture content, high temperature sensitivity (i.e. color, flavor, texture and nutritional value subject to thermal deterioration), and shrinkage of materials during drying. The required amount of thermal energy to dry a particular product depends on many factors, such as, initial moisture content, desired final moisture content, temperature and relative humidity of drying air, and air flow rate (Karim and Hawlader, 2004). Other important factors are load density, thickness and shape of the product to be dried (Vega et al., 2006).

1.1.1 Types of Water and Equilibrium Moisture Content

Water in a food can be either free (independent) or bound (interdependent). Water in the interstitial spaces and within the pores of the material is held by purely physical force related to surface tension. This type of water is called unbound water which exerts the same vapor pressure and possesses the same latent heat of vaporization as does pure water at the same temperature. It is related to physical structures of the product. Another portion of water may be held on the internal and external surfaces of the solid material by interactions between the water molecules and the solid material to form mono or multi-layer of water molecules. This type of water is bound water. It may be retained in fine capillaries, or adsorbed onto surfaces, or within a cell or fiber walls, or in physical/chemical combination with the solid. It exerts less vapor pressure and possesses greater heat of vaporization than the pure water at the same temperature. It is closely associated with the chemical structures of the product. Free moisture is the excess of the equilibrium moisture content of the product. It depends on the type of the product, temperature and water vapor concentration of the air. Only the free moisture content can be removed during a drying process (Keey, 1972).

The solids either loose or gain moisture from the surrounding until equilibrium is reached. The moisture content at the equilibrium is equilibrium moisture content under the specified humidity and temperature of the air and corresponding air humidity is called equilibrium relative humidity. The equilibrium moisture content of a solid decrease with an increase in temperature and the free moisture is the moisture above the equilibrium moisture content (Geankoplis, 1993).

1.1.2 Sorption Isotherms and Water Activity

When a food is placed in an environment at a constant temperature and relative humidity, it will eventually come to equilibrium with that environment. The relationship between total moisture content and the corresponding water activity (a_w) of a food over a range of values at a constant temperature yields a moisture sorption isotherm when graphically expressed. Sorption isotherms relate the partial pressure of the water in the food to its water content at constant temperature (Sahbaz et al., 1999). The equilibrium water activity is a useful parameter for predicting the chemical and microbiological stability of foods. Water activity affects microorganisms' survival and reproduction, enzyme activity and chemical reactions. Sahbaz et al. (1999) studied the moisture sorption behaviors for the blanched and unblanched mushrooms and found that the unblanched material adsorbed more water than that of the blanched. Dincer and Esin (1996) compared the several isotherm models for macaroni and found that the modified BET equation can satisfactorily represent the sorption data up to 97% relative humidity.

Five types of isotherms were described by Brunauer et al. (1940) (Fig. 1.1). Type 1 is the well known Langmuir isotherm, obtained by the monomolecular adsorption of gas by porous solids in a finite volume of voids. Type 2 is the sigmoid isotherm, which is obtained for soluble products and shows an asymptotic trend as water activity tends towards 1. Type 3, known as the Flory-Huggins isotherm, accounts for the adsorption of a solvent or plasticizer like glycerol, for example, above the glass-transition temperature. The Type 4 isotherm describes the adsorption by a swellable hydrophilic solid until a maximum of hydration of sites is reached. Type 5 is the B.E.T. multilayer adsorption isotherm, observed for the adsorption of water vapour on charcoal and related to types 2 and 3 isotherms. The two isotherms most frequently found for food products are Types 2 and 4 isotherms (Mathlouthi and Roge, 2003).

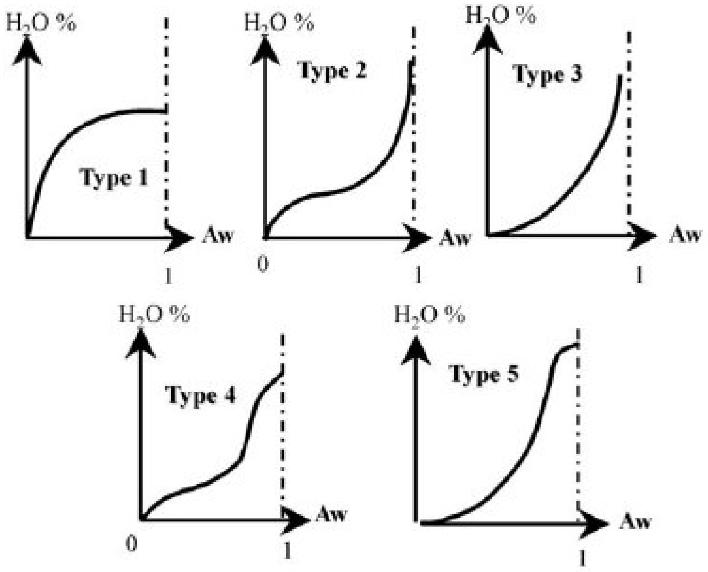

Figure 1.1. Five types of isotherms (Mathlouthi and Roge, 2003).

Another behavior commonly observed is that different paths are followed during adsorption and desorption processes, resulting in a hysteresis (Fig 1.2). Desorption isotherm lies above the adsorption isotherm, and therefore more moisture is retained in the desorption process compared to adsorption at a given equilibrium relative humidity.

The shape of the isotherm reflects the manner in which the water is bound. A typical isotherm for foods can be divided into three regions as shown in Fig. 1.2. Up to a water activity, a_w, of about 0.30, where the first inflection appears, water is held on polar sites of relatively high energies. This is the "monomolecular region." Between about a_w**,** 0.30-0.70 there is a "multi-layer region." Above a_w, 0.7 the water approaches the condition of "condensed water"; it is relatively free and the isotherm reflects solution and surface capillary effects (Wolf et al., 1972).

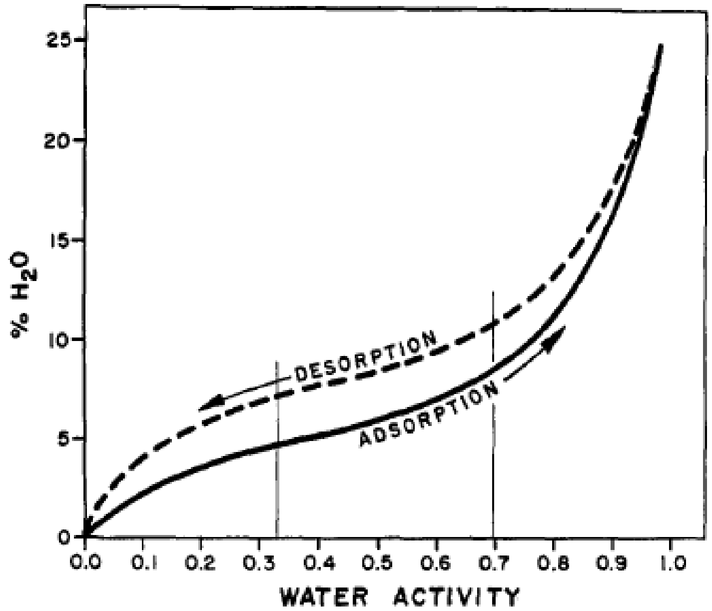

Figure 1.2. A typical sorption isotherm showing the phenomenon of hysterisis (Wolf et al., 1972).

1.1.3 Principles of Drying

When hot air is blown over a wet food, heat is transferred to the surface, and the latent heat of vaporization causes water to evaporate. Water vapor diffuses through a boundary film of air and is carried away by the moving air. This creates a region of lower water vapor pressure at the surface of the food, and a water vapor pressure gradient is established from the moist interior of the food to the dry air. This gradient provides the driving force for the removal of water from the food. Water moves to the surface by the following mechanisms (Keey, 1972):

1) Liquid movement by capillary forces.
2) Diffusion of liquids, caused by differences in the concentration of solutes in different regions of the foods.
3) Diffusion of liquids which are adsorbed in layers at the surfaces of solid components of the food.
4) Water vapor diffusion in air spaces within the food caused by vapor pressure gradients.

The drying rates for different foods will have a wide range of variation, but a typical curve is shown in Figure 2. When the food is placed inside the drier, there is a short settling down period as the surface heats up to the wet bulb temperature (region AB). Drying then commences along BC, and provided that water moves from the interior of the food material at the same rate as it evaporates from the surface, the surface remains wet. This period is known as the constant rate period, as can be seen from the drying curve, this is because drying occurs over a constant rate. The constant rate period continues until the critical moisture content is reached. At this point drying enters what is known as the falling rate period.

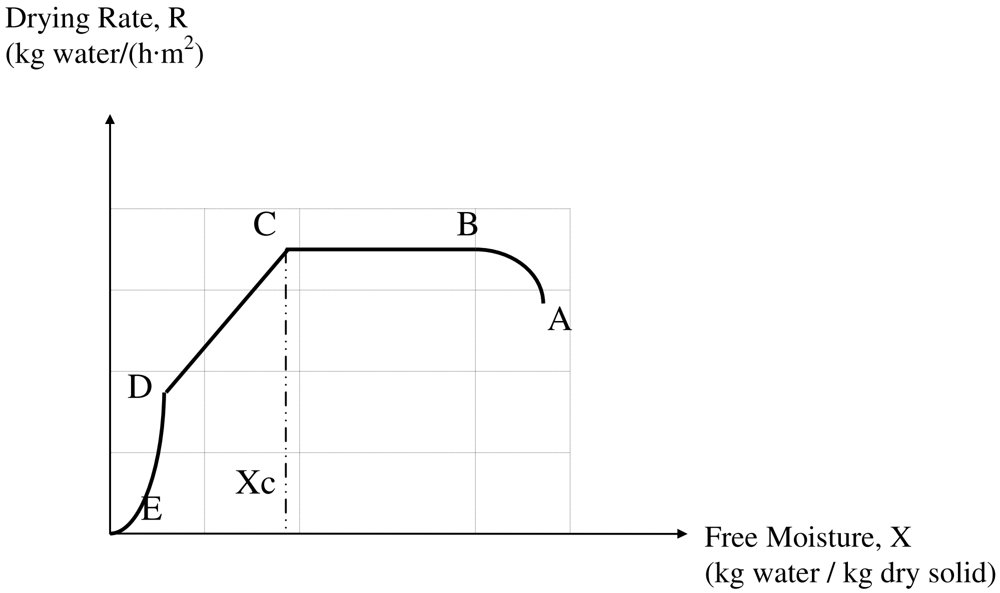

Figure 2. A typical drying rate curve.

The critical point is not fixed for a given food and depends on the amount of food in the drier and the rate of drying. The three characteristics of air that are necessary for successful drying in the constant rate period are a moderately high dry bulb temperature, low relative humidity and high air velocity. The boundary film of air surrounding the food acts as a barrier to the transfer of both heat and water vapor during drying. The thickness of the film is determined primarily by air velocity. If this is too low, water vapor leaves the surface of the food and increases the humidity of the surrounding air, to cause a reduction in the water vapor pressure gradient and the rate of drying. During the constant rate period it is assumed that drying takes place from a saturated surface of the material by diffusion of water vapour through the stationary air film into the air stream.

After constant rate period, non-hygroscopic foods have a single falling rate period, whereas hygroscopic foods have two falling rate periods. The main drying process takes place in the falling rate period. In the falling rate period, the drying rate depends mainly on the physical structure and chemical composition characteristics of the solid. During the falling rate period, the plane of evaporation moves inside the material being dried, and water diffuses through the dry solids to the drying air. It represents a condition whereby the surface is no longer capable of supplying sufficient free moisture to saturate the air in contact with it. Under these conditions, the rate of drying depends very much on the mechanism by which moisture from inside the material is transferred to the surface. This is usually the longest period of a drying operation and in some foods (for example grain drying), where the initial moisture content is below the critical moisture content the falling rate period is the only part of the drying curve to be observed (Geankoplis, 1993). In practice foods may differ from these idealized drying curves owing to shrinkage, changes in the temperature and rate of moisture diffusion in different parts of the food and changes in the temperature and humidity of the drying air.

The surface temperature of the food remains close to the wet bulb temperature of the drying air until the end of the constant rate period, due to the cooling effect of the evaporating water. During the falling rate period the amount of water evaporating from the surface gradually decreases but as, the same amount of heat is being supplied by the air the surface temperature rises until it reaches the dry bulb temperature of the drying air. Most heat damage to food therefore occurs during the falling rate period.

The rate of drying depends on the properties of the drier, the velocity of the air, surface heat transfer coefficient, and the properties of the food (the moisture content, surface area to volume ratio, surface temperature and rate of moisture loss). The size of the food pieces has an important effect on the drying rate in both the constant and falling rate periods. In the constant rate period, smaller pieces of food have a larger surface area available for evaporation whereas, in the falling rate period, smaller pieces have a shorter distance for moisture to travel through the food. Other factors which influence the rate of drying include The fat content of the food (higher fat contents generally result in slower drying as moisture is trapped within the food, the method of preparation (cut surfaces loose moisture more rapidly than through skin) and the amount of food placed in a drier in relation to its size (Geankoplis, 1993; Keey, 1972).

1.1.4 Drying Kinetics

One of the most important aspects of drying technology is the mathematical modeling of the drying processes. Its purpose is to choose the most suitable operating conditions and then size the drying equipment and drying chamber accordingly to meet desired operating conditions. The principle of modeling is based on having a set of mathematical equations that can adequately characterize the system (Gunhan et al., 2005). The mathematical description of food moisture evolution during the process is also known as drying kinetics.

The related models are in two general tendencies: detailed and simplified (Zogzas and Maroulis, 1996). Detailed models use the simultaneous heat and mass transfer equations with variable food properties and shrinkage. These equations are a system of two nonlinear, coupled partial differential equations. The only way to solve such models is by numerical methods like finite differences or finite elements. The detailed models are of great importance in the scientific study of food drying; however, their application in the design or simulation of food dehydration is practically not feasible. Simplified models are obtained from detailed models in a manner such that the mass transfer equation can be solved analytically. The most common simplifications are the following assumptions:

1. The food temperature is constant, i.e., heat transfer is negligible.
2. There is no shrinkage.
3. The water diffusivity into the product is constant.

These assumptions simplify the mass transfer equation but decrease the ability to reproduce the experimental drying kinetic data. However, these simplifications had been used by several authors to predict or fit food-drying kinetics, because the simplified models are suitable to use in design or simulation of food drying operations (Hernandez et al., 2000).

The drying kinetics of materials may be described completely using their transport properties (thermal conductivity, thermal diffusivity, moisture diffusivity, and interface heat and mass transfer coefficients) together with these of the drying medium. In the case of food drying, the drying constant "k" is used instead of transport properties. The drying constant combines all the transport properties and may be defined by the thin layer equation (Togrul and Pehlivan, 2004). Thin layer equations describe the drying phenomena in a unified way, regardless of the controlling mechanism. They have been used to estimate drying times of several products and to generalize drying curves. In the development of thin layer drying models for agricultural products, generally the moisture content of the material at any time after it has been subjected to a constant relative humidity and temperature conditions is measured and correlated to the drying parameters (Midilli et al., 2002).

Different equations are available in the literature. Many investigators have successfully used these equations to explain drying of several agricultural products. Some recently studied products for their drying behavior are as follows: grape (Doymaz and Pala, 2002-I; Pangavhane et al., 1999; Ramos et al., 2005; Yaldiz et al., 2001), potato (Akpinar et al., 2003-I; Diamante and Munro, 1993, 1991; Sahbaz and Kayhan, 1994), onion (Sarsavadia et al., 1999; Sawhney et al., 1999), green pepper, stuffed pepper, pumpkin, green bean and onion (Yaldiz and Ertekin, 2001), rice (Basunia and Abe, 2001), apricot (Togrul and Pehlivan, 2002, 2003), banana (Baini and Langrish, 2006; Dandamrongrak et al., 2002; Karim and Hawlader, 2004; Querioz and Nebra, 2001) , seedless grape, fig, green pea, tomato and onion

(El-Sebaii, 2002), tomato concentrate droplets (Karatas and Esin, 1994), pistachio (Midilli and Kucuk, 2003; Midilli, 2001), pumpkin (Akpinar et al, 2003-II), eggplant (Ertekin and Yaldiz, 2004), bay leaves (Gunhan et al., 2005), black tea (Panchariya et al., 2002; Temple and Van Boxtel, 1999), plum (Sabarez et al., 1997), mushroom and pollen (Midilli et al., 1999), mushroom (Sahbaz et al., 2000), mulberry (Maskan and Gogus, 1998), green bean (Doymaz, 2005), prickly pear fruit (Lahsasni et al., 2004), carrot (Doymaz, 2004; Kayhan and Sahbaz, 1998; Prabhanjan et al., 1995), green bean, potato and pea (Senadeera, 2003), red pepper (Doymaz and Pala, 2002-II, Turhan et al., 1997), apricot, grape, peach, fig and plum (Togrul and Pehlivan, 2004), kiwi (Simal et al., 2005), and apple (Mandala et al., 2005, Togrul, 2005., Velic' et al., 2004).

The thin layer drying models fall into the three categories, namely theoretical, semi-theoretical and empirical. These models are generally derived by simplifying general series solution of Fick's second law. These empirical models derive a direct relationship between average moisture content and drying time.

The empirical method is based on experimental data and dimensional analysis. This method does not lead to a general systematic approach for drying studies, although designers prefer it because it furnishes practical information for project elaboration. The theoretical method takes into account not only the external conditions, but also the mechanism of internal movement of moisture and their consequent effects. Emphasis has been given on the development of semi-theoretical models, which permit harmony between the theory and ease of use (Correa et al., 1999). The semi-theoretical approach concerns approximated theoretical equations. The empirical equations are easily applied to drying simulation as they depend on experimental data (Midilli and Kucuk, 2003).

For porous media transport, the work of Luikov suggests that temperature (T), moisture content (X) and gas pressure (P) are primary variables and the equations are (Keey, 1972):

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

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

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

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

The contributions of two distinct variables on the transport of the third variable are presented in these equations. 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 (Soret effect) and momentum diffusion. The effect of thermal diffusion on the mass transport is known as the Soret effect. In convective drying, due to the small influences of thermal and momentum diffusion on mass transport, Luikov's equations can be simplified (Keey, 1972). Therefore, Eq. 1.2 reduces to:

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

This equation is another form of the Fick's second law:

$$\frac{\partial X}{\partial t} = \nabla\left(D_{eff}\nabla X\right) \tag{2}$$

where D_{eff} (m^2/s) is the effective diffusivity, which is an overall transport property that includes the effects of all possible mechanisms of transport of moisture in both liquid and vapor form. It combines several transfer mechanisms such as capillary flow, transfers due to heat and pressure gradients, gas and liquid diffusion etc.

The drying of fruits and vegetables normally occurs in falling rate period. The moisture and/or vapor migration during this period is controlled by diffusion. The diffusion could include molecular diffusion, liquid diffusion through solid pores, vapor diffusion in air-filled pores, Knudsen flow and all other factors which affect drying characteristics. Since it is difficult to separate individual mechanism, the rate of moisture movement is described by an effective diffusivity, a lumped value. In most situations, Fick's second law of diffusion is used to describe a moisture diffusion process (Senadeera et al., 2003).

$$\frac{\partial X}{\partial t} = D_{eff} \nabla^2 X \tag{3}$$

Fick's equation has simple analytical solutions when shrinkage is negligible or not taken into consideration, the internal movement is its main resistance (no external movement resistance) and negligible external and internal heat transfer effect, and it also neglects the initial thermal transient effect (Sablani et al., 2000).

If D_{eff} is assumed as an effective parameter as it is constant and uniform, and assuming isotropic behavior of the solid with regard to water diffusion, mass transport can be then described by considering Fick's law in an unsteady-state mass balance. When the food product is assumed as one-dimensional and to have uniform initial moisture content, the solutions of Fickian equation for different geometrics are described by Eqs. (4)-(6) (Senadeera et al., 2003):

Infinite slab:

$$MR = \frac{X - X_e}{X_0 - X_e} = \frac{8}{\Pi^2} \sum_{n=1}^{\infty} \frac{1}{(2n-1)^2} \exp\left[-(2n-1)^2 \frac{\Pi^2 D_{eff} t}{L^2} \right] \quad (4)$$

where, D_{eff} = effective diffusion coefficient (m^2/s), t = time, L =slab thickness (m), MR = dimensionless moisture ratio, n = positive integer.

Infinite cylinder:

$$MR = \frac{X - X_e}{X_0 - X_e} = \sum_{n=1}^{\infty} \frac{4}{\beta_n^2} \exp\left[-\frac{\beta_n^2 D_{eff} t}{r_c^2} \right] \quad (5)$$

where, β = roots of the Bessel function, D_{eff} = diffusion coefficient (m^2/s), t = time (s), r_c = cylinder radius n = positive integer.

Sphere:

$$MR = \frac{X - X_e}{X_0 - X_e} = \frac{6}{\Pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp\left[-n^2 \frac{\Pi^2 D_{eff} t}{r_s^2} \right] \quad (6)$$

where, D_{eff} = diffusion coefficient (m^2/s), t = time (s), r_c = sphere radius, n = positive integer.

For long drying times ($MR < 0.6$), when L, r_c and r_s are small and t is large, limiting forms of equations are obtained for slab, cylindrical and spherical geometries by considering only the first term in their series expansion. Then Eqs. (4)-(6) can be written as Eqs. (7)-(9), respectively (Senadeera et al., 2003):

$$MR = \frac{X - X_e}{X_0 - X_e} = \frac{8}{\Pi^2} \exp\left[-\frac{\Pi^2 D_{eff} t}{L^2} \right] \tag{7}$$

$$MR = \frac{X - X_e}{X_0 - X_e} = \frac{4}{\beta_1^2} \exp\left[-\frac{\beta_1^2 D_{eff} t}{r_c^2} \right] \tag{8}$$

$$MR = \frac{X - X_e}{X_0 - X_e} = \frac{6}{\Pi^2} \exp\left[-\frac{\Pi^2 D_{eff} t}{r_s^2} \right] \tag{9}$$

A general form of Eqs. (7)–(9) can be written in logarithmic form (Eq. (10)):

$$\ln MR = A - Bt \tag{10}$$

where, constant B is $\Pi^2 D_{eff} \big/ L^2$ for a slab, $\beta_1^2 D_{eff} \big/ r_c^2$ for a cylinder and is $\Pi^2 D_{eff} \big/ r_s^2$ for a sphere. The slope (B) can be calculated by plotting lnMR versus time according to Eq. (10). The effective diffusivity can be derived from the slope.

For three-dimensional moisture movement, when considering a constant and uniform D_{eff}, Fick's law combined with the microscopic three-dimensional mass transfer in unsteady state for a parallelepiped shape and cylindrical shape is described as follows:

$$\frac{\partial X}{\partial t} = -D_{eff} \left(\frac{\partial^2 X}{\partial x^2} + \frac{\partial^2 X}{\partial y^2} + \frac{\partial^2 X}{\partial z^2} \right) \tag{11}$$

where, X = moisture, x, y, z = dimensional coordinates.

$$\frac{\partial X}{\partial t} = -D_{eff}\left(\frac{\partial^2 X}{\partial r_c^2} + \frac{1}{r_c}\frac{\partial X}{\partial r_c} + \frac{\partial^2 X}{\partial z^2}\right) \tag{12}$$

where, r_c = cylinder radius, z = z-direction coordinate.

Eqs. (11) and (12) can be solved analytically using the method of separation of variables for a constant effective diffusion coefficient assuming sample shape and size remain constant. The series solution of Eqs. (7)–(9) can be extended to multidimensional cases by calculating overall dimensionless moisture ratio (MR) as a product of individual MRs for the geometries involved. For the finite slab it corresponds to the product solution of an infinite slab in three dimensions. For the cylinder it is the product of the solution for an infinite slab and an infinite cylinder. The thin layer drying models are generally derived by simplifying general series solution of Fick's second law. Among semi-theoretical thin layer drying models, namely the Handerson and Pabis model, the Lewis model and the Page model are used widely (Doymaz, 2005).

Lewis (1921) described that the moisture transfer from the foods and agricultural materials can be seen as analogous to the flow of heat from a body immersed in cool fluid. This model assumes negligible internal resistance, which means no resistance to moisture movement from within the material to the surface of the material. By comparing this phenomenon with Newton's law of cooling, the drying rate is proportional to the difference in moisture content between the material being dried and equilibrium moisture content at the drying air condition as (Kashaninejad et al., Article in Press):

$$MR = \frac{X - X_e}{X_0 - X_e} = \exp(-kt) \tag{13}$$

This model was used primarily because it is simple and also Newton model or exponential model or simple model are the other names used in the literature. The only drawback, however, was that it tended to over predict the early stages and under predict the later stages of the drying curve (Doymaz, 2005; Kashaninejad et al., Article in Press; Senadeera et al., 2003; Simal et al, 2005) . It has been commonly used by researchers in describing the thin-layer drying characteristics of agricultural products.

The Henderson and Pabis model is the first term of a general series solution of Fick's second law. This model was used successfully to model drying of corn (Henderson and Pabis, 1961). This can be written as:

$$MR = \frac{X - X_e}{X_0 - X_e} = a\exp(-kt) \qquad (14)$$

The Lewis model is a special case of the Henderson and Pabis model where intercept is unity. Page (1949) suggested a two constant empirical modification to the time term by introducing an exponent ''n'' to overcome the shortcomings of the simple exponential model. The model is given as (Doymaz, 2005; Kashaninejad et al., Article in Press; Senadeera et al., 2003; Simal et al, 2005):

$$MR = \frac{X - X_e}{X_0 - X_e} = \exp(-kt^n) \qquad (15)$$

Isothermal operation appears as the most common model assumption in kinetic studies to solve the variation of the dimensionless moisture as a function of time for different air operating conditions: temperature, velocity and relative humidity. However, in many contributions, only the dry bulb drying air temperature was varied, diversity in biological materials and their drying properties such as shrinkage are much different from each other cause the analysis of drying process is a complex procedure, and so it is very difficult to find a general model (Marquez et al., 2006).

1.1.5 Drying and Quality

Consumer demand has increased for processed products that keep more of their original characteristics. In industrial terms, this requires the development of operations that minimize the adverse effects of processing. The effect of food processing on finished product quality ultimately determines the usefulness and commercial viability of that unit process operation. In the particular case of food drying this indicates that loss of volatiles and flavors, changes in color and texture, and a decrease in nutritional value. Furthermore, residual enzyme activity and microbial activity in dried foods are essential parameters that effect product quality and shelf life (UNISDO, 2004). Processing conditions determine to which extent the nutritional quality of the food is preserved. In drying, the aim should be the minimizing the heat effect on quality. If the temperature is too low in the beginning, microorganisms may survive and even grow before the food is adequately dried. If the temperature is too high and the humidity too low, the food may harden on the surface. This makes it more difficult for moisture to escape and the food does not dry properly. Although drying is a relatively simple method of food preservation, the procedure is not exact. A trial and error approach often is needed to decide which techniques work best.

Microstructural studies may help quantifying food changes during drying and may also improve the understanding of mechanisms and changes in quality factors, namely changes in food texture (Ramos et al., 2005). Although mineral content of fruits and vegetables is stable to dehydration, the vitamins are highly labile and are destroyed through enzymes. Together with the product quality, storage stability and rehydration characteristics should also be considered for the dried foods.

The most commonly examined properties of dried products can be classified into two major categories, engineering and quality properties. The engineering properties of the dried products involve effective moisture diffusivity, effective thermal conductivity, specific heat, and equilibrium moisture content. The properties related to product quality are necessary can be grouped into (UNISDO, 2004): thermal properties (state of product; glassy, crystalline, rubbery), structural properties (density, porosity, pore size, specific volume), textural properties (compression test, stress relaxation test, tensile test), optical properties (color, appearance), sensory properties (aroma, taste, flavor), nutritional characteristics (vitamins, proteins) and rehydration properties (rehydration rate, rehydration capacity).

Bacterial growth usually ceases below $a_w = 0.9$, that of yeasts below 0.8 and that of molds below 0.7. Therefore as a rule in the absence of rarely xerophilic fungi and the yeast, foods with a_w values below 0.7 are not subjected to microbial spoilage. Moreover, most dehydration processing procedures, especially those involving movement of hot gas, cause destruction of vegetative microrganisms.

Browning reactions change color, decrease nutritional value and solubility, create off-flavors, and induce textural changes. There are two important forms of browning, enzymatic and non-enzymatic (Maillard reactions, caramelization). This color development is usually undesirable, but with knowledge of the type of reaction involved, it is easier to work out methods for controlling this change. Rate of browning reactions depends on temperature of drying, pH and moisture content of the product, time of heat treatment, and the concentration and nature of the reactants.

In the case of enzymatic browning, a group of enzymes, collectively called "phenolase" is responsible for browning of some fruits and vegetables, such as potatoes, apples, and banana. When the tissue is bruised, cut, peeled, diseases, or exposed to any number of abnormal conditions, the color of the fruits or vegetables is changed. The injured tissue rapidly darkens on exposure to air, due to the conversion of phenolic compounds to brown melanins (UNISDO, 2004). Enzymes can already act in the presence of loosely bound water, completely free water is not necessary. Primary function of water in these water-deficient systems is to serve as a medium of transport and secondarily as a reaction medium. In general, because mobility and transport are limiting and decisive, the step which paces enzyme action at low moisture is the speed with which the substrate can get to the enzyme. Thus, oxygen-dependent enzymes such as phenolase and lipooxygenase respond to changes in water with decrease in enzyme activity. The control of enzymatic browning has always been a challenge to vegetable and fruit industry. Methods of inhibiting enzymatic browning can be blanching or chemical treatments such as sulphur dioxide and sulphites or acids like citric acid or ascorbic acid. For controlling enzymatic reactions there are also novel techniques such as high pressure treatment and ultrasonication.

1.2 High Hydrostatic Pressure (HHP) Treatment

1.2.1 HHP: A General Review

Thermal processes such as blanching, pasteurization or sterilization have long been employed in practice as economic, efficient, reliable and safe food preservation methods. However, in most cases thermal energy induces various chemical reactions, leading to quality deterioration in certain foods by producing undesirable changes in sensory and nutritional qualities. Thus, preservation technologies that prolong shelf-life without these detrimental effects are to be favored (Ohlsson, 1994). Alternative food-preservation and processing technologies are being developed to produce foods that are nutritionally healthier, more convenient in use (e.g. easier to store and prepare with longer shelf-life), fresher (e.g. chill-stored), more natural (e.g. less use of additives) and therefore less heavily processed (e.g. mildly heated), less heavily preserved (e.g. less acid, salt, sugar) and less reliant on additive preservatives (e.g. sulfite, nitrite, benzoate, sorbate) than previously (Gould, 2001).

Non-thermal methods by mild heat treatment provide fresh-like “minimally”-processed foods with little loss of color, flavor and nutrients. There are several new non-thermal technologies of potential interest to the industry, including high hydrostatic pressure (HHP), pulsed electric fields, high intensity pulsed light, ultrasound and ultraviolet light. Some of these systems such as HHP tratment, already have regulatory approval and are commonly used in the industry, while others such as high intensity pulsed light, continue to be developed and evaluated for potential commercial application (Alpas et al. 1999, 2000; Food and Drug Administration, 2000; Hoover, 1997; Knorr et al., 2002). These technologies offer low temperature applications leading to quality enhancement and energy efficiency and are practically waste-free technologies (Knorr, 1999).

Among these technologies use of HHP treatment has been the most successful and it is gaining in popularity with food processors not only because of its food preservation capability but also because of its potential to achieve interesting functional effects. HHP technology has generated international research and development activity and within a short time produced several commercial products in the market (Gould, 2001).

Table 1.1 and 1.2 show some of the current commercial applications of HHP treatment in food industry.

Table 1.1. Current applications of high pressure processing for food preservation (Ohlsson and Bengtsson, 2002).

Product	Manufacturer	Process conditions
Jams, fruit dressing, fruit sauce topping, yoghurt, fruit jelly	Meidi-ya Company, Japan	400 MPa, 10-30 min, 20°C
Grapefruit juice	Pokka Corp, Japan	120-400 MPa, 2-20 min, 20°C + additional heat treatment
Mandarin juice	Wakayama Food Ind., Japan	300-400 MPa, 2-3 min, 20°C
Non-frozen tropical fruits	Nishin Oil Mills, Japan	50-200 MPa ("freeze" at -18°C)
Tenderized beef	Fuji Ciku Mutterham, Japan	100-50 MPa, 30-40 min, 20°C
Avocado	Avomex, USA	700 MPa, 600-800 L/h
Orange juice	UltiFruit, France	500 MPa, 5 or 10 min cycles, includes a 1 min hold

Table 1.2. Other applications of high pressure processing (Hogan et al., 2005).

Product	Manufacturer
Guacamole, salsa dips, ready meals and fruit juices	Avomex USA
Hummus	Hannah International USA
Fruit and vegetable juices	Odwalla USA
Ham	Hormel Foods USA
Processed poultry products	Purdue Farms USA
Oysters	Motivatit Seafoods USA
Oysters	Goose Point Oysters USA
Oysters	Joey Oysters USA
Fruit juices	Pampryl France
Apple juice	Frubaca Portugal
Sliced ham and tapas	Espuña Spain
Fruit juices and smoothies	Orchard House UK

In Japan, there is now more interest in the potential of HHP to produce entirely novel food products and textures than as a substitute for other preservation processes. Nearly a dozen commercial rice-based foods have been introduced, foremost HHP pre-cooked rice for microwave preparation in the home, as well as salmon, meats and hams of novel texture. Other interesting HHP areas, in addition to food preservation, are as following (Ohlsson and Bengtsson, 2002): tempering of chocolate, gelatinization of starches and proteins, blanching of vegetables, tenderization of meats, coagulation and texturization of fish and meat minces, freezing and thawing (very rapid and without any temperature gradient), increased water absorption rate and reduced cooking time for beans.

For HHP treatment, Knorr (2002) reported that the future opportunities include the pressure assisted blanching, the development of pressure supported freezing and thawing processes and use of high pressure as pretreatment for permeabilization of biological membranes to aid subsequent mass transfer. Beside these, the studies related to design of the suitable packaging materials are important research areas in the future.

1.2.2 Principles of HHP Treatment

HHP treatment, also described as high pressure processing (HPP), or ultra high pressure (UHP) processing, subjects liquid and solid foods, with or without packaging, to pressures between 100 and 800 MPa. Process temperature during pressure treatment can be specified between 5 °C to 90 °C. Pressures used in the HHP treatment of foods appear to have effect on non-covalent bonds (hydrogen, ionic and hydrophobic bonds). HHP may be combined with mild heat to achieve an increased rate of inactivation of microbes and enzymes. Chemical changes in the food generally will be a function of the process temperature, time and pressure (Alpas et al. 1999, 2000; Food and Drug Administration, 2000; Tewari et al., 1999).

Two principles underlie the effect of HHP. Firstly, the principle of le Chatelier, according to which any phenomenon (phase transition, chemical reaction, change in molecular configuration) accompanied by a decrease in volume can be enhanced by pressure. Secondly, pressure is instantaneously and uniformly transmitted independent of size, shape and composition of the food, i.e. the food will be compressed by a uniform pressure from every direction and then return to its original shape when the pressure has been released. This is known as isostatic pressure or Pascal principle. Thus, package size, shape, and composition are not factors in process determination (Guerrero-Beltran et al., 2005).

The work of compression during HHP treatment will increase the temperature of foods through adiabatic heating approximately 3 °C per 100 MPa, depending on the composition of the food. For example, if the food contains a significant amount of fat, such as butter or cream, the temperature rise can be larger. Foods cool down to their original temperature on decompression if no heat is lost to or gained from the walls of the pressure vessel during the hold time at pressure. A uniform initial temperature is required to achieve a uniform temperature increase in a homogenous system during compression (Food and Drug Administration, 2000).

In biological systems the volume-decrease reactions that are most important include the denaturation of proteins, gelation, hydrophobic reactions, phase changes in lipids (and, therefore, in cell membranes) and increases in the ionization of dissociable molecules due to “electrostriction”. The changes that are brought about therefore differ from those brought about by heat, and may have nutritional consequences. For instance, pressure-denatured proteins differ in structure from heat-denatured ones, with possible nutritional consequences (Heremans, 1995). Small molecules are generally less affected than macromolecules, so that low-molecular-weight flavor and odor compounds etc. in foods tend to survive pressure treatment unchanged, with quality advantages in some types of products (Horie et al., 1991).

The critical process factors in HPP include pressure, time at pressure, time to achieve treatment pressure, decompression time, treatment temperature (including adiabatic heating), product initial temperature, vessel temperature distribution at pressure, product pH, product composition, product water activity, packaging material integrity, and concurrent processing aids. Other processing factors present in the process line before or after the pressure treatment was not included. Pressure pulsing would require additional monitoring of pulse shape frequency, and high and low pressure values of the pulse. The displacement of air prior to HPP treatment is done to reduce pumping costs by eliminating air compression. The amount of air in the system is not a critical process factor (Food and Drug Administration, 2000). However, transmittance is not instantaneous when gas are present, and the “Microscopic Ordering Principle”, which implies that at constant temperature, an increase in pressure increases the degree of ordering of the molecules of a substance (Heremans, 1995; Tewari et al., 1999). Another interesting rule concerns the small energy needed to compress a solid or liquid to 500 MPa as compared to heating to 100°C, because compressibility is small (Tewari et al., 1999).

1.2.3 HHP Treatment System

The main components of a HHP system consist of a high pressure vessel and its closure, a pressure generation system, a temperature control device and a material handling system (Ohlsson and Bengtsson, 2002). Current pressure processes include batch and semi-continuous systems, but no commercial continuous HHP systems are operating (Food and Drug Administration, 2000).

Just as for thermal processing, food can be HHP processed in two fundamentally different ways: in-container (HHP is executed after filling and sealing of the food into its final or intermediate package); in bulk followed by aseptic filling and sealing (Knorr et al., 2002).

The batch HHP process takes three steps: an increase in the working pressure, a holding time of this pressure, and depressurizing time. High pressure can be obtained using two different approaches of the pressurization system: direct compression or indirect compression. In direct compression, a medium in a vessel is pressurized directly with a piston. Because of its mechanical configuration, the method is restricted to laboratories or pilot plant systems. In the indirect method, an intensifier pumps the pressure medium through the tubing system to the container (vessel) until the working pressure is achieved (Guerrero-Beltran et al., 2005; Mertens and Deplace, 1993). Solid food products or foods with large solid particles can only be treated in a batch mode. Liquids, slurries and other pumpable products have the additional option of semi-continuous production.

Water or solutions of castor oil, silicone oil, sodium benzoate, ethanol and glycol are also used as the pressure-transmitting medium. Corrosive effect, the process temperature range and the viscosity of the fluid under pressure are some of the factors involved in selecting the medium (Hogan et al., 2005).

Most pressure vessels are made from a high tensile steel alloy “monoblocs” (forged from a single piece of material), which can withstand pressures of 400-600MPa. For higher pressures, pre-stressed multi-layer or wire-wound vessels are used (Mertens, 1995).

Pressure treatment is still costly, mainly because of the initial capital expenditure, and this limits its application to high-value products. However, it can be expected that these costs will go down as a consequence of further progress in technology.

1.2.4 Effect of HHP Treatment on Quality of Fruits and Vegetables

Generally, researches and industrial applications of HHP processing are related to microbial and enzyme inactivation to increase the shelf life of foods. Heat and mass transfer in plant tissues can be influenced by HHP treatment, resulting in improved release of metabolites, increased drying rates of vegetables, or reduced fat uptake of French fries. Furthermore, tissue hardening in vegetables and gel formation in fruit purees – partly due to pressure-induced release of calcium ions and residual pectin methyl esterase activity resulting in the formation of calcium-pectate – has been observed. Also, pressure induced gelation of starches, as well as of proteins and protein-polysaccharide mixtures, offers a wide potential for modifying structure and function of biopolymers (Knorr, 1999).

Regarding HHP treatment as a food-processing technology, the greater the pressure level and time of application, the greater the potential for changes in the appearance of selected foods. This is especially true for raw, high-protein foods where pressure-induced protein denaturation will be visually evident. High hydrostatic pressures also can cause structural changes in structurally fragile foods such as strawberries or lettuce. Cell deformation and cell membrane damage can result in softening and cell serum loss (Food and Drug Administration, 2000).

1.3 HHP and Drying

During the last decades, much attention is paid on the quality of dehydrated foods. By reducing the drying time, protection of the quality and also energy saving could be obtained. The continuous efforts of the food processing industry for producing dried foods have centered on enhancing drying rate, reducing energy consumption and minimizing thermal degradation of food constituents. Several methodologies of pre-treatment are commonly used in order to obtain high quality dehydrated food.

Blanching of fruits and vegetables is a common pretreatment used prior to freezing, and drying. This is done to achieve improved quality and storage ability of the finished product. The primary purpose of blanching is to inactivate naturally occurring enzymes present in food. In addition, there are other advantages for blanching depending upon the method of further processing, such as removal of gases from vegetable surfaces and intercellular spaces to prevent oxidation, discoloration, and off-flavor development as well as reducing the initial number of microorganisms. (Rahman and Perera, 1999). It has been reported that hot water blanching is employed in some cases prior to drying to increase the drying rates of fruits and vegetables, such as banana (Dandamrongrak et al., 2002), red paprika (Ade-Omowaye, et al., 2001-I), fig (Piga et al., 2004), potato (Al-Khuseibi et al., 2005; Eshtiaghi and Knorr, 1993; Severini et al., 2005), strawberries (Alvarez et al., 1995), and green beans, carrots and potatoes (Eshtiaghi et al., 1994). Dehydration kinetics is governed predominantly by the skin permeability, i.e. lye peeling or acid pretreatment. Dipping waxy fruits such as plums, cherries, and grapes, for a few minutes in an emulsion of fatty acid derivatives, used as wetting agents and emulsifiers, such as ethyl oleate, can reduce dehydration time (Ponting and McBean, 1970; Radley, 1964; Saravacos et al., 1988). Chemical (sodium hydroxide, hydrochloric acid, ethyl oleate) and physical (skin puncturing) skin treatments have been reported to influence mass transfer rates during the osmotic dehydration of tomatoes (Shi et al., 1997). Lye peeling and steam assisted peeling are conventional methods adopted as pre-processing steps in the vegetable processing industry. Steam assisted peeling results in the loss of heat sensitive nutrients and possibly affects product texture to some extent. Lye peeling has been reported to adversely affect flavor, texture and sensory qualities of the product (Doymaz and Pala, 2002-II; Ade-Omowaye et al., 2001-I). Osmotic dehydration of fruits and vegetables by immersion in liquids with a water activity lower than that of food has received considerable attention in recent years as a pre-drying treatment so as to reduce energy consumption and to improve food quality (Simal et al., 1997; Wang and Sastry, 2000). Ohmic or microwave heating as pretreatment methods during dehydration of vegetables, i.e. carrot, potato and yam, have been reported to reduce drying times but this involved working at relatively elevated temperatures which might led to thermal degradation of nutrients (Wang and Sastry, 2000).

In the case of osmotic dehydration, where the rate of mass transfer is generally low, a number of techniques have also been tried to improve mass transfer rate. These techniques include: subjecting the food material to HHP or high intensity electrical field pulses prior to osmotic dehydration or applying ultrasound or partial vacuum or centrifugal force during osmotic treatment (Rastogi et al., 2002).

Processes that facilitate mass transfer of foods without adversely affecting quality might be better alternatives to enhancing drying rates and to save energy than adjusting the process parameters of conventional thermal treatments (Rastogi et al., 2000, 2002). HHP and high intensity electric field pulse treatments are such alternatives. High intensity electric field pulses have been widely used for the irreversible permeabilisation of cell membranes, which has consequently improved the drying rate (Ade-Omowaye et al., 2001-I, II; Rastogi et al, 2002; Knorr et al., 2002; Knorr, 1999). Some of the recently studied products are red paprika (Ade-Omowaye et al., 2001-I), carrot (Rastogi et al., 1999), potato (Angersbach et al., 1997), and apple (Taiwo et al., 2002).

HHP treatment is one of the promising non-thermal processing methods inducing membrane permeabilization that positively affects the mass transfer while leaving the product matrix largely unchanged. When fruits and vegetables are pretreated with HHP it results in cell permeabilization that may facilitate the diffusion and provide higher drying rates (Ohlsson and Bengtsson, 2002).

Eshtiaghi et al. (1994) have studied the water blanching (carrots and green beans for 7 min and potatoes for 4 min in boiling water), HHP (600 MPa for 15 min at 70°C), and freezing pretreatment (at -18°C for 24 hours), effects on fluidized bed drying (at 70°C at air velocities (m/s) of 4.0, 4.8, 4.6 during the first 60 min and 3.2, 4.6, 3.7 for the remainder of the drying process for green beans, carrots and potatoes, respectively), rehydration, texture and color of green beans, carrot dices and potato cubes. Pressure treated samples had texture and color nearest to that of raw material as compared to other pretreatments. On the other hand, HHP treatment resulted in incomplete rehydration but improved with combination with freezing. Initial drying rates were highest for water-blanched and frozen, pressure treated and frozen or just frozen samples, followed by hot-water blanched and HHP treated samples. They have claimed that, HHP treatment, in conjunction with subsequent freezing, can improve mass transfer in plant products and enhance product quality.

Osmotic dehydration of HHP treated pineapple has been reported to be faster than untreated ones. HHP pretreatment (100-700 MPa for 5 min and the maximum temperature experienced by the sample during pressurization was 35°C, cooling to about 15°C during decompression) was applied to enhance mass transfer rates during osmotic dehydration of pineapples (at 40°C and 50 °Brix, ratio of the volume of the sample to that of medium = 1:25) and accelerate the process. Experimentally determined diffusivity values, based on a Fickian model, increased fourfold for water and two fold for sugar. The increase was attributed to breaking-up of cell walls which facilitate the diffusion of water. The diffusivity increased with treatment pressures up to 400 MPa above which it did not significantly vary. Evidence for the extent of cell wall break-up with applied pressure was based on differential interference contrast microscopic examination of tissue. Also, the maximum compressive force required to penetrate the HHP treated samples and controls was compared. It was found that very limited further softening occurred above 300 MPa (Rastogi and Niranjan, 1998).

Compression and decompression during HHP treatment causes the removal of significant amount of water. This moisture loss was attributed to the damage of cell structure. The application of HHP obviously damaged the cell wall structure, leaving the cells more permeable. This effect was responsible for the reduction in water content. There was also a progressive reduction in the intercellular material when samples were subjected to a high pressure and decompressed. This made the tissue soften (Eshtiaghi et al., 1994; Rastogi and Niranjan, 1998).

The osmotic dehydration of HHP-treated potato samples was faster than the untreated one due to the combined effect of cell permeabilisation due to osmotic stress and high-pressure-induced permeabilisation. Effective diffusion coefficients of water diffusing out of the sample and solute infusing into the sample were calculated and the drying rate has increased as a function of HHP (200 and 400 MPa for 10 min at 25°C) applied to the potato sample. Tissue softening of all the layers, in the case of pressure treated at 400 MPa, was higher than the control and the sample treated at 200 MPa at the corresponding distances and immersion times. There was a progressive increase in tissue softening as the osmotic dehydration proceeded. Tissue softening following HHP treatment was due to destruction of cell membranes and partial liberation of cell substances. Upon HHP treatment, polymethylesterase enzyme is liberated and not completely inactivated (which is bound to the cell wall) and brought in close contact with its substrate, the methylated pectin. This caused de-esterification not only during HHP treatment but also after the release of high pressure (standing time). The pressure treatment also caused partial inactivation of the enzyme. This reaction continued with time even after HHP treatment and results in time-dependent softening of potato tissue. The alteration in pectin resulted in loss of water and soluble solids (or extractable pectin) after HHP treatment (Rastogi et al., 2000). It is reported in the literature that the softening of some fruits and vegetables, i.e. green beans and carrots, at atmospheric pressure over a length of time takes place following HHP treatment (Basak and Ramaswamy, 1998).

The effects of various pretreatments, hot water blanching (100°C, 3 min), skin treatments such as lye peeling (5% w/v NaOH solution at 25 or 35°C for 20min) and acid pretreatment (5% v/v HCl solution at 25 or35°C for 20 min), HHP (400 MPa for 10 min at 25°C) and high intensity electric field pulse treatment (2.4

kV/cm, pulse width 300 μs, 10 pulses, pulse frequency 1 Hz), on the dehydration characteristics of red paprika were evaluated and compared with untreated samples. The differently pretreated samples were dried in a fluidized bed dryer (60°C, 6 h and 1 m/s). It was shown that cell permeabilization of physical pretreatments (e.g. HHP) resulted in higher drying rates, as well as higher mass and heat transfer coefficients as compared to conventional pretreatments. The application of HHP or high intensity electric field pulse pretreatments resulted in mass transfer coefficients of 0.049 ± 0.003 and 0.058 ± 0.001 kg/m^2s, respectively, and heat transfer coefficient of 83.61 ± 0.78and 98.36 ± 0.93 W/m^2K, respectively. The values of those for the control samples were 0.043 ± 0.005 kg/m^2s and 73.13 ± 0.10 W/m^2K, respectively. HHP and high intensity electric field pulse treatments were equally effective regarding drying rates as compared to blanching, without the disadvantages of blanching and other processes used as a reference. This showed that non-thermal permeabilisation of paprika cells was beneficial as a pre-treatment to increase the drying rates as well as heat and mass transfer coefficients. Comparison of drying times during the constant rate and falling rate periods as well as total drying time for the different pretreatments showed that the drying time during the constant rate period was not significantly different for the different pretreatments, except for high intensity electric field pulse treatment and hot water blanching pretreatments with slightly lower times, whereas the drying time during the falling rate period was significantly different ($p \leq 0.05$). The drying time during the falling rate period was shortest for high intensity electric field pulse treatment pretreated paprika samples. For HHP pretreated paprika samples, drying times were comparable with blanching treatment (Ade-Omowaye, 2001-I).

The effects of water blanching and HHP on drying kinetics and quality of potato (i.e. rehydrability, texture, color, and apparent density) have been investigated (Al-Khuseibi et al., 2005). The potato cubes in 1% citric acid solution as immersion medium were pressure treated at 400 MPa for 15 min. Hot water blanching was conducted in boiling water for 3 min. HHP and thermally treated potato cubes were dried by convective hot-air in a cabinet air dryer for 8-9 h at 75°C. Drying rates were found to be higher in the initial period of drying for the pressure treated samples. The Page model was found to better fit drying data of the thermally treated samples, and the two term model better described the drying behavior of HHP treated samples. HHP treated samples had a similar rehydrability to thermally treated samples. It was found that pressure treated samples had a hardness value close to that of fresh samples, whereas thermal treatment resulted in a softer texture. The total color difference for the thermally blanched samples was higher than for pressure treated samples before drying and after drying. HHP treated and dried potato cubes had a color close to that of fresh potato cubes. HHP pretreated dried samples were found to have higher apparent density than thermally treated samples.

Briefly, application of high pressures (100-800 MPa) inducing membrane permeabilization of the cell structure that positively affects the mass transfer (higher drying rates) (Ade-Omowaye et al., 2001-I; Al-Khuseibi et al., 2005; Dornenburge and Knorr, 1993; Eshtiaghi et al., 1994; Rastogi et al., 2000, 2002; Rastogi and Niranjan, 1998). The results in the literature are different for drying of HHP pretreated fruit and vegetables due to the different pressure-time-temperature combinations and different drying conditions and systems and also due to the variety of the selected fruits and vegetables.

1.4 Objectives of the Study

Conventional drying of fruits and vegetables causes the change of color, texture and taste. The protection of quality and also saving energy could be obtained by reducing the drying time. HHP treatment is one of the promising non-thermal processing methods inducing membrane permeabilization that positively affects the mass transfer while leaving the product matrix largely unchanged.

The objective of this study is to evaluate the effect of HHP pretreatment for enhancing the drying rate of selected fruits (Amasya and red delicious apples) and vegetables (green beans and carrots) and perform kinetic analysis of the drying operation. Also, the applicability of several kinetic models selected from the literature for the drying of fruits and vegetables will be checked by appropriate statistical analyses procedures.

CHAPTER 2

MATERIAL AND METHODS

2.1 Fruits and Vegetables

Fresh apples, Amasya (moisture content = 87.1 ± 0.3%) and red delicious (moisture content = 85.6 ± 0.5%) varieties, carrots (moisture content = 90.5 ± 0.3%) and green beans (moisture content = 90.8 ± 0.2%) were purchased from a local market. The produce was stored at refrigeration temperature (T = 4°C) until usage. After washing, the samples were sliced as; green beans 3 cm in length, apples and carrots 1×1×4 cm in rectangular shape for subsequent HHP treatment and drying processes.

For the estimation of the moisture content, the samples, prepared as mentioned above, were weighed by an electronic balance (GEC AVERY, 0.0001g sensitivity, United Kingdom) and then placed in a laboratory oven (Dedeoglu, TS5050, Turkey) at 100 ± 1°C. The samples were kept in the oven over-night until the constant weight was reached. The moisture content measurements were performed in three replications.

2.2 HHP System and Treatments

HHP treatments were performed in a designed and constructed lab-scale direct compression unit (capacity: 30 cm^3, maximum P: 500 MPa) (Figure 3). The rate of pressure increase and pressure release was approximately 5–10s for the designed system. Motor oil (Shell HELIX, 20W – 50) was used as pressure transmitting medium. The equipment consists of a pressure chamber of cylindrical design, two end closures, a means for restraining the end closures, a pressure pump, and a hydraulic unit to generate high pressure for system compression and also a temperature control device. The pressure vessel was made of hot galvanized carbon steel and piston was hard chrome plated and polished to mirror finish (steel type heat treated special K) which was processed into the required sizes at Electrical and Electronic Engineering Department of Middle East Technical University, Ankara, Turkey. The liquid was either heated by an electrical heating system or cooled by a water circulation system surrounding the chamber to the desired temperature prior to pressurization. Pressurization time reported in this study did not include the pressure increase and release times.

Figure 3. HHP equipment

Before pressurization, the samples were packaged with LDPE film. Then, the samples were placed into the pressure vessel and kept for 3 – 4 minutes for temperature to reach equilibrium. This time-temperature relation was determined earlier. The samples were pressurized at 100, 200, 250, and 300 MPa for 5, 15, 30, and 45 min, at 20 and 35°C before drying. Immediately after HHP treatment, samples were dried in a convective hot-air dryer.

2.3 Dryer

The drying experiments were conducted in a laboratory scale tunnel dryer (Armfield Ltd., D.27412, Hampshire, England) (Figure 4). It consists of a rate adjustable fan and an adjustable electrical heater with setting switches. The flow cross-section throughout the dryer was 22 × 22 cm^2. Air was circulated in the dryer by a motor driven axial flow fan impeller.

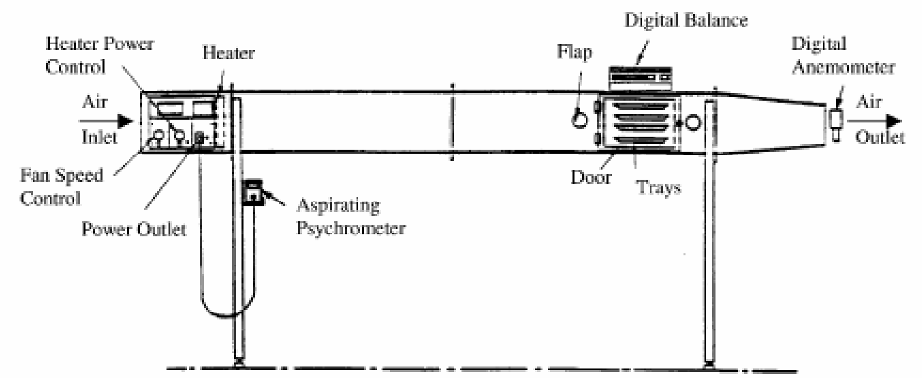

Figure 4. Laboratory scale tunnel dryer (Kaymak-Ertekin and Gedik, 2005).

After HHP treatment, the samples, which were attached to thin wires of about 0.06g in weight, were hanged on to the thin holder-wires, which were located 1.5m away from the air inlet and suspended in the air-stream flowing through the tunnel. Thus, at the sample point, air flowed parallel to surface of the sample, which was positioned horizontally, at its local steady state temperature value.

Before drying of the samples, the attainment of the desired steady-state temperature value was waited. After the system had reached the steady-state, the sample was inserted into the drying tunnel through a latched side door with a glass panel for viewing purposes.

Drying of the samples was carried out under constant external conditions at four different air temperatures (27, 45, 65 and 85°C) at constant relative humidity (35 ± 5%, 12 ± 2%, 5.0 ± 0.5%, 2.5 ± 0.3%, respectively) by using two air velocities (0.4 and 0.8m/s). The moisture loss of samples was determined with 15 or 30 min time intervals, until the constant weight was attained. For sample weight measurements, a digital balance (Sartorius, PT120, 0.01g sensitivity, Germany), with a thin wire attached to bottom of the balance, were connected to the tunnel by wire entering into the drying tunnel and positioning in the air stream next to holder-wires. At the measurement time, side door at the sample point was opened and the sample, hanged on to a holder-wire, was transferred to the wire coming down from the balance, so the sample weight was measured. After measurement, the sample was hanged again on to a holder-wire and then the balance was turned off. All experiments were performed at least in duplicate. The HHP pretreatment and drying experiments for apples, green beans and carrots are summarized in Appendix A (Tables A.1 – A.4).

Dry bulb temperature of the air stream was measured by means of a digital temperature indicator (Nel Electronic Equipments, NR900, 0.1°C sensitivity, Turkey) having thermocouples and a digital display. The temperature during experiments was controlled with an accuracy of ±1°C.

Air velocity was measured by using a vane anemometer (Davis Instruments, in the range of 0 – 44.8m/s, California, USA).

The humidity of the air was not adjusted. The relative humidity of air was measured at flap places before and after the sample point with a digital humidity meter (Testo, model 610, 0 – 100 %RH and -20 – 70°C).

2.4 Preliminary Work

In order to see any potential effect of HHP pretreatment on drying behavior some preliminary experiments were performed on green beans. HHP pretreated (200 MPa for 45 min, 100 MPa for 45 min and 250 MPa for 15 and 45 min at 35°C) and control green bean samples were dried under normal room conditions (25 ± 3°C at a 32 ± 2% relative humidity).

2.5 Drying Kinetics and Modeling

The drying kinetics of the selected fruits and vegetables were studied to find the most convenient kinetic model among 14 different expressions of moisture ratio with time selected from the literature. The models were listed in Table 2. The dimensionless moisture ratio was calculated as:

$$MR = \frac{X_t - X_e}{X_0 - X_e} \qquad (16)$$

where X_t is moisture content at a given time, X_e equilibrium moisture content and X_0 is initial moisture content, on dry basis.

The regression analyses were performed by using Sigma Plot 2000 software and the applicability of the models was tested and also model constants were determined. In order to investigate the drying behavior of samples, drying curves were drawn as variation of dimensionless moisture ratio with time.

Coefficient of determination (R^2), and mean square error (MSE) were used for the adequacy of fit. The coefficient of determination was the primary criterion for selecting the best equation to describe the drying behavior. In addition, MSE was used to determine the best fit. The ideal value of MSE is “zero”, and of R^2 is “one”. The value of MSE was calculated by the following equation:

$$MSE = \frac{\sum_{i=1}^{n}\left(MR_{pre,i} - MR_{\exp,i}\right)^2}{n-p} \tag{17}$$

where $MR_{pre,i}$ is the ith predicted moisture ratio, $MR_{exp,i}$ is the ith experimentally observed moisture ratio, n is the number of observations, and p is the number of parameters to be estimated (Neter et al., 1996).

For each drying conditions, firstly, all the models were tested for control samples and the most suitable ones were determined. Then, the selected models were also tried for the HHP treated samples for comparison.

Table 2. Mathematical models selected for drying curves.

Model name	Model equation	References
Newton (Lewis or Exponential)	$MR = \exp(-kt)$	Senadeera et al. (2003), Pancharia et al (2002), Liu and Bakker-Arkema (1997), O'Callaghan et al. (1971)
Page	$MR = \exp(-kt^n)$	Simal et al. (2005), Wongwises and Thongprasert (2000), Madamba et al. (1996), Diamante and Munro (1993), Zhang and Litchfield (1991), Agrawal and Singh (1977)
Modified Page	$MR = \exp(-(kt)^n)$	White et al. (1981), White et al. (1978), Overhults et al. (1973)
Wang and Singh	$MR = 1 + a \cdot t + b \cdot t^2$	Wang and Singh (1978)
Henderson and Pabis	$MR = a \cdot \exp(-kt)$	Henderson and Pabis (1961)
Logarithmic	$MR = a \cdot \exp(-kt) + c$	Yagcioglu et al. (1999), Togrul (2005)
Diffusion approach (Approximation of diffusion)	$MR = a \cdot \exp(-kt) + (1-a) \cdot \exp(-kbt)$	Yaldiz and Ertekin (2001), Kassem (1998), Sharaf-Eldeen et al. (1979)
Simplified Fick's diffusion (SFFD)	$MR = a \cdot \exp\left(-c\left(t / L^2\right)\right)$	Diamante and Munro (1991)
Modified page equation-II	$MR = \exp\left(-c\left(t / L^2\right)^n\right)$	Diamante and Munro (1991)
Midilli	$MR = a \cdot \exp\left(-k\left(t^n\right)\right) + b \cdot t$	Midilli et al. (2002)
Two term	$MR = a \cdot \exp\left(-k_1 t\right) + b \cdot \exp\left(-k_2 t\right)$	Sharaf-Eldeen et al. (1980), Henderson (1974)
Two term exponential	$MR = a \cdot \exp\left(-kt\right) + \left(1-a\right) \cdot \exp\left(-kat\right)$	Sharaf-Eldeen et al. (1980)
Verma	$MR = a \cdot \exp\left(-kt\right) + \left(1-a\right) \cdot \exp\left(-gt\right)$	Verma et al. (1985)
Modified Henderson and Pabis	$MR = a \cdot \exp\left(-kt\right) + b \cdot \exp\left(-gt\right) + c \cdot \exp(-ht)$	Karathanos (1999)

CHAPTER 3

RESULTS AND DISCUSSION

3.1 Preliminary Work

First of all, preliminary experiments were performed with green beans under room conditions to see if there is any potential effect of HHP pretreatment on drying rate. The changes in the moisture ratio with time are given in Figures 5.1 – 4.

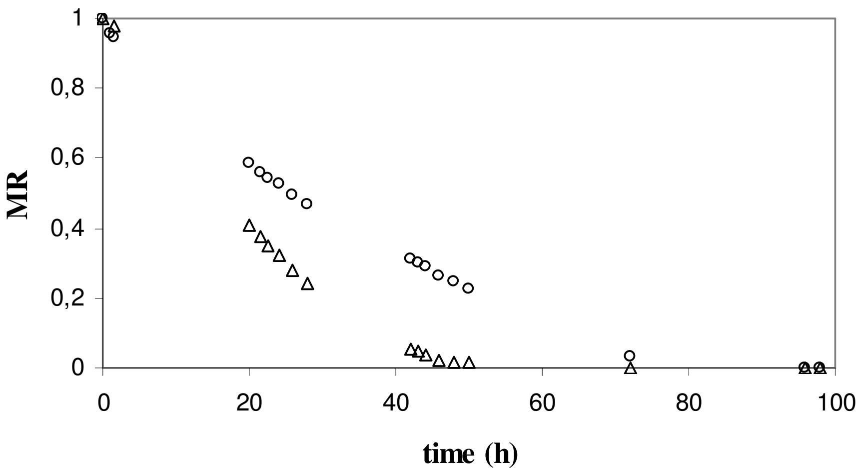

Figure 5.1. Drying curves of green bean with HHP pretreatment at 100 MPa and 35°C for 45 min and without pretreatment at room conditions (24 ± 2°C).
(○) Control (Δ) 100MPa, 45 min, 35°C

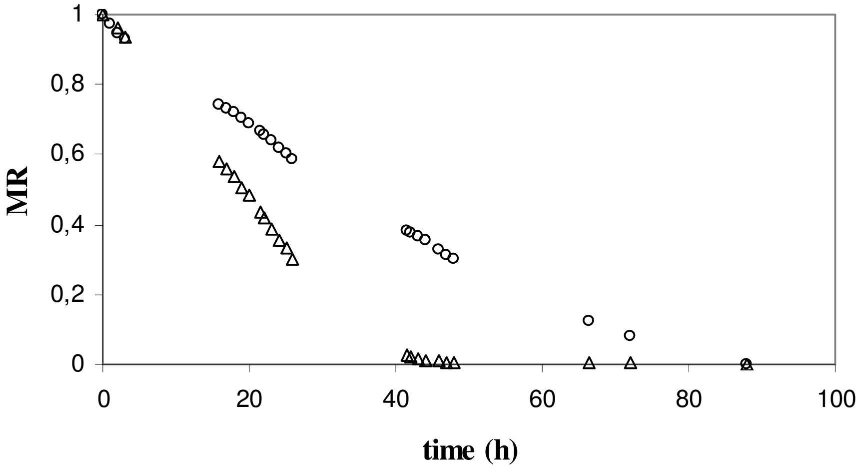

Figure 5.2. Drying curves of green bean with HHP pretreatment at 200 MPa and 35°C for 45 min and without pretreatment at room conditions (24 ± 2°C).
(○) Control (Δ) 200MPa, 45 min, 35°C

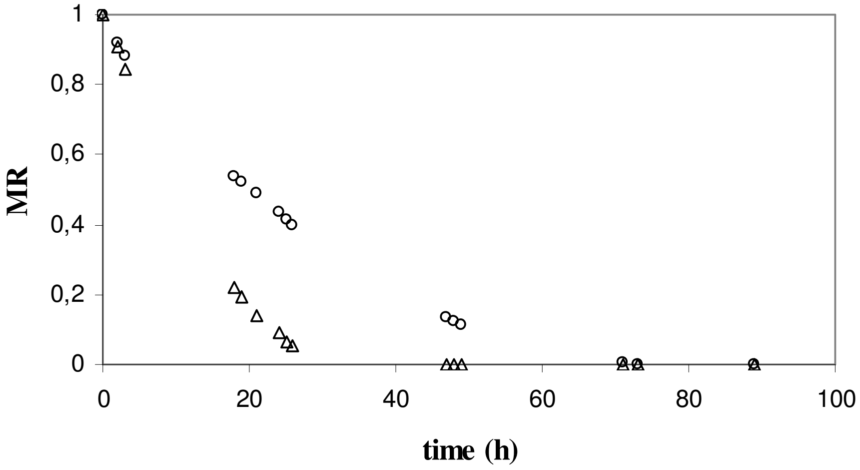

Figure 5.3. Drying curves of green bean with HHP pretreatment at 250 MPa and 35°C for 45 min and without pretreatment at room conditions (24 ± 2°C).
(○) Control (Δ) 250MPa, 45 min, 35°C

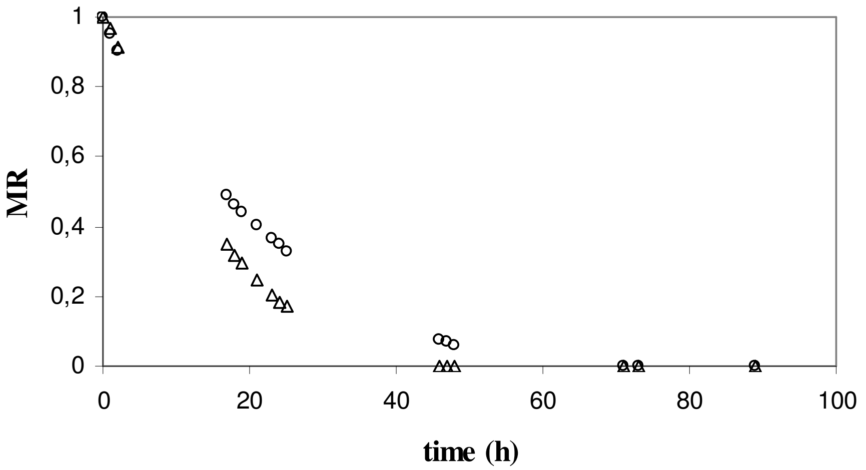

Figure 5.4. Drying curves of green bean with HHP pretreatment at 250 MPa and 35°C for 15 min and without pretreatment at room conditions (24 ± 2°C).
(○) Control (Δ) 250MPa, 15 min, 35°C

It was found that HHP pretreatment increased the drying rate effectively. As compared to control samples, HHP treatment at 200 and 250 MPa for 45 min at 35°C lowered the drying time required to reach the equilibrium moisture content more than two fold. 15 min HHP treatment at 250 MPa and 35°C appeared to be the least effective one to decrease the drying time, among the others. Moreover, 250 MPa treatment was resulted in better enhancement of drying rate than the 100 MPa treatment for the same pressure time combination.

3.2 Drying Behavior of Samples

Drying of the samples, as expected, occurred in falling rate period and there was no constant drying rate period. The variations of drying rates with moisture content are shown in Figures 6.1 – 4.

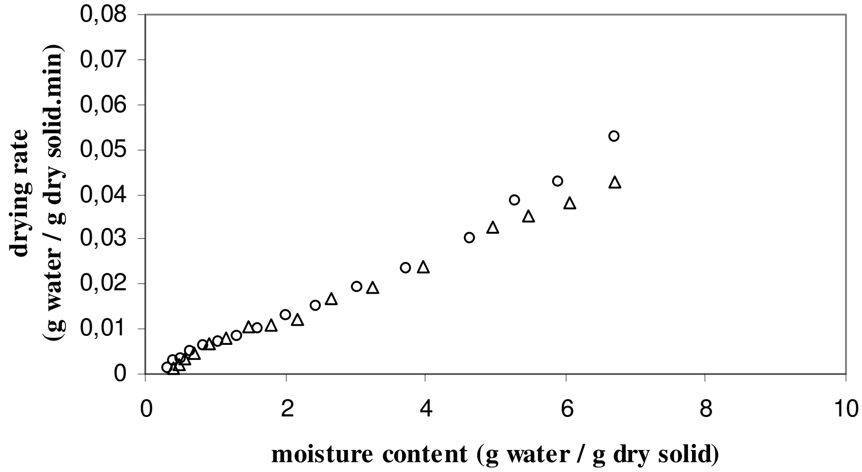

Figure 6.1. Change of drying rate with moisture content for control and HHP pretreated apple (Amasya) slices dried at 45°C with an air velocity of 0.4 m/s.
(○) Control (Δ) 200MPa, 15 min, 20°C

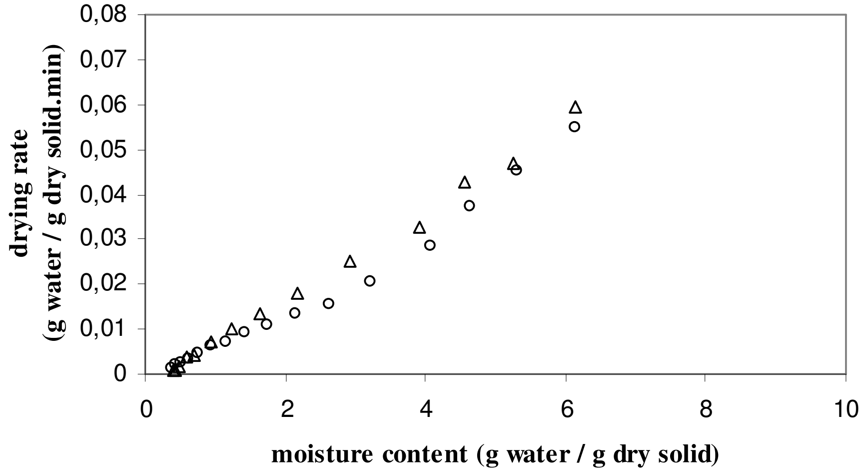

Figure 6.2. Change of drying rate with moisture content for control and HHP pretreated apple (red delicious) slices dried at 45°C with an air velocity of 0.4 m/s.
(○) Control (Δ) 200MPa, 15 min, 20°C

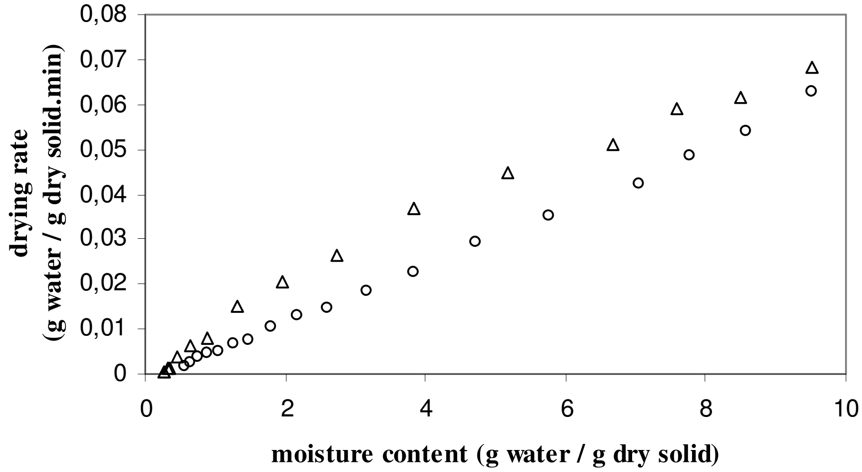

Figure 6.3. Change of drying rate with moisture content for control and HHP pretreated carrot slices dried at 45°C with an air velocity of 0.4 m/s.
(○) Control (Δ) 200MPa, 15 min, 20°C

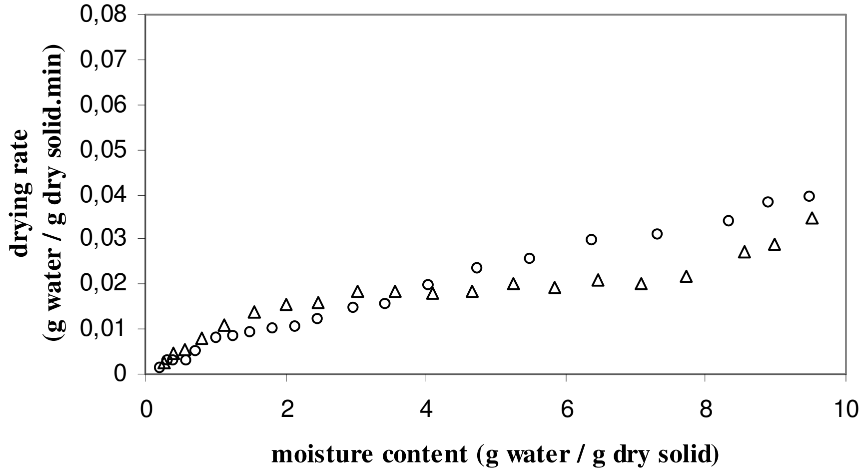

Figure 6.4. Change of drying rate with moisture content for control and HHP pretreated green bean dried at 65°C with an air velocity of 0.4 m/s.
(○) Control (Δ) 200MPa, 15 min, 20°C

Drying rate decreased continuously with decreasing moisture content. During the falling drying rate period, the predominant mechanism of mass transfer in fruits and vegetables is that of internal mass transfer. The internal mass transfer was therefore by molecular (liquid) diffusion or vapor diffusion or by capillary forces in the interior (wet) region of the product and the water was evaporated as it reached the surface (negligible resistance to mass transfer). The most probable mechanism within all mechanisms governing moisture transfer was that of liquid diffusion.

The common feature of the moisture ratio versus time curves is their similarity as being typical drying curve. As it can be visualized from the corresponding figures moisture ratio decreased with time as a kind of exponential decay function. Difference between moisture ratios increased gradually as from beginning of drying.

The main idea was to improve drying process by means of non-thermal pretreatment without exerting additional heat effect; hence the HHP treatments were applied primarily at a target temperature of 20°C. The reason was not only to eliminate the undesired effects of heat on quality and nutritional attributes of foods, but also treatments under mildly heated conditions cause additional operating costs. In order to investigate the effect of mildly heated conditions, HHP treatments at 35°C was also compared with those at 20°C, as mentioned in the following sections.

3.3 Hot Air Drying

3.3.1 Amasya Apple

Amasya apple is one of the most famous fruits unique to Turkey with its highly approved quality attributes. The changes in the moisture ratio with time during hot air drying at different temperatures and air velocities after different HHP treatment conditions are given in Figures 7.1.1 – 7.4.5.

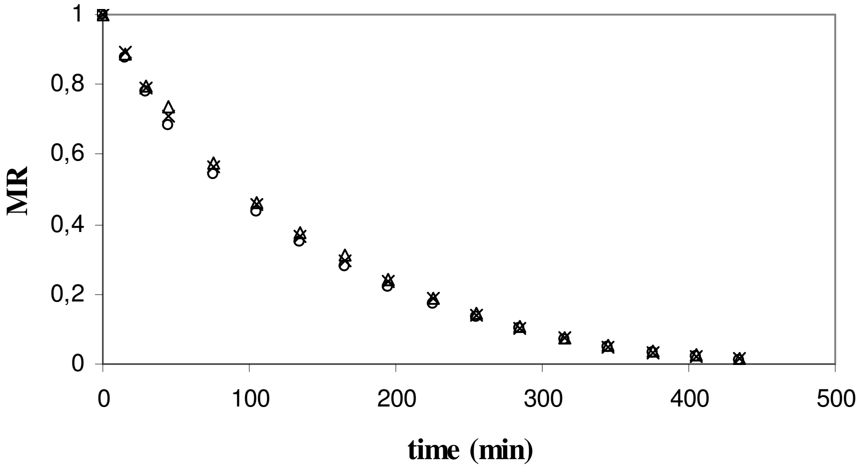

Figure 7.1.1. Drying curves of apple (Amasya) slices at 45°C with air velocity of 0.4 m/s after HHP treatments at 100 MPa and 20°C for 15 and 45 min.
(○) Control (Δ) 100MPa, 15 min, 20°C (×) 100MPa, 45min, 20°C

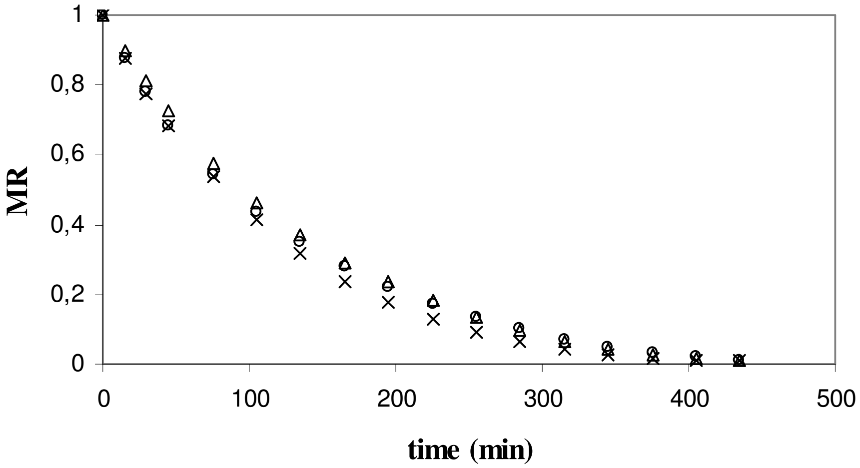

Figure 7.1.2. Drying curves of apple (Amasya) slices at 45°C with air velocity of 0.4 m/s after HHP treatments at 200 MPa and 20°C for 15 and 45 min.
(○) Control (Δ) 200MPa, 15 min, 20°C (×) 200MPa, 45min, 20°C

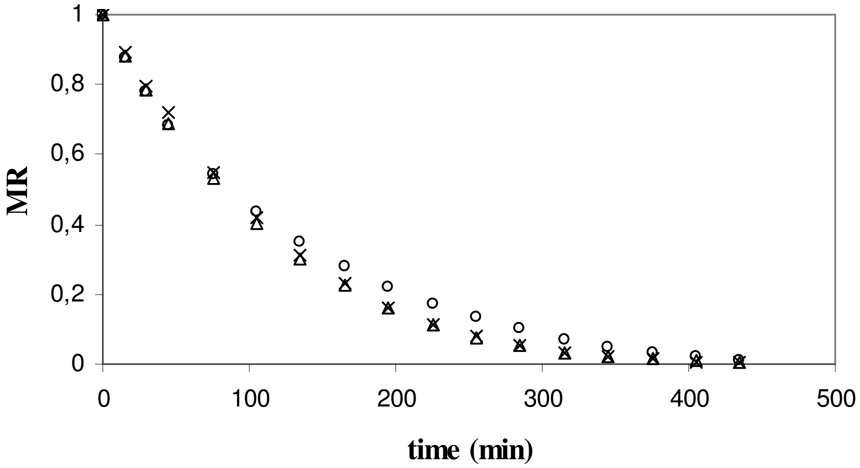

Figure 7.1.3. Drying curves of apple (Amasya) slices at 45°C with air velocity of 0.4 m/s after HHP treatments at 300 MPa and 20°C for 15 and 45 min.
(○) Control (Δ) 300MPa, 15 min, 20°C (×) 300MPa, 45min, 20°C

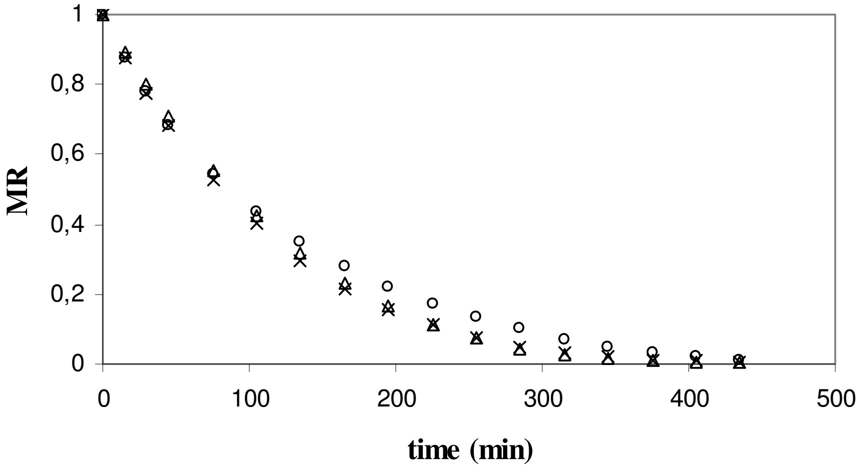

Figure 7.1.4. Drying curves of apple (Amasya) slices at 45°C with air velocity of 0.4 m/s after HHP treatments at 200 MPa and 35°C for 15 and 45 min.
(○) Control (Δ) 200MPa, 15 min, 35°C (×) 200MPa, 45min, 35°C

HHP treatments at 100 MPa for 15 and 45 min at 20°C had no effect on drying rates of the samples dried at 45°C, and so the drying curves for these pressure treated samples coincided with the that of control sample (Figure 7.1.1). HHP pretreatment at 200 MPa and 20°C for 45 min resulted in a negligible increase in drying rate of the Amasya apple dried at 45°C with an air velocity of 0.4 m/s, however 15 min HHP treatment at the same conditions had no effect on drying behavior (Figure 7.1.2). HHP pretreatments at 300 MPa and 20°C and at 200 MPa and 35°C slightly improved the drying characteristics of the samples, whereas increasing the pressure time from 15 to 45 min did not possess any additional effect (Figures 7.1.3 – 4). Mainly HHP treatments were centered on reasonable pressure magnitudes of 100 and 200 MPa.

To show the effect of pressure more clearly, data was presented in Figures 7.1.5 and 7.1.6. Although effective results were not obtained by HHP pretreatment to decrease the drying time of Amasya apple, among the 15 min HHP treatments, 200 MPa at 35°C and 300 MPa at 20°C were seen to be the most effective treatments (Figure 7.1.5). Whereas, among the 45 min treatments 200 MPa at 35°C was found to be the best treatment as providing slightly better drying curve data than 200 and 300 MPa treatments at 20°C which were equally effective to enhance drying process (Figure 7.1.6).

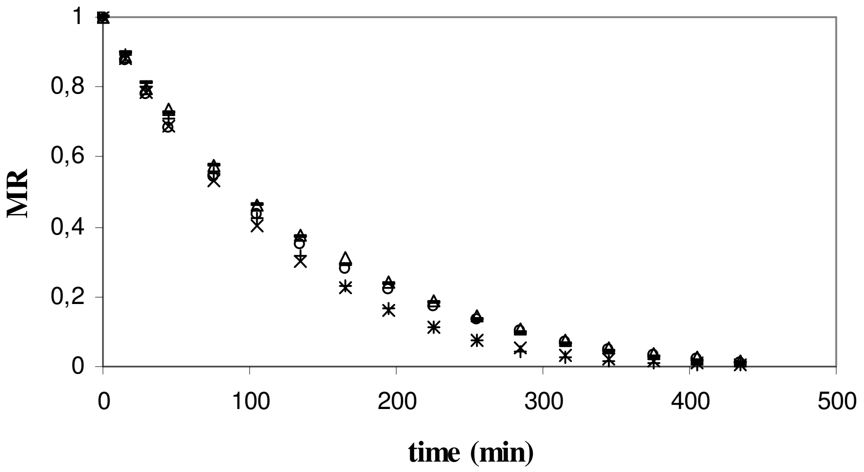

Figure 7.1.5. Drying curves of apple (Amasya) slices at 45°C with air velocity of 0.4 m/s after HHP treatments at different pressure and temperature combinations for 15 min.

(○) Control (Δ) 100MPa, 15 min, 20°C (—) 200MPa, 15min, 20°C

(×) 300MPa, 15min, 20°C (+) 200MPa, 15min, 35°C

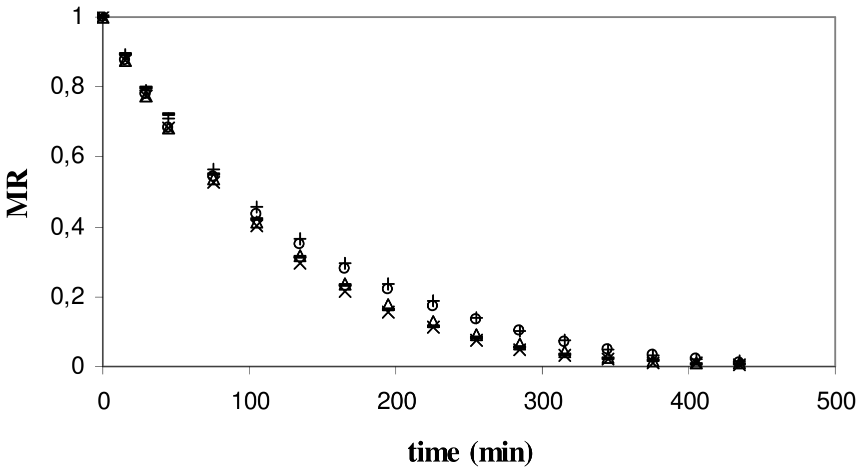

Figure 7.1.6. Drying curves of apple (Amasya) slices at 45°C with air velocity of 0.4 m/s after HHP treatments at different pressure and temperature combinations for 45 min.

(○) Control (+) 100MPa, 45 min, 20°C (Δ) 200MPa, 45min, 20°C

(**–**) 300MPa, 45min, 20°C (×) 200MPa, 45min, 35°C

The change in the air velocity affects the drying process. As expected, increasing the air velocity by two fold resulted in shorter drying times at the same temperature. Drying at 45°C with air velocity of 0.8 m/s revealed that HHP treatments at 200 MPa increased the drying rate effectively, as 45 min treatment being slightly better than 15 min treatment but not much. The HHP treated samples reached their equilibrium moisture content more than 100 min earlier than the control (Figure 7.2.1).The rate was not altered at the initial periods of drying but at the later stages there was a remarkable increase. The observation may be attributed to permeabilization of cell structure facilitating diffusion by increase in diffusivity. This effect was not as obvious in drying at 45°C and 0.4 m/s as in 0.8 m/s at the same temperature. At the later stages, drying rate decreased for HHP treated samples and reached to the constant weight at a time not much different from that of the control, being slightly lower, for drying at 45°C and air velocity of 0.4 m/s.

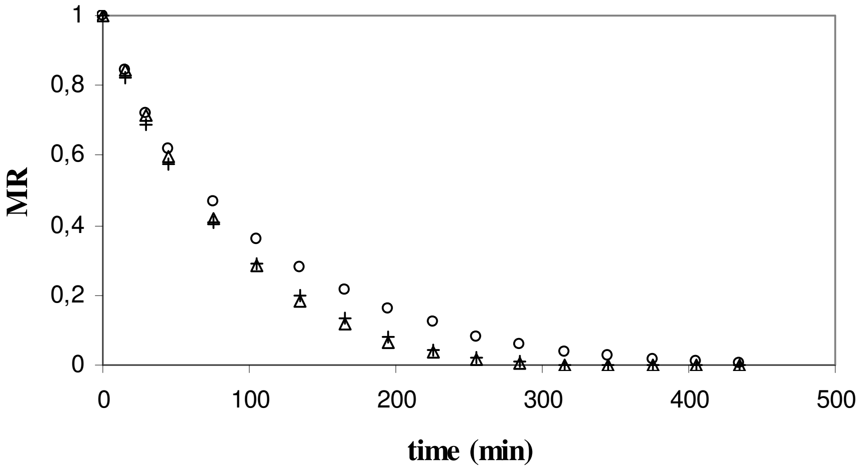

Figure 7.2.1. Drying curves of apple (Amasya) slices at 45°C with air velocity of 0.8 m/s after HHP treatments at 200 MPa and 20°C for 15 and 45 min.
(○) Control (+) 200MPa, 15 min, 20°C (Δ) 200MPa, 45min, 20°C

When the drying temperature was increased to 65°C, there was no effect of HHP pretreatments at 100 MPa and 20°C on samples for all pressurization times selected (Figure 7.3.1). Moreover, 200 MPa treatments at 20°C had very limited effect (Figure 7.3.2). Similar to HHP treatment at 20°C (Figure 7.3.2), there was no difference between 15 and 45 min treatments at 35°C. To show the effect of increasing pressure, the same results were represented in Figures 7.3.4 – 6. Increase in pressure from 100 to 200 MPa showed a negligible increase for drying behavior of Amasya apple.

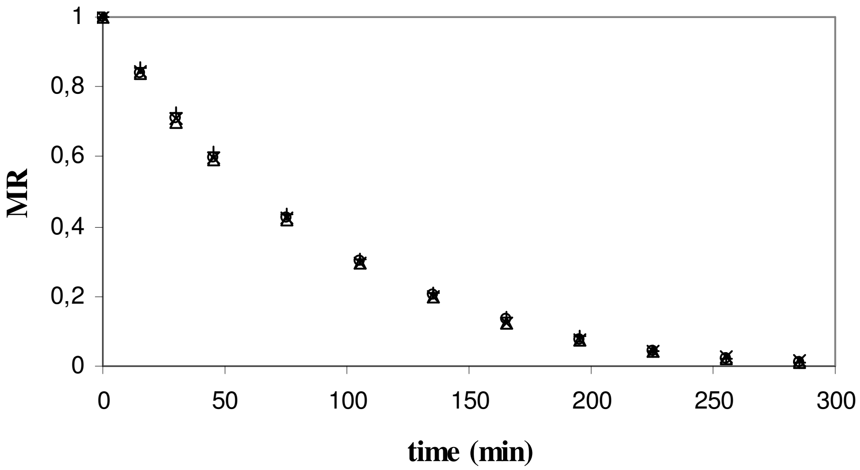

Figure 7.3.1. Drying curves of apple (Amasya) slices at 65°C with air velocity of 0.4 m/s after HHP treatments at 100 MPa and 20°C for 5, 15 and 45 min.
(○) Control (+) 100MPa, 5 min, 20°C (Δ) 100MPa, 15min, 20°C
(×) 100MPa, 45min, 20°C

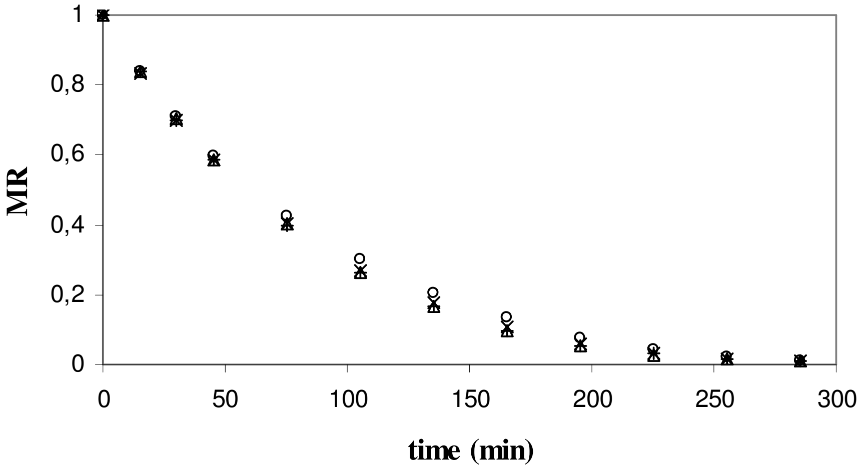

Figure 7.3.2. Drying curves of apple (Amasya) slices at 65°C with air velocity of 0.4 m/s after HHP treatments at 200 MPa and 20°C for 5, 15 and 45 min.
(○) Control (+) 200MPa, 5 min, 20°C (Δ) 200MPa, 15min, 20°C
(×) 200MPa, 45min, 20°C

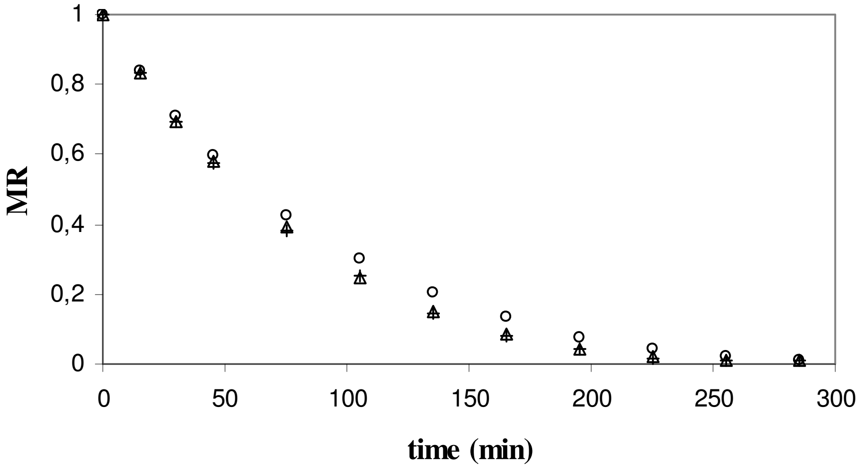

Figure 7.3.3. Drying curves of apple (Amasya) slices at 65°C with air velocity of 0.4 m/s after HHP treatments at 200 MPa and 35°C for 15 and 45 min.
(○) Control (+) 200MPa, 15 min, 35°C (Δ) 200MPa, 45min, 35°C

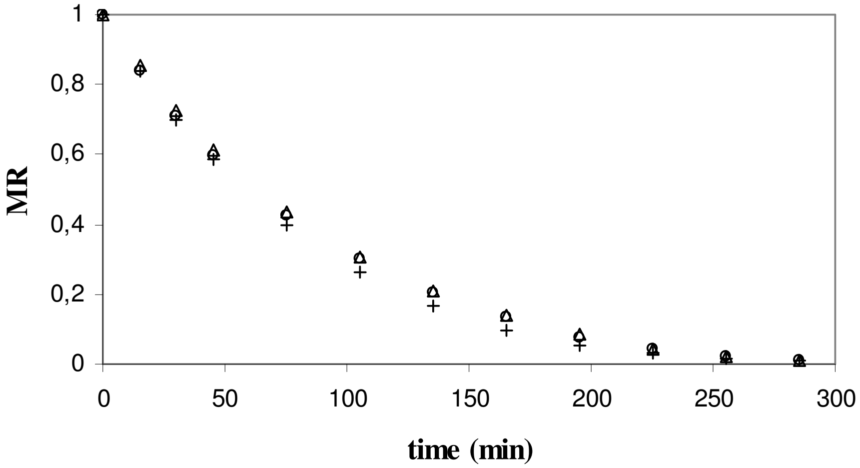

Figure 7.3.4. Drying curves of apple (Amasya) slices at 65°C with air velocity of 0.4 m/s after HHP treatments at 100 and 200 MPa and 20°C for 5 min.
(○) Control (Δ) 100MPa, 5min, 20°C (+) 200MPa, 5 min, 20°C

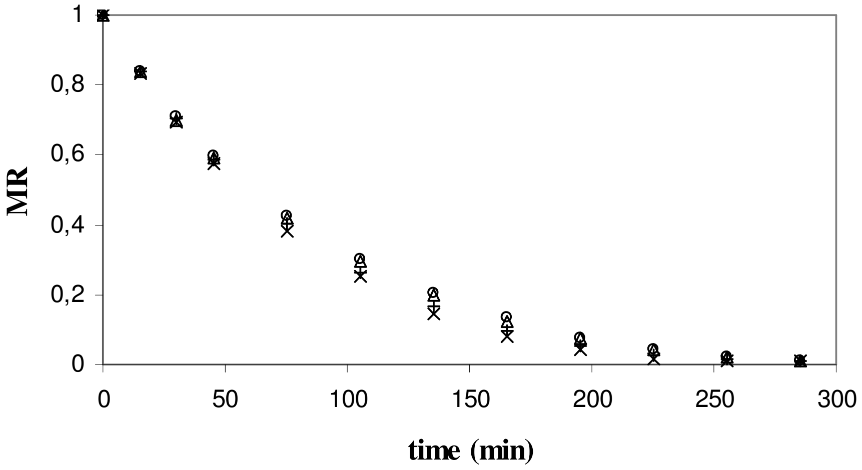

Figure 7.3.5. Drying curves of apple (Amasya) slices at 65°C with air velocity of 0.4 m/s after HHP treatments at different pressure and temperature combinations for 15 min.

(○) Control (Δ) 100MPa, 15 min, 20°C (+) 200MPa, 15min, 20°C

(×) 200MPa, 15min, 35°C

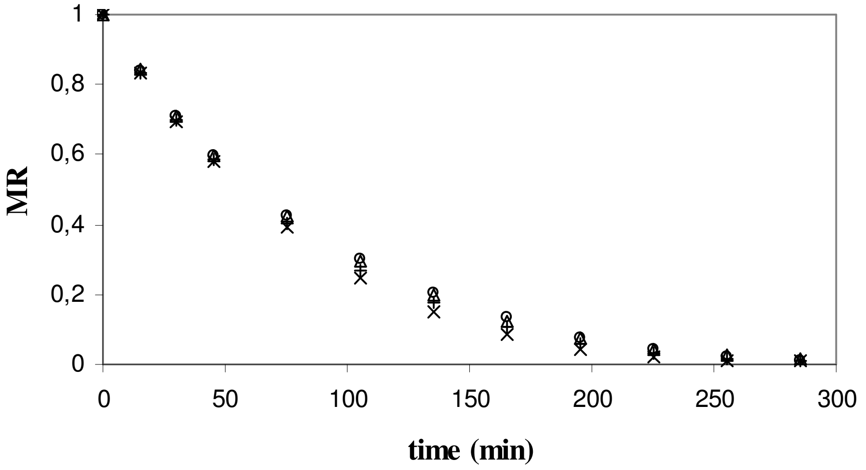

Figure 7.3.6. Drying curves of apple (Amasya) slices at 65°C with air velocity of 0.4 m/s after HHP treatments at different pressure and temperature combinations for 45 min.

(○) Control (Δ) 100MPa, 45 min, 20°C (+) 200MPa, 45min, 20°C
(×) 200MPa, 45min, 35°C

Further increasing the drying temperature to 85°C shortened the drying time more than twice as compared to drying at 45°C. The effect of HHP treatment on drying rate was not observed at 85°C, as drying curves of control and pretreated samples coincide with each other, because high drying temperature masked the effect of HHP pretreatment. Also at that drying temperature, HHP treatment at 100 MPa and 20°C for 5 min has a negative effect on drying as slightly decreasing the drying rate initially, which can be attributed to the contraction of the capillaries, so the moisture removal by capillary action (Figures 7.4.1 – 5).

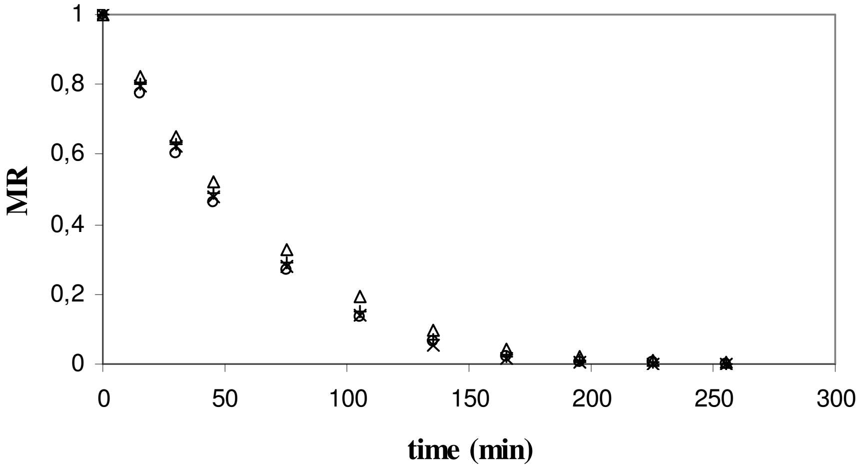

Figure 7.4.1. Drying curves of apple (Amasya) slices at 85°C with air velocity of 0.4 m/s after HHP treatments at 100 MPa and 20°C for 5, 15 and 45 min.
(○) Control (Δ) 100MPa, 5 min, 20°C (+) 100MPa, 15min, 20°C
(×) 100MPa, 45min, 20°C

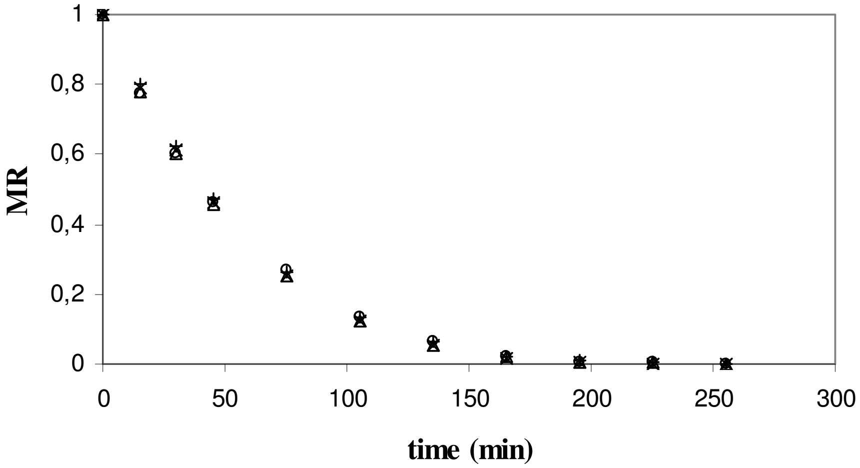

Figure 7.4.2. Drying curves of apple (Amasya) slices at 85°C with air velocity of 0.4 m/s after HHP treatments at 200 MPa and 20°C for 5, 15 and 45 min.
(○) Control (Δ) 200MPa, 5 min, 20°C (+) 200MPa, 15min, 20°C
(×) 200MPa, 45min, 20°C

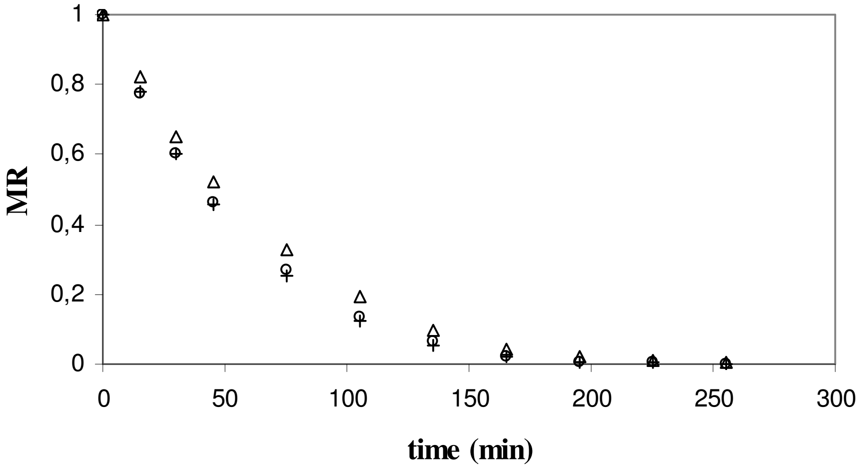

Figure 7.4.3. Drying curves of apple (Amasya) slices at 85°C with air velocity of 0.4 m/s after HHP treatments at 100 and 200 MPa and 20°C for 5 min.
(○) Control (Δ) 100MPa, 5 min, 20°C (+) 200MPa, 5min, 20°C

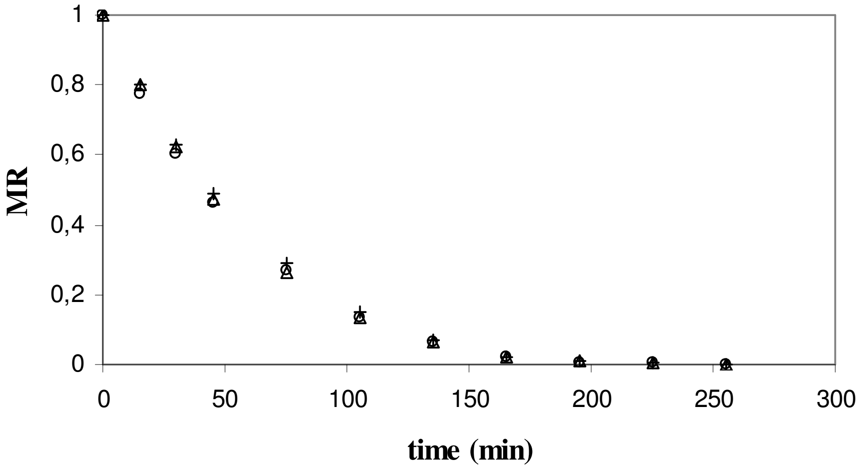

Figure 7.4.4. Drying curves of apple (Amasya) slices at 85°C with air velocity of 0.4 m/s after HHP treatments at 100 and 200 MPa and 20°C for 15 min.
(○) Control (+) 100MPa, 15min, 20°C (Δ) 200MPa, 15 min, 20°C

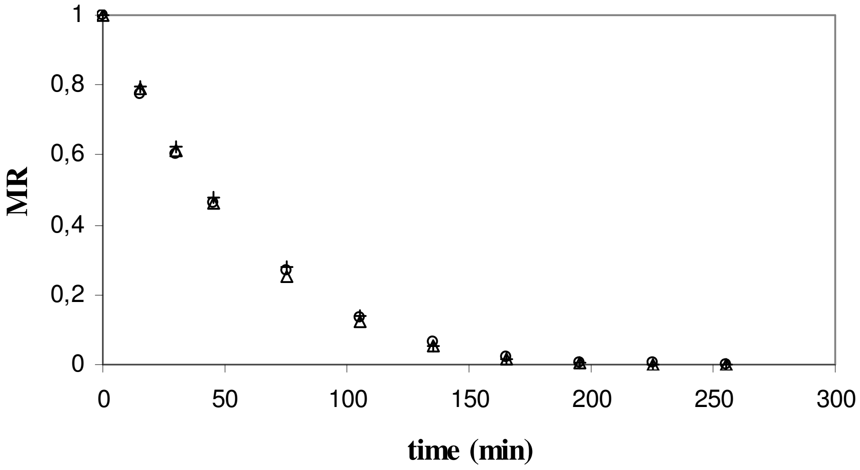

Figure 7.4.5. Drying curves of apple (Amasya) slices at 85°C with air velocity of 0.4 m/s after HHP treatments at 100 and 200 MPa and 20°C for 45 min.
(○) Control (+) 100MPa, 45min, 20°C (Δ) 200MPa, 45 min, 20°C

Ade-Omowaye et al. (2001) claimed that the application of HHP (400 MPa for 10 min at 25°C) pretreatment resulted in cell permeabilization and increased drying rate of fluidized bed dried (60°C, 6 h and 1 m/s) red paprika. Drying time during the constant rate period was not significantly different for HHP pretreated red paprika as compared to skin treatments, such as lye peeling and acid treatment, and control, whereas the drying time during the falling rate period was significantly different. Total drying time, calculated up to a moisture content of 0.112 kg water / kg dry solid, for control was about 360 min while that of for HHP pretreated sample was less than 320 min. As a result, they suggested that non-thermal permeabilization of paprika cells was beneficial as a pretreatment to increase the drying rates as well as heat and mass transfer coefficients. Also, this was the case in our work, especially for HHP treatments at higher than 100 MPa. The same research group also found that large portion of the moisture was removed in constant rate period, and the critical moisture contents were changing between 5 and 6 (kg water / kg dry solid) with an initial moisture content of 10 (kg water / kg dry solid). This was not the case in our work, since no constant drying rate period was observed and all the drying process was occurred in a single falling rate period.

3.3.2 Red Delicious Apple

The effect of HHP pretreatment prior to drying of apples of red delicious variety was also investigated, to see the behavior of different varieties of samples under same conditions. The changes in the moisture ratio with time during hot air drying at 45°C with air velocity of 0.4 m/s for control and pressure treated samples are given in Figure 8.1.1. HHP treatment at 200 MPa at different time and temperature combinations were investigated, since 100 MPa was found to be ineffective for Amasya variety.

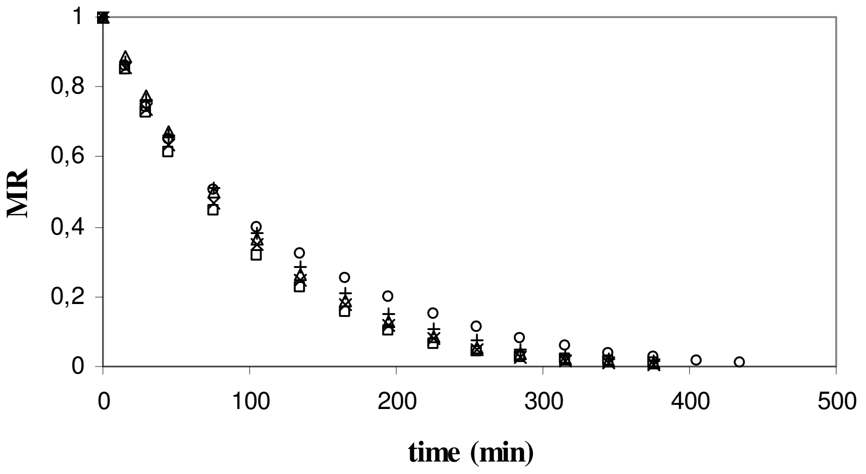

Figure 8.1.1. Drying curves of apple (red delicious) slices at 45°C with air velocity of 0.4 m/s after HHP treatments at different pressure, time and temperature combinations.

(○) Control (□) 200MPa, 15min, 20°C (Δ) 200MPa, 45min, 20°C

(×) 200MPa, 15 min, 35°C (+) 200Mpa, 45min, 35°C

Among the selected pretreatment conditions for red delicious apples, HHP treatment at 200 MPa and 20°C for 15 min was found to be the most effective pretreatment condition, whereas others were nearly equally effective and increased the drying rate. For Amasya variety 200 MPa treatments at 35°C were found to be the most effective treatment, but this was not the case in red delicious variety. Thus, changing the variety resulted in observation of different effects of HHP treatment in that the best effective treatment combination was changed.

HHP pretreatment (100-700 MPa for 5 min at 15 – 35°C) was applied to enhance mass transfer rates during osmotic dehydration of pineapples. (Rastogi and Niranjan, 1998). Osmotic dehydration of pineapples were accelerated by pretreating at high pressures, however rehydration characteristics were poorer due to loss of cell integrity. Experimentally determined diffusivity values, based on a Fickian model, were found to be increased four fold for water and two fold for sugar. They have noted that very limited further softening occurred above 300 MPa and the diffusivity increased with treatment pressures up to 400 MPa above which it did not significantly vary. Compression and decompression during HHP treatment caused removal of a significant amount of water, which was attributed to the damage of cell structure. This result is consistent throughout the concept of this work. HHP treatment caused 2 – 5% of moisture loss during treatment for all samples with an amount changing with treatment conditions related to amount of cell disintegration.

3.3.3 Carrot

Carrot slices were dried at 27, 45 and 65°C with air velocity of 0.4 m/s and corresponding drying curves are shown in Figures 9.1.1 – 9.3.1.

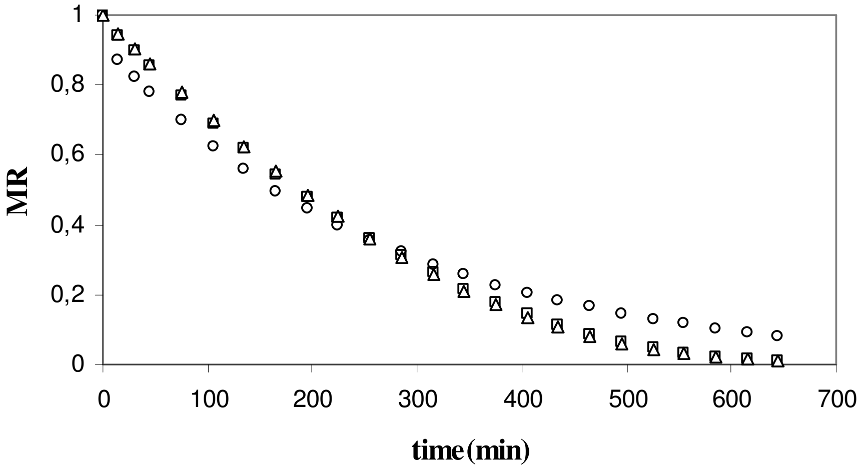

Figure 9.1.1. Drying curves of carrot slices at 27°C with air velocity of 0.4 m/s after HHP treatments at 200 MPa and 20°C for 15 and 45 min.
(○) Control (□) 200MPa, 15min, 20°C (Δ) 200MPa, 45min, 20°C

200 MPa for 15 and 45 min at 20°C pretreated carrot slices were dried at 27°C. Initially pressure treatment caused contraction of the sample tissue, and so smaller capillaries, decreasing the drying rate as shown in Figure 9.1.1. Also, the reason may be related to the moisture loss during pressurization. As the drying continued drying rate was increased at the later stages compared to the control. This is due to the permeabilization of the cell structure increasing the diffusivity of water from interior of the cells. The HHP pretreated samples reached to equilibrium moisture content significantly earlier than the control. Increasing the pressure time from 15 min to 45 min had exerted no additional effect. Both HHP treatments caused the samples to reach final weight at the same time (Figure 9.1.1).

When the drying temperature was increased to 45°C, the initial drying rate was close to each other for all pretreated samples together with control. Thus, by increasing the temperature to 45°C, capillary contraction effect might be overcomed or decreased to a negligible value by an increase in diffusivity as a result of temperature increase. HHP treatment at 100 MPa and 20°C did not increase the drying rate (Figure 9.2.1). In addition to that 100 MPa treatment for 5 min at 20°C decreased the drying rate of carrots, causing a little longer drying time as compared to control. On the other hand 5 min treatment at 200 MPa increased the drying rate causing shorter drying times (Figure 9.2.2). All 200 MPa treatments greatly decreased the drying time by an amount of 200 min. Drying curves of 15 and 45 min treatments at 250 MPa were nearly the same (Figure 9.2.3). Effects of increase in pressure are given in Figures 9.2.5 – 7. For the 45 min HHP treatments under same conditions where 200 and 250 MPa treatments at 20°C were equally effective initially giving slightly better drying rates as compared to 200 MPa treatment at 35°C, but all concerned samples reached to equilibrium moisture content at the same time (Figure 9.2.7).

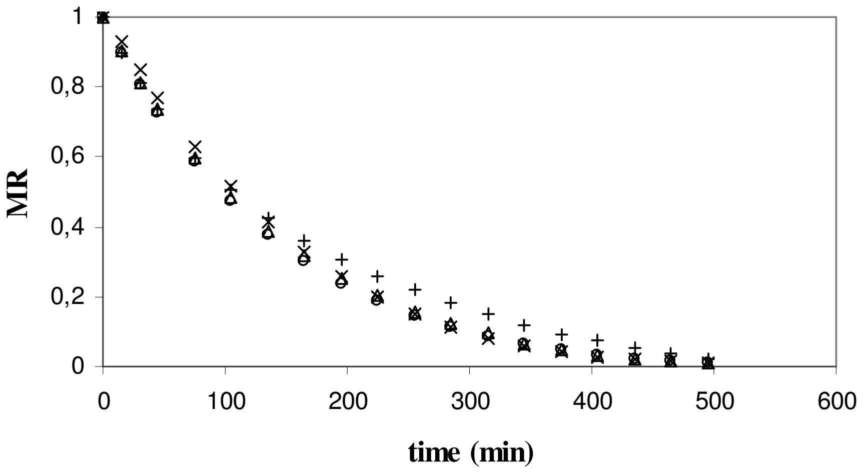

Figure 9.2.1. Drying curves of carrot slices at 45°C with air velocity of 0.4 m/s after HHP treatments at 100 MPa and 20°C for 5, 15 and 45 min.
(○) Control (+) 100MPa, 5min, 20°C (Δ) 100MPa, 15 min, 20°C
(×) 100MPa, 45min, 20°C

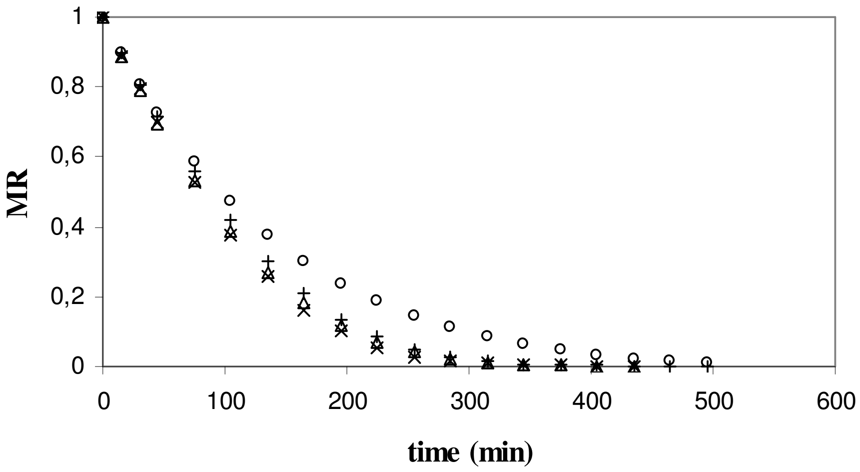

Figure 9.2.2. Drying curves of carrot slices at 45°C with air velocity of 0.4 m/s after HHP treatments at 200 MPa and 20°C for 5, 15 and 45 min.
(○) Control (+) 200MPa, 5min, 20°C (Δ) 200MPa, 15 min, 20°C
(×) 200MPa, 45min, 20°C

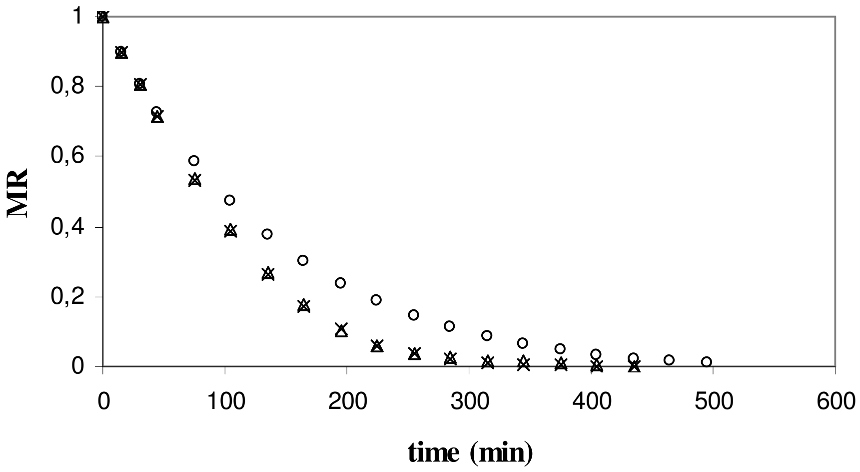

Figure 9.2.3. Drying curves of carrot slices at 45°C with air velocity of 0.4 m/s after HHP treatments at 250 MPa and 20°C for 15 and 45 min.
(○) Control (×) 250MPa, 15min, 20°C (Δ) 250MPa, 45 min, 20°C

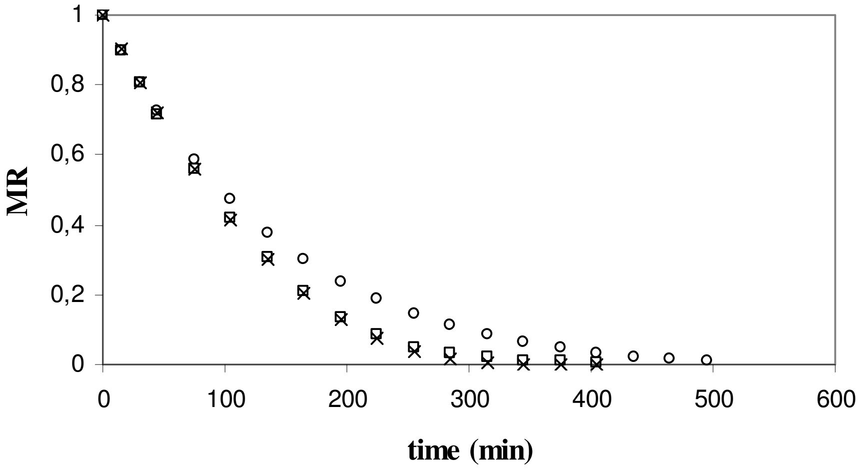

Figure 9.2.4. Drying curves of carrot slices at 45°C with air velocity of 0.4 m/s after HHP treatments at 200 MPa and 35°C for 15 and 45 min.
(○) Control (×) 200MPa, 15min, 35°C (□) 200MPa, 45 min, 35°C

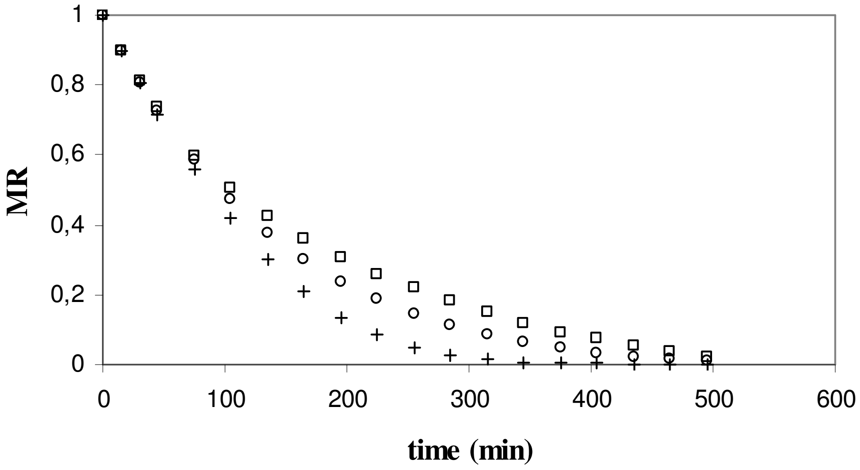

Figure 9.2.5. Drying curves of carrot slices at 45°C with air velocity of 0.4 m/s after HHP treatments at 100 and 200 MPa and 20°C for 5 min.
(○) Control (□) 100MPa, 5 min, 20°C (+) 200MPa, 5min, 20°C

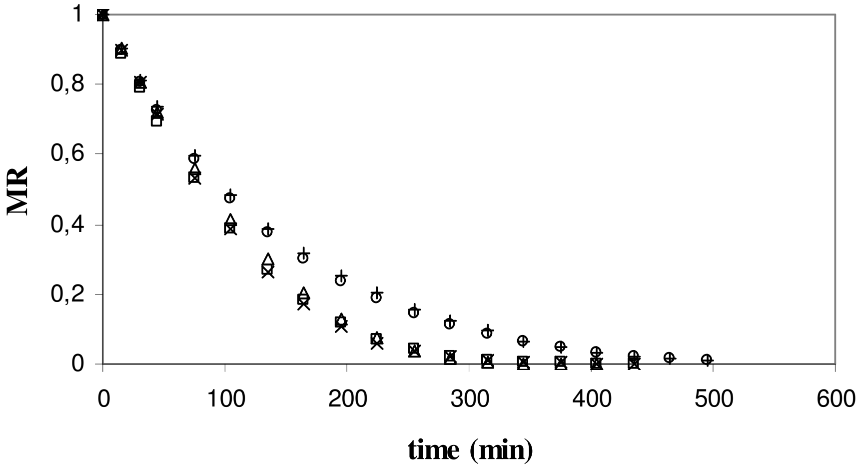

Figure 9.2.6. Drying curves of carrot slices at 45°C with air velocity of 0.4 m/s after HHP treatments at different pressure and temperature combinations for 15 min.

(○) Control (+) 100MPa, 15min, 20°C (□) 200MPa, 15 min, 20°C

(×) 250MPa, 15min, 20°C (Δ)200MPa, 15 min, 35°C

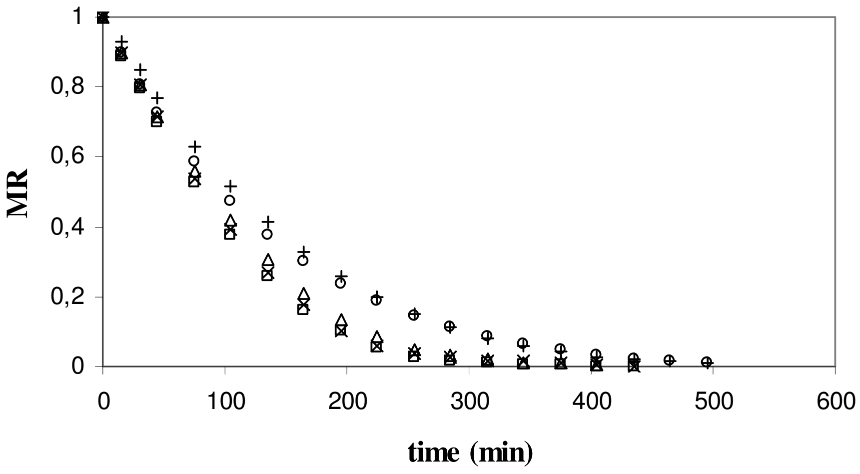

Figure 9.2.7. Drying curves of carrot slices at 45°C with air velocity of 0.4 m/s after HHP treatments at different pressure and temperature combinations for 45 min.

(○) Control (+) 100MPa, 45min, 20°C (□) 200MPa, 45 min, 20°C

(×) 250MPa, 45min, 20°C (Δ)200MPa, 45 min, 35°C

When the drying temperature was increased to 65°C, the effect of HHP treatment became less noticeable (Figure 9.3.1), since improving the drying conditions may have concealed the effect of pretreatment. 200 MPa treatments were revealed to give slightly better results as compared to 250 MPa treatments, while all treatments had nearly the same effect; 250 MPa treatment for 45 min being slightly the worse than the others.

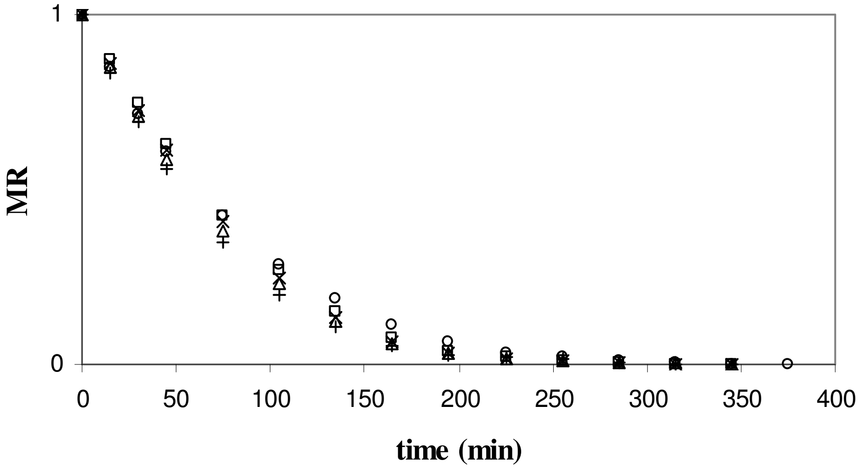

Figure 9.3.1. Drying curves of carrot slices at 65°C with air velocity of 0.4 m/s after HHP treatments at different pressure and time combinations at 20°C.
(○) Control (+) 200MPa, 15min, 20°C (Δ) 200MPa, 45 min, 20°C
(×) 250MPa, 15min, 20°C (□)250MPa, 45 min, 20°C

3.3.4 Green Bean

Green bean has an important place in Turkish traditional meal habits and is grown in surplus amount in Turkey. The changes in the moisture ratio with time during hot air drying at 45°C with air velocity of 0.4 m/s are given in Figure 10.1.1. Drying rate for green bean samples dried at 45°C decreased by HHP treatment at 200 MPa and 20°C. Tissue contraction was increased by an increase in pressure time, and so the 45 min treatment resulted in a worst drying curve.

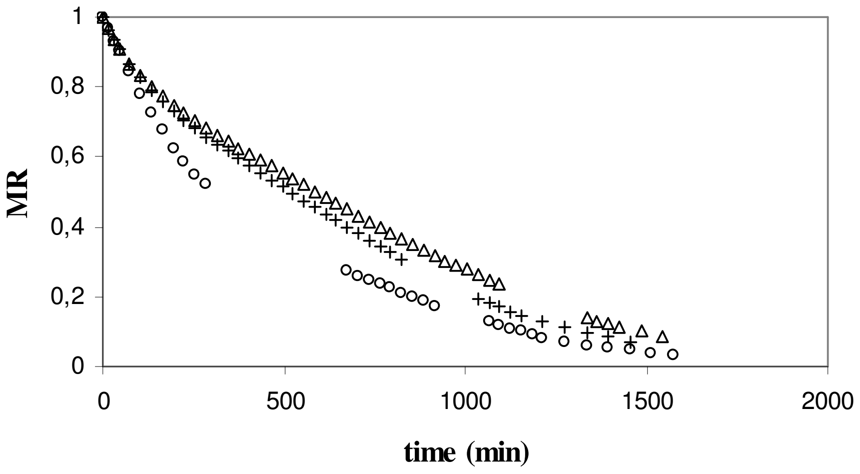

Figure 10.1.1. Drying curves of green bean at 45°C with air velocity of 0.4 m/s after HHP treatments at 200 MPa and 20°C for 15 and 45 min.
(○) Control (+) 200MPa, 15min, 20°C (Δ) 200MPa, 45 min, 20°C

The same phenomenon was observed for samples dried at 65°C treated with 100 and 200 MPa (Figure 10.2.1 – 2). On the contrary, HHP treatment at 35°C showed different behavior (Figure 10.2.3). At the initial period of drying, the rate was same for both pressure treated and control samples, but at the later stages of drying rate was higher for pressure treated samples as compared to control, giving shorter drying times of about more than 100 min. HHP treatment at 200 MPa and 35°C for 15 and 45 min were equally effective. Hence, increase in pressurization temperature positively altered the drying curve. The same data was presented again in Figures 10.2.4 – 5, to show the effect of increasing pressure; but effective results were not obtained.

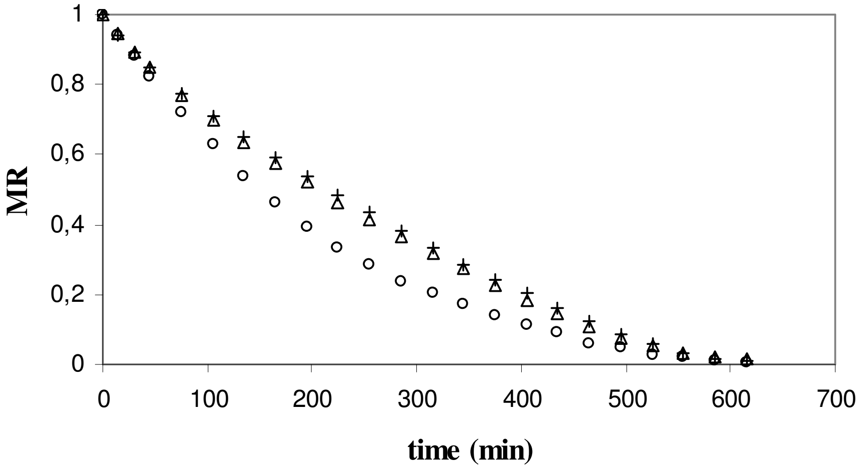

Figure 10.2.1. Drying curves of green bean at 65°C with air velocity of 0.4 m/s after HHP treatments at 100 MPa and 20°C for 15 and 45 min.
(○) Control (Δ) 100MPa, 15 min, 20°C (+) 100MPa, 45min, 20°C

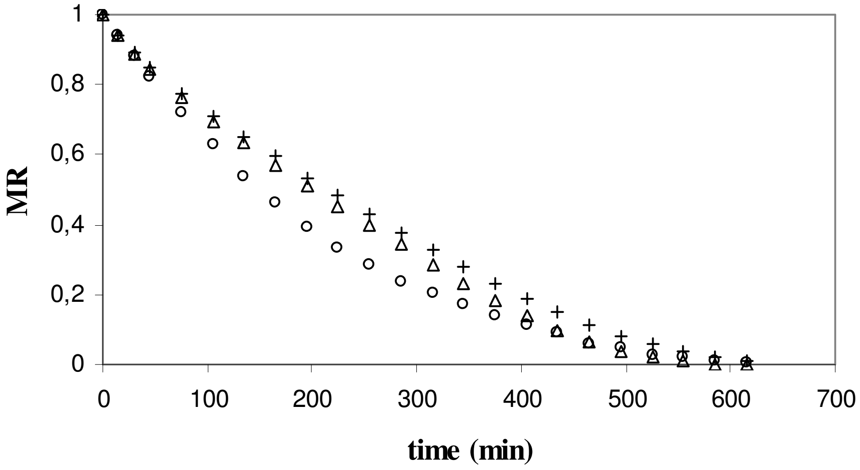

Figure 10.2.2. Drying curves of green bean at 65°C with air velocity of 0.4 m/s after HHP treatments at 200 MPa and 20°C for 15 and 45 min.
(○) Control (Δ) 200MPa, 15 min, 20°C (+) 200MPa, 45min, 20°C

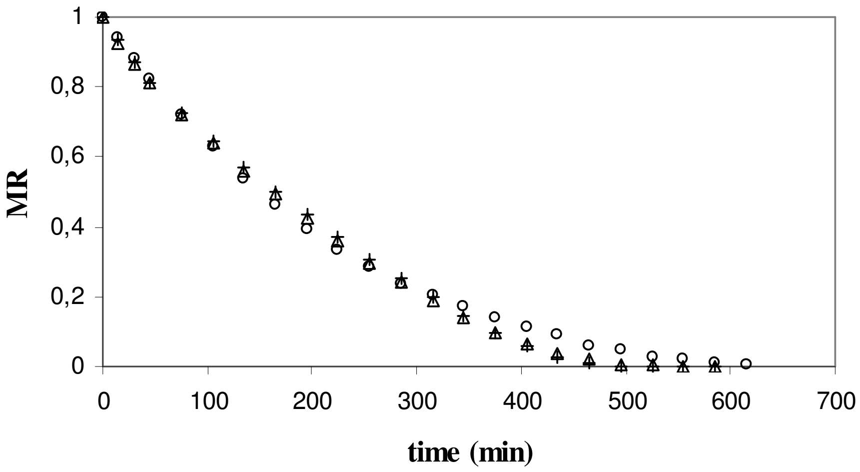

Figure 10.2.3. Drying curves of green bean at 65°C with air velocity of 0.4 m/s after HHP treatments at 200 MPa and 35°C for 15 and 45 min.

(○) Control (Δ) 200MPa, 15 min, 35°C (+) 200MPa, 45min, 35°C

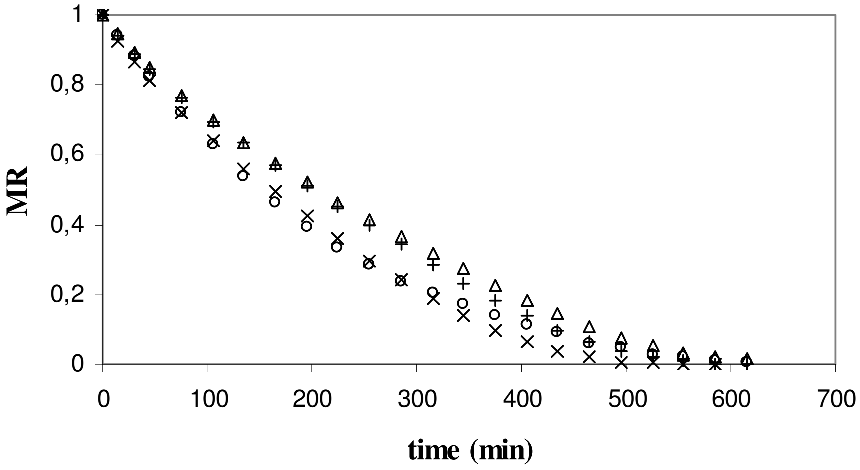

Figure 10.2.4. Drying curves of green bean at 65°C with air velocity of 0.4 m/s after HHP treatments at different pressure and temperature combinations for 15 min.

(○) Control (Δ) 100MPa, 15 min, 20°C (+) 200MPa, 15min, 20°C

(×) 200MPa, 15min, 35°C

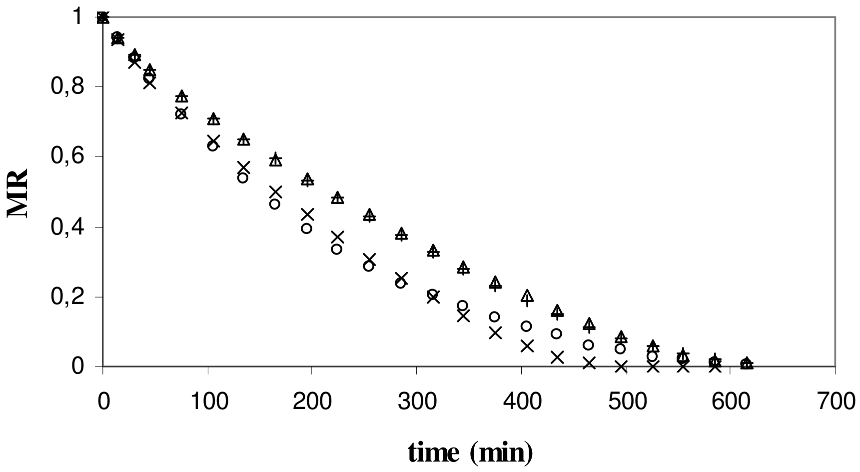

Figure 10.2.5. Drying curves of green bean at 65°C with air velocity of 0.4 m/s after HHP treatments at different pressure and temperature combinations for 45 min.
(○) Control (Δ) 100MPa, 45 min, 20°C (+) 200MPa, 45min, 20°C
(×) 200MPa, 45min, 35°C

Eshtiaghi et al. (1994) found that only HHP pretreatment (400 MPa, 20°C, 15 min) decreased the drying rate of green beans which were fluidized bed dried (70°C, 4.0 and 3.2 m/s), however HHP treatment in conjunction with subsequent freezing improved mass transfer and enhance product quality. HHP treated and frozen green bean samples reached to equilibrium moisture content more than twofold earlier as compared to control or only HHP treated samples. They have found that, initial drying rates were highest for water-blanched and frozen, pressure-treated and frozen, or just frozen samples, followed by hot water blanched, raw and HHP treated samples. These effects were quite different considering that the time of treatment to weight loss of 80% varied from about 30 min for water blanched and frozen to 90 to 100 min for raw or pressure-treated samples. In our study, HHP treatments at 100 and 200 MPa and 20°C for 15 and 45 min decreased the drying rate causing longer drying times. On the contrary, they revealed that the rate of carrot drying was not influenced much by pretreatments, i.e. HHP treatment, water blanching and freezing. Moreover, the investigators found that pressure treated samples had texture nearest that of raw material and no major differences in color were observed.

3.4 Modeling

The drying kinetics of the selected fruits and vegetables were studied to find the most convenient kinetic model among 14 different expressions for the moisture ratio change with respect to time (Table 2). The coefficient of determination, R^2 was the primary criterion for selecting the best equation to describe the drying behavior. In addition, mean square error, MSE was used to determine the best fit. The ideal value of MSE is “zero”, and of R^2 is “one”. Firstly, all the models were analyzed for control samples and than the ones that better characterize the drying curves were chosen to be further used for pressure treated samples. For the selected models, all the model parameters had low standard errors, i.e. $P < 0.0001$. For Amasya apples the model constants were given in Table 3.1.1.

Some of the constants of a model behaved far from linear, causing very large confidence intervals, so standard errors. This was a compromise between having to choose a model that is in principle better but that resulted in badly behaved parameter estimates and a model that could be slightly worse from a statistical point of view but gave much better parameter estimates (Van Boekel, 2002).

Newton, Page and Modified Page models resulted in nearly the same fit of adequacy, and Page and Modified Page models much more resembling each other in terms of their R^2 and MSE. It was found that, “k” parameter of Newton and Modified Page models were very close to each other, while for Page and Modified

Page the values of parameter “n” were very similar. Modified Page model behaved as combination of model constants of Newton and Page models, and resulting in good R^2 and MSE values which were quite similar to those of page model. Among three models, modified page was used to simulate the drying behavior of the pressure treated samples

Table 3.1.1. Modeling of moisture ratio according to drying time for apple (Amasya) samples without pretreatment dried at 45°C with air velocity of 0.4 m/s.

Model	Model constants			R^2	MSE
Newton	k = 0.0080 ± 0.0001			0.998890	0.000119
Page	k = 0.0079 ± 0.0007	n = 1.0026 ± 0.0164		0.998892	0.000127
Modified Page	k = 0.0080 ± 0.0001	n = 1.0027 ± 0.0164		0.998892	0.000127
Wang and Singh	a = -0.0056 ± 0.0002	b = 8E-006 ± 0.0000		0.979201	0.002360
Henderson and Pabis	a = 0.9954 ± 0.0073	k = 0.0080 ± 0.0001		0.998919	0.000120
Logarithmic	a = 1.0117 ± 0.0058	k = 0.0074 ± 0.0001	c = -0.0250 ± 0.0055	0.999581	0.000050
Midilli	a = 1.0006 ± 0.0031	k = 0.0102 ± 0.0004		0.999915	0.000008
	n = 0.9407 ± 0.0090	b = -0.0001 ± 0.0000			
Two term	a = 0.4977 ± 0.8760	k_1 = 0.0080 ± 0.0263		0.998919	0.000138
	b = 0.4977 ± 0.8760	k_2 = 0.0080 ± 0.0263			
Two term exponential	a = 1.2872 ± 0.1226	k = 0.0086 ± 0.0004		0.998959	0.000120
Verma	a = 1.0004 ± 0.0011	k = 0.0079 ± 0.0001	g = -0.0092 ± 0.0057	0.999563	0.000050

Wang and Singh model did not give any better result or resemble the drying behavior correctly, and having the worst statistical test results. Hence, it was not applied to pressure treated samples. Two term, diffusion approach and Verma models generally resulted in high standard errors of parameters, however more reliable results were shown on the corresponding tables. For all of the drying conditions, two term equation gave large standard errors for the model constants.

SFFD, Modified Page-II and Modified Henderson and Pabis models showed badly behaved parameter estimates giving very high standard errors although the statistical analysis were better with higher R^2 and lower MSE values (results are not shown).

Midilli and two term exponential models generally resulted in good statistical results, but not always represent the drying behavior of the samples correctly while having high standard errors for model constants. For the drying conditions at which those models represent the drying data of control samples correctly, then they tried for HHP treated samples to investigate the adequacy of fit.

For the drying of potato, Al Khuseibi et al. (2005) found that, the two term model was able to capture the drying behavior with lower percentage of mean relative error (7 – 8%) than Page and Newton models which were resulted in higher percentage of mean relative error ranging from 11 to 56%. They suggested that was due to the occurrence of two stages of drying with different drying rates. On the contrast, they did not give the standard errors or confidence intervals for values of predicted parameters of derived models. Moreover they claimed that, the four parameters of the model were estimated using theoretical values for constants a (0.8106) and b (0.0901) and the drying rate constants k_1 and k_2 were estimated by linear regression. Since such a study and most importantly drying process is a trial and error procedure, such an approach would not represent the exact behavior of samples because two of the four parameters were assumed as theoretical values.

The theoretical values may only be used as an initial guess of the parameters to be iterated by a non-linear procedure, to find the parameters that are belong to and represents totally your sample under specified external conditions. They claimed that HHP pretreatment could produce quality similar to that of fresh materials and better to that of water blanched materials with advantage of enhanced drying rates. They suggested that the drying rates for the HHP treated (400 MPa, 15 min) potato cubes were greater than that of blanched samples in the initial drying period, however it started to slow at later stages of drying. In our work, same phenomenon was observed for Amasya apples but for carrot slices this was not the case.

3.4.1 Amasya Apple

Modified Page, Henderson and Pabis, Midilli and Two term exponential models were found as the most suitable models to represent the drying behavior of control samples of the Amasya apples dried at 45°C and 0.4 m/s (Table 3.1.1). Logarithmic and Verma models showed badly behaved parameter estimates, since "c" parameter for logarithmic model and "g" parameter for Verma model behaved far from linear and gave large standard errors ($P > 0.0001$). For the HHP treated samples, Midilli equation did not fit to the drying data, since "b" parameter resulted in high standard errors with $P > 0.0001$ for all the HHP pretreated samples, except treatments of 100 MPa for 45 min at 20°C and 200 Mpa for 15 min at 20°C, although the model gave high R^2 and low MSE indicating good fit from a statistical point of view. Two term exponential model did not represent the drying curves of 200 Mpa treatments for 45 min at 20 and 35°C, with lower R^2 and higher standard errors together with high standard errors of estimates (results not shown), for the other treatment combinations two term exponential model resulted in good fit. Modified Page equation was found to be the most suitable model to represent the drying curves of HHP treated Amasya apples dried at 45°C with an air velocity of 0.4 m/s (Table 3.1.2). As the pressure, pressurization time and temperature increased the "k" and “n” parameters of the modified page model was increased indicating an increase in the moisture removal rate.

Modified Page, Henderson and Pabis and Midilli equations were selected for HHP pretreated samples after the evaluation of results for the control samples of the Amasya apples dried at 45°C and 0.8 m/s. “c” parameter of the logarithmic model, “a” and “k” parameters of the two term exponential model and “a” and “b” parameters of the Verma model gave high standard errors, thus can not be used adequately to represent the drying data (Table 3.2.1). For HHP pretreated Amasya apples, the constant “b” of the Midilli equation gave high standard errors as $P > 0.0001$ (Table 3.2.2). Modified Page equation was found to be the best model to represent the drying curve. As the pressure time increased from 15 min to 45 min, the parameter “k” was not changed, however there was an increase in the constant “n” indicating an increase in the mass transfer rate.

Table 3.1.2. Modeling of moisture ratio according to drying time for HHP pretreated apple (Amasya) samples dried at 45°C with air velocity of 0.4 m/s. HHP treatment was given as pressure (Mpa), time (min), temperature (°C).

Model	HHP Treatment	Model constants		R^2	MSE
Modified Page	100, 15, 20	k = 0.0074 ± 0.0001	n = 1.0499 ± 0.0208	0.998394	0.000187
	100, 45, 20	k = 0.0076 ± 0.0001	n = 1.0312 ± 0.0190	0.998604	0.000160
	200, 15, 20	k = 0.0076 ± 0.0001	n = 1.0838 ± 0.0199	0.998697	0.000160
	200, 45, 20	k = 0.0087 ± 0.0001	n = 1.0598 ± 0.0152	0.999240	0.000093
	300, 15, 20	k = 0.0089 ± 0.0001	n = 1.1020 ± 0.0143	0.999417	0.000073
	300, 45, 20	k = 0.0086 ± 0.0001	n = 1.1531 ± 0.0144	0.999480	0.000067
	200, 15, 35	k = 0.0086 ± 0.0001	n = 1.1626 ± 0.0198	0.999050	0.000120
	200, 45, 35	k = 0.0091 ± 0.0001	n = 1.0921 ± 0.0159	0.999258	0.000093
Henderson and Pabis	100, 15, 20	a = 1.0067 ± 0.0103	k = 0.0075 ± 0.0001	0.997801	0.000253
	100, 45, 20	a = 1.0027 ± 0.0089	k = 0.0077 ± 0.0001	0.998351	0.000193
	200, 15, 20	a = 1.0178 ± 0.0115	k = 0.0078 ± 0.0002	0.997392	0.000313
	200, 45, 20	a = 1.0102 ± 0.0090	k = 0.0089 ± 0.0001	0.998516	0.000180
	300, 15, 20	a = 1.0218 ± 0.0115	k = 0.0093 ± 0.0002	0.997727	0.000280
	300, 45, 20	a = 1.0342 ± 0.0150	k = 0.0091 ± 0.0002	0.996169	0.000487
	200, 15, 35	a = 1.0348 ± 0.0168	k = 0.0091 ± 0.0003	0.995243	0.000607
	200, 45, 35	a = 1.0181 ± 0.0113	k = 0.0094 ± 0.0002	0.997788	0.000273
Midilli	100, 15, 20	a = 0.9971 ± 0.0067	k = 0.0075 ± 0.0008	0.999594	0.000054
		n = 0.9851 ± 0.0217	b = -0.0001 ± 0.0000		
	100, 45, 20	a = 0.9998 ± 0.0039	k = 0.0087 ± 0.0005	0.999868	0.000015
		n = 0.9608 ± 0.0119	b = -0.0001 ± 0.0000		
	200, 15, 20	a = 0.9995 ± 0.0050	k = 0.0065 ± 0.0005	0.999780	0.000031
		n = 1.0188 ± 0.0162	b = -0.0001 ± 0.0000		

Table 3.1.2 (continued)

Model	**HHP Treatment**	**Model constants**		**R^2**	**MSE**
	200, 45, 20	a = 0.9938 ± 0.0050	k = 0.0072 ± 0.0005	0.999781	0.000031
		n = 1.0318 ± 0.0151	b = -5E-005 ± 0.0000		
	300, 15, 20	a = 0.9932 ± 0.0051	k = 0.0058 ± 0.0005	0.999776	0.000031
		n = 1.0850 ± 0.0159	b = -4E-005 ± 0.0000		
	300, 45, 20	a = 0.9917 ± 0.0052	k = 0.0042 ± 0.0004	0.999758	0.000038
		n = 1.1447 ± 0.0176	b = -3E-005 ± 0.0000		
	200, 15, 35	a = 0.9900 ± 0.0067	k = 0.0041 ± 0.0005	0.999606	0.000062
		n = 1.1465 ± 0.0227	b = -4E-005 ± 0.0000		
	200, 45, 35	a = 0.9914 ± 0.0060	k = 0.0061 ± 0.0006	0.999687	0.000046
		n = 1.0769 ± 0.0185	b = -4E-005 ± 0.0000		
Two term exponential	100, 15, 20	a = 1.4698 ± 0.0596	k = 0.0087 ± 0.0003	0.998645	0.000160
	100, 45, 20	a = 1.4127 ± 0.0693	k = 0.0087 ± 0.0003	0.998809	0.000140
	200, 15, 20	a = 1.5471 ± 0.0436	k = 0.0093 ± 0.0002	0.998881	0.000133
	300, 15, 20	a = 1.5868 ± 0.0256	k = 0.0112 ± 0.0002	0.999574	0.000053
	300, 45, 20	a = 1.6757 ± 0.0214	k = 0.0115 ± 0.0002	0.999568	0.000053
	200, 15, 35	a = 1.6844 ± 0.0303	k = 0.0115 ± 0.0002	0.999110	0.000113

Table 3.2.1. Modeling of moisture ratio according to drying time for apple (Amasya) samples without pretreatment dried at 45°C with air velocity of 0.8 m/s.

Model	**Model constants**			**R^2**	**MSE**
Newton	k = 0.0099 ± 0.0001			0.998132	0.000194
Page	k = 0.0126 ± 0.0010	n = 0.9488 ± 0.0160		0.998879	0.000127
Modified Page	k = 0.0100 ± 0.0001	n = 0.9488 ± 0.0160		0.998879	0.000127
Wang and Singh	a = -0.0063 ± 0.0003	b = 1E-005 ± 0.0000		0.953853	0.005087
Henderson and Pabis	a = 0.9798 ± 0.0085	k = 0.0096 ± 0.0002		0.998638	0.000153
Logarithmic	a = 0.9840 ± 0.0094	k = 0.0094 ± 0.0003	c = -0.0072 ± 0.0070	0.998733	0.000150
Diffusion approach	a = 0.0539 ± 0.0244	k = 0.0749 ± 0.0626	b = 0.1243 ± 0.1016	0.999202	0.000093
Midilli	a = 1.0005 ± 0.0056	k = 0.0152 ± 0.0010		0.999729	0.000031
	n = 0.9019 ± 0.0140	b = -0.0001 ± 0.0000			
Two term exponential	a = 0.0407 ± 0.0103	k = 0.2312 ± 0.0613		0.999124	0.000093
Verma	a = 0.0538 ± 0.0244	k = 0.0750 ± 0.0623	g = 0.0093 ± 0.0002	0.999202	0.000093

Table 3.2.2. Modeling of moisture ratio according to drying time for HHP pretreated apple (Amasya) samples dried at 45°C with air velocity of 0.8 m/s. HHP treatment was given as pressure (Mpa), time (min), temperature (°C).

Model	**HHP Treatment**	**Model constants**		**R^2**	**MSE**
Modified Page	200, 15, 20	k = 0.0123 ± 0.0002	n = 1.0264 ± 0.0205	0.998792	0.000143
	200, 45, 20	k = 0.0122 ± 0.0002	n = 1.1078 ± 0.0211	0.999056	0.000125
Henderson and Pabis	200, 15, 20	a = 1.0008 ± 0.0095	k = 0.0124 ± 0.0002	0.998638	0.000164
	200, 45, 20	a = 1.0210 ± 0.0146	k = 0.0126 ± 0.0004	0.997162	0.000375
Midilli	200, 15, 20	a = 0.9943 ± 0.0083	k = 0.0119 ± 0.0012	0.999450	0.000075
		n = 1.0019 ± 0.0218	b = -5E-005 ± 0.0000		
	200, 45, 20	a = 0.9940 ± 0.0066	k = 0.0082 ± 0.0008	0.999683	0.000050
		n = 1.0808 ± 0.0202	b = -0.0001 ± 0.0000		

When the drying temperature for Amasya apples was increased to 65°C, Logarithmic and two term exponential models, in addition to modified Page model were found to be the most adequate expressions to represent the drying curve of the control sample (Table 3.3.1). Henderson and Pabis model had slightly lower R^2 and higher MSE values, so it was not tried for HHP treated samples. “b” parameter of the Midilli model and “a” and “k” parameters of the Verma model gave high standard errors. Logarithmic model was not suitable for all the HHP treated samples; for 200 Mpa at 20°C for 5 and 15 min and 200 Mpa at 35°C for 15 and 45 min treatments, constant “c” resulted in high standard errors as $P > 0.0001$ (Table 3.3.2). Modified Page and Two term exponential models were found to be equally effective to represent the drying data of HHP pretreated samples and they resulted in nearly perfect representation of the drying curves with high R^2 and low MSE.

Among the 14 model expressions, modified Page and two term exponential models were the best ones to represent the drying curves of Amasya apple slices, dried at 85°C with an air velocity of 0.4 m/s (Table 3.4.1). For the logarithmic model constant “c”, Midilli model constants “k” and “b” gave high standard errors. Henderson and Pabis model had slightly lower R^2 and higher MSE for control sample, so not selected for HHP treated samples. Both of the selected models were found to represent the drying data in a very good adequacy with equivalent efficiency (Table 3.4.2).

Table 3.3.1. Modeling of moisture ratio according to drying time for apple (Amasya) samples without pretreatment dried at 65°C with air velocity of 0.4 m/s.

Model	**Model constants**			**R^2**	**MSE**
Newton	k = 0.0119 ± 0.0002			0.997590	0.000291
Page	k = 0.0090 ± 0.0010	n = 1.0622 ± 0.0249		0.998571	0.000190
Modified Page	k = 0.0118 ± 0.0002	n = 1.0623 ± 0.0249		0.998571	0.000190
Wang and Singh	a = -0.0084 ± 0.0003	b = 2E-005 ± 0.0000		0.987942	0.001590
Henderson and Pabis	a = 1.0097 ± 0.0129	k = 0.0120 ± 0.0003		0.997721	0.000300
Logarithmic	a = 1.0427 ± 0.0058	k = 0.0106 ± 0.0002	c = -0.0473 ± 0.0058	0.999765	0.000033
Midilli	a = 0.9970 ± 0.0066	k = 0.0111 ± 0.0010		0.999715	0.000050
	n = 1.0012 ± 0.0214	b = -0.0001 ± 0.0000			
Two term exponential	a = 1.4986 ± 0.0625	k = 0.0141 ± 0.0005		0.998822	0.000160
Verma	a = -0.0630 ± 0.0888	k = 0.0010 ± 0.0041	g = 0.0106 ± 0.0007	0.999700	0.000033

Table 3.3.2. Modeling of moisture ratio according to drying time for HHP pretreated apple (Amasya) samples dried at 65°C with air velocity of 0.4 m/s. HHP treatment was given as pressure (Mpa), time (min), temperature (°C).

Model	**HHP Treatment**	**Model constants**			**R^2**	**MSE**
Modified Page	100, 5, 20	k = 0.0114 ± 0.0001	n = 1.1001 ± 0.0206		0.999101	0.000120
	100, 15, 20	k = 0.0120 ± 0.0002	n = 1.0587 ± 0.0228		0.998804	0.000160
	100, 45, 20	k = 0.0119 ± 0.0001	n = 1.0688 ± 0.0183		0.999238	0.000100
	200, 5, 20	k = 0.0128 ± 0.0001	n = 1.1040 ± 0.0192		0.999280	0.000100
	200, 15, 20	k = 0.0127 ± 0.0002	n = 1.1101 ± 0.0206		0.999181	0.000110
	200, 45, 20	k = 0.0126 ± 0.0002	n = 1.0864 ± 0.0208		0.999108	0.000120
	200, 15, 35	k = 0.0132 ± 0.0002	n = 1.1197 ± 0.0232		0.999020	0.000140
	200, 45, 35	k = 0.0131 ± 0.0002	n = 1.1191 ± 0.0226		0.999064	0.000130
Logarithmic	100, 5, 20	a = 1.0604 ± 0.0041	k = 0.0103 ± 0.0001	c = -0.0555 ± 0.0042	0.999893	0.000011
	100, 15, 20	a = 1.0381 ± 0.0060	k = 0.0110 ± 0.0002	c = -0.0414 ± 0.0058	0.999745	0.000033
	100, 45, 20	a = 1.0403 ± 0.0049	k = 0.0109 ± 0.0002	c = -0.0399 ± 0.0048	0.999828	0.000022
	200, 5, 20	a = 1.0485 ± 0.0088	k = 0.0118 ± 0.0003	c = -0.0414 ± 0.0081	0.999420	0.000089
	200, 15, 20	a = 1.0512 ± 0.0096	k = 0.0117 ± 0.0003	c = -0.0439 ± 0.0089	0.999317	0.000100
	200, 45, 20	a = 1.0452 ± 0.0063	k = 0.0115 ± 0.0002	c = -0.0423 ± 0.0059	0.999708	0.000044
	200, 15, 35	a = 1.0523 ± 0.0111	k = 0.0122 ± 0.0004	c = -0.0434 ± 0.0099	0.999057	0.000144
	200, 45, 35	a = 1.0515 ± 0.0115	k = 0.0121 ± 0.0004	c = -0.0427 ± 0.0103	0.998997	0.000156

Table 3.3.2 (continued)

Model	**HHP Treatment**	**Model constants**		**R^2**	**MSE**
Two term exponential	100, 5, 20	a = 1.5805 ± 0.0402	k = 0.0144 ± 0.0004	0.999232	0.000100
	100, 15, 20	a = 1.4890 ± 0.0589	k = 0.0143 ± 0.0005	0.999028	0.000130
	100, 45, 20	a = 1.5146 ± 0.0416	k = 0.0143 ± 0.0004	0.999428	0.000080
	200, 5, 20	a = 1.5882 ± 0.0349	k = 0.0161 ± 0.0004	0.999443	0.000080
	200, 15, 20	a = 1.5993 ± 0.0366	k = 0.0162 ± 0.0004	0.999354	0.000090
	200, 45, 20	a = 1.5518 ± 0.0428	k = 0.0155 ± 0.0004	0.999289	0.000100
	200, 15, 35	a = 1.6146 ± 0.0407	k = 0.0170 ± 0.0005	0.999173	0.000110
	200, 45, 35	a = 1.6144 ± 0.0390	k = 0.0169 ± 0.0004	0.999236	0.000110

Table 3.4.1. Modeling of moisture ratio according to drying time for apple (Amasya) samples without pretreatment dried at 85°C with air velocity of 0.4 m/s.

Model	**Model constants**			**R^2**	**MSE**
Newton	k = 0.0181 ± 0.0005			0.997213	0.000350
Page	k = 0.0122 ± 0.0013	n = 1.0967 ± 0.0266		0.998977	0.000144
Modified Page	k = 0.0179 ± 0.0003	n = 1.0968 ± 0.0266		0.998977	0.000144
Wang and Singh	a = -0.0113 ± 0.0006	b = 3E-005 ± 0.0000		0.968890	0.004344
Henderson and Pabis	a = 1.0152 ± 0.0158	k = 0.0184 ± 0.0006		0.997481	0.000355
Logarithmic	a = 1.0348 ± 0.0105	k = 0.0170 ± 0.0005	c = -0.0291 ± 0.0075	0.999179	0.000125
Midilli	a = 0.9954 ± 0.0101	k = 0.0130 ± 0.0017		0.999399	0.000114
	n = 1.0745 ± 0.0314	b = -0.0001 ± 0.0000			
Two term exponential	a = 1.5666 ± 0.0544	k = 0.0224 ± 0.0008		0.999113	0.000122

Table 3.4.2. Modeling of moisture ratio according to drying time for HHP pretreated apple (Amasya) samples dried at 85°C with air velocity of 0.4 m/s. HHP treatment was given as pressure (Mpa), time (min), temperature (°C).

Model	**HHP Treatment**	**Model constants**		**R^2**	**MSE**
Modified Page	100, 5, 20	k = 0.0153 ± 0.0002	n = 1.1248 ± 0.0224	0.999230	0.000111
	100, 15, 20	k = 0.0168 ± 0.0002	n = 1.1512 ± 0.0248	0.999188	0.000122
	100, 45, 20	k = 0.0173 ± 0.0003	n = 1.1586 ± 0.0308	0.998813	0.000178
	200, 5, 20	k = 0.0182 ± 0.0002	n = 1.1310 ± 0.0199	0.999487	0.000078
	200, 15, 20	k = 0.0174 ± 0.0001	n = 1.1615 ± 0.0154	0.999703	0.000044
	200, 45, 20	k = 0.0180 ± 0.0002	n = 1.1532 ± 0.0200	0.999510	0.000067
Two term exponential	100, 5, 20	a = 1.6223 ± 0.0407	k = 0.0198 ± 0.0006	0.999268	0.000100
	100, 15, 20	a = 1.6638 ± 0.0413	k = 0.0222 ± 0.0006	0.999193	0.000111
	100, 45, 20	a = 1.6715 ± 0.0507	k = 0.0230 ± 0.0008	0.998797	0.000178
	200, 5, 20	a = 1.6325 ± 0.0340	k = 0.0237 ± 0.0006	0.999549	0.000067
	200, 15, 20	a = 1.6850 ± 0.0251	k = 0.0233 ± 0.0004	0.999690	0.000044
	200, 45, 20	a = 1.6689 ± 0.0329	k = 0.0240 ± 0.0006	0.999515	0.000067

3.4.2 Red Delicious Apple

Modified Page, Midilli and Henderson and Pabis models were selected in accordance to the results of control samples of red delicious apple dried at 45°C with an air velocity of 0.4 m/s (Table 4.1). Although logarithmic model gave good statistical results with high R^2 and low MSE, the model showed badly behaved parameter estimates, i.e. for "c" parameter the standard error was high ($P > 0.1$), while for other parameters of the model $P < 0.0001$. Thus, the constant "c" behaved far from linear, i.e. high standard error causing large confidence intervals. Constants "a" and "b" of the two term exponential model also resulted in high standard errors. For all the HHP pretreated samples, "b" parameter of the Midilli equation had high standard errors ($P > 0.0001$), thus model showed badly behaved parameter estimates. Modified Page model was found better to represent the drying curves of HHP pretreated samples than Henderson and Pabis model did, since it has slightly lower R^2 and higher MSE (Table 4.2).

The main effect of an increment in temperature was on the parameter "n"; on the other hand of in time was on the parameter "k", in the modified Page model (Table 4.2). HHP pretreatment caused a larger change in the model constants of modified Page model for red delicious apples as compared to that of Amasya apples, under same treatment and drying conditions, as it can be observed in the related tables.

Table 4.1. Modeling of moisture ratio according to drying time for apple (red delicious) samples without pretreatment dried at 45°C with air velocity of 0.4 m/s.

Model	Model constants			R^2	MSE
Newton	k = 0.0088 ± 0.0001			0.998092	0.000194
Page	k = 0.0110 ± 0.0009	n = 0.9546 ± 0.0169		0.998706	0.000140
Modified Page	k = 0.0089 ± 0.0001	n = 0.9546 ± 0.0168		0.998706	0.000140
Wang and Singh	a = -0.0059 ± 0.0002	b = 8E-006 ± 0.0000		0.965345	0.003813
Henderson and Pabis	a = 0.9809 ± 0.0084	k = 0.0086 ± 0.0001		0.998582	0.000153
Logarithmic	a = 0.9876 ± 0.0095	k = 0.0083 ± 0.0002	c = -0.0110 ± 0.0081	0.998750	0.000150
Diffusion approach	a = 0.0464 ± 0.0227	k = 0.0767 ± 0.0764	b = 0.1091 ± 0.1068	0.999058	0.000114
Midilli	a = 1.0013 ± 0.0047	k = 0.0140 ± 0.0008		0.999808	0.000023
	n = 0.8947 ± 0.0124	b = -0.0001 ± 0.0000			
Two term	a = 0.4904 ± 1.0130	k_1 = 0.0086 ± 0.0335		0.998582	0.000177
	b = 0.4904 ± 1.0130	k_2 = 0.0086 ± 0.0335			
Two term exponential	a = 0.0362 ± 0.0103	k = 0.2331 ± 0.0688		0.998995	0.000113
Verma	a = 0.0462 ± 0.0229	k = 0.0775 ± 0.0752	g = 0.0084 ± 0.0002	0.999058	0.000114

Table 4.2. Modeling of moisture ratio according to drying time for HHP pretreated apple (red delicious) samples dried at 45°C with air velocity of 0.4 m/s. HHP treatment was given as pressure (Mpa), time (min), temperature (°C).

Model	**HHP Treatment**	**Model constants**		**R^2**	**MSE**
Modified Page	200, 15, 20	k = 0.0111 ± 0.0001	n = 1.0467 ± 0.0110	0.999658	0.000038
	200, 45, 20	k = 0.0097 ± 0.0001	n = 1.1256 ± 0.0100	0.999761	0.000031
	200, 15, 35	k = 0.0104 ± 0.0001	n = 1.0600 ± 0.0190	0.998988	0.000123
	200, 45, 35	k = 0.0094 ± 0.0001	n = 1.0631 ± 0.0142	0.999404	0.000077
Henderson and Pabis	200, 15, 20	a = 1.0085 ± 0.0070	k = 0.0112 ± 0.0002	0.999240	0.000092
	200, 45, 20	a = 1.0301 ± 0.0127	k = 0.0102 ± 0.0002	0.997486	0.000323
	200, 15, 35	a = 1.0100 ± 0.0105	k = 0.0106 ± 0.0002	0.998261	0.000215
	200, 45, 35	a = 1.0123 ± 0.0090	k = 0.0096 ± 0.0002	0.998623	0.000169
Midilli	200, 15, 20	a = 0.9958 ± 0.0046	k = 0.0093 ± 0.0006	0.999837	0.000027
		n = 1.0333 ± 0.0132	b = -3E-005 ± 0.0000		
	200, 45, 20	a = 0.9975 ± 0.0032	k = 0.0058 ± 0.0003	0.999917	0.000009
		n = 1.1086 ± 0.0106	b = -3E-005 ± 0.0000		
	200, 15, 35	a = 0.9952 ± 0.0062	k = 0.0090 ± 0.0008	0.999705	0.000045
		n = 1.0239 ± 0.0183	b = -0.0001 ± 0.0000		
	200, 45, 35	a = 0.9963 ± 0.0043	k = 0.0078 ± 0.0005	0.999851	0.000018
		n = 1.0310 ± 0.0136	b = -0.0001 ± 0.0000		

3.4.3 Carrot

For control samples of carrots dried at 27°C with an air velocity of 0.4 m/s, two term exponential and Henderson and Pabis models, in addition to modified Page model, were found to give the best results (Table 5.1.1), so used for HHP pretreated samples. The parameter "c" of the logarithmic model and parameter "b" of the Midilli model behaved far from linear with high standard errors of the estimates ($P > 0.0001$). Also, parameters "k" and "b" of the diffusion approach gave high standard errors disabling its use for further investigation. Modified Page and two term exponential models gave the best results for HHP pretreated samples to represent the drying curves (Table 5.1.2). Henderson and Pabis model was worse than the other two with its lower R^2 and higher MSE.

When the drying temperature was increased to the 45°C, modified Page, logarithmic, Midilli and two term exponential models were found to fit to the drying data of the control samples more adequately (Table 5.2.1). On the contrary, for pressure treated samples, Midilli equation was resulted in badly behaved parameter estimates giving high standard errors for parameters a" and "b". Midilli model was only reliable for 100 Mpa at 20°C for 5 and 15min HHP pretreatments with small standard errors of the parameters ($P < 0.0001$), since the two treatments were the least effective ones and the drying behavior much more resembling that of the control sample (results are not shown). Logarithmic model was not suitable for HHP pretreated samples to fit to the drying data, since parameter "c" of the model had large standard errors for all HHP treatment combinations, except for 100 Mpa at 20°C for 15 and 45 min treatments. As the pressure applied was increased, the adequacy of fit decreased by increasing P value for the parameter "c" of the model. Modified page and two term exponential models fit to the drying data with the same efficiency (Table 5.2.2).

Table 5.1.1. Modeling of moisture ratio according to drying time for carrot samples without pretreatment dried at 27°C with air velocity of 0.4 m/s.

Model	**Model constants**			**R^2**	**MSE**
Newton	k = 0.0041 ± 0.0001			0.991170	0.000687
Page	k = 0.0084 ± 0.0007	n = 0.8716 ± 0.0149		0.997727	0.000186
Modified Page	k = 0.0042 ± 0.0000	n = 0.8716 ± 0.0148		0.997727	0.000186
Wang and Singh	a = -0.0033 ± 0.0001	b = 3E-006 ± 0.0000		0.973511	0.002159
Henderson and Pabis	a = 0.9433 ± 0.0075	k = 0.0038 ± 0.0001		0.997500	0.000205
Logarithmic	a = 0.9298 ± 0.0118	k = 0.0040 ± 0.0002	c = 0.0189 ± 0.0127	0.997713	0.000195
Diffusion approach	a = 0.0781 ± 0.0012	k = 0.4727 ± 1.9431	b = 0.0079 ± 0.0324	0.999970	0.000005
Midilli	a = 0.9824 ± 0.0081	k = 0.0094 ± 0.0013		0.999087	0.000080
	n = 0.8351 ± 0.0262	b = -0.0001 ± 0.0000			
Two term	a = 0.4717 ± 0.8562	k_1 = 0.0038 ± 0.0124		0.997500	0.000225
	b = 0.4717 ± 0.8562	k_2 = 0.0038 ± 0.0124			
Two term exponential	a = 0.0853 ± 0.0118	k = 0.0435 ± 0.0066		0.998884	0.000091

Table 5.1.2. Modeling of moisture ratio according to drying time for HHP pretreated carrot samples dried at 27°C with air velocity of 0.4 m/s. HHP treatment was given as pressure (Mpa), time (min), temperature (°C).

Model	**HHP Treatment**	**Model constants**		**R^2**	**MSE**
Modified Page	200, 15, 20	k = 0.0042 ± 0.0001	n = 1.2518 ± 0.0316	0.996500	0.000409
	200, 45, 20	k = 0.0041 ± 0.0001	n = 1.2930 ± 0.0311	0.996920	0.000368
Henderson and Pabis	200, 15, 20	a = 1.0455 ± 0.0215	k = 0.0045 ± 0.0002	0.986810	0.001536
	200, 45, 20	a = 1.0537 ± 0.0233	k = 0.0045 ± 0.0002	0.984917	0.001795
Two term exponential	200, 15, 20	a = 1.7765 ± 0.0414	k = 0.0059 ± 0.0002	0.996080	0.000455
	200, 45, 20	a = 1.8174 ± 0.0394	k = 0.0061 ± 0.0002	0.996096	0.000464

Table 5.2.1. Modeling of moisture ratio according to drying time for carrot samples without pretreatment dried at 45°C with air velocity of 0.4 m/s.

Model	Model constants			R^2 =	MSE
Newton	k = 0.0074 ± 0.0001			0.998881	0.000122
Page	k = 0.0057 ± 0.0003	n = 1.0510 ± 0.0110		0.999527	0.000053
Modified Page	k = 0.0074 ± 0.0001	n = 1.0510 ± 0.0110		0.999527	0.000053
Wang and Singh	a = -0.0051 ± 0.0001	b = 7E-006 ± 0.0000		0.982398	0.002012
Henderson and Pabis	a = 1.0101 ± 0.0068	k = 0.0075 ± 0.0001		0.999010	0.000112
Logarithmic	a = 1.0279 ± 0.0012	k = 0.0069 ± 0.0000	c = -0.0279 ± 0.0011	0.999979	0.000000
Diffusion approach	a = -0.0176 ± 0.0120	k = 0.2280 ± 1.8572	b = 0.0331 ± 0.2521	0.999105	0.000106
Midilli	a = 0.9977 ± 0.0016	k = 0.0066 ± 0.0002		0.999975	0.000000
	n = 1.0165 ± 0.0049	b = -4E-005 ± 0.0000			
Two term	a = 0.5050 ± 0.8169	k_1 = 0.0075 ± 0.0224		0.999010	0.000127
	b = 0.5050 ± 0.8169	k_2 = 0.0075 ± 0.0224			
Two term exponential	a = 1.4678 ± 0.0292	k = 0.0086 ± 0.0001		0.999661	0.000041
Verma	a = -0.0563 ± 0.0207	k = 0.0013 ± 0.0006	g = 0.0068 ± 0.0001	0.999983	0.000000

Table 5.2.2. Modeling of moisture ratio according to drying time for HHP pretreated carrot samples dried at 45°C with air velocity of 0.4 m/s. HHP treatment was given as pressure (Mpa), time (min), temperature (°C).

Model	**HHP Treatment**	**Model constants**			**R^2**	**MSE**
Modified Page	100, 5, 20	k = 0.0064 ± 0.0001	n = 0.9575 ± 0.0163		0.998509	0.000153
	100, 15, 20	k = 0.0071 ± 0.0001	n = 1.0630 ± 0.0135		0.999294	0.000082
	100, 45, 20	k = 0.0068 ± 0.0000	n = 1.1776 ± 0.0132		0.999514	0.000059
	200, 5, 20	k = 0.0089 ± 0.0001	n = 1.2436 ± 0.0275		0.998578	0.000193
	200, 15, 20	k = 0.0095 ± 0.0001	n = 1.2156 ± 0.0234		0.998926	0.000140
	200, 45, 20	k = 0.0097 ± 0.0001	n = 1.2497 ± 0.0270		0.998716	0.000173
	250, 15, 20	k = 0.0094 ± 0.0001	n = 1.2756 ± 0.0210		0.999262	0.000100
	250, 45, 20	k = 0.0094 ± 0.0001	n = 1.2696 ± 0.0221		0.999169	0.000113
	200, 15, 35	k = 0.0089 ± 0.0001	n = 1.2723 ± 0.0341		0.998033	0.000271
	200, 45, 45	k = 0.0088 ± 0.0001	n = 1.2319 ± 0.0256		0.998750	0.000171
Logarithmic	100, 5, 20	a = 0.9910 ± 0.0104	k = 0.0060 ± 0.0002	c = -0.0134 ± 0.0105	0.998568	0.000156
	100, 15, 20	a = 1.0362 ± 0.0022	k = 0.0066 ± 0.0000	c = -0.0356 ± 0.0021	0.999933	0.000006
	100, 45, 20	a = 1.0844 ± 0.0096	k = 0.0062 ± 0.0002	c = -0.0593 ± 0.0094	0.998918	0.000144
	200, 5, 20	a = 1.0893 ± 0.0181	k = 0.0082 ± 0.0004	c = -0.0593 ± 0.0157	0.996290	0.000536
	200, 15, 20	a = 1.0757 ± 0.0161	k = 0.0090 ± 0.0004	c = -0.0470 ± 0.0127	0.996908	0.000436
	200, 45, 20	a = 1.0806 ± 0.0197	k = 0.0093 ± 0.0005	c = -0.0464 ± 0.0150	0.997698	0.000657
	250, 15, 20	a = 1.0902 ± 0.0203	k = 0.0090 ± 0.0005	c = -0.0491 ± 0.0159	0.995209	0.000693
	250, 45, 20	a = 1.0855 ± 0.0211	k = 0.0091 ± 0.0005	c = -0.0447 ± 0.0165	0.994746	0.000757
	200, 15, 35	a = 1.1089 ± 0.0205	k = 0.0080 ± 0.0005	c = -0.0781 ± 0.0194	0.996015	0.000600
	200, 45, 45	a = 1.0929 ± 0.0182	k = 0.0081 ± 0.0004	c = -0.0652 ± 0.0171	0.996756	0.000469

Table 5.2.2. (continued)

Model	HHP Treatment	Model constants		R^2	MSE
Two term exponential	100, 5, 20	a = 0.6642 ± 0.1088	k = 0.0073 ± 0.0008	0.998035	0.000200
	100, 15, 20	a = 1.4999 ± 0.0332	k = 0.0085 ± 0.0002	0.999454	0.000065
	100, 45, 20	a = 1.7109 ± 0.0209	k = 0.0093 ± 0.0001	0.999448	0.000071
	200, 5, 20	a = 1.7782 ± 0.0372	k = 0.0126 ± 0.0003	0.998274	0.000233
	200, 15, 20	a = 1.7500 ± 0.0330	k = 0.0133 ± 0.0003	0.998787	0.000160
	200, 45, 20	a = 1.7857 ± 0.0361	k = 0.0139 ± 0.0004	0.998424	0.000213
	250, 15, 20	a = 1.8185 ± 0.0288	k = 0.0138 ± 0.0003	0.998894	0.000147
	250, 45, 20	a = 1.8125 ± 0.0290	k = 0.0137 ± 0.0003	0.998882	0.000153
	200, 15, 35	a = 1.8034 ± 0.0448	k = 0.0130 ± 0.0004	0.997425	0.000357
	200, 45, 45	a = 1.7680 ± 0.0350	k = 0.0125 ± 0.0003	0.998538	0.000200

For the HHP pretreated samples, dried at 65°C with an air velocity of 0.4 m/s, modified Page and two term exponential models were selected. Since parameter “c” of the logarithmic model and parameter “b” of the Midilli model gave high standard errors ($P > 0.0001$). Henderson and Pabis model was slightly worse than the both with slightly lower R^2 and higher MSE (Table 5.3.1). Both models had the same adequacy of fit to the drying data. As the pressure and pressure time were increased, parameter “k” of the modified Page model was decreasing while parameter “n” of the modified Page model was increasing and while parameter “a” of the two term exponential model was increasing and parameter “k” of the two term exponential model was decreasing (Table 5.3.2).

Table 5.3.1. Modeling of moisture ratio according to drying time for carrot samples without pretreatment dried at 65°C with air velocity of 0.4 m/s.

Model	**Model constants**			**R^2 =**	**MSE**
Newton	k = 0.0122 ± 0.0003			0.996440	0.000429
Page	k = 0.0071 ± 0.0006	n = 1.1202 ± 0.0189		0.999240	0.000100
Modified Page	k = 0.0120 ± 0.0001	n = 1.1202 ± 0.0189		0.999240	0.000100
Wang and Singh	a = -0.0077 ± 0.0003	b = 1E-005 ± 0.0000		0.973595	0.003400
Henderson and Pabis	a = 1.0245 ± 0.0145	k = 0.0125 ± 0.0003		0.997099	0.000377
Logarithmic	a = 1.0433 ± 0.0100	k = 0.0115 ± 0.0003	c = -0.0299 ± 0.0072	0.998908	0.000150
Midilli	a = 0.9927 ± 0.0076	k = 0.0072 ± 0.0008		0.999561	0.000064
	n = 1.1099 ± 0.0230	b = -3E-005 ± 0.0000			
Two term	a = 0.5122 ± 1.7837	k_1 = 0.0125 ± 0.0848		0.997099	0.000445
	b = 0.5122 ± 1.7837	k_2 = 0.0125 ± 0.0848			
Two term exponential	a = 1.6162 ± 0.0331	k = 0.0154 ± 0.0003		0.999360	0.000085

Table 5.3.2. Modeling of moisture ratio according to drying time for HHP pretreated carrot samples dried at 65°C with air velocity of 0.4 m/s. HHP treatment was given as pressure (Mpa), time (min), temperature (°C).

Model	**HHP Treatment**	**Model constants**		**R^2**	**MSE**
Modified Page	200, 15, 20	k = 0.0143 ± 0.0001	n = 1.1817 ± 0.0160	0.999602	0.000050
	200, 45, 20	k = 0.0134 ± 0.0002	n = 1.2055 ± 0.0225	0.999236	0.000108
	250, 15, 20	k = 0.0128 ± 0.0002	n = 1.2471 ± 0.0267	0.999010	0.000142
	250, 45, 20	k = 0.0122 ± 0.0001	n = 1.2657 ± 0.0244	0.999188	0.000117
Two term exponential	200, 15, 20	a = 1.7152 ± 0.0229	k = 0.0196 ± 0.0003	0.999623	0.000050
	200, 45, 20	a = 1.7403 ± 0.0324	k = 0.0186 ± 0.0004	0.999152	0.000117
	250, 15, 20	a = 1.7855 ± 0.0368	k = 0.0183 ± 0.0005	0.998732	0.000175
	250, 45, 20	a = 1.8075 ± 0.0337	k = 0.0177 ± 0.0004	0.998844	0.000167

3.4.4 Green Bean

Modified Page, Midilli, two term exponential and Henderson and Pabis models were found to be the best models to fit to the drying data of control samples of green beans dried at 45°C with an air velocity of 0.4 m/s (Table 6.1.1). Parameter “c” of the logarithmic model gave high standard errors. Midilli equation most adequately represented the drying curve of HHP pretreated samples, and Henderson and Pabis being the worst among four models (Table 6.1.2). Modified Page and two term exponential models gave nearly the same adequacy of fit and represent the drying behavior effectively.

For the drying temperature of 65°C of green beans, modified Page, logarithmic, Midilli and two term exponential models were the best models for control samples (Table 6.2.1). Midilli equation was not suitable for HHP treated samples dried at 65°C. since parameters “k” and “b” for all treatments gave high standard errors, except 100 Mpa at 20°C for 15 and 45 min treatments, which of two treatments resulted in high standard errors only in parameter “b” (Table 6.2.2). Logarithmic model was the best one to represent the drying curve. Modified Page and two term exponential models gave nearly the same adequacy of fit and represent the drying behavior effectively.

Thus, for both drying temperatures of 45 an 65°C, modified Page and two term exponential models were the most suitable models to represent the drying curves of HHP treated and control samples.

Table 6.1.1. Modeling of moisture ratio according to drying time for green bean samples without pretreatment dried at 45°C with air velocity of 0.4 m/s.

Model	**Model constants**			**R^2**	**MSE**
Newton	k = 0.0020 ± 0.0000			0.994892	0.000537
Page	k = 0.0037 ± 0.0003	n = 0.9075 ± 0.0131		0.997972	0.000219
Modified Page	k = 0.0021 ± 0.0000	n = 0.9075 ± 0.0130		0.997972	0.000219
Wang and Singh	a = -0.0015 ± 0.0000	b = 6E-007 ± 0.0000		0.970496	0.003206
Henderson and Pabis	a = 0.9693 ± 0.0083	k = 0.0020 ± 0.0000		0.996421	0.000390
Logarithmic	a = 0.9615 ± 0.0115	k = 0.0020 ± 0.0001	c = 0.0123 ± 0.0121	0.996518	0.000390
Diffusion approach	a = 0.1185 ± 0.0437	k = 0.0093 ± 0.0039	b = 0.1962 ± 0.0768	0.998458	0.000173
Midilli	a = 1.0206 ± 0.0081	k = 0.0063 ± 0.0008		0.999083	0.000107
	n = 0.8123 ± 0.0207	b = -4E-005 ± 0.0000			
Two term	a = 0.4846 ± 1.0037	k_1 = 0.0020 ± 0.0083		0.996421	0.000417
	b = 0.4846 ± 1.0037	k_2 = 0.0020 ± 0.0083			
Two term exponential	a = 0.0864 ± 0.0149	k = 0.0214 ± 0.0040		0.997795	0.000239
Verma	a = 0.1185 ± 0.0438	k = 0.0093 ± 0.0039	g = 0.0018 ± 0.0001	0.998458	0.000173

Table 6.1.2. Modeling of moisture ratio according to drying time for HHP pretreated green bean samples dried at 45°C with air velocity of 0.4 m/s. HHP treatment was given as pressure (MPa), time (min), temperature (°C).

Model	**HHP Treatment**	**Model constants**		**R^2**	**MSE**
Modified Page	200, 15, 20	k = 0.0015 ± 0.0000	n = 1.0415 ± 0.0277	0.990000	0.000766
	200, 45, 20	k = 0.0013 ± 0.0000	n = 1.0100 ± 0.0266	0.988532	0.000765
Henderson and Pabis	200, 15, 20	a = 0.9875 ± 0.0109	k = 0.0014 ± 0.0000	0.989789	0.000782
	200, 45, 20	a = 0.9785 ± 0.0097	k = 0.0012 ± 0.0000	0.989685	0.000688
Midilli	200, 15, 20	a = 0.9937 ± 0.0079	k = 0.0041 ± 0.0009	0.998731	0.000103
		n = 0.7789 ± 0.0374	b = -0.0002 ± 0.0000		
	200, 45, 20	a = 0.9978 ± 0.0061	k = 0.0057 ± 0.0010	0.999216	0.000054
		n = 0.6965 ± 0.0291	b = -0.0002 ± 0.0000		
Two term exponential	200, 15, 20	a = 1.4920 ± 0.0749	k = 0.0018 ± 0.0001	0.991090	0.000682
	200, 45, 20	a = 1.4294 ± 0.0986	k = 0.0015 ± 0.0001	0.989293	0.000714

Table 6.2.1. Modeling of moisture ratio according to drying time for green bean samples without pretreatment dried at 65°C with air velocity of 0.4 m/s.

Model	**Model constants**			**R^2**	**MSE**
Newton	k = 0.0050 ± 0.0001			0.993176	0.000745
Page	k = 0.0022 ± 0.0002	n = 1.1514 ± 0.0203		0.998348	0.000190
Modified Page	k = 0.0049 ± 0.0001	n = 1.1514 ± 0.0203		0.998348	0.000190
Wang and Singh	a = -0.0036 ± 0.0001	b = 3E-006 ± 0.0000		0.995282	0.000538
Henderson and Pabis	a = 1.0330 ± 0.0142	k = 0.0052 ± 0.0001		0.994615	0.000614
Logarithmic	a = 1.0959 ± 0.0048	k = 0.0042 ± 0.0001	c = -0.0875 ± 0.0052	0.999743	0.000030
Midilli	a = 0.9967 ± 0.0033	k = 0.0031 ± 0.0002		0.999866	0.000016
	n = 1.0717 ± 0.0120	b = -0.0001 ± 0.0000			
Two term	a = 0.5165 ± 1.6616	k_1 = 0.0052 ± 0.0297		0.994615	0.000679
	b = 0.5165 ± 1.6616	k_2 = 0.0052 ± 0.0297			
Two term exponential	a = 1.6666 ± 0.0327	k = 0.0065 ± 0.0001		0.998455	0.000176

Table 6.2.2. Modeling of moisture ratio according to drying time for HHP pretreated green bean samples dried at 65°C with air velocity of 0.4 m/s. HHP treatment was given as pressure (MPa), time (min), temperature (°C).

Model	HHP Treatment	Model constants			R^2	MSE
Modified Page	100, 15, 20	k = 0.0038 ± 0.0001	n = 1.2405 ± 0.0496		0.990809	0.001019
	100, 45, 20	k = 0.0037 ± 0.0001	n = 1.2633 ± 0.0562		0.988574	0.001262
	200, 15, 20	k = 0.0040 ± 0.0001	n = 1.3163 ± 0.0623		0.988316	0.001395
	200, 45, 20	k = 0.0037 ± 0.0001	n = 1.2707 ± 0.0554		0.989096	0.001210
	200, 15, 35	k = 0.0049 ± 0.0001	n = 1.2538 ± 0.0530		0.991595	0.001025
	200, 45, 35	k = 0.0048 ± 0.0001	n = 1.2725 ± 0.0627		0.989121	0.001328
Logarithmic	100, 15, 20	a = 1.3217 ± 0.0255	k = 0.0023 ± 0.0001	c = -0.3346 ± 0.0281	0.999092	0.000105
	100, 45, 20	a = 1.4209 ± 0.0338	k = 0.0020 ± 0.0001	c = -0.4384 ± 0.0365	0.999124	0.000100
	200, 15, 20	a = 1.3431 ± 0.0432	k = 0.0024 ± 0.0002	c = -0.3513 ± 0.0478	0.997126	0.000360
	200, 45, 20	a = 1.4007 ± 0.0369	k = 0.0020 ± 0.0001	c = -0.4170 ± 0.0400	0.998817	0.000140
	200, 15, 35	a = 1.1856 ± 0.0232	k = 0.0036 ± 0.0002	c = -0.1889 ± 0.0263	0.997137	0.000368
	200, 45, 35	a = 1.3013 ± 0.0332	k = 0.0030 ± 0.0002	c = -0.3107 ± 0.0369	0.998183	0.000235

Table 6.2.2 (continued)

Model	HHP Treatment	Model constants		R^2	MSE
Midilli	100, 15, 20	a = 0.9890 ± 0.0091	k = 0.0028 ± 0.0006	0.998975	0.000126
		n = 1.0044 ± 0.0451	b = -0.0003 ± 0.0000		
	100, 45, 20	a = 0.9884 ± 0.0088	k = 0.0029 ± 0.0007	0.999062	0.000116
		n = 0.9737 ± 0.0474	b = -0.0004 ± 0.0000		
	200, 15, 20	a = 0.9713 ± 0.0142	k = 0.0013 ± 0.0005	0.997205	0.000368
		n = 1.1572 ± 0.0738	b = -0.0002 ± 0.0001		
	200, 45, 20	a = 0.9820 ± 0.0101	k = 0.0022 ± 0.0006	0.998668	0.000163
		n = 1.0287 ± 0.0549	b = -0.0003 ± 0.0001		
	200, 15, 35	a = 0.9699 ± 0.0142	k = 0.0017 ± 0.0006	0.997462	0.000344
		n = 1.1727 ± 0.0625	b = -0.0001 ± 0.0000		
	200, 45, 35	a = 0.9827 ± 0.0136	k = 0.0026 ± 0.0009	0.998001	0.000275
		n = 1.0693 ± 0.0649	b = -0.0003 ± 0.0001		
Two term exponential	100, 15, 20	a = 1.7498 ± 0.0648	k = 0.0054 ± 0.0002	0.990512	0.001052
	100, 45, 20	a = 1.7667 ± 0.0702	k = 0.0052 ± 0.0002	0.987987	0.001324
	200, 15, 20	a = 1.8063 ± 0.0739	k = 0.0059 ± 0.0003	0.986652	0.001590
	200, 45, 20	a = 1.7730 ± 0.0686	k = 0.0053 ± 0.0002	0.988434	0.001286
	200, 15, 35	a = 1.7588 ± 0.0698	k = 0.0069 ± 0.0003	0.990987	0.001100
	200, 45, 35	a = 1.7729 ± 0.0788	k = 0.0069 ± 0.0004	0.988217	0.001439

Different investigators used different models to represent the drying behavior of their samples, according to their experimental conditions and specifications and samples. Doymaz (2004) studied the drying characteristics of green bean for average moisture content from 90.53 ± 0.5 to 14 ± 0.3% using hot air of the temperature range of 50 – 70°C with an air velocity of 1.0 m/s, and it was found that the Page model represents the drying characteristics better than Newton, and Henderson and Pabis models. Yaldiz et al. (2001) compared the eight different drying models according to their coefficient of determination to estimate solar drying curves of Sultana grapes, and found that two term model could satisfactorily describe the solar drying curve of Sultana grapes with a correlation coefficient of 0.979. Togrul and Pehlivan (2002) found that among fourteen models, the logarithmic model satisfactorily describe the solar drying curve of apricots with a correlation coefficient of 0.994. Lahsasni et al. (2004) studied the drying kinetics of prickly pear fruit, and found that the experimental drying curves show only a falling rate period and the two term model among eight different models was found to satisfactorily describe the solar drying curves of prickly pear fruit with a correlation coefficient of 0.9999. Akpinar et al. (2003-III) investigated the drying behavior of red pepper slices in a convective dryer with drying air of 55, 60 and 70°C and at a drying air velocity of 1.5 m/s, and found that diffusion approach model among the eleven different models, could satisfactorily describe the drying curve of red peppers with a correlation coefficient of 0.9987. Gunhan et al. (2005) studied the mathematical modeling of drying of bay leaves in a hot air dryer operated at 40, 50 and 60°C with a constant air velocity of 1.5 m/s, and suggested that Page model among fifteen different drying models, could sufficiently describe the drying of bay leaves. Togrul (2005) performed the simple modeling of infrared drying of fresh apple slices and found that Midilli equation was best for characterizating drying behavior of apple for whole range of temperatures. Togrul and Pehlivan (2004) performed open-air sun drying process on apricots pre-sulphured with SO_2 or $NaHSO_3$, grapes, peaches, figs and plums, and showed that the drying rate curves of these fruits no constant rate period and tested twelve mathematical models to fit the drying rates of the fruits, among which diffusion approach model for apricots (non-pretreated or SO_2 sulphured) and figs, modified Henderson and Pabis model for apricot ($NaHSO_3$-sulphured), grape and plum, and Verma model for peach were found to best explain open-air sun drying behavior of the fruits. On the other hand, in none of those studied, the results included standard errors or confidence intervals for calculated estimates; this is the biggest missing point in the analysis of the results.

CHAPTER 4

CONCLUSION AND RECOMMENDATIONS

Conventional drying of fruits and vegetables affects their physical and biochemical status leading to shrinkage, change of color, texture and taste. Alteration of physical properties of foods with minimal influence on the quality could be a means of reducing drying time, minimizing quality degradation and saving energy. HHP treatment that is one of the promising non-thermal methods can be used for blanching purposes before drying provides membrane permeabilization leaving the product matrix largely unchanged while positively affecting mass transfer in subsequent processing of foods.

HHP treatments higher than 100 MPa caused a decrease in drying times of apples and carrots. At the lower drying temperatures this effect was seen more obviously, since increasing the drying temperature and improving the drying conditions by increasing the drying temperature can mask the effect of HHP pretreatment. On the other hand HHP treatments at 20°C on green beans resulted in contraction of the tissue decreasing the drying rate, however at 35°C of that has increased the drying rate slightly.

Among the 14 different models selected from literature to describe the drying behavior of samples, modified page equation was found to fit all the drying curves for all samples adequately. Two term exponential model also represented the drying curves of green beans and carrots adequately in addition to modified Page model. HHP pretreatment affected the parameters of the models and generally indicated an increase in the diffusivity, so moisture removal rate.

Further research may be done, as regarding the best HHP treatments, on quality factors such as color, rehydrability and texture of the dried samples. Also, the residual enzyme activity after HHP treatment may also be investigated. Moreover, in order to have a better understanding of the change in drying rate and characteristics, a microscopic scale analysis may be required in conjunction with macroscopic analysis. Furthermore, the applicability of such a process to industrial scale may be optimized. In addition, HHP treatment at pressures higher that 300 MPa may also be investigated to enhance the drying rates of samples.

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APPENDIX A

TREATMENT CONDITIONS

Table A.1. The HHP pretreatment (given as pressure, time, temperature) and drying experiments (drying conditons are given as drying temperature and air flow rate) for apples, Amasya variety.*

	Tray Dryer			
Sample	45°C, 0.4m/s	45°C, 0.8m/s	65°C, 0.4m/s	85°C, 0.4m/s
Control	++++	++	++++	+++
HHP Treatment				
100, 5, 20			++	+++
100, 15, 20	++		++	+++
100, 45, 20	++		++	+++
200, 5, 20			++	+++
200, 15, 20	++	++	++	+++
200, 45, 20	++	++	++	+++
300, 15, 20	++			
300, 45, 20	++			
200, 15, 35	++		++	
200, 45, 35	++		++	

* (++) Two replication (+++) Three replication

Table A.2. The HHP pretreatment (given as pressure, time, temperature) and drying experiments (drying conditons are given as drying temperature and air flow rate) for apples, red delicious variety.*

	Tray Dryer
Sample	45°C, 0.4m/s
Control	++++
HHP Treatment	
200, 15, 20	++
200, 45, 20	++
200, 15, 35	++
200, 45, 35	++

* (++) Two replication (++++) Four replication

Table A.3. The HHP pretreatment (given as pressure, time, temperature) and drying experiments (drying conditons are given as drying temperature and air flow rate) for carrots.*

	Tray Dryer		
Sample	27°C, 0.4m/s	45°C, 0.4m/s	65°C, 0.4m/s
Control	++	++	++++
HHP Treatment			
100, 5, 20		++	
100, 15, 20		++	
100, 45, 20		++	
200, 5, 20		++	
200, 15, 20	++	++	++
200, 45, 20	++	++	++
250, 15, 20		++	++
250, 45, 20		++	++
200, 15, 35		++	
200, 45, 35		++	

* (++) Two replication (++++) Four replication

Table A.4. The HHP pretreatment (given as pressure, time, temperature) and drying experiments (drying conditons are given as drying temperature and air flow rate) for green beans.*

	Tray Dryer	
Sample	45°C, 0.4m/s	65°C, 0.4m/s
Control	++	++
HHP Treatment		
100, 15, 20		++
100, 45, 20		++
200, 15, 20	++	++
200, 45, 20	++	++
200, 15, 35		++
200, 45, 35		++

* (++) Two replication

APPENDIX B

DRYING DATA

Table B.1. Drying data of green bean with HHP pretreatment at 100 MPa and 35°C for 45 min and without pretreatment at room conditions (24 ± 2°C).

	Control		HHP Treated	
Time (hour)	Weight (g)	MR	Weight (g)	MR
0	1.92	1.0000	1.42	1.0000
1.5	1.83	0.9480	1.39	0.9760
20	1.20	0.5838	0.68	0.4080
21.5	1.16	0.5607	0.64	0.3760
22.5	1.13	0.5434	0.61	0.3520
24	1.10	0.5260	0.57	0.3200
26	1.05	0.4971	0.52	0.2800
28	1.00	0.4682	0.47	0.2400
42	0.73	0.3121	0.24	0.0560
43	0.71	0.3006	0.23	0.0480
44	0.69	0.2890	0.22	0.0400
46	0.65	0.2659	0.20	0.0240
48	0.62	0.2486	0.19	0.0160
50	0.58	0.2254	0.19	0.0160
72	0.25	0.0347	0.17	0.0000
96	0.19	0.0000	0.17	0.0000
98	0.19	0.0000	0.17	0.0000

Table B.2. Drying data of green bean with HHP pretreatment at 200 MPa and 35°C for 45 min and without pretreatment at room conditions (24 ± 2°C).

	Control		HHP Treated	
Time (hour)	Weight (g)	MR	Weight (g)	MR
0	2.78	1.0000	2.18	1.0000
2	2.65	0.9484	2.11	0.9648
3	2.60	0.9286	2.05	0.9347
16	2.13	0.7421	1.35	0.5829
17	2.10	0.7302	1.30	0.5578
18	2.07	0.7183	1.26	0.5377
19	2.04	0.7063	1.20	0.5075
20	2.00	0.6905	1.15	0.4824
21.5	1.94	0.6667	1.06	0.4372
22	1.91	0.6548	1.02	0.4171
23	1.87	0.6389	0.96	0.3869
24	1.82	0.6190	0.90	0.3568
25	1.78	0.6032	0.85	0.3317
26	1.74	0.5873	0.79	0.3015
41.5	1.22	0.3810	0.24	0.0251
42	1.21	0.3770	0.23	0.0201
43	1.18	0.3651	0.22	0.0151
44	1.15	0.3532	0.21	0.0101
46	1.08	0.3254	0.21	0.0101
47	1.05	0.3135	0.20	0.0050
48	1.02	0.3016	0.20	0.0050
66.5	0.57	0.1230	0.20	0.0050
72	0.46	0.0794	0.20	0.0050
88	0.26	0.0000	0.19	0.0000

Table B.3. Drying data of green bean with HHP pretreatment at 250 MPa and 35°C for 45 min and without pretreatment at room conditions (24 ± 2°C).

	Control		HHP Treated	
Time (hour)	Weight (g)	MR	Weight (g)	MR
0	2.15	1.0000	0.88	1.0000
2	1.99	0.9179	0.81	0.9103
3	1.92	0.8821	0.76	0.8462
18	1.25	0.5385	0.27	0.2179
19	1.22	0.5231	0.25	0.1923
21	1.15	0.4872	0.21	0.1410
24	1.05	0.4359	0.17	0.0897
25	1.01	0.4154	0.15	0.0641
26	0.98	0.4000	0.14	0.0513
47	0.46	0.1333	0.10	0.0000
48	0.44	0.1231	0.10	0.0000
49	0.42	0.1128	0.10	0.0000
71	0.21	0.0051	0.10	0.0000
73	0.20	0.0000	0.10	0.0000
89	0.20	0.0000	0.10	0.0000

Table B.4. Drying data of green bean with HHP pretreatment at 250 MPa and 35°C for 15 min and without pretreatment at room conditions (24 ± 2°C).

	Control		HHP Treated	
Time (hour)	Weight (g)	MR	Weight (g)	MR
0	1.72	1.0000	1.05	1.0000
1	1.64	0.9494	1.02	0.9681
2	1.57	0.9051	0.97	0.9149
17	0.91	0.4873	0.44	0.3511
18	0.87	0.4620	0.41	0.3191
19	0.84	0.4430	0.39	0.2979
21	0.78	0.4051	0.34	0.2447
23	0.72	0.3671	0.30	0.2021
24	0.69	0.3481	0.28	0.1809
25	0.66	0.3291	0.27	0.1702
46	0.26	0.0759	0.11	0.0000
47	0.25	0.0696	0.11	0.0000
48	0.23	0.0570	0.11	0.0000
71	0.14	0.0000	0.11	0.0000
73	0.14	0.0000	0.11	0.0000
89	0.14	0.0000	0.11	0.0000

Table B.5. Drying data of apple (Amasya) slices without pretreatment at 45°C with air velocity of 0.4 m/s.

	Sample 1		Sample 2		Sample 3		Sample 4	
Time (min)	Weight (g)	MR	Weight (g)	MR	Weight (g)	MR	Weight (g)	MR
0	2.87	1.0000	2.69	1.0000	3.09	1.0000	2.87	1.0000
15	2.60	0.8851	2.39	0.8684	2.80	0.8902	2.55	0.8704
30	2.38	0.7915	2.19	0.7807	2.53	0.7879	2.29	0.7652
45	2.18	0.7064	1.91	0.6579	2.31	0.7045	2.06	0.6721
75	1.87	0.5745	1.57	0.5088	1.96	0.5720	1.70	0.5263
105	1.61	0.4638	1.31	0.3947	1.68	0.4659	1.44	0.4211
135	1.40	0.3745	1.12	0.3114	1.45	0.3788	1.21	0.3279
165	1.24	0.3064	0.96	0.2412	1.27	0.3106	1.03	0.2551
195	1.09	0.2426	0.83	0.1842	1.10	0.2462	0.89	0.1984
225	0.99	0.2000	0.73	0.1404	0.96	0.1932	0.78	0.1538
255	0.89	0.1574	0.65	0.1053	0.86	0.1553	0.68	0.1134
285	0.81	0.1234	0.59	0.0789	0.77	0.1212	0.59	0.0769
315	0.73	0.0894	0.52	0.0482	0.69	0.0909	0.54	0.0567
345	0.67	0.0638	0.48	0.0307	0.62	0.0644	0.49	0.0364
375	0.62	0.0426	0.45	0.0175	0.57	0.0455	0.46	0.0243
405	0.58	0.0255	0.43	0.0088	0.53	0.0303	0.43	0.0121
435	0.56	0.0170	0.43	0.0088	0.50	0.0189	0.42	0.0081
∞	0.52		0.41		0.45		0.40	

Table B.6. Drying data of apple (Amasya) slices at 45°C with air velocity of 0.4 m/s after HHP treatment at 100 MPa and 20°C for 15 min.

	Sample 1		Sample 2	
Time (min)	Weight (g)	MR	Weight (g)	MR
0	3.11	1.0000	2.81	1.0000
15	2.84	0.8907	2.54	0.8884
30	2.63	0.8057	2.29	0.7851
45	2.45	0.7328	2.18	0.7397
75	2.11	0.5951	1.74	0.5579
105	1.84	0.4858	1.46	0.4421
135	1.64	0.4049	1.23	0.3471
165	1.52	0.3563	1.05	0.2727
195	1.33	0.2794	0.89	0.2066
225	1.19	0.2227	0.77	0.1570
255	1.08	0.1781	0.67	0.1157
285	0.98	0.1377	0.59	0.0826
315	0.90	0.1053	0.51	0.0496
345	0.82	0.0729	0.47	0.0331
375	0.77	0.0526	0.44	0.0207
405	0.73	0.0364	0.42	0.0124
435	0.70	0.0243	0.41	0.0083
∞	0.64		0.39	

Table B.7. Drying data of apple (Amasya) slices at 45°C with air velocity of 0.4 m/s after HHP treatment at 100 MPa and 20°C for 45 min.

	Sample 1		Sample 2	
Time (min)	Weight (g)	MR	Weight (g)	MR
0	2.73	1.0000	3.11	1.0000
15	2.44	0.8717	2.87	0.9098
30	2.20	0.7655	2.61	0.8120
45	2.01	0.6814	2.40	0.7331
75	1.69	0.5398	2.03	0.5940
105	1.44	0.4292	1.74	0.4850
135	1.23	0.3363	1.50	0.3947
165	1.08	0.2699	1.30	0.3195
195	0.95	0.2124	1.13	0.2556
225	0.85	0.1681	0.99	0.2030
255	0.75	0.1239	0.87	0.1579
285	0.67	0.0885	0.77	0.1203
315	0.60	0.0575	0.69	0.0902
345	0.54	0.0310	0.63	0.0677
375	0.52	0.0221	0.57	0.0451
405	0.50	0.0133	0.53	0.0301
435	0.49	0.0088	0.50	0.0188
∞	0.47		0.45	

Table B.8. Drying data of apple (Amasya) slices at 45°C with air velocity of 0.4 m/s after HHP treatment at 200 MPa and 20°C for 15 min.

	Sample 1		Sample 2	
Time (min)	Weight (g)	MR	Weight (g)	MR
0	3.10	1.0000	2.48	1.0000
15	2.82	0.8898	2.29	0.9091
30	2.57	0.7913	2.12	0.8278
45	2.37	0.7126	1.94	0.7416
75	2.03	0.5787	1.58	0.5694
105	1.75	0.4685	1.34	0.4545
135	1.53	0.3819	1.14	0.3589
165	1.34	0.3071	0.97	0.2775
195	1.18	0.2441	0.86	0.2249
225	1.05	0.1929	0.75	0.1722
255	0.93	0.1457	0.64	0.1196
285	0.84	0.1102	0.56	0.0813
315	0.75	0.0748	0.50	0.0526
345	0.68	0.0472	0.47	0.0383
375	0.64	0.0315	0.44	0.0239
405	0.61	0.0197	0.42	0.0144
435	0.59	0.0118	0.41	0.0096
∞	0.56		0.39	

Table B.9. Drying data of apple (Amasya) slices at 45°C with air velocity of 0.4 m/s after HHP treatment at 200 MPa and 20°C for 45 min.

	Sample 1		Sample 2	
Time (min)	Weight (g)	MR	Weight (g)	MR
0	3.14	1.0000	2.31	1.0000
15	2.84	0.8846	2.05	0.8680
30	2.61	0.7962	1.82	0.7513
45	2.38	0.7077	1.64	0.6599
75	2.03	0.5731	1.32	0.4975
105	1.75	0.4654	1.05	0.3604
135	1.52	0.3769	0.85	0.2589
165	1.32	0.3000	0.68	0.1726
195	1.16	0.2385	0.57	0.1168
225	1.02	0.1846	0.49	0.0761
255	0.90	0.1385	0.43	0.0457
285	0.80	0.1000	0.40	0.0305
315	0.72	0.0692	0.38	0.0203
345	0.65	0.0423	0.37	0.0152
375	0.61	0.0269	0.36	0.0102
405	0.58	0.0154	0.36	0.0102
435	0.57	0.0115	0.35	0.0051
∞	0.54		0.34	

Table B.10. Drying data of apple (Amasya) slices at 45°C with air velocity of 0.4 m/s after HHP treatment at 300 MPa and 20°C for 15 min.

	Sample 1		Sample 2	
Time (min)	Weight (g)	MR	Weight (g)	MR
0	2.92	1.0000	3.20	1.0000
15	2.65	0.8893	2.86	0.8736
30	2.42	0.7951	2.59	0.7732
45	2.21	0.7090	2.31	0.6691
75	1.85	0.5615	1.85	0.4981
105	1.56	0.4426	1.50	0.3680
135	1.32	0.3443	1.21	0.2602
165	1.13	0.2664	1.00	0.1822
195	0.97	0.2008	0.85	0.1264
225	0.83	0.1434	0.74	0.0855
255	0.72	0.0984	0.66	0.0558
285	0.64	0.0656	0.61	0.0372
315	0.59	0.0451	0.57	0.0223
345	0.56	0.0328	0.55	0.0149
375	0.53	0.0205	0.53	0.0074
405	0.51	0.0123	0.53	0.0074
435	0.50	0.0082	0.52	0.0037
∞	0.48		0.51	

Table B.11. Drying data of apple (Amasya) slices at 45°C with air velocity of 0.4 m/s after HHP treatment at 300 MPa and 20°C for 45 min.

	Sample 1		Sample 2	
Time (min)	Weight (g)	MR	Weight (g)	MR
0	3.15	1.0000	3.00	1.0000
15	2.89	0.9008	2.71	0.8867
30	2.65	0.8092	2.45	0.7852
45	2.51	0.7557	2.20	0.6875
75	2.05	0.5802	1.76	0.5156
105	1.73	0.4580	1.42	0.3828
135	1.46	0.3550	1.14	0.2734
165	1.23	0.2672	0.93	0.1914
195	1.05	0.1985	0.77	0.1289
225	0.91	0.1450	0.66	0.0859
255	0.81	0.1069	0.58	0.0547
285	0.72	0.0725	0.53	0.0352
315	0.65	0.0458	0.50	0.0234
345	0.61	0.0305	0.48	0.0156
375	0.58	0.0191	0.46	0.0078
405	0.56	0.0115	0.45	0.0039
435	0.55	0.0076	0.45	0.0039
∞	0.53		0.44	

Table B.12. Drying data of apple (Amasya) slices at 45°C with air velocity of 0.4 m/s after HHP treatment at 200 MPa and 35°C for 15 min.

	Sample 1		Sample 2	
Time (min)	Weight (g)	MR	Weight (g)	MR
0	2.89	1.0000	2.88	1.0000
15	2.61	0.8871	2.62	0.8956
30	2.39	0.7984	2.40	0.8072
45	2.18	0.7137	2.16	0.7108
75	1.81	0.5645	1.73	0.5382
105	1.50	0.4395	1.40	0.4056
135	1.24	0.3347	1.14	0.3012
165	1.03	0.2500	0.92	0.2129
195	0.86	0.1815	0.78	0.1566
225	0.71	0.1210	0.65	0.1044
255	0.61	0.0806	0.56	0.0683
285	0.53	0.0484	0.49	0.0402
315	0.49	0.0323	0.45	0.0241
345	0.45	0.0161	0.43	0.0161
375	0.44	0.0121	0.41	0.0080
405	0.43	0.0081	0.40	0.0040
435	0.42	0.0040	0.40	0.0040
∞	0.41		0.39	

Table B.13. Drying data of apple (Amasya) slices at 45°C with air velocity of 0.4 m/s after HHP treatment at 200 MPa and 35°C for 45 min.

	Sample 1		Sample 2	
Time (min)	Weight (g)	MR	Weight (g)	MR
0	3.30	1.0000	2.83	1.0000
15	2.96	0.8786	2.52	0.8730
30	2.69	0.7821	2.25	0.7623
45	2.45	0.6964	2.03	0.6721
75	2.04	0.5500	1.62	0.5041
105	1.70	0.4286	1.30	0.3730
135	1.42	0.3286	1.03	0.2623
165	1.20	0.2500	0.84	0.1844
195	1.03	0.1893	0.70	0.1270
225	0.89	0.1393	0.59	0.0820
255	0.78	0.1000	0.52	0.0533
285	0.69	0.0679	0.46	0.0287
315	0.63	0.0464	0.44	0.0205
345	0.58	0.0286	0.42	0.0123
375	0.55	0.0179	0.41	0.0082
405	0.53	0.0107	0.41	0.0082
435	0.52	0.0071	0.40	0.0041
∞	0.50		0.39	

Table B.14. Drying data of apple (Amasya) slices without pretreatment at 45°C with air velocity of 0.8 m/s.

	Sample 1		Sample 2	
Time (min)	Weight (g)	MR	Weight (g)	MR
0	2.76	1.0000	2.99	1.0000
15	2.41	0.8523	2.57	0.8366
30	2.09	0.7173	2.27	0.7198
45	1.84	0.6118	2.02	0.6226
75	1.48	0.4599	1.63	0.4708
105	1.23	0.3544	1.37	0.3696
135	1.03	0.2700	1.16	0.2879
165	0.88	0.2068	0.99	0.2218
195	0.76	0.1561	0.86	0.1712
225	0.66	0.1139	0.75	0.1284
255	0.56	0.0717	0.66	0.0934
285	0.51	0.0506	0.59	0.0661
315	0.46	0.0295	0.53	0.0428
345	0.44	0.0211	0.50	0.0311
375	0.42	0.0127	0.47	0.0195
405	0.41	0.0084	0.45	0.0117
435	0.40	0.0042	0.44	0.0078
∞	0.39		0.42	

Table B.15. Drying data of apple (Amasya) slices at 45°C with air velocity of 0.8 m/s after HHP treatment at 200 MPa and 20°C for 15 min.

	Sample 1		Sample 2	
Time (min)	Weight (g)	MR	Weight (g)	MR
0	2.29	1.0000	2.61	1.0000
15	1.93	0.8154	2.24	0.8311
30	1.68	0.6872	1.94	0.6941
45	1.44	0.5641	1.70	0.5845
75	1.12	0.4000	1.34	0.4201
105	0.87	0.2718	1.09	0.3059
135	0.69	0.1795	0.89	0.2146
165	0.57	0.1179	0.74	0.1461
195	0.47	0.0667	0.62	0.0913
225	0.41	0.0359	0.54	0.0548
255	0.37	0.0154	0.49	0.0320
285	0.36	0.0103	0.45	0.0137
315	0.34	0.0000	0.43	0.0046
345	0.34	0.0000	0.43	0.0046
375	0.34	0.0000	0.42	0.0000
405	0.34	0.0000	0.42	0.0000
435	0.34	0.0000	0.42	0.0000
∞	0.34		0.42	

Table B.16. Drying data of apple (Amasya) slices at 45°C with air velocity of 0.8 m/s after HHP treatment at 200 MPa and 20°C for 45 min.

	Sample 1		Sample 2	
Time (min)	Weight (g)	MR	Weight (g)	MR
0	2.46	1.0000	2.52	1.0000
15	2.10	0.8278	2.21	0.8558
30	1.82	0.6938	1.95	0.7349
45	1.58	0.5789	1.70	0.6186
75	1.21	0.4019	1.30	0.4326
105	0.94	0.2727	1.00	0.2930
135	0.74	0.1770	0.77	0.1860
165	0.61	0.1148	0.63	0.1209
195	0.50	0.0622	0.52	0.0698
225	0.44	0.0335	0.45	0.0372
255	0.40	0.0144	0.41	0.0186
285	0.38	0.0048	0.38	0.0047
315	0.37	0.0000	0.37	0.0000
345	0.37	0.0000	0.37	0.0000
375	0.37	0.0000	0.37	0.0000
405	0.37	0.0000	0.37	0.0000
435	0.37	0.0000	0.37	0.0000
∞	0.37		0.37	

Table B.17. Drying data of apple (Amasya) slices without pretreatment at 65°C with air velocity of 0.4 m/s.

	Sample 1		Sample 2		Sample 3		Sample 4	
Time (min)	Weight (g)	MR	Weight (g)	MR	Weight (g)	MR	Weight (g)	MR
0	3.44	1.0000	2.88	1.0000	2.75	1.0000	3.13	1.0000
15	2.99	0.8464	2.47	0.8340	2.38	0.8412	2.66	0.8272
30	2.64	0.7270	2.15	0.7045	2.07	0.7082	2.29	0.6912
45	2.33	0.6212	1.89	0.5992	1.80	0.5923	1.98	0.5772
75	1.84	0.4539	1.47	0.4291	1.38	0.4120	1.53	0.4118
105	1.46	0.3242	1.16	0.3036	1.08	0.2833	1.19	0.2868
135	1.21	0.2389	0.92	0.2065	0.85	0.1845	0.94	0.1949
165	0.99	0.1638	0.74	0.1336	0.67	0.1073	0.75	0.1250
195	0.82	0.1058	0.59	0.0729	0.54	0.0515	0.62	0.0772
225	0.69	0.0614	0.49	0.0324	0.48	0.0258	0.53	0.0441
255	0.61	0.0341	0.46	0.0202	0.44	0.0086	0.47	0.0221
285	0.56	0.0171	0.44	0.0121	0.44	0.0086	0.44	0.0110
∞	0.51		0.41		0.42		0.41	

Table B.18. Drying data of apple (Amasya) slices at 65°C with air velocity of 0.4 m/s after HHP treatment at 100 MPa and 20°C for 5 min.

	Sample 1		Sample 2	
Time (min)	Weight (g)	MR	Weight (g)	MR
0	3.49	1.0000	3.19	1.0000
15	3.05	0.8548	2.80	0.8582
30	2.67	0.7294	2.43	0.7236
45	2.35	0.6238	2.11	0.6073
75	1.81	0.4455	1.61	0.4255
105	1.42	0.3168	1.24	0.2909
135	1.13	0.2211	0.99	0.2000
165	0.91	0.1485	0.79	0.1273
195	0.74	0.0924	0.65	0.0764
225	0.61	0.0495	0.55	0.0400
255	0.53	0.0231	0.50	0.0218
285	0.48	0.0066	0.47	0.0109
∞	0.46		0.44	

Table B.19. Drying data of apple (Amasya) slices at 65°C with air velocity of 0.4 m/s after HHP treatment at 100 MPa and 20°C for 15 min.

	Sample 1		Sample 2	
Time (min)	Weight (g)	MR	Weight (g)	MR
0	2.87	1.0000	2.75	1.0000
15	2.48	0.8402	2.36	0.8354
30	2.15	0.7049	2.02	0.6920
45	1.91	0.6066	1.75	0.5781
75	1.51	0.4426	1.32	0.3966
105	1.21	0.3197	1.02	0.2700
135	0.97	0.2213	0.79	0.1730
165	0.78	0.1434	0.62	0.1013
195	0.67	0.0984	0.50	0.0506
225	0.57	0.0574	0.44	0.0253
255	0.51	0.0328	0.41	0.0127
285	0.47	0.0164	0.40	0.0084
∞	0.43		0.38	

Table B.20. Drying data of apple (Amasya) slices at 65°C with air velocity of 0.4 m/s after HHP treatment at 100 MPa and 20°C for 45 min.

	Sample 1		Sample 2	
Time (min)	Weight (g)	MR	Weight (g)	MR
0	3.41	1.0000	2.74	1.0000
15	2.96	0.8432	2.36	0.8410
30	2.60	0.7178	2.02	0.6987
45	2.32	0.6202	1.73	0.5774
75	1.86	0.4599	1.28	0.3891
105	1.51	0.3380	0.95	0.2510
135	1.23	0.2404	0.72	0.1548
165	1.01	0.1638	0.56	0.0879
195	0.85	0.1080	0.46	0.0460
225	0.73	0.0662	0.41	0.0251
255	0.66	0.0418	0.38	0.0126
285	0.60	0.0209	0.37	0.0084
∞	0.54		0.35	

Table B.21. Drying data of apple (Amasya) slices at 65°C with air velocity of 0.4 m/s after HHP treatment at 200 MPa and 20°C for 5 min.

	Sample 1		Sample 2	
Time (min)	Weight (g)	MR	Weight (g)	MR
0	3.09	1.0000	3.19	1.0000
15	2.65	0.8321	2.75	0.8400
30	2.29	0.6947	2.38	0.7055
45	1.98	0.5763	2.07	0.5927
75	1.48	0.3855	1.56	0.4073
105	1.14	0.2557	1.18	0.2691
135	0.90	0.1641	0.90	0.1673
165	0.73	0.0992	0.69	0.0909
195	0.63	0.0611	0.56	0.0436
225	0.57	0.0382	0.50	0.0218
255	0.53	0.0229	0.47	0.0109
285	0.50	0.0115	0.46	0.0073
∞	0.47		0.44	

Table B.22. Drying data of apple (Amasya) slices at 65°C with air velocity of 0.4 m/s after HHP treatment at 200 MPa and 20°C for 15 min.

	Sample 1		Sample 2	
Time (min)	Weight (g)	MR	Weight (g)	MR
0	3.15	1.0000	2.86	1.0000
15	2.72	0.8377	2.45	0.8347
30	2.39	0.7132	2.10	0.6935
45	2.10	0.6038	1.79	0.5685
75	1.65	0.4340	1.30	0.3710
105	1.29	0.2981	0.94	0.2258
135	1.04	0.2038	0.69	0.1250
165	0.85	0.1321	0.54	0.0645
195	0.70	0.0755	0.45	0.0282
225	0.61	0.0415	0.41	0.0121
255	0.57	0.0264	0.40	0.0081
285	0.54	0.0151	0.39	0.0040
∞	0.50		0.38	

Table B.23. Drying data of apple (Amasya) slices at 65°C with air velocity of 0.4 m/s after HHP treatment at 200 MPa and 20°C for 45 min.

	Sample 1		Sample 2	
Time (min)	Weight (g)	MR	Weight (g)	MR
0	3.10	1.0000	3.27	1.0000
15	2.66	0.8327	2.81	0.8380
30	2.31	0.6996	2.42	0.7007
45	2.02	0.5894	2.07	0.5775
75	1.57	0.4183	1.53	0.3873
105	1.24	0.2928	1.14	0.2500
135	1.00	0.2015	0.86	0.1514
165	0.81	0.1293	0.67	0.0845
195	0.67	0.0760	0.55	0.0423
225	0.58	0.0418	0.48	0.0176
255	0.53	0.0228	0.46	0.0106
285	0.50	0.0114	0.45	0.0070
∞	0.47		0.43	

Table B.24. Drying data of apple (Amasya) slices at 65°C with air velocity of 0.4 m/s after HHP treatment at 200 MPa and 35°C for 15 min.

	Sample 1		Sample 2	
Time (min)	Weight (g)	MR	Weight (g)	MR
0	2.82	1.0000	2.90	1.0000
15	2.40	0.8286	2.49	0.8353
30	2.05	0.6857	2.15	0.6988
45	1.77	0.5714	1.86	0.5823
75	1.28	0.3714	1.39	0.3936
105	0.96	0.2408	1.06	0.2610
135	0.70	0.1347	0.81	0.1606
165	0.54	0.0694	0.64	0.0924
195	0.46	0.0367	0.53	0.0482
225	0.41	0.0163	0.46	0.0201
255	0.40	0.0122	0.44	0.0120
285	0.39	0.0082	0.43	0.0080
∞	0.37		0.41	

Table B.25. Drying data of apple (Amasya) slices at 65°C with air velocity of 0.4 m/s after HHP treatment at 200 MPa and 35°C for 45 min.

	Sample 1		Sample 2	
Time (min)	Weight (g)	MR	Weight (g)	MR
0	2.98	1.0000	3.12	1.0000
15	2.52	0.8210	2.70	0.8427
30	2.15	0.6770	2.35	0.7116
45	1.85	0.5603	2.05	0.5993
75	1.35	0.3658	1.56	0.4157
105	0.98	0.2218	1.18	0.2734
135	0.74	0.1284	0.91	0.1723
165	0.59	0.0700	0.72	0.1011
195	0.49	0.0311	0.59	0.0524
225	0.46	0.0195	0.52	0.0262
255	0.44	0.0117	0.49	0.0150
285	0.43	0.0078	0.48	0.0112
∞	0.41		0.45	

Table B.26. Drying data of apple (Amasya) slices without pretreatment at 85°C with air velocity of 0.4 m/s.

	Sample 1		Sample 2		Sample 3	
Time (min)	Weight (g)	MR	Weight (g)	MR	Weight (g)	MR
0	3.59	1.0000	3.10	1.0000	2.68	1.0000
15	2.87	0.7750	2.52	0.7778	2.16	0.7668
30	2.38	0.6219	2.04	0.5939	1.75	0.5830
45	1.95	0.4875	1.68	0.4559	1.43	0.4395
75	1.35	0.3000	1.17	0.2605	0.99	0.2422
105	0.92	0.1656	0.83	0.1303	0.70	0.1121
135	0.72	0.1031	0.61	0.0460	0.54	0.0404
165	0.49	0.0313	0.51	0.0077	0.49	0.0179
195	0.42	0.0094	0.49	0.0000	0.46	0.0045
225	0.41	0.0062	0.49	0.0000	0.46	0.0045
255	0.40	0.0031	0.49	0.0000	0.45	0.0000
∞	0.39		0.49		0.45	

Table B.27. Drying data of apple (Amasya) slices at 85°C with air velocity of 0.4 m/s after HHP treatment at 100 MPa and 20°C for 5 min.

	Sample 1		Sample 2		Sample 3	
Time (min)	Weight (g)	MR	Weight (g)	MR	Weight (g)	MR
0	4.11	1.0000	3.01	1.0000	2.69	1.0000
15	3.49	0.8254	2.57	0.8261	2.25	0.8103
30	2.94	0.6704	2.12	0.6482	1.82	0.6250
45	2.51	0.5493	1.80	0.5217	1.51	0.4914
75	1.88	0.3718	1.29	0.3202	1.04	0.2888
105	1.42	0.2423	0.95	0.1858	0.71	0.1466
135	1.08	0.1465	0.72	0.0949	0.50	0.0560
165	0.85	0.0817	0.58	0.0395	0.40	0.0129
195	0.70	0.0394	0.52	0.0158	0.38	0.0043
225	0.62	0.0169	0.51	0.0119	0.37	0.0000
255	0.59	0.0085	0.50	0.0079	0.37	0.0000
∞	0.56		0.48		0.37	

Table B.28. Drying data of apple (Amasya) slices at 85°C with air velocity of 0.4 m/s after HHP treatment at 100 MPa and 20°C for 15 min.

	Sample 1		Sample 2		Sample 3	
Time (min)	Weight (g)	MR	Weight (g)	MR	Weight (g)	MR
0	3.17	1.0000	3.24	1.0000	3.37	1.0000
15	2.61	0.7986	2.70	0.8118	2.77	0.7993
30	2.11	0.6187	2.21	0.6411	2.27	0.6321
45	1.73	0.4820	1.79	0.4948	1.86	0.4950
75	1.14	0.2698	1.23	0.2997	1.26	0.2943
105	0.78	0.1403	0.83	0.1603	0.84	0.1538
135	0.57	0.0647	0.57	0.0697	0.60	0.0736
165	0.46	0.0252	0.42	0.0174	0.44	0.0201
195	0.45	0.0216	0.37	0.0000	0.39	0.0033
225	0.43	0.0144	0.37	0.0000	0.38	0.0000
255	0.41	0.0072	0.37	0.0000	0.38	0.0000
∞	0.39		0.37		0.38	

Table B.29. Drying data of apple (Amasya) slices at 85°C with air velocity of 0.4 m/s after HHP treatment at 100 MPa and 20°C for 45 min.

	Sample 1		Sample 2		Sample 3	
Time (min)	Weight (g)	MR	Weight (g)	MR	Weight (g)	MR
0	3.64	1.0000	3.53	1.0000	3.07	1.0000
15	3.03	0.8152	2.87	0.7944	2.44	0.7789
30	2.52	0.6606	2.32	0.6231	1.88	0.5825
45	2.06	0.5212	1.85	0.4766	1.49	0.4456
75	1.37	0.3121	1.19	0.2710	0.94	0.2526
105	0.91	0.1727	0.74	0.1308	0.56	0.1193
135	0.60	0.0788	0.47	0.0467	0.34	0.0421
165	0.43	0.0273	0.35	0.0093	0.24	0.0070
195	0.36	0.0061	0.32	0.0000	0.23	0.0035
225	0.34	0.0000	0.32	0.0000	0.22	0.0000
255	0.34	0.0000	0.32	0.0000	0.22	0.0000
∞	0.34		0.32		0.22	

Table B.30. Drying data of apple (Amasya) slices at 85°C with air velocity of 0.4 m/s after HHP treatment at 200 MPa and 20°C for 5 min.

	Sample 1		Sample 2		Sample 3	
Time (min)	Weight (g)	MR	Weight (g)	MR	Weight (g)	MR
0	3.64	1.0000	2.71	1.0000	3.26	1.0000
15	3.00	0.7987	2.14	0.7543	2.69	0.7881
30	2.44	0.6226	1.71	0.5690	2.23	0.6171
45	1.98	0.4780	1.34	0.4095	1.87	0.4833
75	1.29	0.2610	0.85	0.1983	1.36	0.2937
105	0.90	0.1384	0.57	0.0776	0.99	0.1561
135	0.65	0.0597	0.43	0.0172	0.78	0.0781
165	0.52	0.0189	0.41	0.0086	0.66	0.0335
195	0.47	0.0031	0.40	0.0043	0.61	0.0149
225	0.46	0.0000	0.40	0.0043	0.59	0.0074
255	0.46	0.0000	0.39	0.0000	0.58	0.0037
∞	0.46		0.39		0.57	

Table B.31. Drying data of apple (Amasya) slices at 85°C with air velocity of 0.4 m/s after HHP treatment at 200 MPa and 20°C for 15 min.

	Sample 1		Sample 2		Sample 3	
Time (min)	Weight (g)	MR	Weight (g)	MR	Weight (g)	MR
0	2.83	1.0000	3.86	1.0000	3.18	1.0000
15	2.27	0.7760	3.25	0.8201	2.65	0.8094
30	1.78	0.5800	2.71	0.6608	2.17	0.6367
45	1.37	0.4160	2.24	0.5221	1.75	0.4856
75	0.84	0.2040	1.57	0.3245	1.15	0.2698
105	0.54	0.0840	1.10	0.1858	0.77	0.1331
135	0.42	0.0360	0.81	0.1003	0.56	0.0576
165	0.34	0.0040	0.63	0.0472	0.44	0.0144
195	0.34	0.0040	0.55	0.0236	0.40	0.0000
225	0.33	0.0000	0.51	0.0118	0.40	0.0000
255	0.33	0.0000	0.49	0.0059	0.40	0.0000
∞	0.33		0.47		0.40	

Table B.32. Drying data of apple (Amasya) slices at 85°C with air velocity of 0.4 m/s after HHP treatment at 200 MPa and 20°C for 45 min.

	Sample 1		Sample 2		Sample 3	
Time (min)	Weight (g)	MR	Weight (g)	MR	Weight (g)	MR
0	3.44	1.0000	2.86	1.0000	3.44	1.0000
15	2.84	0.8033	2.27	0.7686	2.81	0.7955
30	2.32	0.6328	1.80	0.5843	2.26	0.6169
45	1.86	0.4820	1.41	0.4314	1.80	0.4675
75	1.21	0.2689	0.84	0.2078	1.24	0.2857
105	0.80	0.1344	0.54	0.0902	0.81	0.1461
135	0.57	0.0590	0.40	0.0353	0.56	0.0649
165	0.46	0.0230	0.33	0.0078	0.42	0.0195
195	0.43	0.0131	0.32	0.0039	0.37	0.0032
225	0.39	0.0000	0.32	0.0039	0.36	0.0000
255	0.39	0.0000	0.31	0.0000	0.36	0.0000
∞	0.39		0.31		0.36	

Table B.33. Drying data of apple (red delicious) slices without pretreatment at 45°C with air velocity of 0.4 m/s.

	Sample 1		Sample 2		Sample 3		Sample 4	
Time (min)	Weight (g)	MR	Weight (g)	MR	Weight (g)	MR	Weight (g)	MR
0	2.46	1.0000	2.65	1.0000	2.51	1.0000	2.90	1.0000
15	2.16	0.8492	2.33	0.8571	2.24	0.8663	2.58	0.8661
30	1.93	0.7337	2.06	0.7366	2.01	0.7525	2.31	0.7531
45	1.72	0.6281	1.84	0.6384	1.82	0.6584	2.11	0.6695
75	1.42	0.4774	1.50	0.4866	1.54	0.5198	1.77	0.5272
105	1.23	0.3819	1.27	0.3839	1.31	0.4059	1.52	0.4226
135	1.08	0.3065	1.08	0.2991	1.16	0.3317	1.33	0.3431
165	0.95	0.2412	0.94	0.2366	1.01	0.2574	1.16	0.2720
195	0.84	0.1859	0.81	0.1786	0.90	0.2030	1.03	0.2176
225	0.75	0.1407	0.71	0.1339	0.80	0.1535	0.92	0.1715
255	0.68	0.1055	0.63	0.0982	0.73	0.1188	0.83	0.1339
285	0.62	0.0754	0.57	0.0714	0.65	0.0792	0.75	0.1004
315	0.57	0.0503	0.52	0.0491	0.61	0.0594	0.68	0.0711
345	0.54	0.0352	0.49	0.0357	0.57	0.0396	0.63	0.0502
375	0.52	0.0251	0.46	0.0223	0.54	0.0248	0.59	0.0335
405	0.50	0.0151	0.44	0.0134	0.52	0.0149	0.56	0.0209
435	0.49	0.0101	0.43	0.0089	0.51	0.0099	0.54	0.0126
∞	0.47		0.41		0.49		0.51	

Table B.34. Drying data of apple (red delicious) slices at 45°C with air velocity of 0.4 m/s after HHP treatment at 200 MPa and 20°C for 15 min.

	Sample 1		Sample 2	
Time (min)	Weight (g)	MR	Weight (g)	MR
0	2.18	1.0000	2.39	1.0000
15	1.91	0.8439	2.09	0.8500
30	1.69	0.7168	1.86	0.7350
45	1.48	0.5954	1.66	0.6350
75	1.20	0.4335	1.31	0.4600
105	0.97	0.3006	1.06	0.3350
135	0.82	0.2139	0.86	0.2350
165	0.71	0.1503	0.71	0.1600
195	0.63	0.1040	0.60	0.1050
225	0.56	0.0636	0.53	0.0700
255	0.53	0.0462	0.48	0.0450
285	0.50	0.0289	0.44	0.0250
315	0.49	0.0231	0.42	0.0150
345	0.48	0.0173	0.41	0.0100
375	0.47	0.0116	0.40	0.0050
∞	0.45		0.39	

Table B.35. Drying data of apple (red delicious) slices at 45°C with air velocity of 0.4 m/s after HHP treatment at 200 MPa and 20°C for 45 min.

	Sample 1		Sample 2	
Time (min)	Weight (g)	MR	Weight (g)	MR
0	2.70	1.0000	2.44	1.0000
15	2.47	0.8930	2.19	0.8775
30	2.24	0.7860	1.96	0.7647
45	2.01	0.6791	1.75	0.6618
75	1.64	0.5070	1.41	0.4951
105	1.35	0.3721	1.13	0.3578
135	1.13	0.2698	0.92	0.2549
165	0.98	0.2000	0.77	0.1814
195	0.85	0.1395	0.64	0.1176
225	0.76	0.0977	0.55	0.0735
255	0.69	0.0651	0.49	0.0441
285	0.65	0.0465	0.46	0.0294
315	0.62	0.0326	0.43	0.0147
345	0.59	0.0186	0.42	0.0098
375	0.58	0.0140	0.41	0.0049
∞	0.55		0.40	

Table B.36. Drying data of apple (red delicious) slices at 45°C with air velocity of 0.4 m/s after HHP treatment at 200 MPa and 35°C for 15 min.

	Sample 1		Sample 2	
Time (min)	Weight (g)	MR	Weight (g)	MR
0	2.35	1.0000	2.67	1.0000
15	2.07	0.8503	2.36	0.8597
30	1.84	0.7273	2.11	0.7466
45	1.64	0.6203	1.89	0.6471
75	1.34	0.4599	1.52	0.4796
105	1.11	0.3369	1.25	0.3575
135	0.93	0.2406	1.03	0.2579
165	0.80	0.1711	0.86	0.1810
195	0.69	0.1123	0.74	0.1267
225	0.62	0.0749	0.64	0.0814
255	0.56	0.0428	0.57	0.0498
285	0.53	0.0267	0.52	0.0271
315	0.51	0.0160	0.49	0.0136
345	0.50	0.0107	0.48	0.0090
375	0.49	0.0053	0.47	0.0045
∞	0.48		0.46	

Table B.37. Drying data of apple (red delicious) slices at 45°C with air velocity of 0.4 m/s after HHP treatment at 200 MPa and 35°C for 45 min.

	Sample 1		Sample 2	
Time (min)	Weight (g)	MR	Weight (g)	MR
0	2.57	1.0000	2.69	1.0000
15	2.30	0.8689	2.41	0.8739
30	2.08	0.7621	2.17	0.7658
45	1.88	0.6650	1.94	0.6622
75	1.58	0.5194	1.58	0.5000
105	1.32	0.3932	1.29	0.3694
135	1.13	0.3010	1.07	0.2703
165	0.98	0.2282	0.90	0.1937
195	0.86	0.1699	0.77	0.1351
225	0.76	0.1214	0.67	0.0901
255	0.69	0.0874	0.60	0.0586
285	0.63	0.0583	0.55	0.0360
315	0.59	0.0388	0.52	0.0225
345	0.57	0.0291	0.50	0.0135
375	0.55	0.0194	0.49	0.0090
∞	0.51		0.47	

Table B.38. Drying data of carrot slices without pretreatment at 27°C with air velocity of 0.4 m/s.

	Sample 1		Sample 2	
Time (min)	Weight (g)	MR	Weight (g)	MR
0	3.19	1.0000	3.88	1.0000
15	3.02	0.9368	3.22	0.8024
30	2.89	0.8885	3.08	0.7605
45	2.77	0.8439	2.94	0.7186
75	2.53	0.7546	2.69	0.6437
105	2.31	0.6729	2.46	0.5749
135	2.13	0.6059	2.25	0.5120
165	1.95	0.5390	2.06	0.4551
195	1.80	0.4833	1.89	0.4042
225	1.67	0.4349	1.75	0.3623
255	1.54	0.3866	1.62	0.3234
285	1.44	0.3494	1.51	0.2904
315	1.35	0.3160	1.39	0.2545
345	1.26	0.2825	1.31	0.2305
375	1.18	0.2528	1.22	0.2036
405	1.11	0.2268	1.14	0.1796
435	1.05	0.2045	1.09	0.1647
465	0.99	0.1822	1.03	0.1467
495	0.94	0.1636	0.98	0.1317
525	0.89	0.1450	0.93	0.1168
555	0.85	0.1301	0.89	0.1048
585	0.81	0.1152	0.85	0.0928
615	0.77	0.1004	0.81	0.0808
645	0.74	0.0892	0.78	0.0719
∞	0.50		0.54	

Table B.39. Drying data of carrot slices at 27°C with air velocity of 0.4 m/s after HHP treatment at 200 MPa and 20°C for 15 min.

	Sample 1		Sample 2	
Time (min)	Weight (g)	MR	Weight (g)	MR
0	3.53	1.0000	3.59	1.0000
15	3.36	0.9430	3.41	0.9421
30	3.23	0.8993	3.26	0.8939
45	3.10	0.8557	3.13	0.8521
75	2.84	0.7685	2.86	0.7653
105	2.59	0.6846	2.63	0.6913
135	2.37	0.6107	2.41	0.6206
165	2.15	0.5369	2.20	0.5531
195	1.95	0.4698	2.00	0.4887
225	1.76	0.4060	1.83	0.4341
255	1.59	0.3490	1.64	0.3730
285	1.44	0.2987	1.48	0.3215
315	1.31	0.2550	1.31	0.2669
345	1.18	0.2114	1.17	0.2219
375	1.07	0.1745	1.04	0.1801
405	0.98	0.1443	0.92	0.1415
435	0.89	0.1141	0.82	0.1093
465	0.82	0.0906	0.74	0.0836
495	0.76	0.0705	0.66	0.0579
525	0.70	0.0503	0.61	0.0418
555	0.66	0.0369	0.57	0.0289
585	0.63	0.0268	0.54	0.0193
615	0.61	0.0201	0.52	0.0129
645	0.59	0.0134	0.51	0.0096
∞	0.55		0.48	

Table B.40. Drying data of carrot slices at 27°C with air velocity of 0.4 m/s after HHP treatment at 200 MPa and 20°C for 45 min.

	Sample 1		Sample 2	
Time (min)	Weight (g)	MR	Weight (g)	MR
0	3.39	1.0000	3.46	1.0000
15	3.24	0.9479	3.30	0.9463
30	3.10	0.8993	3.17	0.9027
45	2.99	0.8611	3.04	0.8591
75	2.75	0.7778	2.80	0.7785
105	2.52	0.6979	2.56	0.6980
135	2.31	0.6250	2.35	0.6275
165	2.09	0.5486	2.14	0.5570
195	1.90	0.4826	1.93	0.4866
225	1.71	0.4167	1.76	0.4295
255	1.53	0.3542	1.58	0.3691
285	1.38	0.3021	1.41	0.3121
315	1.24	0.2535	1.25	0.2584
345	1.12	0.2118	1.11	0.2114
375	1.01	0.1736	0.99	0.1711
405	0.91	0.1389	0.87	0.1309
435	0.83	0.1111	0.78	0.1007
465	0.76	0.0868	0.70	0.0738
495	0.70	0.0660	0.64	0.0537
525	0.66	0.0521	0.59	0.0369
555	0.62	0.0382	0.56	0.0268
585	0.59	0.0278	0.53	0.0168
615	0.57	0.0208	0.52	0.0134
645	0.55	0.0139	0.51	0.0101
∞	0.51		0.48	

Table B.41. Drying data of carrot slices without pretreatment at 45°C with air velocity of 0.4 m/s.

	Sample 1		Sample 2	
Time (min)	Weight (g)	MR	Weight (g)	MR
0	3.64	1.0000	3.15	1.0000
15	3.37	0.9146	2.82	0.8778
30	3.10	0.8291	2.57	0.7852
45	2.86	0.7532	2.34	0.7000
75	2.41	0.6108	1.97	0.5630
105	2.04	0.4937	1.66	0.4481
135	1.72	0.3924	1.41	0.3556
165	1.47	0.3133	1.22	0.2852
195	1.27	0.2500	1.06	0.2259
225	1.12	0.2025	0.93	0.1778
255	0.98	0.1582	0.82	0.1370
285	0.87	0.1234	0.73	0.1037
315	0.78	0.0949	0.67	0.0815
345	0.71	0.0728	0.61	0.0593
375	0.65	0.0538	0.57	0.0444
405	0.60	0.0380	0.53	0.0296
435	0.56	0.0253	0.50	0.0185
465	0.53	0.0158	0.48	0.0111
495	0.51	0.0095	0.47	0.0074
∞	0.48		0.45	

Table B.42. Drying data of carrot slices at 45°C with air velocity of 0.4 m/s after HHP treatment at 100 MPa and 20°C for 5 min.

	Sample 1		Sample 2	
Time (min)	Weight (g)	MR	Weight (g)	MR
0	3.86	1.0000	3.66	1.0000
15	3.54	0.8997	3.33	0.8907
30	3.29	0.8213	3.05	0.7980
45	3.06	0.7492	2.81	0.7185
75	2.63	0.6144	2.39	0.5795
105	2.33	0.5204	2.11	0.4868
135	2.07	0.4389	1.87	0.4073
165	1.86	0.3730	1.69	0.3477
195	1.67	0.3135	1.53	0.2947
225	1.52	0.2665	1.39	0.2483
255	1.40	0.2288	1.27	0.2086
285	1.27	0.1881	1.16	0.1722
315	1.16	0.1536	1.07	0.1424
345	1.06	0.1223	0.99	0.1159
375	0.97	0.0940	0.91	0.0894
405	0.91	0.0752	0.86	0.0728
435	0.85	0.0564	0.80	0.0530
465	0.79	0.0376	0.75	0.0364
495	0.75	0.0251	0.71	0.0232
∞	0.67		0.64	

Table B.43. Drying data of carrot slices at 45°C with air velocity of 0.4 m/s after HHP treatment at 100 MPa and 20°C for 15 min.

	Sample 1		Sample 2	
Time (min)	Weight (g)	MR	Weight (g)	MR
0	3.77	1.0000	3.60	1.0000
15	3.48	0.9102	3.28	0.8940
30	3.24	0.8359	2.97	0.7914
45	3.00	0.7616	2.74	0.7152
75	2.56	0.6254	2.31	0.5728
105	2.18	0.5077	1.96	0.4570
135	1.86	0.4087	1.68	0.3642
165	1.61	0.3313	1.49	0.3013
195	1.41	0.2693	1.30	0.2384
225	1.22	0.2105	1.17	0.1954
255	1.07	0.1641	1.04	0.1523
285	0.94	0.1238	0.94	0.1192
315	0.85	0.0960	0.86	0.0927
345	0.76	0.0681	0.78	0.0662
375	0.70	0.0495	0.73	0.0497
405	0.64	0.0310	0.69	0.0364
435	0.61	0.0217	0.65	0.0232
465	0.59	0.0155	0.63	0.0166
495	0.57	0.0093	0.61	0.0099
∞	0.54		0.58	

Table B.44. Drying data of carrot slices at 45°C with air velocity of 0.4 m/s after HHP treatment at 100 MPa and 20°C for 45 min.

	Sample 1		Sample 2	
Time (min)	Weight (g)	MR	Weight (g)	MR
0	3.14	1.0000	3.59	1.0000
15	3.03	0.9572	3.30	0.9073
30	2.83	0.8794	3.03	0.8211
45	2.62	0.7977	2.79	0.7444
75	2.24	0.6498	2.37	0.6102
105	1.92	0.5253	2.03	0.5016
135	1.66	0.4241	1.74	0.4089
165	1.41	0.3268	1.50	0.3323
195	1.21	0.2490	1.30	0.2684
225	1.05	0.1868	1.12	0.2109
255	0.92	0.1362	0.97	0.1629
285	0.82	0.0973	0.86	0.1278
315	0.74	0.0661	0.76	0.0958
345	0.69	0.0467	0.68	0.0703
375	0.65	0.0311	0.62	0.0511
405	0.62	0.0195	0.56	0.0319
435	0.61	0.0156	0.53	0.0224
465	0.60	0.0117	0.51	0.0160
495	0.59	0.0078	0.49	0.0096
∞	0.57		0.46	

Table B.45. Drying data of carrot slices at 45°C with air velocity of 0.4 m/s after HHP treatment at 200 MPa and 20°C for 5 min.

	Sample 1		Sample 2	
Time (min)	Weight (g)	MR	Weight (g)	MR
0	2.98	1.0000	3.07	1.0000
15	2.71	0.8933	2.79	0.8974
30	2.49	0.8063	2.55	0.8095
45	2.27	0.7194	2.29	0.7143
75	1.87	0.5613	1.86	0.5568
105	1.52	0.4229	1.48	0.4176
135	1.22	0.3043	1.15	0.2967
165	0.99	0.2134	0.89	0.2015
195	0.82	0.1462	0.68	0.1245
225	0.69	0.0949	0.54	0.0733
255	0.59	0.0553	0.45	0.0403
285	0.53	0.0316	0.39	0.0183
315	0.50	0.0198	0.37	0.0110
345	0.47	0.0079	0.36	0.0073
375	0.46	0.0040	0.35	0.0037
405	0.46	0.0040	0.35	0.0037
435	0.45	0.0000	0.34	0.0000
465	0.45	0.0000	0.34	0.0000
495	0.45	0.0000	0.34	0.0000
∞	0.45		0.34	

Table B.46. Drying data of carrot slices at 45°C with air velocity of 0.4 m/s after HHP treatment at 200 MPa and 20°C for 15 min.

	Sample 1		Sample 2	
Time (min)	Weight (g)	MR	Weight (g)	MR
0	3.24	1.0000	3.04	1.0000
15	2.94	0.8958	2.73	0.8835
30	2.66	0.7986	2.46	0.7820
45	2.38	0.7014	2.20	0.6842
75	1.93	0.5451	1.76	0.5188
105	1.51	0.3993	1.38	0.3759
135	1.18	0.2847	1.05	0.2519
165	0.95	0.2049	0.81	0.1617
195	0.77	0.1424	0.62	0.0902
225	0.61	0.0868	0.51	0.0489
255	0.52	0.0556	0.46	0.0301
285	0.45	0.0313	0.42	0.0150
315	0.40	0.0139	0.40	0.0075
345	0.39	0.0104	0.39	0.0038
375	0.37	0.0035	0.39	0.0038
405	0.37	0.0035	0.38	0.0000
435	0.36	0.0000	0.38	0.0000
∞	0.36		0.38	

Table B.47. Drying data of carrot slices at 45°C with air velocity of 0.4 m/s after HHP treatment at 200 MPa and 20°C for 45 min.

	Sample 1		Sample 2	
Time (min)	Weight (g)	MR	Weight (g)	MR
0	3.23	1.0000	2.93	1.0000
15	2.92	0.8889	2.63	0.8837
30	2.66	0.7957	2.39	0.7907
45	2.39	0.6989	2.14	0.6938
75	1.92	0.5305	1.70	0.5233
105	1.50	0.3799	1.32	0.3760
135	1.19	0.2688	1.00	0.2519
165	0.92	0.1720	0.75	0.1550
195	0.75	0.1111	0.58	0.0891
225	0.62	0.0645	0.46	0.0426
255	0.54	0.0358	0.41	0.0233
285	0.50	0.0215	0.39	0.0155
315	0.48	0.0143	0.37	0.0078
345	0.47	0.0108	0.36	0.0039
375	0.45	0.0036	0.36	0.0039
405	0.45	0.0036	0.35	0.0000
435	0.44	0.0000	0.35	0.0000
∞	0.44		0.35	

Table B.48. Drying data of carrot slices at 45°C with air velocity of 0.4 m/s after HHP treatment at 250 MPa and 20°C for 15 min.

	Sample 1		Sample 2	
Time (min)	Weight (g)	MR	Weight (g)	MR
0	2.72	1.0000	3.34	1.0000
15	2.51	0.9121	3.00	0.8844
30	2.29	0.8201	2.73	0.7925
45	2.07	0.7280	2.46	0.7007
75	1.60	0.5314	1.98	0.5374
105	1.25	0.3849	1.55	0.3912
135	0.97	0.2678	1.17	0.2619
165	0.74	0.1715	0.90	0.1701
195	0.61	0.1172	0.70	0.1020
225	0.48	0.0628	0.56	0.0544
255	0.44	0.0460	0.49	0.0306
285	0.40	0.0293	0.45	0.0170
315	0.36	0.0126	0.43	0.0102
345	0.34	0.0042	0.42	0.0068
375	0.34	0.0042	0.41	0.0034
405	0.33	0.0000	0.41	0.0034
435	0.33	0.0000	0.40	0.0000
∞	0.33		0.40	

Table B.49. Drying data of carrot slices at 45°C with air velocity of 0.4 m/s after HHP treatment at 250 MPa and 20°C for 45 min.

	Sample 1		Sample 2	
Time (min)	Weight (g)	MR	Weight (g)	MR
0	2.66	1.0000	3.30	1.0000
15	2.44	0.9068	2.97	0.8862
30	2.24	0.8220	2.70	0.7931
45	2.02	0.7288	2.42	0.6966
75	1.57	0.5381	1.96	0.5379
105	1.21	0.3856	1.55	0.3966
135	0.92	0.2627	1.19	0.2724
165	0.71	0.1737	0.91	0.1759
195	0.55	0.1059	0.70	0.1034
225	0.46	0.0678	0.56	0.0552
255	0.40	0.0424	0.49	0.0310
285	0.38	0.0339	0.45	0.0172
315	0.35	0.0212	0.43	0.0103
345	0.35	0.0212	0.42	0.0069
375	0.34	0.0169	0.41	0.0034
405	0.33	0.0127	0.40	0.0000
435	0.31	0.0042	0.40	0.0000
∞	0.30		0.40	

Table B.50. Drying data of carrot slices at 45°C with air velocity of 0.4 m/s after HHP treatment at 200 MPa and 35°C for 15 min.

	Sample 1		Sample 2	
Time (min)	Weight (g)	MR	Weight (g)	MR
0	3.15	1.0000	3.17	1.0000
15	2.88	0.9039	2.88	0.8972
30	2.62	0.8114	2.61	0.8014
45	2.39	0.7295	2.35	0.7092
75	1.96	0.5765	1.89	0.5461
105	1.57	0.4377	1.46	0.3936
135	1.24	0.3203	1.15	0.2837
165	0.97	0.2242	0.86	0.1809
195	0.75	0.1459	0.66	0.1099
225	0.58	0.0854	0.52	0.0603
255	0.47	0.0463	0.44	0.0319
285	0.40	0.0214	0.39	0.0142
315	0.37	0.0107	0.36	0.0035
345	0.35	0.0036	0.35	0.0000
375	0.34	0.0000	0.35	0.0000
405	0.34	0.0000	0.35	0.0000
∞	0.34		0.35	

Table B.51. Drying data of carrot slices at 45°C with air velocity of 0.4 m/s after HHP treatment at 200 MPa and 35°C for 45 min.

	Sample 1		Sample 2	
Time (min)	Weight (g)	MR	Weight (g)	MR
0	3.31	1.0000	3.26	1.0000
15	2.99	0.8893	2.99	0.9056
30	2.73	0.7993	2.73	0.8147
45	2.46	0.7059	2.48	0.7273
75	1.99	0.5433	2.03	0.5699
105	1.58	0.4014	1.64	0.4336
135	1.26	0.2907	1.32	0.3217
165	0.99	0.1972	1.04	0.2238
195	0.77	0.1211	0.82	0.1469
225	0.64	0.0761	0.67	0.0944
255	0.54	0.0415	0.57	0.0594
285	0.49	0.0242	0.50	0.0350
315	0.46	0.0138	0.47	0.0245
345	0.45	0.0104	0.44	0.0140
375	0.44	0.0069	0.43	0.0105
405	0.43	0.0035	0.42	0.0070
∞	0.42		0.40	

Table B.52. Drying data of carrot slices without pretreatment at 65°C with air velocity of 0.4 m/s.

	Sample 1		Sample 2		Sample 3		Sample 4	
Time (min)	Weight (g)	MR	Weight (g)	MR	Weight (g)	MR	Weight (g)	MR
0	3.00	1.0000	3.31	1.0000	3.32	1.0000	3.40	1.0000
15	2.55	0.8221	2.89	0.8557	2.92	0.8592	2.99	0.8624
30	2.17	0.6719	2.52	0.7285	2.54	0.7254	2.61	0.7349
45	1.91	0.5692	2.19	0.6151	2.26	0.6268	2.26	0.6174
75	1.52	0.4150	1.59	0.4089	1.72	0.4366	1.72	0.4362
105	1.20	0.2885	1.17	0.2646	1.32	0.2958	1.30	0.2953
135	0.95	0.1897	0.89	0.1684	1.04	0.1972	0.98	0.1879
165	0.77	0.1186	0.69	0.0997	0.83	0.1232	0.76	0.1141
195	0.63	0.0632	0.56	0.0550	0.69	0.0739	0.61	0.0638
225	0.55	0.0316	0.48	0.0275	0.60	0.0423	0.53	0.0369
255	0.51	0.0158	0.45	0.0172	0.55	0.0246	0.48	0.0201
285	0.49	0.0079	0.42	0.0069	0.52	0.0141	0.46	0.0134
315	0.48	0.0040	0.41	0.0034	0.50	0.0070	0.44	0.0067
345	0.48	0.0040	0.41	0.0034	0.48	0.0000	0.43	0.0034
375	0.47	0.0000	0.40	0.0000	0.48	0.0000	0.42	0.0000

Table B.53. Drying data of carrot slices at 65°C with air velocity of 0.4 m/s after HHP treatment at 200 MPa and 20°C for 15 min.

	Sample 1		Sample 2	
Time (min)	Weight (g)	MR	Weight (g)	MR
0	2.96	1.0000	3.26	1.0000
15	2.53	0.8327	2.80	0.8369
30	2.16	0.6887	2.40	0.6950
45	1.82	0.5564	2.02	0.5603
75	1.29	0.3502	1.42	0.3475
105	0.93	0.2101	0.98	0.1915
135	0.70	0.1206	0.71	0.0957
165	0.55	0.0623	0.57	0.0461
195	0.47	0.0311	0.50	0.0213
225	0.46	0.0272	0.47	0.0106
255	0.45	0.0233	0.46	0.0071
285	0.41	0.0078	0.45	0.0035
315	0.39	0.0000	0.44	0.0000
345	0.39	0.0000	0.44	0.0000

Table B.54. Drying data of carrot slices at 65°C with air velocity of 0.4 m/s after HHP treatment at 200 MPa and 20°C for 45 min.

	Sample 1		Sample 2	
Time (min)	Weight (g)	MR	Weight (g)	MR
0	2.80	1.0000	3.38	1.0000
15	2.36	0.8247	3.00	0.8707
30	2.00	0.6813	2.60	0.7347
45	1.70	0.5618	2.24	0.6122
75	1.18	0.3546	1.64	0.4082
105	0.83	0.2151	1.17	0.2483
135	0.57	0.1116	0.84	0.1361
165	0.42	0.0518	0.63	0.0646
195	0.37	0.0319	0.53	0.0306
225	0.33	0.0159	0.48	0.0136
255	0.32	0.0120	0.46	0.0068
285	0.31	0.0080	0.45	0.0034
315	0.31	0.0080	0.44	0.0000
345	0.29	0.0000	0.44	0.0000

Table B.55. Drying data of carrot slices at 65°C with air velocity of 0.4 m/s after HHP treatment at 250 MPa and 20°C for 15 min.

	Sample 1		Sample 2	
Time (min)	Weight (g)	MR	Weight (g)	MR
0	3.40	1.0000	3.51	1.0000
15	2.96	0.8514	3.10	0.8673
30	2.56	0.7162	2.70	0.7379
45	2.24	0.6081	2.33	0.6181
75	1.61	0.3953	1.71	0.4175
105	1.15	0.2399	1.21	0.2557
135	0.82	0.1284	0.85	0.1392
165	0.61	0.0574	0.64	0.0712
195	0.53	0.0304	0.52	0.0324
225	0.49	0.0169	0.46	0.0129
255	0.47	0.0101	0.44	0.0065
285	0.45	0.0034	0.43	0.0032
315	0.44	0.0000	0.42	0.0000
345	0.44	0.0000	0.42	0.0000

Table B.56. Drying data of carrot slices at 65°C with air velocity of 0.4 m/s after HHP treatment at 250 MPa and 20°C for 45 min.

	Sample 1		Sample 2	
Time (min)	Weight (g)	MR	Weight (g)	MR
0	3.36	1.0000	3.40	1.0000
15	2.98	0.8685	3.02	0.8721
30	2.63	0.7474	2.65	0.7475
45	2.28	0.6263	2.31	0.6330
75	1.71	0.4291	1.69	0.4242
105	1.26	0.2734	1.22	0.2660
135	0.91	0.1522	0.86	0.1448
165	0.71	0.0830	0.64	0.0707
195	0.59	0.0415	0.53	0.0337
225	0.54	0.0242	0.48	0.0168
255	0.51	0.0138	0.45	0.0067
285	0.49	0.0069	0.44	0.0034
315	0.48	0.0035	0.43	0.0000
345	0.47	0.0000	0.43	0.0000

Table B.57. Drying data of green bean without pretreatment at 45°C with air velocity of 0.4 m/s.

	Sample 1		Sample 2	
Time (min)	Weight (g)	MR	Weight (g)	MR
0	2.82	1.0000	3.39	1.0000
15	2.73	0.9643	3.29	0.9673
30	2.65	0.9325	3.18	0.9314
45	2.57	0.9008	3.10	0.9052
75	2.40	0.8333	2.94	0.8529
105	2.23	0.7659	2.77	0.7974
135	2.06	0.6984	2.62	0.7484
165	1.93	0.6468	2.49	0.7059
195	1.78	0.5873	2.35	0.6601
225	1.69	0.5516	2.23	0.6209
255	1.60	0.5159	2.12	0.5850
285	1.53	0.4881	2.02	0.5523
675	1.01	0.2817	1.14	0.2647
705	0.98	0.2698	1.10	0.2516
735	0.95	0.2579	1.06	0.2386
765	0.92	0.2460	1.02	0.2255
795	0.89	0.2341	0.98	0.2124
825	0.86	0.2222	0.94	0.1993
855	0.83	0.2103	0.90	0.1863
885	0.80	0.1984	0.86	0.1732
915	0.77	0.1865	0.82	0.1601
1065	0.68	0.1508	0.65	0.1046
1095	0.66	0.1429	0.62	0.0948
1125	0.64	0.1349	0.59	0.0850
1155	0.62	0.1270	0.56	0.0752
1185	0.60	0.1190	0.53	0.0654
1215	0.58	0.1111	0.50	0.0556
1275	0.55	0.0992	0.46	0.0425
1335	0.53	0.0913	0.42	0.0294
1395	0.51	0.0833	0.40	0.0229
1455	0.49	0.0754	0.38	0.0163
1515	0.47	0.0675	0.36	0.0098
1575	0.44	0.0556	0.35	0.0065
∞	0.30		0.33	

Table B.58. Drying data of green bean at 45°C with air velocity of 0.4 m/s after HHP treatment at 200 MPa and 20°C for 15 min.

	Sample 1		Sample 2	
Time (min)	Weight (g)	MR	Weight (g)	MR
0	2.04	1.0000	2.93	1.0000
15	1.97	0.9617	2.83	0.9624
30	1.92	0.9344	2.75	0.9323
45	1.87	0.9071	2.69	0.9098
75	1.79	0.8634	2.57	0.8647
105	1.72	0.8251	2.47	0.8271
135	1.65	0.7869	2.38	0.7932
165	1.59	0.7541	2.30	0.7632
195	1.53	0.7213	2.24	0.7406
225	1.48	0.6940	2.18	0.7180
255	1.42	0.6612	2.13	0.6992
285	1.37	0.6339	2.08	0.6805
315	1.32	0.6066	2.03	0.6617
345	1.28	0.5847	1.99	0.6466
375	1.23	0.5574	1.95	0.6316
405	1.18	0.5301	1.91	0.6165
435	1.13	0.5027	1.87	0.6015
465	1.09	0.4809	1.83	0.5865
495	1.05	0.4590	1.79	0.5714
525	1.00	0.4317	1.75	0.5564
555	0.96	0.4098	1.71	0.5414
585	0.91	0.3825	1.67	0.5263
615	0.87	0.3607	1.63	0.5113
645	0.83	0.3388	1.59	0.4962
675	0.79	0.3169	1.55	0.4812
705	0.75	0.2951	1.51	0.4662
735	0.71	0.2732	1.47	0.4511
765	0.67	0.2514	1.43	0.4361
795	0.63	0.2295	1.39	0.4211
825	0.59	0.2077	1.35	0.4060
1035	0.36	0.0820	1.09	0.3083
1065	0.34	0.0710	1.05	0.2932
1095	0.32	0.0601	1.02	0.2820
1125	0.30	0.0492	0.98	0.2669
1155	0.28	0.0383	0.95	0.2556
1215	0.26	0.0273	0.88	0.2293
1275	0.24	0.0164	0.82	0.2068
1335	0.23	0.0109	0.76	0.1842

Table B.58 (continued)

	Sample 1		Sample 2	
Time (min)	Weight (g)	MR	Weight (g)	MR
1395	0.22	0.0055	0.70	0.1617
1455	0.21	0.0000	0.64	0.1391
∞	0.21		0.27	

Table B.59. Drying data of green bean at 45°C with air velocity of 0.4 m/s after HHP treatment at 200 MPa and 20°C for 45 min.

	Sample 1		Sample 2	
Time (min)	Weight (g)	MR	Weight (g)	MR
0	2.52	1.0000	2.84	1.0000
15	2.44	0.9644	2.76	0.9691
30	2.37	0.9333	2.67	0.9344
45	2.31	0.9067	2.61	0.9112
75	2.21	0.8622	2.51	0.8726
105	2.13	0.8267	2.42	0.8378
135	2.06	0.7956	2.34	0.8069
165	1.99	0.7644	2.28	0.7838
195	1.93	0.7378	2.22	0.7606
225	1.88	0.7156	2.16	0.7375
255	1.82	0.6889	2.11	0.7181
285	1.77	0.6667	2.06	0.6988
315	1.72	0.6444	2.02	0.6834
345	1.67	0.6222	1.98	0.6680
375	1.62	0.6000	1.94	0.6525
405	1.58	0.5822	1.90	0.6371
435	1.53	0.5600	1.86	0.6216
465	1.49	0.5422	1.82	0.6062
495	1.44	0.5200	1.78	0.5907
525	1.40	0.5022	1.74	0.5753
555	1.35	0.4800	1.70	0.5598
585	1.30	0.4578	1.66	0.5444
615	1.26	0.4400	1.62	0.5290
645	1.21	0.4178	1.58	0.5135
675	1.17	0.4000	1.54	0.4981
705	1.12	0.3778	1.50	0.4826
735	1.08	0.3600	1.47	0.4710
765	1.03	0.3378	1.43	0.4556

Table B.59 (continued)

	Sample 1		Sample 2	
Time (min)	Weight (g)	MR	Weight (g)	MR
795	0.99	0.3200	1.39	0.4402
825	0.95	0.3022	1.36	0.4286
855	0.91	0.2844	1.32	0.4131
885	0.87	0.2667	1.28	0.3977
915	0.84	0.2533	1.24	0.3822
945	0.81	0.2400	1.20	0.3668
975	0.78	0.2267	1.17	0.3552
1005	0.75	0.2133	1.14	0.3436
1035	0.72	0.2000	1.10	0.3282
1065	0.69	0.1867	1.06	0.3127
1095	0.66	0.1733	1.03	0.3012
1335	0.46	0.0844	0.76	0.1969
1365	0.44	0.0756	0.73	0.1853
1395	0.42	0.0667	0.71	0.1776
1425	0.40	0.0578	0.68	0.1660
1485	0.37	0.0444	0.66	0.1583
1545	0.34	0.0311	0.61	0.1390
∞	0.27		0.25	

Table B.60. Drying data of green bean without pretreatment at 65°C with air velocity of 0.4 m/s.

	Sample 1		Sample 2	
Time (min)	Weight (g)	MR	Weight (g)	MR
0	2.60	1.0000	2.65	1.0000
15	2.46	0.9407	2.50	0.9364
30	2.32	0.8814	2.36	0.8771
45	2.18	0.8220	2.23	0.8220
75	1.93	0.7161	2.00	0.7246
105	1.71	0.6229	1.78	0.6314
135	1.49	0.5297	1.58	0.5466
165	1.31	0.4534	1.40	0.4703
195	1.15	0.3856	1.23	0.3983
225	1.00	0.3220	1.10	0.3432
255	0.89	0.2754	0.99	0.2966
285	0.75	0.2161	0.89	0.2542
315	0.68	0.1864	0.81	0.2203
345	0.60	0.1525	0.74	0.1907
375	0.52	0.1186	0.66	0.1568
405	0.46	0.0932	0.61	0.1356
435	0.40	0.0678	0.55	0.1102
465	0.33	0.0381	0.49	0.0847
495	0.29	0.0212	0.46	0.0720
525	0.26	0.0085	0.40	0.0466
555	0.25	0.0042	0.37	0.0339
585	0.24	0.0000	0.34	0.0212
615	0.24	0.0000	0.32	0.0127
645	0.24	0.0000	0.31	0.0085
∞	0.24		0.29	

Table B.61. Drying data of green bean at 65°C with air velocity of 0.4 m/s after HHP treatment at 100 MPa and 20°C for 15 min.

	Sample 1		Sample 2	
Time (min)	Weight (g)	MR	Weight (g)	MR
0	2.48	1.0000	2.54	1.0000
15	2.36	0.9450	2.42	0.9459
30	2.25	0.8945	2.30	0.8919
45	2.15	0.8486	2.20	0.8468
75	1.98	0.7706	2.02	0.7658
105	1.83	0.7018	1.87	0.6982
135	1.69	0.6376	1.73	0.6351
165	1.56	0.5780	1.59	0.5721
195	1.43	0.5183	1.48	0.5225
225	1.31	0.4633	1.35	0.4640
255	1.19	0.4083	1.25	0.4189
285	1.08	0.3578	1.14	0.3694
315	0.97	0.3073	1.04	0.3243
345	0.87	0.2615	0.95	0.2838
375	0.76	0.2110	0.85	0.2387
405	0.67	0.1697	0.76	0.1982
435	0.58	0.1284	0.68	0.1622
465	0.50	0.0917	0.60	0.1261
495	0.43	0.0596	0.53	0.0946
525	0.39	0.0413	0.47	0.0676
555	0.36	0.0275	0.41	0.0405
585	0.33	0.0138	0.38	0.0270
615	0.32	0.0092	0.36	0.0180
∞	0.30		0.32	

Table B.62. Drying data of green bean at 65°C with air velocity of 0.4 m/s after HHP treatment at 100 MPa and 20°C for 45 min.

	Sample 1		Sample 2	
Time (min)	Weight (g)	MR	Weight (g)	MR
0	2.30	1.0000	2.44	1.0000
15	2.18	0.9412	2.32	0.9455
30	2.08	0.8922	2.21	0.8955
45	1.99	0.8480	2.12	0.8545
75	1.83	0.7696	1.96	0.7818
105	1.69	0.7010	1.82	0.7182
135	1.57	0.6422	1.69	0.6591
165	1.45	0.5833	1.57	0.6045
195	1.33	0.5245	1.45	0.5500
225	1.21	0.4657	1.34	0.5000
255	1.11	0.4167	1.23	0.4500
285	1.00	0.3627	1.12	0.4000
315	0.90	0.3137	1.02	0.3545
345	0.80	0.2647	0.92	0.3091
375	0.70	0.2157	0.82	0.2636
405	0.62	0.1765	0.74	0.2273
435	0.54	0.1373	0.64	0.1818
465	0.46	0.0980	0.56	0.1455
495	0.39	0.0637	0.49	0.1136
525	0.33	0.0343	0.42	0.0818
555	0.29	0.0147	0.35	0.0500
585	0.27	0.0049	0.30	0.0273
615	0.27	0.0049	0.27	0.0136
∞	0.26		0.24	

Table B.63. Drying data of green bean at 65°C with air velocity of 0.4 m/s after HHP treatment at 200 MPa and 20°C for 15 min.

	Sample 1		Sample 2	
Time (min)	Weight (g)	MR	Weight (g)	MR
0	1.93	1.0000	2.14	1.0000
15	1.83	0.9425	2.02	0.9368
30	1.73	0.8851	1.93	0.8895
45	1.66	0.8448	1.84	0.8421
75	1.51	0.7586	1.69	0.7632
105	1.39	0.6897	1.57	0.7000
135	1.27	0.6207	1.47	0.6474
165	1.15	0.5517	1.36	0.5895
195	1.04	0.4885	1.26	0.5368
225	0.93	0.4253	1.15	0.4789
255	0.82	0.3621	1.06	0.4316
285	0.73	0.3103	0.95	0.3737
315	0.63	0.2529	0.85	0.3211
345	0.53	0.1954	0.75	0.2684
375	0.45	0.1494	0.66	0.2211
405	0.36	0.0977	0.58	0.1789
435	0.29	0.0575	0.50	0.1368
465	0.24	0.0287	0.43	0.1000
495	0.21	0.0115	0.37	0.0684
525	0.20	0.0057	0.32	0.0421
555	0.19	0.0000	0.28	0.0211
585	0.19	0.0000	0.25	0.0053
615	0.19	0.0000	0.25	0.0053
∞	0.19		0.24	

Table B.64. Drying data of green bean at 65°C with air velocity of 0.4 m/s after HHP treatment at 200 MPa and 20°C for 45 min.

	Sample 1		Sample 2	
Time (min)	Weight (g)	MR	Weight (g)	MR
0	2.29	1.0000	2.34	1.0000
15	2.17	0.9417	2.21	0.9390
30	2.08	0.8981	2.09	0.8826
45	1.98	0.8495	2.02	0.8498
75	1.85	0.7864	1.84	0.7653
105	1.71	0.7184	1.70	0.6995
135	1.59	0.6602	1.57	0.6385
165	1.48	0.6068	1.45	0.5822
195	1.35	0.5437	1.33	0.5258
225	1.26	0.5000	1.21	0.4695
255	1.15	0.4466	1.08	0.4085
285	1.05	0.3981	0.97	0.3568
315	0.96	0.3544	0.86	0.3052
345	0.86	0.3058	0.74	0.2488
375	0.77	0.2621	0.64	0.2019
405	0.68	0.2184	0.54	0.1549
435	0.60	0.1796	0.46	0.1174
465	0.53	0.1456	0.39	0.0845
495	0.45	0.1068	0.33	0.0563
525	0.40	0.0825	0.28	0.0329
555	0.34	0.0534	0.25	0.0188
585	0.29	0.0291	0.23	0.0094
615	0.26	0.0146	0.22	0.0047
∞	0.23		0.21	

Table B.65. Drying data of green bean at 65°C with air velocity of 0.4 m/s after HHP treatment at 200 MPa and 35°C for 15 min.

	Sample 1		Sample 2	
Time (min)	Weight (g)	MR	Weight (g)	MR
0	2.07	1.0000	2.58	1.0000
15	1.93	0.9243	2.41	0.9258
30	1.81	0.8595	2.28	0.8690
45	1.72	0.8108	2.16	0.8166
75	1.54	0.7135	1.95	0.7249
105	1.39	0.6324	1.76	0.6419
135	1.26	0.5622	1.57	0.5590
165	1.14	0.4973	1.41	0.4891
195	1.01	0.4270	1.25	0.4192
225	0.89	0.3622	1.10	0.3537
255	0.79	0.3081	0.94	0.2838
285	0.70	0.2595	0.81	0.2271
315	0.60	0.2054	0.68	0.1703
345	0.51	0.1568	0.57	0.1223
375	0.43	0.1135	0.48	0.0830
405	0.37	0.0811	0.41	0.0524
435	0.31	0.0486	0.35	0.0262
465	0.27	0.0270	0.32	0.0131
495	0.24	0.0108	0.30	0.0044
525	0.23	0.0054	0.30	0.0044
555	0.22	0.0000	0.29	0.0000
585	0.22	0.0000	0.29	0.0000

Table B.66. Drying data of green bean at 65°C with air velocity of 0.4 m/s after HHP treatment at 200 MPa and 35°C for 45 min.

	Sample 1		Sample 2	
Time (min)	Weight (g)	MR	Weight (g)	MR
0	2.46	1.0000	2.49	1.0000
15	2.31	0.9318	2.35	0.9372
30	2.16	0.8636	2.21	0.8744
45	2.04	0.8091	2.08	0.8161
75	1.85	0.7227	1.89	0.7309
105	1.67	0.6409	1.71	0.6502
135	1.50	0.5636	1.55	0.5785
165	1.34	0.4909	1.39	0.5067
195	1.19	0.4227	1.25	0.4439
225	1.05	0.3591	1.11	0.3812
255	0.92	0.3000	0.96	0.3139
285	0.79	0.2409	0.84	0.2601
315	0.68	0.1909	0.72	0.2063
345	0.57	0.1409	0.59	0.1480
375	0.47	0.0955	0.48	0.0987
405	0.39	0.0591	0.39	0.0583
435	0.33	0.0318	0.32	0.0269
465	0.29	0.0136	0.28	0.0090
495	0.26	0.0000	0.26	0.0000
525	0.26	0.0000	0.26	0.0000
555	0.26	0.0000	0.26	0.0000
585	0.26	0.0000	0.26	0.0000