DETERMINATION OF EFFECTIVE PARAMETERS FOR DRYING OF APPLES

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ABSTRACT

DETERMINATION OF EFFECTIVE PARAMETERS FOR DRYING OF APPLES

Drying is one of the oldest methods for the preservation of agricultural products such as fruits and vegetables. Apple has a significant share in fruit production both in the World and in Turkey. It is also an important raw material for many food products.

Temperature, velocity and relative humidity of drying air are important parameters for hot air drying process. To determine the drying kinetic of agricultural products, drying and drying rate curves should be plotted.

Experiments are conducted in a tunnel dryer using cubic shaped (10x10x10mm) red delicious (Malus Domestica) apple for various drying air temperature (40.1-65.3^{o}C), velocity (1.1, 1.4, 1.9, 2.3 and 2.5 m/s) and relative humidity (4.6-20.5%) values. The temperature and relative humidity are measured and recorded every 1 min. at fan inlet, upstream and downstream of the tray, the velocity is measured only at the tunnel exit. The measured data is used to obtain drying and drying rate curves. The curves indicate that drying process takes place in the falling rate period except very short unsteady-state initial and constant rate periods. Thus, effective diffusion coefficients are calculated using the data collected during the falling rate period and the experimental data are fitted to fourteen thin layer drying models which are found in the literature. Rehydration time and colour are used as parameters for the dried apple quality.

The effective diffusion coefficients are obtained within the range of $0.486\text{x}10^{-9}$ - $5.63\text{x}10^{-9}$ m^2/s Regarding with drying time, rehydration time and colour data, the best results are obtained at 2.5 m/s velocity, 20.5% relative humidity and a temperature range of 53.5-65.3^{o}C under experimental conditions. Midilli and Kucuk model is the best fitted model with a minimum R^2 of 0.9991 and a maximum RMSE of 0.0087976.

ÖZET

ELMA KURUTMADA ETKİN PARAMETRELERİN BELİRLENMESİ

Kurutma, meyva ve sebzelerin saklanmasında kullanılan en eski yöntemlerden biridir. Hem çiğ olarak tüketilen hem de birçok gıda ürününde hammadde olarak kullanılan elma, Dünya ve Türkiye'nin meyva üretiminde önemli bir paya sahiptir.

Konvansiyonel sıcak hava ile kurutma işlemlerinde; kurutma havası sıcaklığı, hızı ve bağıl nemi en önemli parametreler arasındadır. Tarımsal ürünlerin kurutma kinetiğinin belirlenmesi için kurutma ve kurutma hızı eğrilerinin elde edilmesi gerekmektedir.

Bu çalışmada; tasarlanan tünel kurutucuda küp şeklinde kesilmiş kırmızı elma (Malus Domestica) kullanılarak, çeşitli sıcaklık (40.1-65.3^{o}C), hava hızı (1.1, 1.4, 1.9, 2.3, 2.5 m/s) ve bağıl nem değerlerinde (%4.6-20.5) kurutma deneyleri gerçekleştirilmiştir. Sıcaklık ve bağıl nem değerleri; fan girişi, tepsi öncesi ve sonrasında birer dakika aralıklarla ölçülmüştür. Hava hızı ise sadece tünel kurutucunun çıkışında ölçülmüştür. Elde edilen veriler kurutma ve kurutma hızı eğrilerinin çizilmesinde kullanılmıştır. Eğriler, kurutmanın çoğunlukla azalan kuruma hızı (falling rate) bölgesinde gerçekleştiğini göstermektedir. Difüzyon kontrollü olan bu bölge için efektif difüzyon katsayıları, Fick difüzyon denklemi kullanılarak hesaplanmıştır. Deneysel veriler literatürdeki 14 farklı kurutma modeline uygulanmıştır. Kurutulmuş elmanın kalitesini belirlemek için rehidrasyon süresi ve renk parametreleri belirlenmiştir.

Efektif difüzyon katsayıları $0.486x10^{-9}$ ile $5.63x10^{-9}$ m^2/s aralığında bulunmuştur. Kurutma hızı, rehidrasyon süresi ve renk verileri göz önünde bulundurularak, kurutmanın en iyi 53.5-65.3^{o}C sıcaklık aralığı ile 2.5 m/s hava hızı ve %20.5 bağıl nemde gerçekleştiği belirlenmiştir. Midilli ve Küçük Modeli deneysel verilere en iyi uyum sağlayan model olup korelasyon katsayısı 0.9991 ve kök ortalama kare hatası 0.0087976 olarak bulunmuştur.

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LIST OF SYMBOLS

D	Diffusion coefficient, m^2/s
DR	Drying rate, g water/g dm/min
L	Half thickness of slab, m
m	Mass, g
M	Moisture content of apple, g water/g dm
MR	Moisture ratio, -
t	Time, s
a, b, c, g, h, L, k, k_o, k_1	Model constant

Subscripts

e	Equilibrium
eff	Effective
exp	Experimental
f	Final
i	Initial
o	Initial
T	Total
t	At time t
Δt	Time interval

CHAPTER 1

INTRODUCTION

Drying involves the application of heat to vaporize the volatile substances (moisture) and some means of removing water vapor after its separation from the solid (Jayamaran and Gupta 2006). The drying process is a heat and mass transfer phenomenon where water migrates from the interior of the drying product on to the surface from which it evaporates. Heat is transferred from the surrounding air to the surface of the product. A part of this heat is transferred to the interior of the product, causing a rise in temperature and formation of water vapor, and the remaining amount is utilized in evaporation of the moisture from the surface (El-Ghetany 2006).

Drying is one of the oldest methods known for the preservation of agricultural products such as fruits and vegetables. Drying of agricultural products enhances their storage life, minimizes losses during storage, and save shipping and transportation costs (Doymaz 2005).

The main objectives of drying are summarized as follows (Sokhansanj and Jayas 2006);

- A dry food product is less susceptible to spoilage caused by the growth of bacteria, molds, and insects. The activity of many microorganisms and insects is inhibited in an environment in which the equilibrium relative humidity is below 70%. Likewise, the risk of unfavorable oxidative and enzymatic reactions that shorten the shelf life of food is reduced.
- Many favorable qualities and nutritional values of food may be enhanced by drying. Palatability is improved, and likewise digestibility and metabolic conversions are increased. Drying also changes color, flavor, and often the appearance of a food item. The acceptance to that change varies by the end user.
- Packaging, handling and transportation of a dry product are easier and cheaper because the weight and volume of a product are less in its dried

form. A dry product flows easier than a wet product; thus gravity forces can be utilized for loading and unloading and short-distance hauling.

- Food products are dried for improved milling, mixing or segregation. A dry product takes far less energy than a wet product to be milled. A dry product mixes with other materials uniformly and is less sticky compared with a wet product.
- Drying has also been used as a means of food sanitation. Insects and other microorganisms are destroyed during the application of heat and moisture diffusion.

Fruits and vegetables play an important role in human nutrition. Apart from providing flavor and variety to human diet, they serve as important sources of vitamins and minerals. The celluloses, hemicelluloses, pectic substances and lignin characteristic of plant products together form dietary fiber, the value of which in human diet is increasingly realized in recent years.

Most fruits and vegetables contain more than 80% water and therefore highly perishable. Water loss and decay account for most of their losses, which are estimated to be more than 30% in the developing countries due to inadequate handling, transportation and storage (Jayaraman and Gupta 2006, Kaya, et al. 2007). Apart from these losses, serious losses do occur in the availability of essential nutrients, vitamins and minerals.

World production of fruit and vegetables are increasing substantially as a result of demand and developments in agricultural technologies.

World fruit production was reported to be 484 million metric tons annually between the years of 2001-2004. Figure 1.1 exhibits the World fruit production breakdown for the year of 2004. Banana, grape, orange and apple were the most widely grown fruits with a total share of approximately 51%. The leading fruit producers of the World are China, India, Brazil, Italy, Spain, Mexico, Indonesia, Iran, Philippines, France and Turkey.

Turkey’s fruit production reached to 10.9 million tons in the year of 2004. During the 2001-2004 periods, grape is the most widely grown fruit with approximately 32% share in total production as given in Figure 1.2. Apple occupies second position with approximately 22%. (Gül and Akpınar 2006, FAO 2007).

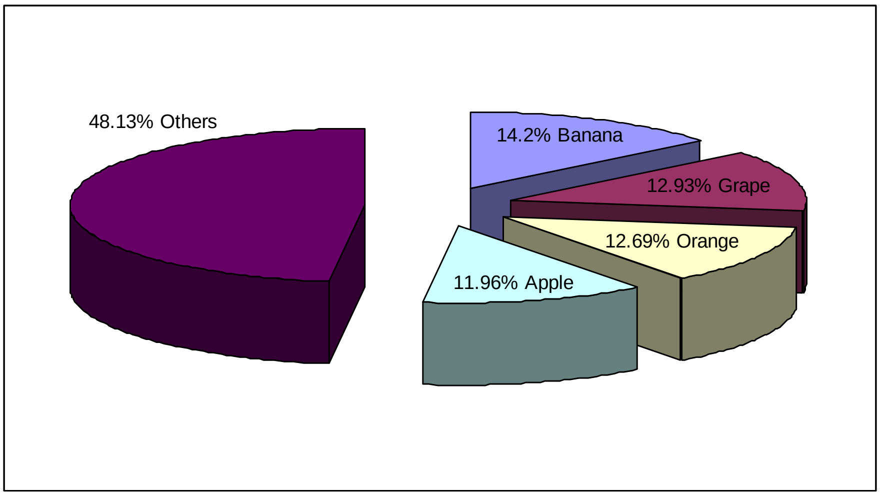

Figure 1.1. World Fruit Production in 2004

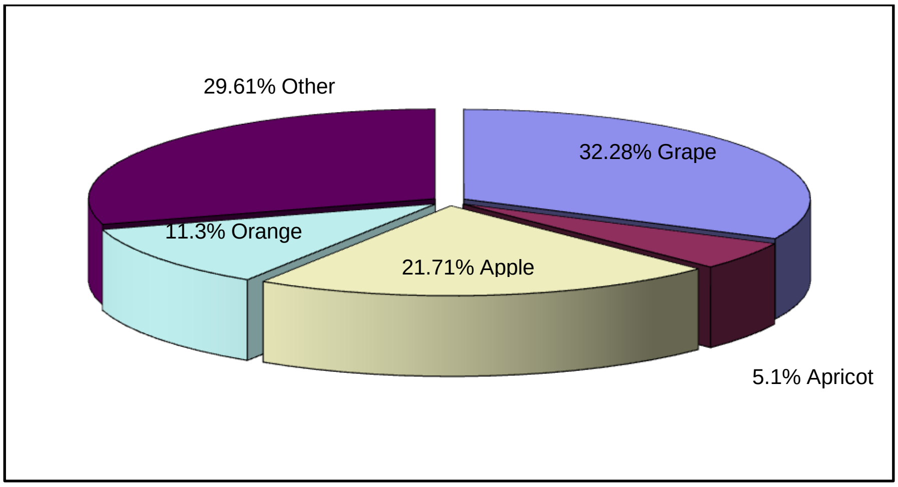

Figure 1.2. Turkey's Fruit Production between 2001-2004

As it can be seen from the Figures 1.1 and 1.2, apple has a significant share in fruit production both in the World and in Turkey. Apple is also an important raw material for many food products. Defining the optimal preservation and storage conditions for fresh apple is beneficial since unsuitable preservation and storage methods cause losses of fruits and vegetables that range from 10% to 30% (Kaya, et al. 2007).

The main objective of this study is to determine effective drying parameters for apples in a tunnel dryer and examine the effects of these parameters on the drying kinetics. Drying parameters and models derived using these parameters are very useful for the design and optimization of industrial dryers.

In Chapter 2, a literature survey comprising the previous studies on the drying kinetics of apple is given.

Chapter 3, describes the principles and mechanisms of drying process. Furthermore dryers and drying methods are summarized.

In Chapter 4, experimental unit and procedure of experiments are given.

In Chapter 5, the experimental results are presented. Experimental data is fitted to some models available in the literature and diffusion coefficients are obtained for each experimental condition.

Finally, the conclusions are stated in Chapter 6.

CHAPTER 2

LITERATURE SURVEY

Literature survey is classified into three groups with respect to drying processes; atmospheric dehydration, sub-atmospheric dehydration and sun and solar drying.

The most widely studied process is atmospheric dehydration process which is used in many experimental studies.

Akpınar and Biçer (2003) investigated the single layer drying behavior of apple slices in a convective type cyclone dryer and performed the mathematical modeling by using single layer drying models. The experiments were conducted at drying air temperatures of 60, 70 and 80^{o}C and drying air velocities of 1 and 1.5 m/s. The mathematical model describing the single layer drying curves was determined by nonlinear regression analysis. Considering the parameters such as drying time, drying rate, moisture transfer and velocity and drying air temperature it is suggested that the apple slices be dried at the above optimum processing conditions. The Logarithmic model could adequately describe the single layer drying behavior of apple samples, when the effect of the drying air, velocity and sample area on the constant and coefficients of the logarithmic model were examined. The moisture transfer from the apple slices occurring during the falling rate period of drying was characterized by determining the diffusion coefficient into the air experimentally.

Andrés et al. (2003) dried apple cylinders in a combined hot air-microwave system. Drying experiments were carried out at various temperatures combined with different levels of microwave incident power until 0.11 dry basis (d-b) moisture content was observed. Vacuum impregnation with isotonic solution was used as a pretreatment before drying. Microstructural changes were investigated on the drying kinetics. An empirical model was proposed to estimate the drying kinetic constants as a function of the air temperature and the microwave power level for both sorts of samples, fresh apples and impregnated apples. As a result of the study, microwave power effect was higher than air temperature, decreasing significantly the drying time. The higher density and lower porosity of vacuum impregnated samples implied slower kinetics and higher volume reduction.

Mandala et al. (2004) investigated the influence of different osmotic pre-treatments on apple air drying kinetics and their physical characteristics during drying. Apple samples were immersed in glucose or sucrose solution of 30%, 45% (w/w) at different times. Sugar gain and water loss were calculated. Samples were further air-dried and the experimental data were fitted successfully using the Page model. Porosity, compressive fracture stress and colour were measured. Samples osmosed in high sugar concentration had better physical characteristics than those treated at lower concentration. Among them, osmosed samples in glucose had even better characteristics and additionally had a higher drying rate. The only disadvantage of these samples was the firmness increase during drying.

Velic et al. (2004) investigated airflow velocity influence on the kinetics of convection drying of apples, heat transfer and average effective diffusion coefficients. Drying was conducted in a convection tray drier at drying temperature of 60^{o}C using regtangle-shaped (20x20x5mm) apple samples. Rehydration ratio was used as a parameter for the dried sample quality. Kinetic equations were estimated by using an exponential mathematical model. The result of calculations corresponded well with experimental data. Two well-defined falling rate periods and a very short constant rate period at lower air velocities was observed. With an increase of airflow velocity an increase of heat transfer coefficient and effective diffusion coefficient was found. During rehydration, about 72% of water removed by the drying process was returned.

Schultz et al. (2005) studied the effects of different pre-treatments on convective drying of apple slices and compared to drying without pre-treatments. An impregnation with starch, an HTST (High Temperature Short Time) process, and a combination of the two were used. When HTST applied, air drying at mild temperature was used to finish the drying process. The apparent density was also investigated and showed lower values for several conditions applied. ANOVA indicated which factors are significant to the observed decrease in apparent density. The Duncan test highlights experimental situations where these variables have an influence. Apparent density is almost constant as dimensionless moisture content diminishes, but it decreases when values are below around 0.2. Volume variations showed a linear behavior with the moisture content changes at the studied conditions.

Srikiatden and Roberts (2005) determined effective moisture diffusivity of apple during convective hot air drying and isothermal drying and compared moisture loss predicted from the diffusion and first-order kinetic models to experimental data. The prediction of moisture loss obtained from Fick's diffusion model failed to follow experimental drying curves. Temperature profiles during convective hot air drying showed temperature gradients. This lack of isothermal conditions may lead to inaccurate prediction of moisture loss. Therefore, a combined microwave-convection hot air apparatus, capable of providing isothermal drying conditions, was used to quantify the drying kinetics. Using effective diffusivities obtained under isothermal conditions, the Fickian model still did not predict during drying, it was hypothesized that drying of a hygroscopic porous materials is limited by evaporation of water to water vapor. Therefore, an irreversible first-order kinetic model was proposed to predict isothermal drying of apple. Using the rate constant calculated from the slope of the normalized drying curves, the model predicted accurate moisture loss at each temperature throughout the entire moisture range.

Bialobrzewski (2006) determined the influence of drying shrinkage on the kinetics of convection apple slab drying. The arbitrary Lagrange-Eulerian (ALE) method was used to enter a problem with moving boundaries. It was found that drying shrinkage had a major influence on the both simulated temperature and water content in the material. The lower moisture content in particles during drying, the more pronounced the effect of shrinkage on simulation of heat and mass transfer.

Stawczyk et al. (2006) investigated the effect of Atmospheric Freeze-Drying kinetics on the quality of apple cubes. The experimental data are compared with the result of convective and vacuum freeze-drying processes, and suitable operating parameters are determined. The experiments were carried out in an internet controlled, fully automated heat pump assisted drying system. The atmospheric freeze-drying process of apple dewatering run at temperature around -10^{o}C leads to a highly porous product structure. The same process performed at temperatures around 0^{o}C results in deterioration of product quality. The quality evaluation of apple cubes shows that dried products of atmospheric freeze-drying at lower temperature have similar characteristic of rehydration kinetics and hygroscopic properties to the product obtained from vacuum freeze-drying. The atmospheric freeze-drying product results have a statistically higher value of antioxidant activity and polyphenol content compared with convective drying result. The optimum drying trajectories for apple cubes were found for the ascending temperature drying mode, where a middle melting region and constant drying rate occur.

Kaya et al. (2007) investigated drying kinetics of apple slice experimentally for varying values of the drying air parameters including temperature, velocity and relative humidity. Experiments were conducted using air temperatures at 35, 45 and 55^oC, velocities at 0.2, 0.4 and 0.6m/s and relative humidity values at 40%, 55% and 70%. The experimental moisture data were fitted to Henderson and Pabis model, the Newton model and the term exponential models. The values of the moisture diffusivity D_{eff} were obtained from Fick's diffusion model. The objectives of the study was to examine the influence of the relative humidity as well as the effects of temperature and the velocity of the drying air on the drying kinetics of the red delicious apple. A static gravimetric method was used to determine the sorption isotherms of apple slice at 35, 45, and 55^oC. As a result of the experiment following conclusion were a constant relative humidity, equilibrium moisture content decreases with increasing temperature. At a constant temperature, equilibrium moisture content increases with increasing equilibrium relative humidity. Increasing the temperature or velocity of the drying air decreases the total drying time, while decreasing the relative humidity decreases it. An increase either in velocity or temperature or decrease in relative humidity, increases effective diffusivity coefficient.

Wang et al. (2007a) evaluated the hot air convective drying characteristics of thin layer apple pomace in a laboratory scale dryer. The drying experiments were carried out at different air temperatures. Different mathematical models were tested with the drying behavior of apple pomace in the dryer. The results indicated that the Logarithmic model can present better predictions for the moisture transfer than others. The drying time of apple pomace decreases and the effective diffusivity increases as the drying temperature increases. The whole drying process of apple pomace took place in a falling rate period.

Wang et al. (2007b) evaluated characteristics of thin layer microwave drying of apple pomace with and without hot air pre-drying in a laboratory scale microwave dryer. The drying experiments were carried out at 150, 300, 450 and 600 W, and the hot air pre-drying was performed at 105^oC. Ten commonly used mathematical models were evaluated with the experimental data. The results indicated that the Page model was most adequate in predicting moisture transfer for fresh and pre-dried apple pomace; the drying time of apple pomace decreases and the effective diffusivity increases as the microwave output power increases.

There are few experimental studies in the literature on determining the drying characteristics of apple under subatmospheric dehydration process.

Mavroudis et al. (1998) studied the significance of the initial structure on mass transfer rates of two apple varieties, Kim (Sweden) and Granny Smith (Argentina) when subjected to osmotic dehydration. Results verified the importance of the initial structure for osmotic processing responses. Shrinkage properties such as volume changes, bulk density, particle density and porosity, have been studied macroscopically for both structures, inner (close to core) and outer (close to skin) and presented as a function of water content in a manner similar to air drying practice. A comparison with shrinkage properties observed in air drying is attempted. A strong linear relationship between volume changes and water removal was found in osmotic dehydration, similar to findings in air drying. The bulk density depends on the initial structure, variety and drying conditions in contrast with reported findings on air drying. The porosity of the outer tissue was found to increase with time in contrast with the inner tissue, indicative of the more pronounced solution penetration in the inner tissue parenchyma.

Falade et al. (2003) evaluated the osmotic pretreatment stage, and sensory attributes of osmotically dehydrated oven dried and osmotically dehydrated vacuum dried cashew apple products. Matured ripe cashew apples were transversely cut into 10mm, 15mm and 20mm slices and immersed in sugar solution of 52^{o}Brix, 60^{o}Brix and 68^{o}Brix, for 10 h. The osmotic temperature was maintained at 27^{o}C in a water bath. Osmosed samples were subsequently dried in either an air oven (50^{o}C) or a vacuum drier (50^{o}C) both for 6 h. The instantaneous moisture content of cashew apples decreased with increasing immersion time and osmotic solution concentration, but also increased with increasing slice thickness. The water loss, solid gain and percentage weight reduction increased with increasing osmotic solution concentration and immersion time, but decreased with increasing slice thickness. Sample pre-osmosed in 60^{o}Brix and 68^{o}Brix solutions were significantly better than pre-osmosed in a 51^{o}Brix solution. A significant difference between the osmo-oven and osmo-vacuum dried cashew apples could not be ascertained.

Tortoe et al. (2007) studied the kinetics involved in osmotic dehydration of apple, banana and potato. Osmotic dehydration rate constant were established for the rate constant k_1, k_2 and k_3 for the first, second and third falling rate periods of osmotic dehydration of Golden delicious, Cox, banana and potato by the method of slopes from the rate of water loss curves of the various materials. The rate constants k_1, k_2 and k_3 were identified in Golden Delicious and Cox and k_1 and k_2 were identified in banana and potato. The Arrhenius equation was applied to evaluate the reaction rate (k) and its temperature dependence. The coefficient of determination (R^2) for the rate constant k_3 for Golden Delicious in 60% sucrose solution was 0.99. Similar values of R^2 were obtained for Cox, banana and potato. The rate constant k_1 of the plant materials produced the highest activation energies and good coefficient of determination was recorded for the rate constant.

Dehydration of apple with sun and solar drying is rarely used.

Eliçin and Salçılık (2005) carried out the thin layer solar drying experiment under the conditions of Ankara, Turkey. During the experiments, apples were dried to the final moisture content of 11% from 82% w.b. in 1.5 days (28h) of drying in the solar tunnel dryer as compared to 2 days (32h) of drying in the open sun drying. The experimental data were used to fit the Page, logarithmic and Wang and Singh models and constant of drying models tested were determined by non-linear regression analysis. Among the various models tested to represent the solar tunnel drying behavior of organic apple, one was selected which presented best statistical indicators. Depending on the weather conditions, solar tunnel dryer resulted in a reduction in the drying time to an extent of 14.28% in comparison to open sun drying.

Most of the above studies examined the influence of temperature, velocity, moisture of the drying air, shrinkage and pre-treatments on the drying kinetics. Only one of the studies included the effect of the temperature, velocity and moisture of the drying air at the same study. On that study (Kaya, et al. 2007), moisture content is ranging between 40% and 70%. The objective of the thesis is to examine the effect of temperature, velocity and moisture of the drying air on the drying kinetic of the red delicious (Malus Domestica) apples. Influence of velocity is studied on wider range and lower values of relative humidity are studied compared to above studies.

CHAPTER 3

DRYING

3.1 General Principles

Drying can be described as the process of thermally removing moisture to yield a solid product. Moisture can be found as bound or unbound in the solid. Moisture, which exerts a vapor pressure less than that of pure liquid, is called bound moisture while moisture in excess of bound moisture is called unbound moisture.

When a wet solid is subjected to thermal drying, two processes occur simultaneously:

1. Transfer of energy (mostly as heat) from the surrounding environment to evaporate the surface moisture.
2. Transfer of internal moisture to the surface of the solid and its subsequent evaporation due to process 1.

Energy transfer as heat from the surrounding environment to the wet solid can occur as a subsequence of convection, conduction, or radiation and in some case as a result of a combination of these effects. In most cases heat is transferred to the surface of the wet solid and then to the interior. However, in dielectric, radio frequency (RF), or microwave freeze drying, energy is supplied to generate heat internally within the solid and flows to the exterior surface.

Process 1, the removal of water as vapor from the material surface, depends on the external conditions of temperature, humidity and velocity of the air, area of exposed surface, and pressure.

Process 2, the movement of moisture internally within the solid is a function of the physical nature of the solid, the temperature, and its moisture content. In a drying operation, any one of these processes may be the limiting factor governing the rate of drying, although they both proceed simultaneously throughout the drying cycle.

Drying is a complex operation involving transient transfer of heat and mass along with several rate processes, such as physical or chemical transformations which, in turn, may cause changes in product quality as well as the mechanisms of heat and mass transfer. Physical changes that may occur include shrinkage, puffing, crystallization, and glass transitions. In some cases, desirable or undesirable chemical or biochemical reactions may occur, leading to changes in color, texture, odor, or other properties of the solid product. Drying occurs by affecting vaporization of the liquid by supplying heat to the wet feedstock. Heat may be supplied by convection (direct dryers), by conduction (contact or indirect dryers), radiation or volumetrically by placing the wet material in a microwave or RF electromagnetic field.

Transport of moisture within the solid may occur by any one or more of the following mechanisms of mass transfer:

- Liquid diffusion, if the wet solid is at a temperature below the boiling point of the liquid,
- Vapor diffusion, if the liquid vaporizes within material,
- Knudsen diffusion, if drying takes place at very low temperatures and pressures, e.g., in freeze drying,
- Surface diffusion (possible although not proven),
- Hydrostatic pressure differences, when internal vaporization rates exceed the rate of vapor transport through the solid to the surroundings,
- Combinations of the above mechanisms.

Since the physical structure of the drying solid is subject to change during drying, the mechanisms of moisture transfer may also change with elapsed time of drying.

Process 1: External Conditions

The essential external variables are temperature, humidity, velocity and direction of air, the physical form of the solid, the desirability of agitation, and the method of supporting the solid during the drying operation.

External drying conditions are especially important during the initial stages of drying when unbound surface moisture is removed. In certain cases, for example, in materials like ceramics and timber in which considerable shrinkage occurs, excessive surface evaporation after the initial free moisture has been removed sets up high moisture gradients from the interior to the surface. This is liable to cause over drying and excessive shrinkage and consequently high tension within the material, resulting in cracking and warping. In these cases surface evaporation should be retarded through the employment of high air relative humidities while maintaining the highest safe rate of internal moisture movement by heat transfer.

Surface evaporation is controlled by the diffusion of vapor from the surface of the solid to the surrounding atmosphere through a thin film of air in contact with the surface. Since drying involves the inter-phase transfer of mass when a gas is brought in contact with a liquid in which it is essentially insoluble, it is necessary to be familiar with the equilibrium characteristics of the wet solid. Also, since the mass transfer is usually accompanied by the simultaneous transfer of heat, due consideration must be given to the enthalpy characteristics.

Process 2: Internal Conditions

As a result of heat transfer to a wet solid, a temperature gradient develops within the solid while moisture evaporation occurs from the surface. This produces a migration of moisture from within the solid to the surface, which occurs through one or more mechanisms, namely, diffusion, capillary flow, internal pressures set up by shrinkage during drying, and, in the case of indirect (conduction) dryers, through a repeated and progressive occurring vaporization and recondensation of moisture to the exposed surface. An appreciation of this internal movement of moisture is important when it is the controlling factor, as it occurs after the critical moisture content, in a drying operation carried to low final moisture contents. Variables such as air velocity and temperature, which normally enhance the rate of surface evaporation, are of decreasing importance except to promote the heat transfer rates. Longer residence times, and, where permissible, higher temperatures become necessary. The temperature gradient set up in the solid will also create a vapor–pressure gradient, which will in turn result in moisture vapor diffusion to the surface; this will occur simultaneously with liquid moisture movement.

3.2 Drying Mechanism

Moisture in solid may be either unbound or bound. There are two methods of removing unbound moisture: evaporation and vaporization. Evaporation occurs when the vapor pressure of the moisture on the solid surface is equal to atmospheric pressure. This is done by raising the temperature of the moisture to the boiling point.

The boiling point where evaporation occurs is the temperature which could be lowered by lowering the pressure; if the dried material is sensitive to heat. Further, in vaporization, convection drives the drying by the mean of the heat transfer from passing warm air through the product. While the temperature of warm air decreases, the specific humidity increases because of moisture content of the product.

Drying behavior of solids can be described by measuring the function of moisture content loss versus time. Continuous weighing, humidity difference and intermittent weighing are the used methods (Mujumdar 2006).

In air drying processes, two drying periods generally occurs as an initial constant-rate period and falling rate period. Constant rate drying occurs with evaporation of pure water. Moisture movement is controlled by internal resistances in the falling rate period. Moisture content as a function of drying time is shown in Figure 3.1. At zero time the initial moisture content is shown at point A. If the beginning the solid is usually at a colder temperature than its ultimate temperature. Alternatively, if the solid is quite hot to start with, the rate may start at point A′. Segment AB represents the initial unsteady-state, warming-up period. This initial unsteady-state adjustment period is usually quite short and it is often ignored in the analysis of times of drying (Geankoplis 1993). BC is the constant rate period. The same points are marked in Figure 3.2, where the drying rate is plotted against the moisture contents (Rizvi 1995). During the constant rate period, the surface of the solid is initially very wet and a continuous film of water exists on the drying surface. This water is entirely unbound water and the water acts as if the solid were not present. The rate of evaporation under the given air conditions is independent of the solid and essentially the same as the rate from a free liquid surface (Geankoplis 1993). The transition moisture content at which the departure from constant rate drying is first noticed is termed the critical moisture content, indicated by point C. At this point there is insufficient water on the surface to maintain a continuous film of water. In food systems, where liquid movement is likely to be controlled by capillary and gravity forces, a measurable constant rate period is found to exist. With structured foods, liquid movement is by diffusion, and therefore the water that is evaporated from the surface is not immediately replenished by movement of liquid from the interior of the food. Such foods are likely to dry without exhibiting any constant rate period. Hot air drying of apples, tapioca, sugar beet root and avocado are such foods without exhibiting any constant rate period (Rizvi 1995, Kaya et al. 2007, Akpinar and Bicer 2003).Between point C and D is termed the first falling rate period. During this period the rate of liquid movement to the surface is less than the rate of evaporation from the surface, and the surface becomes continually depleted in liquid water. The entire surface is no longer wetted, and the wetted area continually decrease in the first falling rate period until the surface is completely dry at point D. Beyond point D, the path for transport of both the heat and mass becomes longer and more tortuous as the moisture content continues to decrease. This period is called the second falling rate period. Finally, the vapor pressure of the solid becomes equal to the partial vapor pressure of the drying air and no longer further drying takes place. The limiting moisture content at this stage to which a material can be dried under a given drying condition is referred to as the equilibrium moisture content (M_e) (Rizvi 1995).

3.3 Drying Techniques and Dryers

Several types of dryers and drying methods, each better suited for a particular situation, are commercially used to remove moisture from a wide variety of fruits and vegetables. Conventional drying process ranges from natural sun drying to industrial drying (Leon et al. 2002). Some of the most common types of drying processes and dryers are introduced in the following sections.

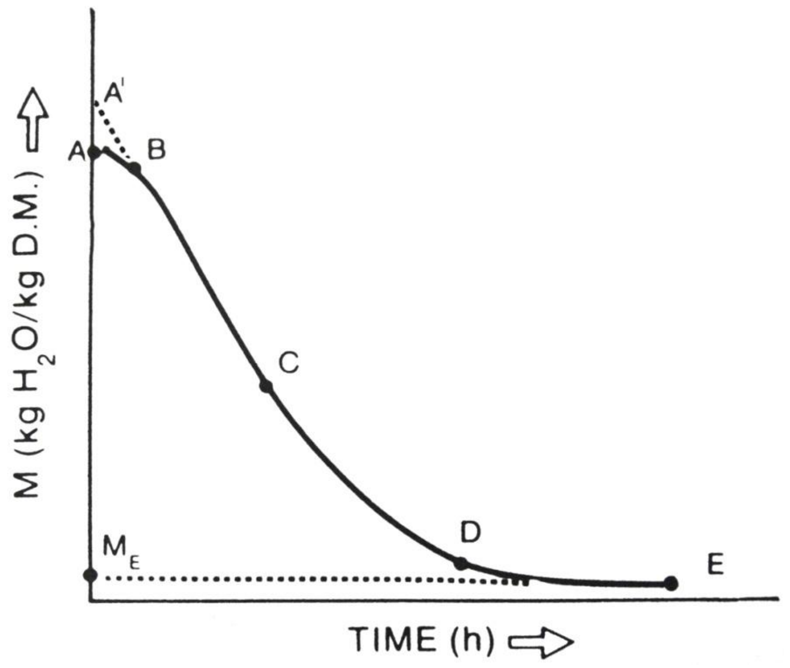

Figure 3.1 - Drying Curve, Showing Moisture Content as a Function of Drying Time
(Source: Geankoplis 1993, Rizvi 1995)

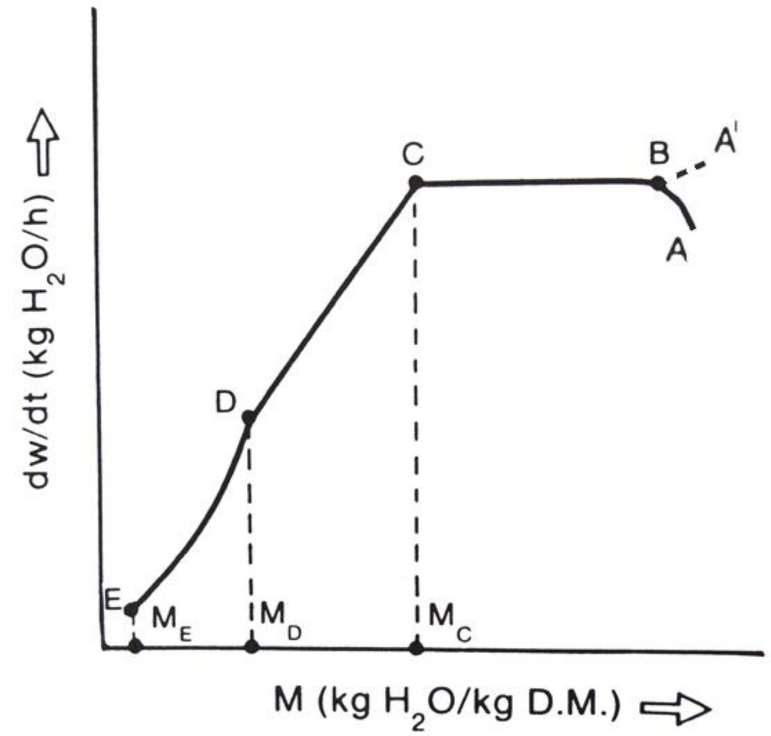

Figure 3.2 - Drying Rate as a Function of Moisture Content
(Source: Geankoplis 1993, Rizvi 1995)

3.3.1 Sun Drying

Sun drying has the advantages of simplicity and the small capital investment. On the other hand, there are many technical problems which are uncertainties like rain and cloudiness, contamination from outer sources and lack of control over drying conditions. It requires large areas and long drying time. The final product may be contaminated from dust and insects and suffer from enzyme and microbial activity. It is limited to climates with hot sun and dry atmosphere with strong winds. In any case of drying, economically feasible drying should be fast. (Jayaraman and Gupta 2006, Mujumdar 2006).

3.3.2 Hot Air Drying

In this method, heated air is brought into contact with the wet material to be dried to facilitate heat and mass transfer; convection is mainly involved. Two important aspects of mass transfer are the transfer of water to the surface of the material that is dried and the removal of water vapor from the surface.

The hot air dryers generally used for the drying of piece-form fruits and vegetables are cabinet, kiln, tunnel, belt-trough, bin, pneumatic and conveyor dryers. Energy source to heat the air would be electricity or a renewable energy resource such as solar and geothermal energy. At solar dryers, solar radiation is consumed by air and heated air is ducted to the drying chamber.

3.3.2.1 Cabinet Dryer

A cabinet dryer can be a small batch tray dryer. Heat from the drying medium to the product is transferred by convection. The convection current passes over the product, not through the product. It is suitable for drying of fruits, vegetables, and meat and its product. The main feature of a cabinet dryer is its small size and versatility. The main problem with cabinet dryer is difficulty in even distribution of heated air over or through the drying material.

3.3.2.2 Tunnel Dryer

The tunnel dryers are of many different configurations in general having rectangular drying chambers. Tunnel dryers are basically a group of truck and tray dryers widely used due to their flexibility for the large-scale commercial drying of various types of fruits and vegetables. Truckloads of the wet material are moved at intervals into one end of the tunnel. The whole string of trucks is periodically advanced through the tunnel until these are removed at the other end of the tunnel. Air movement, circulation, and heating methods vary in tunnel dryers. Three different flow arrangements are counter-flow, parallel flow, and combined flow. These dryers are simple and versatile in comparison with other types of dryers. Food pieces of any shape and size can be handled. If solid trays are incorporated, fluids can also be dried.

3.3.2.3 Belt-Trough Dryers

Belt-trough dryers are agitated bed, through flow dryers used for the drying of cut vegetables of small dimensions. They consist of metal mesh belts supported on two horizontal rolls; a blast of hot air is forced through the bed of material on the mesh. The belts are arranged in such a way to form an inclined trough so that the product travels in a spiral path and partial fluidization is caused by an upward blast of air.

3.3.2.4 Pneumatic Conveyor Dryers

Pneumatic conveyor dryers are generally used for the finish drying of powders or granulated materials and are extensively used in the making of potato granules. The feed material is introduced into a fast moving stream of heated air and conveyed through ducting of sufficient length to bring about desired drying. The dried product is separated from the exhaust air by a cyclone or filter.

3.3.3 Fluidized Bed Dryer

The fluidized bed type of dryer was originally used for the finish drying of potato granules. In fluidized bed drying, hot air is forced through a bed of food particles at a sufficiently high velocity to overcome the gravitational forces on the products. A major limitation is the limited range of particle that can effectively be fluidized.

3.3.4 Microwave Drying

In microwave drying, the product is exposed to very high-frequency electromagnetic waves. The transfer of these waves to the product is similar to the transfer radiant heat. The advantages of using microwave energy are penetrating quality, which effects a uniform heating of materials upon which radiation impinges; selective absorption of the radiation by liquid water; and capacity for easy control so that heating may be rapid if desired.

3.3.5 Spray Drying

The spray drying method is most important for drying liquid food products and has received much experiment study. Spray drying by definition is the transformation of a feed from a liquid state into a dried form by spraying into a hot, dry medium. In general it involves atomization of the liquid into a spray and contact between the spray and the drying medium, followed by separation of dried power from the drying medium.

3.3.6 Freeze-Drying

Freeze-drying, which involves a two-stage process of first freezing of water of the food materials followed by the application of heat to the product so that ice can be directly sublimed to vapor, is already a commercially established process. The advantages of freeze-drying are; shrinkage is minimized; movement of soluble solid minimized; the porous structure of the product facilitates rapid dehydration; and retention of volatile flavor compounds is high.

3.3.7 Osmotic Dehydration

Osmotic dehydration is a water removal process that consists of placing foods, such as pieces of fruits or vegetables, in a hypertonic solution. As this solution has higher osmotic pressure and hence lower water activity, a driving force for water removal arises between solution and food, whereas the natural cell wall acts as a semi permeable membrane. Direct osmotic dehydration is therefore a simultaneous water and solute diffusion process (Jayaraman and Gupta 2006).

3.4 Modeling of Drying Curves

The drying curves can be processed for drying rates to find the most convenient model for the drying process under given conditions. There are many statistical-based models correlating experimentally obtained moisture ratio values in terms of time (t) in the literature. The most common models used for food drying processes are tabulated in Table 3.1. In these models, the moisture ratio (MR) is termed as;

$$MR = (M - Me)/(Mo - Me) \text{ (-)} \tag{3.1}$$

The values of M_e are relatively small when compared with M and M_o values for long drying times. Therefore the Equation 3.1 can be simplified to MR= M/M_o.

Table 3.1 - Thin Layer Drying Models
(Source: Wang, et al. 2007, Diamante and Munro 1993, Akpınar and Bicer 2003, Toğrul and Pehlivan 2002, Midilli, et al. 2002)

No:	Model Name	Model
1	Lewis	MR = exp(-kt)
2	Page	MR = exp(-kt^n)
3	Modified Page	MR = exp[-(kt)^n]
4	Henderson&Pabis	MR = aexp(-kt)
5	Logarithmic	MR = aexp(-kt)+c
6	Two Term	MR = aexp(-k$_0$t)+bexp(-k$_1$t)
7	Two Term Exponential	MR = aexp(-kt)+(1-a)exp(-kat)
8	Wang&Singh	MR = 1+at+bt^2
9	Approximation of diffusion	MR = aexp(-kt)+(1-a)exp(-kbt)
10	Verma et al.	MR = aexp(-kt)+(1-a)exp(-gt)
11	Modified Henderson&Pabis	MR = aexp(-kt)+bexp(-gt)+ cexp(-ht)
12	Simplified Fick's Diffusion	MR = aexp[-c(t/L^2)]
13	Modified Page II	MR = exp[-k(t/L^2)^n]
14	Midilli&Kucuk	MR = aexp(-kt^n)+bt

The correlation coefficient (R^2) is one of the primary criteria for selecting the best equation to define the drying curves. In addition to R^2, the reduced chi-square (χ^2) and the root mean square error (RMSE) are used to determine the quality of the fit. These parameters can be calculated using Equations 3.2 and 3.3 (Wang, et al. 2007a, Wang, et al. 2007b, Eliçin and Saçılık 2005, Toğrul and Pehlivan, 2002).

$$\chi^2 = \frac{\sum_{i=1}^{N}(MR_{\exp,i} - MR_{pre,i})^2}{N - z} \tag{3.2}$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(MR_{\exp,i} - MR_{pre,i})^2} \tag{3.3}$$

3.5 Determination of Effective Diffusion Coefficients

Drying characteristics of biological products in the falling rate period can be described by using Fick's diffusion equation (Wang, et al. 2007a). The solution of this equation is developed by Crank (1975) with assumptions of moisture migration only by diffusion, negligible shrinking, constant temperature and diffusion coefficient and long drying times. It can be used for various regularly shaped bodies such as rectangular, cylindrical and spherical products. The solution of Fick's diffusion equation for rectangular geometry is shown in equation 3.4.

$$MR = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \exp\left(-\frac{(2n+1)^2 \pi^2 D_{eff} t}{4L_0^2} \right) \tag{3.4}$$

For long drying time, equation 3.4 can be simplified to only first term of the series as given in Equation 3.5.

$$MR = \frac{8}{\pi^2} \exp\left(-\frac{\pi^2 D_{eff} t}{4L_0^2} \right) \tag{3.5}$$

Then, equation 3.5 is written in a logarithmic form as follows:

$$\ln MR = \ln \frac{8}{\pi^2} - \frac{\pi^2 D_{eff} t}{4L_0^2} \tag{3.6}$$

Effective diffusion coefficient is typically determined by plotting experimental drying data in terms of ln MR versus drying time t. As it can be seen from the equation 3.6, the plot gives a straight line with a slope as $(\pi^2 D_{eff})/(4L_0^2)$ (Wang, et al. 2007a, Wang, et al. 2007b).

CHAPTER 4

MATERIALS AND METHODS

4.1 Experimental set-up

A tunnel dryer with a height of 500 mm, a width of 400 mm and a total length of 3307 mm is constructed to study the drying behavior of apple cubes. The dryer is composed of two major parts; an air preparation unit and a drying tunnel. A picture and a schematic diagram of the dryer are given in Figure 4.1 and 4.2, respectively.

Air preparation unit consists of a centrifugal fan, a heater and a humidifier. The air is sucked by the centrifugal fan, passed through a filter to remove the contaminants prior to the heater. The centrifugal fan has a 5-step velocity controller, whereas the heater has a 4-step temperature controller, each of which has a power of 12 kW. After passing through the heater, the air reaches the humidification section in which the moisture is added manually to reach the specified relative humidity. The humidified air is subsequently introduced to the drying tunnel.

The drying tunnel is a modular unit with a length of 1700 mm. It is divided into two parts:

- First part is evacuation channel with a length of 700 mm. The dried yield is taken out using the lateral cover.
- The second part consists of two modules with the same length of 500 mm. Each module has 3 racks inside.

The drying unit is insulated to prevent heat loss to the surroundings by fiber glass panels covered with thin layer aluminum sheet.

The apples (cv. red delicious = malus domestica) are brought from the market and stored in the refrigerator at $4^{o}C$. They are peeled and divided into four parts, taken their cores out and then cut into 1000 mm^3 via mechanical cutter.

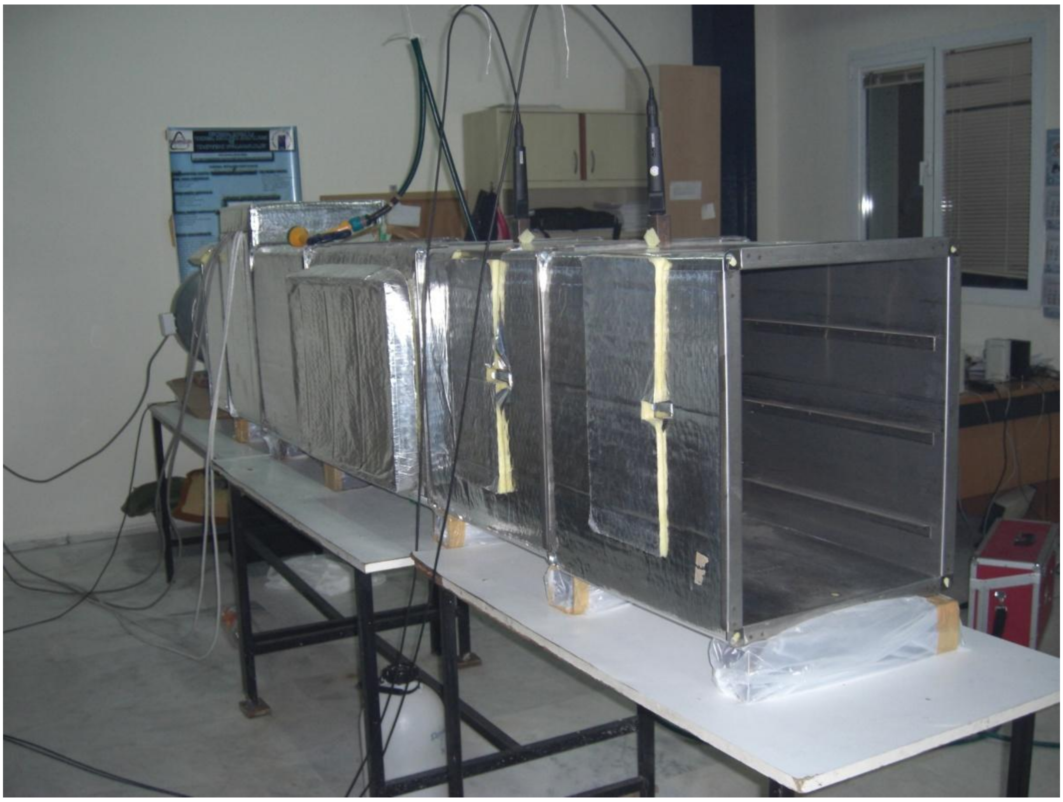

Figure 4.1. A View of the Tunnel Dryer

4.2. Experimental Procedure

4.2.1 Determination of dry matter of apple

Dry matter of apple is determined according to AOAC 37.1.10 (AOAC Official Method 934.06 Moisture in Dried Fruit) and TS 3688 ISO 7701. The only difference between two standards is that AOAC uses glass fiber, whereas TS does dry sand.

First, steel dishes in 10 cm diameter used in determination of dry matter are subjected to constant weighing process. The dishes are cleaned with ethyl alcohol and placed in the temperature controlled oven in which the temperature is hold at $70\pm1^{o}C$. The steel dishes are taken out from the oven at every 30 minutes and then weighed. Prior to weighing, the steel dishes are allowed to cool down to the room temperature within desiccators for 5 minutes. 300g $CaCl_2$ is added into desiccators to prevent moisture. It is supposed that steel dishes possess a stable weight value when the change in their weight is about less than $2x10^{-4}$ g.

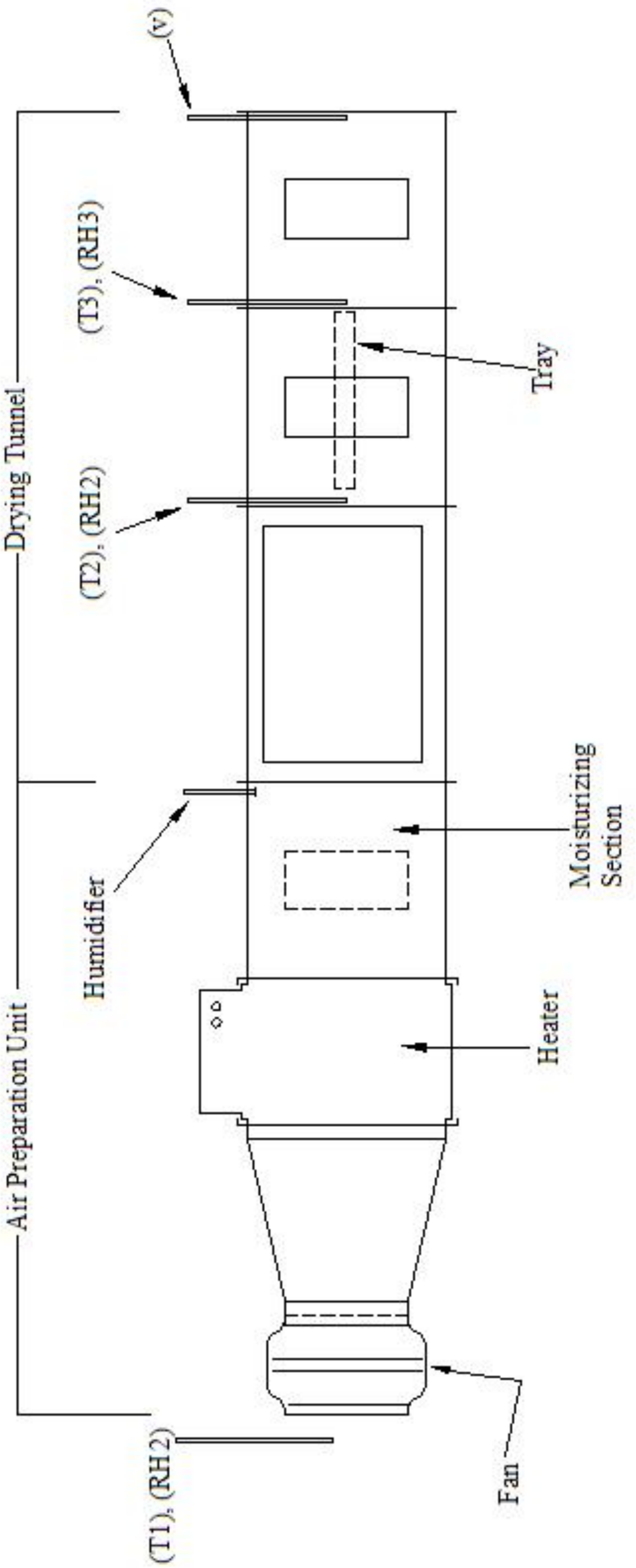

Figure 4.2. A Schematic Diagram of the Tunnel Dryer

Afterwards, the glass fiber is put into the steel dish to prevent skin of apples from sticking on the steel surface by losing their own moisture. The amount of glass fiber is obtained by a sensitive level balance.

The apples utilized in determination of dry matter are randomly selected. The cores and skin of the apples are taken out by using a knife. Then, apples are homogeneously spread over the steel dishes that contain glass fiber. To see the system accuracy, various amounts of apples are used.

Fruits containing high amount of sugar are immersed into water bath until they barely evaporate to dryness prior to vacuum oven (AOAC 37.1.10). The reason for using water bath is to prevent the dissolution of sugar. The temperature of the water bath is set to around 100^{o}C and the steel dishes are put into beaker glasses to make sure that no water contact occurred. This process can be regarded as a pre-drying process. The apples are indicated to dry in 2 hours, based upon the decrease in their volumes and the change in their colour observed. Steel dishes are subsequently taken out of the water bath and placed into vacuum oven at 70^{o}C for 6 hours under a pressure of about 100 mbar. During drying process, the air flows continuously into the oven with 2 bubble/s, firstly passes through a 500 ml glass trap containing H_2SO_4 with a purity of 25%, which keeps the air dry at the level necessary for the process. During air flow, pressure is kept between 45-100 mbar. The moisture caused by apples is trapped in the membrane of the oven and the process is stopped every 2 hours to get the moisture away from the oven. After six hours vacuuming is completed and steel dishes are taken into desiccators to cool down the samples into room temperature at which they are weighed with a sensitive balance. Moisture contents are reported as wet-basis (w-b) percentages. The amount of moisture is calculated using Equation 4.1.

$$M = \frac{m_{T_i} - m_{T_f}}{m_{T_i}} \qquad (-) \qquad (4.1)$$

The change in the moisture amount is calculated using randomly selected data for eight apples to reveal characteristics of all the yield groups.

4.2.2 Drying Experiments

Apple cubes are dried as single layer at various temperature, relative humidity and velocity values of drying air. Drying of apple cubes started with an initial moisture content of approximately 85% (w-b) and continued until no further changes in their mass were observed e.g. to the final moisture content of about 11% (w-b) (Eliçin and Saçılık 2005).

The apples used in the experiments are kept two hours in room temperature for stabilization prior to the experiments. The stabilized apples are peeled; the cores are taken out and then cut into 10^3 mm^3 cubes with a mechanical cutter. The tray is loaded as a single layer. Apple cubes are approximately 0.95 g each and approximately 200 pieces are placed on the tray.

During the experiments; temperature, velocity and relative humidity of drying air is recorded every 1 minute. The temperature and relative humidity sensors are located at the inlet of the fan (T1, RH1), upstream (T2, RH2) and downstream of the tray (T3, RH3). The velocity sensor (v) is located at the exit of the tunnel.

The samples taken from five different locations of the tray as shown in Figure 4.2, are weighed at every 10 minutes. Drying is terminated when the moisture content dropped to 11% (w-b).

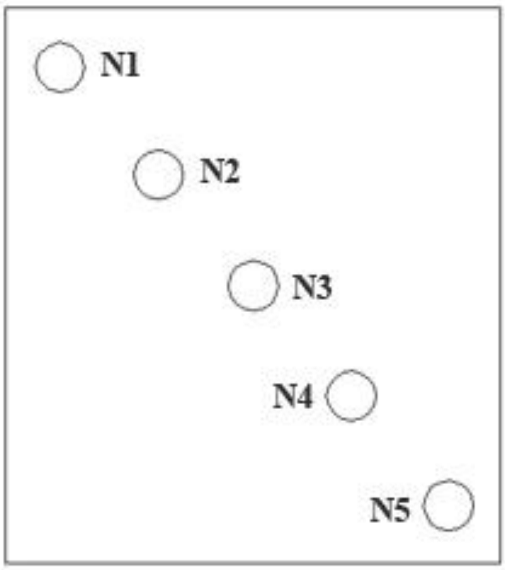

Figure 4.3. Specified Sampling Points on the Tray

4.3 Rehydration

Dried samples are allowed to stabilize at room temperature prior to rehydration experiment. Rehydration of samples is performed in 1000 mL glass beaker containing 600 mL distilled water. Glass beaker is placed on a temperature controlled stirrer. A perforated lid is used to keep the samples at the bottom of the glass beaker during rehydration. The experiments are performed at various temperatures including 30^{o}C, 50^{o}C, and 70^{o}C. The weight of the samples is measured using a sensitive balance at 10 min intervals. The rehydration process is terminated once the samples gain about 40% of the moisture removed during drying. The rehydration curve is formed by plotting total moisture over dry matter of sample versus rehydration time (min). Smaller rehydration times better the quality of the products.

4.4 Colour Measurements

The visual appearance of raw, dry and rehydrated apple cubes is evaluated by a colour-difference meter technique using a chromameter. A chromameter measures 3 parameters which are L, a and b. L indicates brightness, a chromaticity on a green (-) to red (+) axis and b chromaticity on a blue (-) to yellow (+) axis. The chromameter was calibrated automatically before each colour measurements with the standard white plate having "L", "a" and "b" values of 97.55, 0.09 and 1.8 respectively.

The measurements are taken for raw, dried and rehydrated apple cubes. In each measurement, 15 samples are selected and for each sample, measurements are repeated four times. Colour difference ΔE, hue angle H^{o} and colour saturation C is determined by using following equations;

$$\Delta E = \sqrt{(\Delta L)^2 + (\Delta a)^2 + (\Delta b)^2} \quad (4.2)$$

$$H^{o} = \tan^{-1}(\frac{b}{a}) \quad (4.3)$$

$$C = \sqrt{a^2 + b^2} \tag{4.4}$$

The raw apple cubes are taken as the reference and a higher ΔE stands for greater colour change from the reference material. The hue angle values of 0^o, 90^o, 180^o and 270^o represents the red, yellow, green and blue colour respectively (Eliçin and Saçılık 2005). Lower ΔE and higher hue angle and colour saturation show good quality of the apple cubes while the raw apples data are taken as the reference.

CHAPTER 5

RESULTS AND DISCUSSION

Experiments are conducted to determine the influence of temperature, velocity and the relative humidity of drying air on the kinetics of apple drying. Under various drying air conditions; moisture ratio and drying rate is determined depending on drying time. Using these data, the mechanism of drying process is evaluated determining the periods and controlling parameters like diffusion coefficients. Furthermore, the moisture ratio values are fitted to 14 thin layer drying models and the model constants and the comparison criteria such as correlation coefficient (R^2), the reduced chi-square (χ^2) and the root mean square error (RMSE) are obtained. Then, to determine the quality of dried product, rehydration experiments for various rehydration temperatures and colour measurements are conducted for each experimental condition.

5.1 Influence of Temperature

Three set of experiments are conducted to exhibit the temperature effect. The velocity and relative humidity values are kept constant and temperature is the only variable as given in Table 5.1. Each group consists of three experiments. First of which is conducted without humidification while the second and third experiments are conducted with humidification. Initial moisture content of apple cubes for each group is determined as 6.19±1.04 g water/g dry matter.

Table 5.1. Experimental Conditions of Temperature Influence

Group No.	Exp No.	RH1 (%)	RH2 (%)	v (m/s)	T1 (°C)	T2 (°C)	Drying time (min)
1	1.1	33.3	20.5	0.8	31.2	40.1	290
	1.2	35.8			33.0	48.1	230
	1.3	47.4			31.6	57.3	210
2	2.1	40.8	12.6	1.1	32.1	55.3	160
	2.2	38.7			30.6	60.5	160
	2.3	49.1			30.0	65.3	140
3	3.1	38.4	17.0	1.4	29.6	45.6	240
	3.2	45.2			28.3	53.4	230
	3.3	47.6			26.6	56.1	160

As it can be noticed from Table 5.1, the relative humidity at the dryer inlet (RH1) is not constant, because of the uncontrolled laboratory environment. Distributions of the relative humidity at the dryer inlet (RH1) and drying air (RH2) are plotted in Figure 5.1 for Experiment 1.1. As it can be seen from the Figure, relative humidity values at the dryer inlet change drastically during the experiment. While keeping the average relative humidity of drying air (RH2) around 20.5%, RH1 changes between 25-42.5%. Therefore, during the experiments, it is difficult to keep the relative humidity of drying air constant.

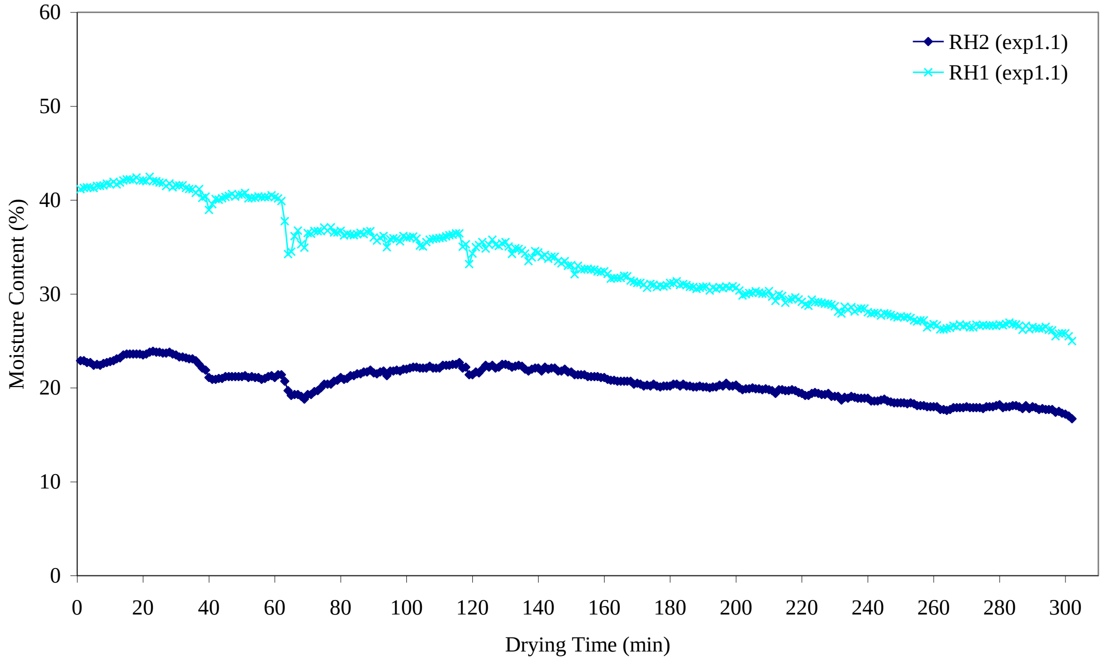

Figure 5.1. Relative Humidity at Dryer Inlet (RH1) and Drying Air (RH2) versus Drying Time of Experiment 1.1

Distributions of the temperature at the dryer inlet (T1) and drying air (T2) are plotted in Figure 5.2 for Experiment 1.1. When temperature values are compared with relative humidity values, the change of temperature values at the dryer inlet and at the drying air is smaller.

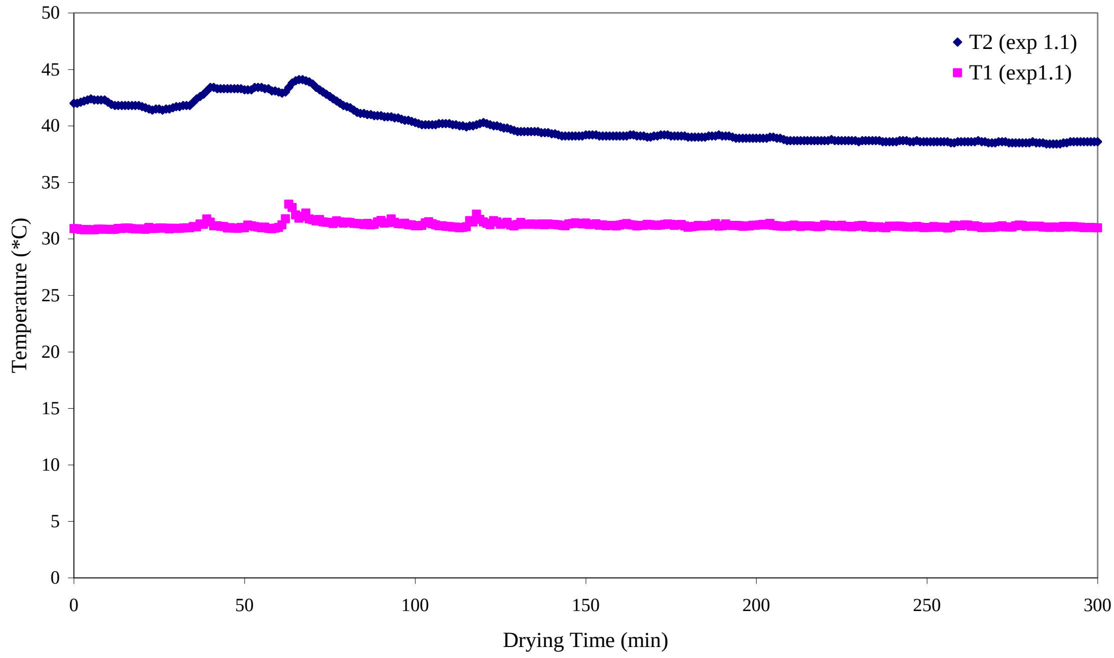

Figure 5.2. Temperature at Dryer Inlet (T1) and Drying Air (T2) versus Drying Time of Experiment 1.1

5.1.1. Group No. 1

For the Group No. 1, while the relative humidity and velocity of drying air is kept constant at 20.5% and 0.8 m/s, three experiments are conducted for the drying air temperatures of 40.1, 48.1 and 57.3°C**,** respectively. Drying time with respect to temperature is shown in Figure 5.3.

As it can be seen from the Figure 5.3, at constant relative humidity and velocity, increasing the temperature decreases the drying time as expected. Drying time is decreased about 21% with a temperature increase of 8°C from Experiment 1.1 to 1.2. But further increase in temperature at Experiment 1.3 which is 9.2°C, causes only 8.7% decrease in drying time. The relation between the temperature and drying time is not linear which proves the exponential characteristic of drying curves (Mujumdar 2006, Brennan 2006).

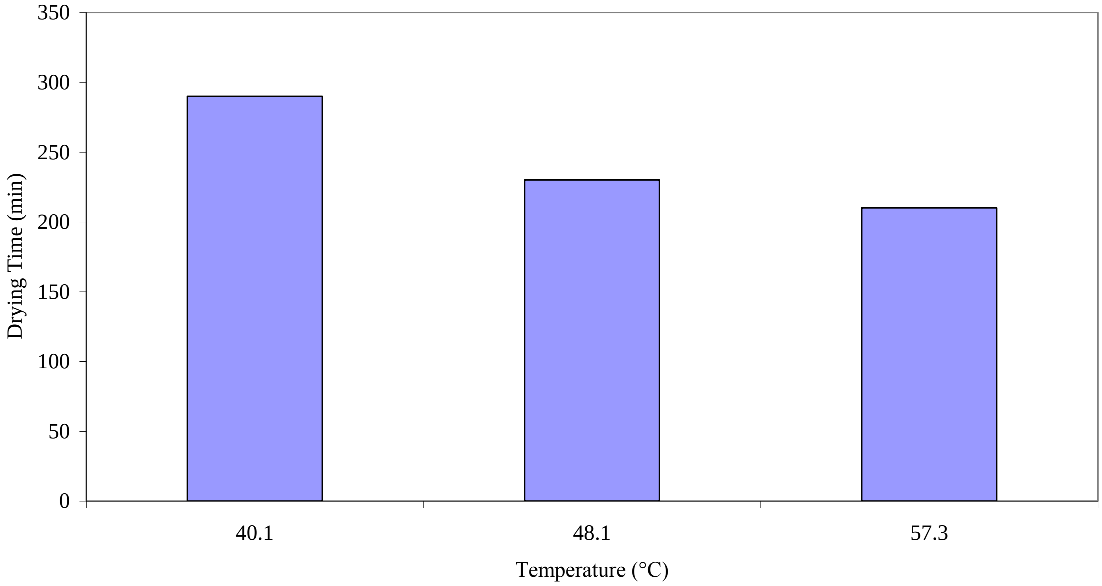

Figure 5.3. Drying Time versus Drying Air Temperature at 20.5% Drying Air Relative Humidity and 0.8 m/s Drying Air Velocity

The variation of the moisture content of the apple cubes with time is plotted in Figure 5.4. The results indicate that although at the first 20 minutes of the drying process decrease of moisture of the product is the same at each temperature, for the rest of the drying process decrease of moisture changes with temperature. Increasing drying air temperature increases moisture loss of the product non-linearly as shown in Figure 5.3. Initial moisture content of the apples is determined as 85.8%. When it is reduced to 11%, the experiment is terminated. The collapse of the drying curves at the beginning of the process indicates that drying is controlled by external conditions. When the curves deviate from each other, drying is mainly controlled by internal mass transfer resistance.

Figure 5.5 exhibits the distribution of drying rate with respect to moisture content. Drying rate is calculated using Equation 5.1. High drying rates at the first 10 minutes is related to the difference between temperature of apple cubes and drying air.

$$DR = \frac{M_t - M_{t+\Delta t}}{\Delta t} \quad \text{(g water /g dm min)} \qquad (5.1)$$

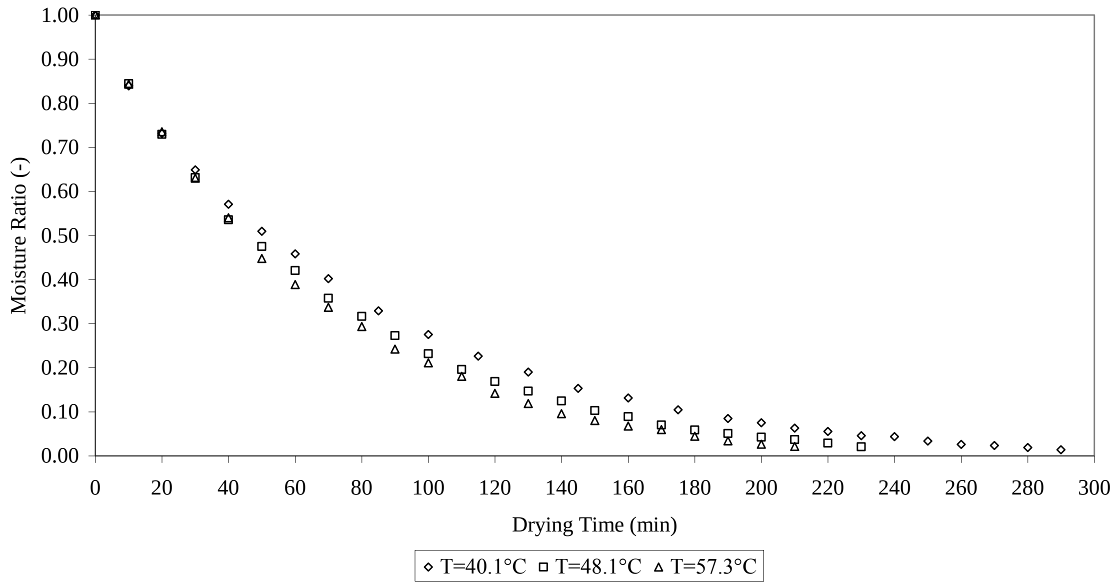

Figure 5.4. Moisture Ratio versus Drying Time at 20.5% Drying Air Relative Humidity and 0.8 m/s Drying Air Velocity for Various Drying Air Temperatures

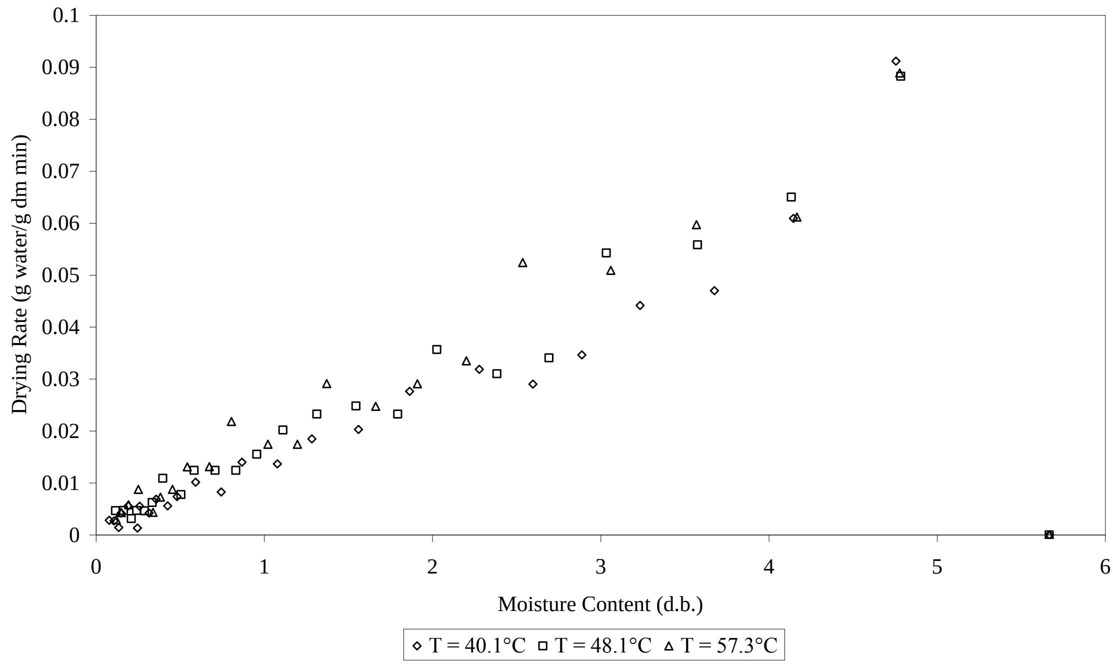

Figure 5.5. Drying Rate versus Moisture Content at 20.5% Drying Air Relative Humidity and 0.8 m/s Drying Air Velocity for Various Drying Air Temperatures

Drying process generally occurs in two different periods; namely constant rate period and falling rate period as it is given in Chapter 3.2.

It is seen from Figure 5.4 and 5.5 that constant drying rate period is very short and falling rate period can be divided into two parts. First falling rate period is continued till moisture content of apples reach to approximately 33% (w-b) which is longer than second falling rate period. Duration of the periods is given in Table 5.2.

Since the falling rate period is diffusion controlled, the effective diffusion coefficients (D_{eff}) are calculated using Equation 4.4 and are given in the Table 5.3.

Table 5.2. Duration of Drying Periods for the Group No.1

Temperature (^oC)	**1^{st} Falling Rate (min)**	**2^{nd} Falling Rate (min)**	**Total Drying Time (min)**
40.1	180	100	290
48.1	140	80	230
57.3	140	60	210

Table 5.3. Effective Diffusion Coefficients of Apple Cubes at 20.5% Drying Air Relative Humidity and 0.8 m/s Drying Air Velocity for Various Drying Air Temperatures

Temperature (^oC)	**Effective diffusion coefficient (m^2/s)**	
	1st Falling Rate Period	**2nd Falling Rate Period**
40.1	$1.4x10^{-9}$	$5.78x10^{-10}$
48.1	$1.7x10^{-9}$	$7.78x10^{-10}$
57.3	$1.84x10^{-9}$	$8.33x10^{-10}$

The effective diffusion coefficients increase with increasing drying air temperature.

The moisture ratio (MR) values are fitted to 14 thin layer drying models listed in Table 3.1 and the model constants and the comparison criteria are given in Table A.1, A.2 and A.3. Correlation coefficient (R^2), the reduced chi-square (χ^2) and the root mean square error (RMSE) are used to evaluate the best fit. The best fit for the three experiments is obtained by Modified Henderson&Pabis and Midilli&Kucuk models. The results of the best fits are given in Table 5.4.

Table 5.4. Results of Best Fitted Models for Group No.1

Group No.	Model No.	Model Constants	R^2	RMSE	χ^2
1.1	11	a=0.051264 k=0.398272 b=0.791639 g=0.012236 c=0.157377 h=0.000421	0.9999	0.0024311	0.0000077
	14	a=0.996915 k=0.019533 n=0.861378 b=0.000300	0.9999	0.0028697	0.0000097
1.2	11	a=0.011563 k=-0.008395 b=0.150377 g=0.042220 c=0.836498 h=0.009621	0.9998	0.0030616	0.0000125
	14	a=0.999525 k=0.018040 n=0.905952 b=0.000368	0.9998	0.0031640	0.0000120
1.3	11	a=0.303005 k=0.023503 b=0.012740 g=-0.008155 c=0.681873 h=0.009340	0.9997	0.0041414	0.0000236
	14	a=0.999325 k=0.015751 n=0.952684 b=0.000435	0.9997	0.0040944	0.0000205

Rehydration curve of dried apples for rehydration temperatures of 30, 50 and 70°C at various drying air temperatures can be seen in Figures 5.6, 5.7 and 5.8. The time required to gain 40% moisture back that is lost in drying process is 23.6, 17.6, and 17.5 min for Experiment 1.1, 27.6, 23.2 and 17.5 min for Experiment 1.2, 24.4, 18.7 and 15.9 min for Experiment 1.3 for rehydration temperatures of 30, 50 and 70^{o}C, respectively. Rehydration time decreases with increasing rehydration temperatures.

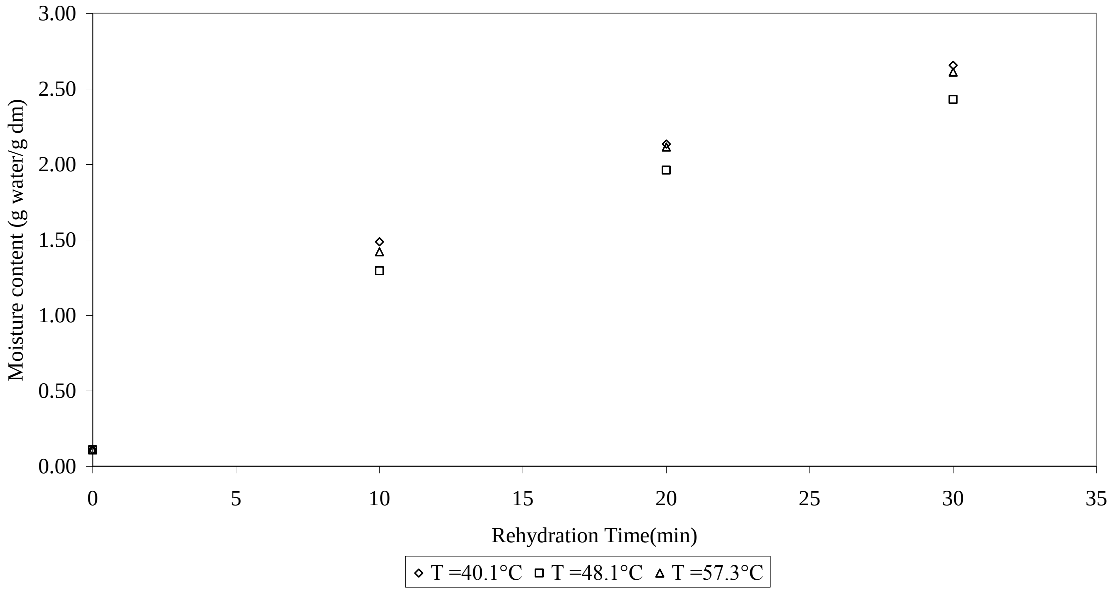

Figure 5.6. Rehydration Curve of Dried Apples for Rehydration Temperature of 30^{o}C for Group No.1

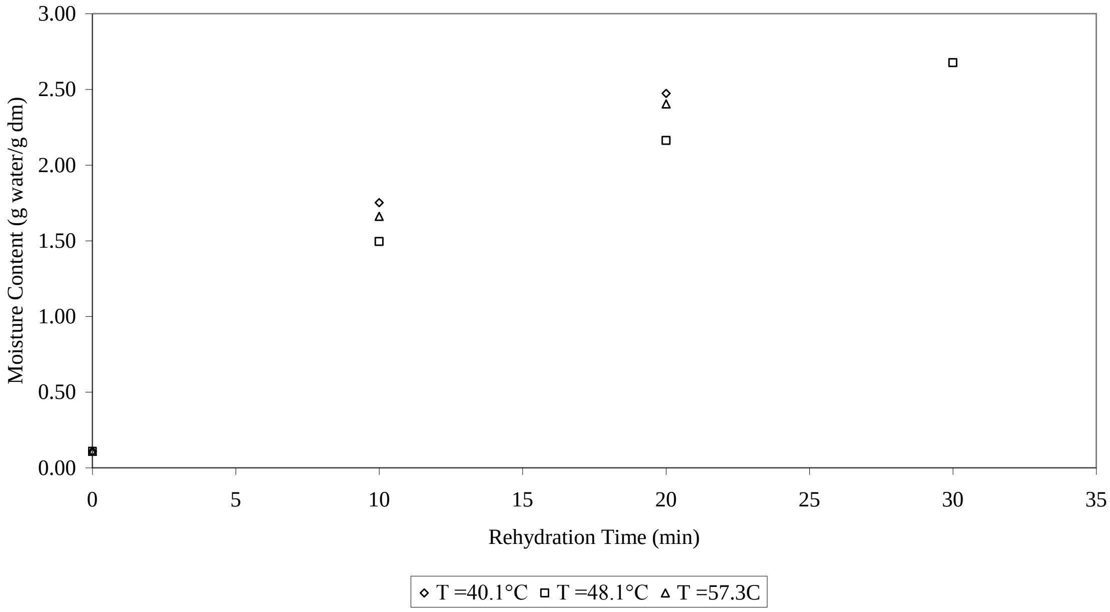

Figure 5.7. Rehydration Curve of Dried Apples for Rehydration Temperatures of 50^{o}C for Group No.1

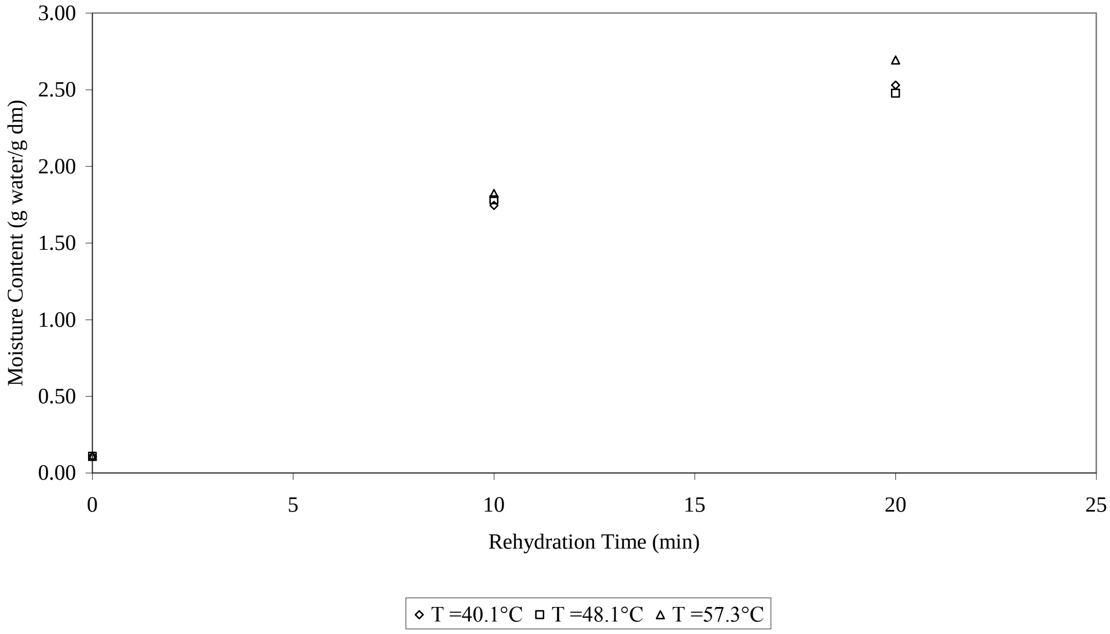

Figure 5.8. Rehydration Curve of Dried Apples for Rehydration Temperatures of 70^{o}C for Group No.1

The change of colour of raw apples could be attributed to darkening reactions that takes place during the drying and rehydration process. ‘L’, ‘a’, ‘b’, ‘ΔE’, ‘H^o’ and ‘C’ values of apples are given in Table 5.5.

‘L’,‘b’, ‘H^o’ and ‘C’ values usually decreased during drying and rehydration process when values of the raw apple are considered. ‘a’ values increased during drying and decreased during rehydration. Colour difference (ΔE) values at the temperatures of 40.1^{o}C, 48.1^{o}C and 58.3^{o}C are 25.53, 26.12 and 24.11, respectively. Colour difference values increases at rehydration process comparing with dried apple.

Table 5.5. Colour Values of Apples for Drying Temperatures of 40.1, 48.1 and 57.3^{o}C

Exp no:		**L**	**A**	**b**	**ΔE**	**H^o**	**C**
	Raw apple	69.27	-2.18	52.82		92.36	52.86
	Dried Apple	73.77	8.61	30.11	25.53	74.05	31.32
1.1	Rehydrated Apple at 30°C	54.81	8.34	25.23	32.87	71.71	26.57
	Rehydrated Apple at 50°C	61.17	5.45	23.78	31.09	77.10	24.40
	Rehydrated Apple at 70°C	59.16	6.52	23.84	31.90	74.70	24.71
	Raw apple	69.27	-2.18	52.82		92.36	52.86
	Dried Apple	67.51	8.29	28.95	26.12	74.03	30.11
1.2	Rehydrated Apple at 30°C	63.37	3.41	20.63	33.20	80.61	20.91
	Rehydrated Apple at 50°C	62.09	4.14	21.21	33.02	78.95	21.61
	Rehydrated Apple at 70°C	59.86	3.95	20.75	33.97	79.23	21.12
	Raw apple	69.27	-2.18	52.82		92.36	52.86
	Dried Apple	64.68	8.10	31.49	24.11	75.58	32.51
1.3	Rehydrated Apple at 30°C	57.72	5.59	24.13	31.89	76.95	24.76
	Rehydrated Apple at 50°C	62.81	4.24	24.67	29.58	80.26	25.03
	Rehydrated Apple at 70°C	60.16	2.90	21.48	33.02	82.31	21.68

5.1.2. Group No.2&3

Experimental conditions for Group No. 2 and 3 are given in Table 5.1. Drying time as a function of temperature is shown in Figures 5.9 and 5.10 for Group No. 2 and 3, respectively.

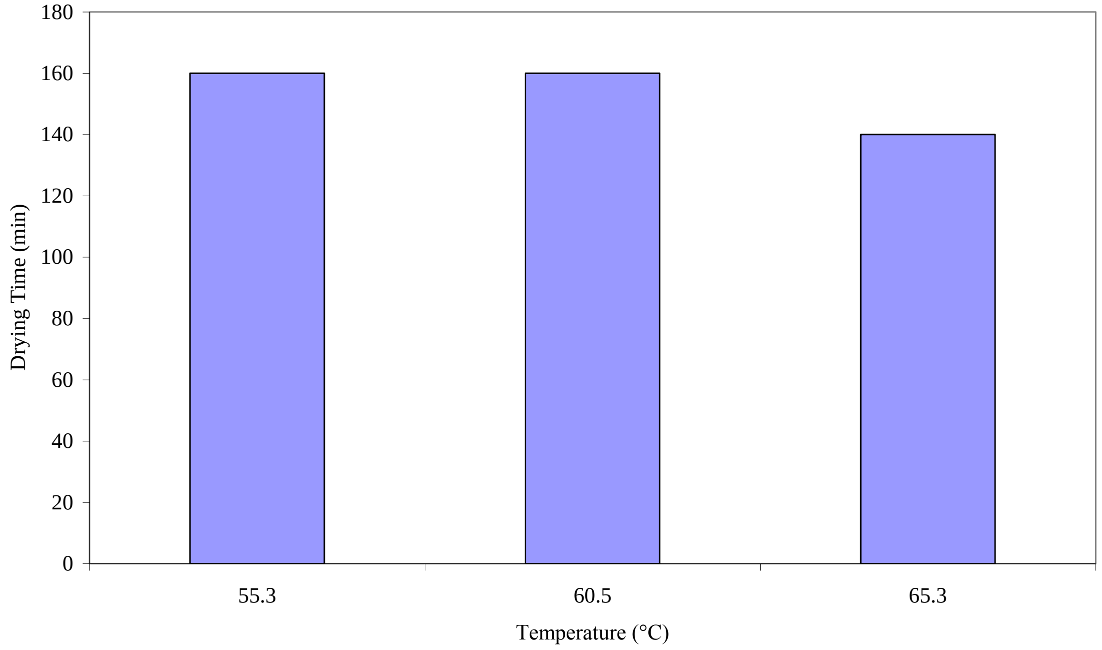

Figure 5.9. Drying Time versus Temperature at 12.6% Relative Humidity and 1.1 m/s Airflow Velocity

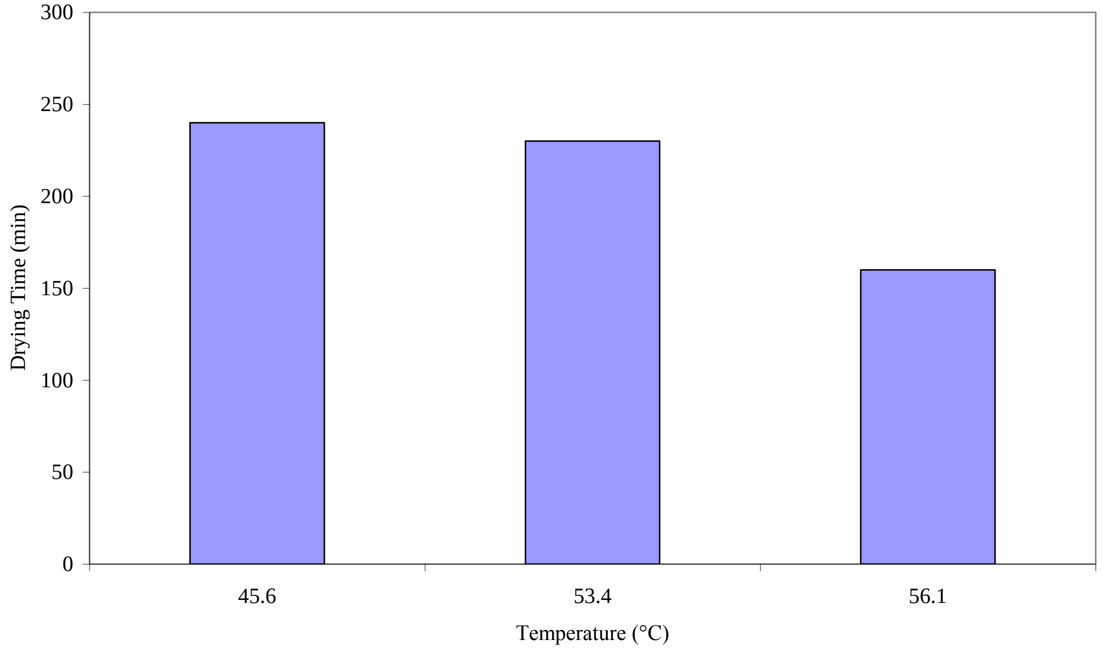

Figure 5.10. Drying Process Time Respect to Temperature at 17% Relative Humidity and 1.4 m/s Airflow Velocity

Figures 5.9 and 5.10 shows the similar trend as Figure 5.3, increasing the temperature, decreases the drying time for constant relative humidity and velocity conditions. For Group No. 2, drying time is not changed with a temperature increase of 5.2°C from Experiment 2.1 to 2.2. However, further increase in temperature in Experiment 2.3 which is 4.8°C, results in a decrease about 12.5% in drying time. For Group No. 3, drying time is decreased about 4% with a temperature increase of 7.8°C from Experiment 3.1 to 3.2. But further increase in temperature at Experiment 3.3 which is 2.7°C, causes 30% decrease in drying time.

The moisture ratio and drying rate as a function of time and moisture content are shown in Figures 5.11 and 5.12 for Group No.2 and Figures 5.13 and 5.14 for Group No.3, respectively. Both Groups exhibit the same trend and a short constant drying rate period is followed by falling rate period as observed in Group No.1 experiments.

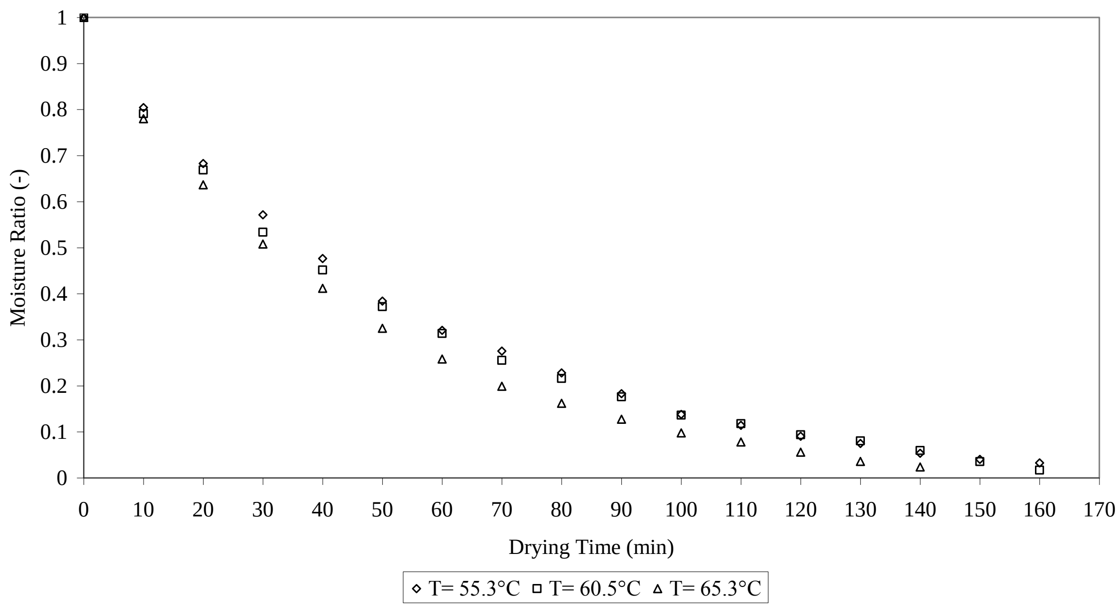

Figure 5.11. Moisture Ratio versus Drying Time at 12.6% Relative Humidity and 1.1 m/s Airflow Velocity and Different Temperatures

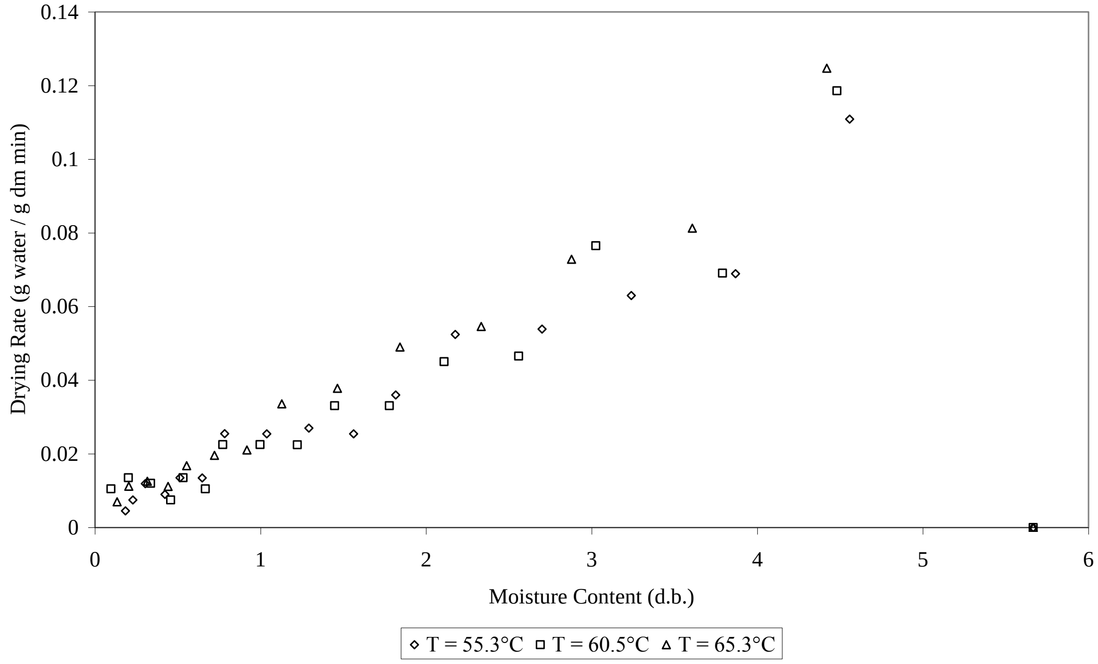

Figure 5.12. Drying Rate versus Moisture Content at 12.6% Relative Humidity and 1.1 m/s Airflow Velocity and Different Temperatures

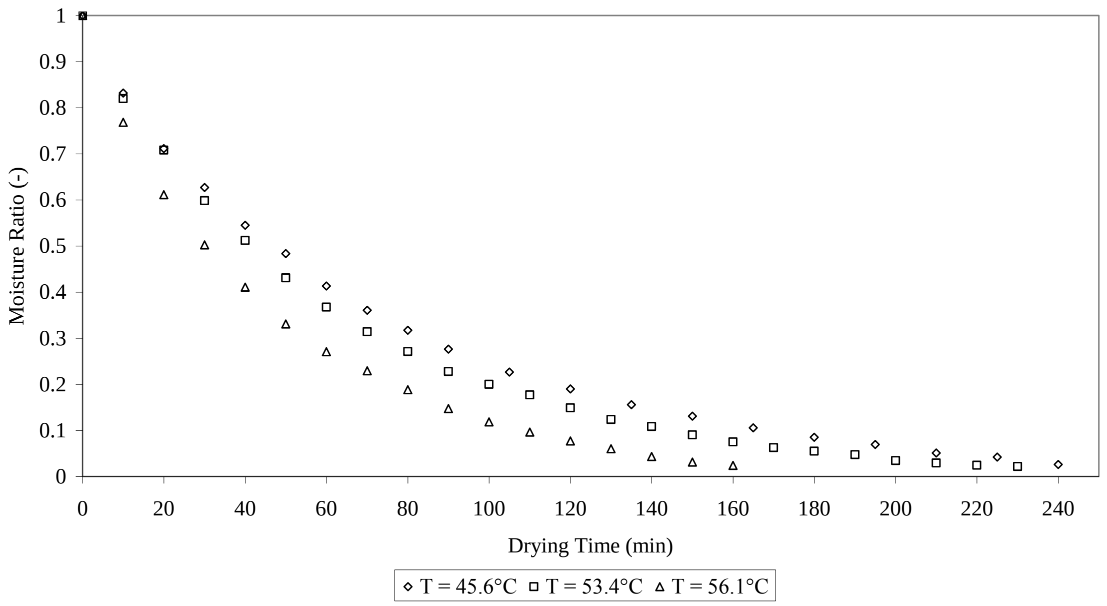

Figure 5.13. Moisture Ratio versus Drying Time at 17% Relative Humidity and 1.4 m/s Airflow Velocity and Different Temperatures

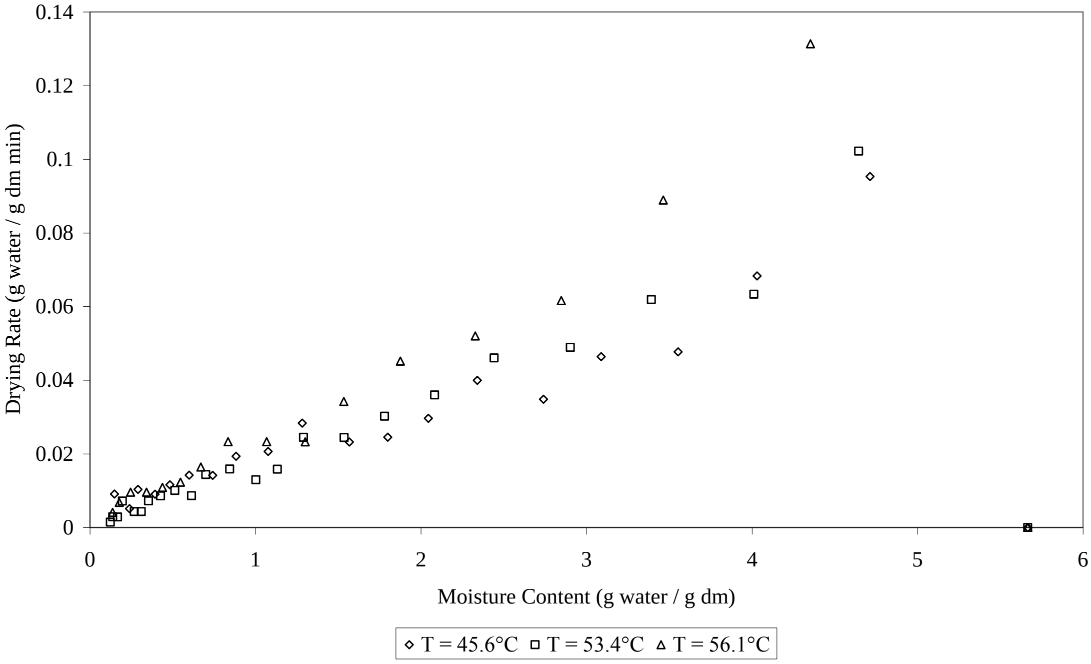

Figure 5.14. Drying Rate versus Moisture Content at 17% Relative Humidity and 1.4 m/s Airflow Velocity and Different Temperatures

Duration of the falling rate periods and effective diffusion coefficients are given in Table 5.6 and 5.7.

Table 5.6. Duration of Drying Periods for Group No.2&3

Group No.	**Temperature (^{o}C)**	**1st Falling Rate**	**2nd Falling Rate**	**Total Drying Time (min)**
	55.3	90	60	290
2	60.5	90	60	230
	65.3	80	50	210
	45.6	140	90	240
3	53.4	140	80	230
	56.1	80	70	160

Table 5.7. Effective Diffusion Coefficients of Apple Cubes for Group No.2&3

Group No.	**Temperature (^oC)**	**Effective diffusivity (m^2/s)**	
		1st Falling Rate Period	**2nd Falling Rate Period**
2	55.3	$2.11x10^{-9}$	$1.19x10^{-9}$
	60.5	$2.1x10^{-9}$	$1.35x10^{-9}$
	65.3	$2.45x10^{-9}$	$1.42x10^{-9}$
3	45.6	$1.44x10^{-9}$	$7.7x10^{-10}$
	53.4	$1.59x10^{-9}$	$6.3x10^{-10}$
	56.1	$2.16x10^{-9}$	$1.12x10^{-9}$

The effective diffusion coefficients increase with the temperature except a decrease observed in the second falling rate period between the Experiments 3.1 and 3.2 of Group No.3.

The results of the models applied to the experimental data are given in Table A.4-A.6 for Group No.2, Table A.7-A.9 for Group No.3. Similar to Group No.1, the best fits obtained by Modified Henderson & Pabis and Midilli & Kucuk models. The best fitted model constants and comparison criteria are given in Table 5.8.

Rehydration curves are plotted as moisture gain of dried product with respect to time. Rehydration curves for 30, 50 and 70°C temperatures are given in Figures 5.15-5.17 for Group No.2 and Figures 5.18-5.20 for Group No.3.

Table 5.8. Results of Best Fitted Models for Group 2&3

Group No.	**Model No.**	**Model Constants**	**R^2**	**RMSE**	**χ^2**
2.1	11	a=0.327671 k=0.017067 b=0.228609 g=0.003179 c=0.435977 h=0.021748	0.9994	0.0058290	0.0000525
	14	a=0.997375 k=0.020498 n=0.927146 b=0.000443	0.9996	0.0046842	0.0000287
2.2	11	a=0.426265 k=0.006169 b=0.026533 g=0.198568 c=0.546518 h=0.025307	0.9996	0.0048133	0.0000358
	14	a=1.000542 k=0.026695 n=0.868224 b=0.000377	0.9995	0.0052510	0.0000361
2.3	11	a=0.369707 k=0.015885 b=0.469939 g=0.027958 c=0.155806 h=0.001842	0.9998	0.0039016	0.0000254
	14	a=0.999056 k=0.024544 n=0.925582 b=0.000569	0.9998	0.0031221	0.0000133
3.1	11	a=0.680982 k=0.015899 b=0.043128 g=0.210691 c=0.275955 h=0.002282	0.9999	0.0026105	0.0000097
	14	a=1.000175 k=0.022344 n=0.850934 b=0.000351	0.9998	0.0034770	0.0000151
3.2	11	a=0.203864 k=0.001315 b=0.770087 g=0.017048 c=0.026050 h=2.166648	0.9999	0.0028552	0.0000116
	14	a=1.000707 k=0.021671 n=0.887668 b=0.000450	0.9998	0.0039072	0.0000191
3.3	11	a=0.728427 k=0.019678 b=0.174929 g=0.001495 c=0.096684 h=0.111054	0.9999	0.0022544	0.0000079
	14	a=1.000772 k=0.033339 n=0.838954 b=0.000473	0.9999	0.0024400	0.0000078

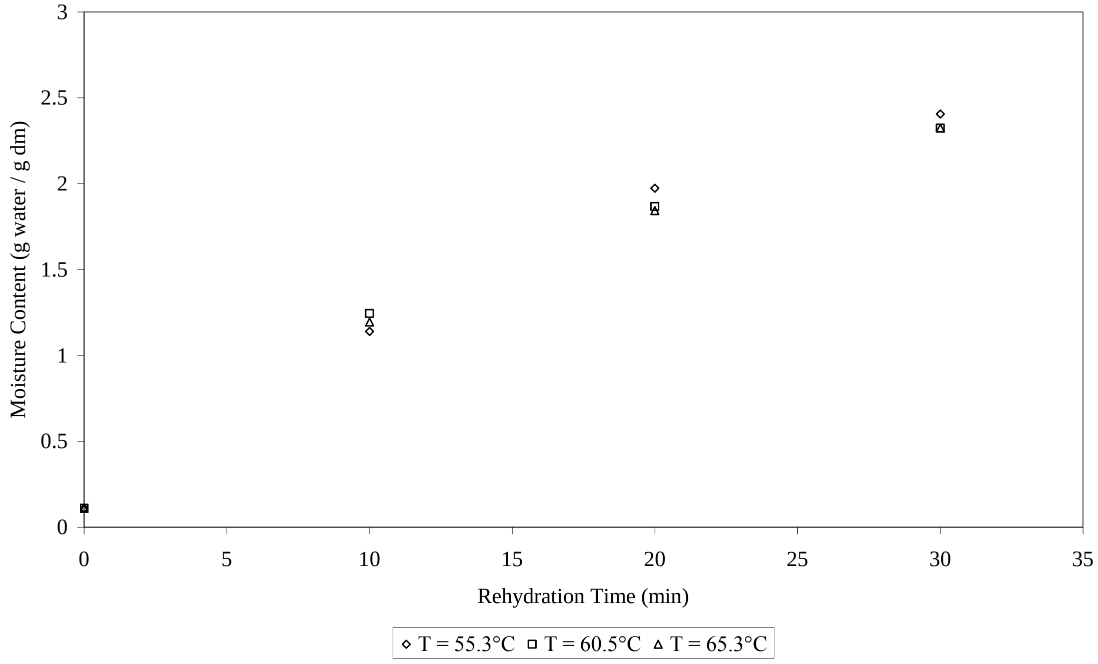

Figure 5.15. Rehydration Curve of Dried Apples for Rehydration Temperatures of 30°C for Group No.2

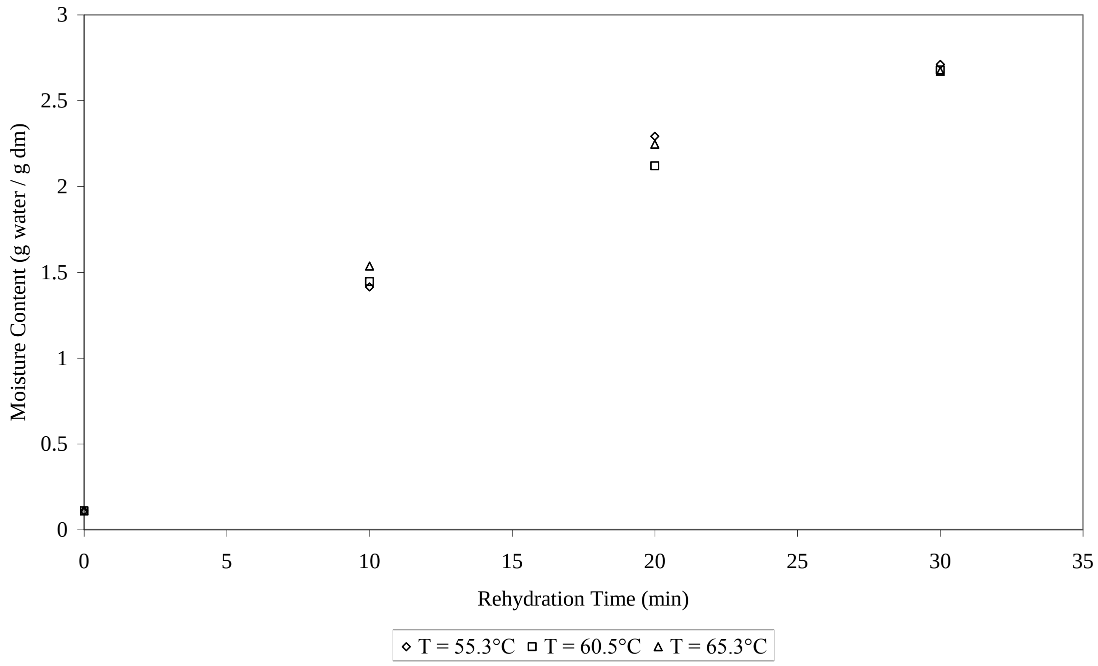

Figure 5.16. Rehydration Curve of Dried Apples for Rehydration Temperatures of 50°C for Group No.2

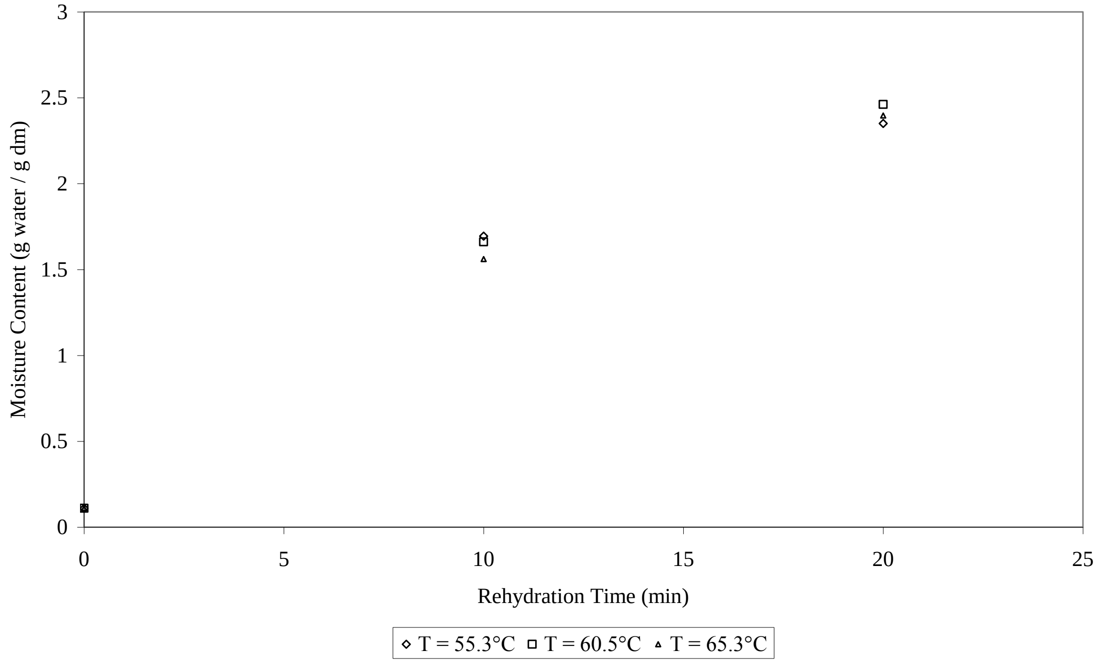

Figure 5.17. Rehydration Curve of Dried Apples for Rehydration Temperatures of 70°C for Group No.2

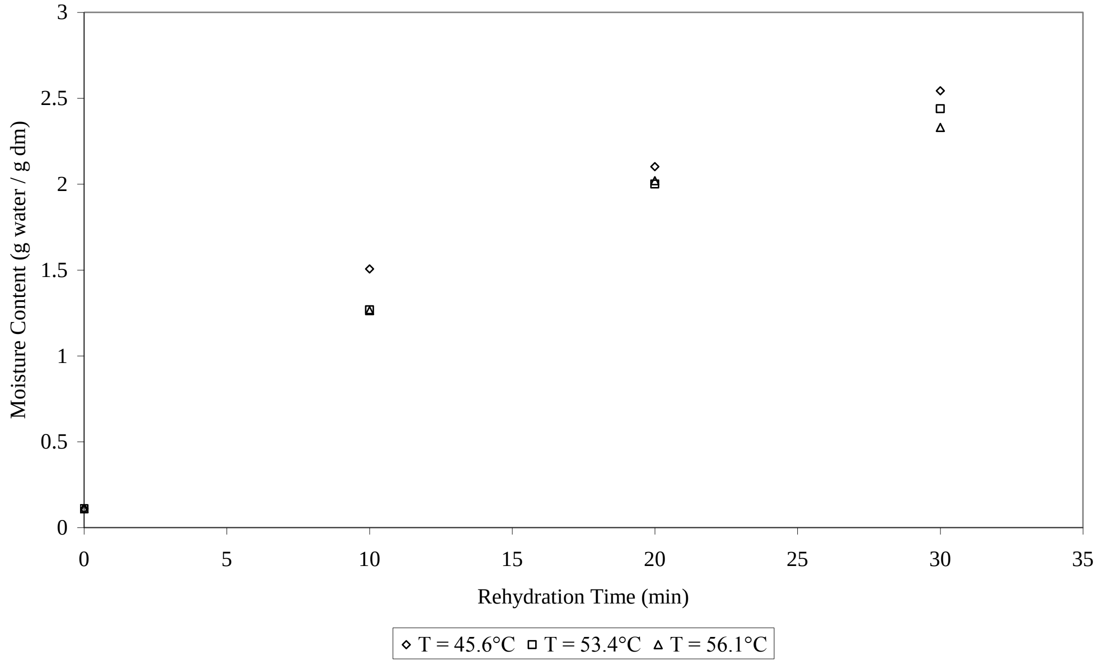

Figure 5.18. Rehydration Curve of Dried Apples for Rehydration Temperatures of 30°C for Group No.3

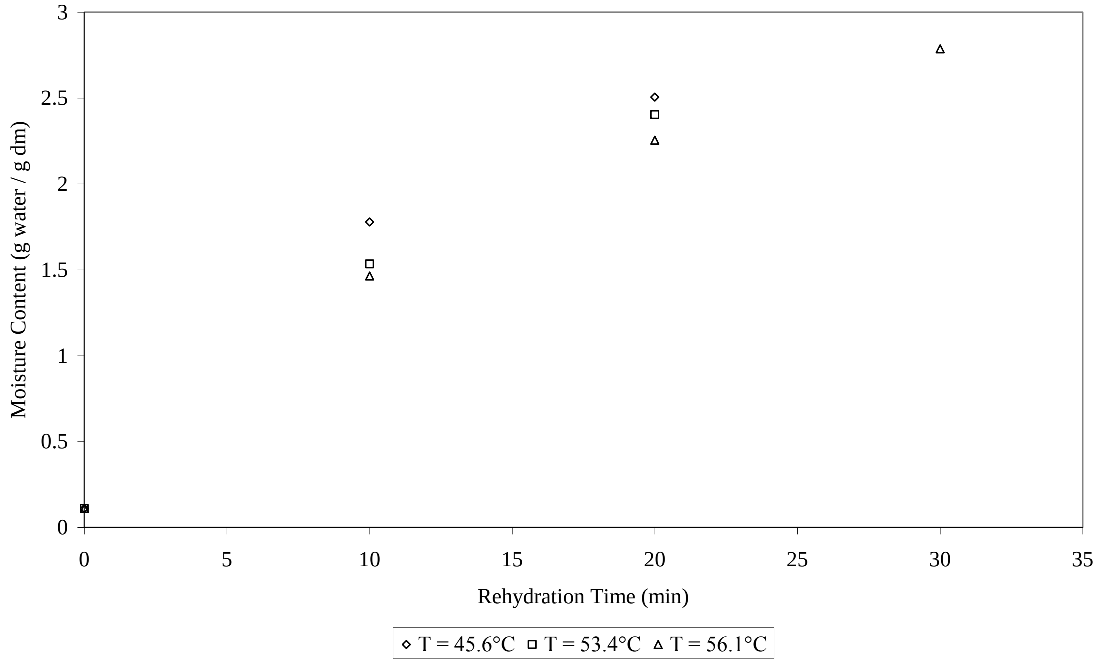

Figure 5.19. Rehydration Curve of Dried Apples for Rehydration Temperatures of 50°C for Group No.3

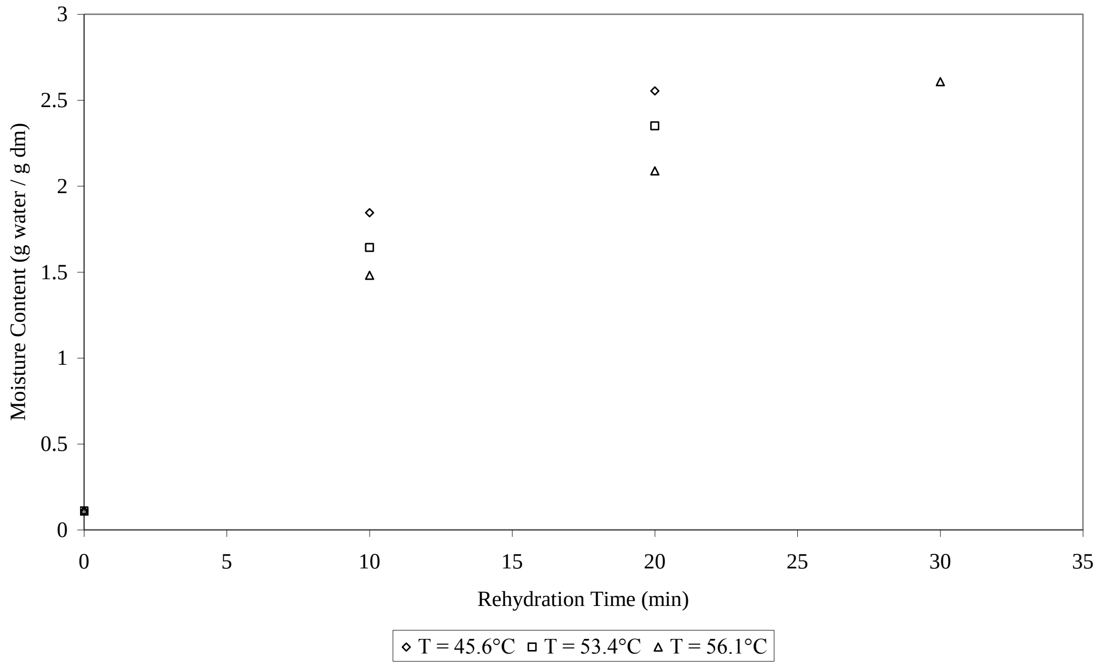

Figure 5.20. Rehydration Curve of Dried Apples for Rehydration Temperatures of 70°C for Group No.3

Time required to gain 40% moisture back that is lost in drying process is given in Table 5.9 for both Groups. Rehydration time generally increases with increasing drying air temperatures.

Table 5.9. Rehydration Time for Group No.2&3

Group No.	**Exp. No.**	**Rehydration time (min)**		
		30°C	**50°C**	**70°C**
2	2.1	27.4	22.8	18.0
	2.2	30.0	24.0	17.5
	2.3	30.0	23.0	18.3
3	3.1	25.3	16.9	16.4
	3.2	27.1	18.4	19.6
	3.3	30.0	21.6	24.2

The colour change values of apple cubes are given in Table 5.10. Colour difference values increases at rehydration process comparing with dried apple.

Table 5.10. Colour Values of Apples for Group No.2&3

Exp No:		L	a	B	ΔE	H°	C
	Raw apple	69.3	-2.2	52.8		92.4	52.86
	Dried Apple	57.8	10.7	28.3	30.01	69.2	30.22
2.1	Rehydrated Apple at 30°C	55.2	7.1	25.3	32.28	74.3	26.26
	Rehydrated Apple at 50°C	57.0	6.0	24.6	31.85	76.3	25.28
	Rehydrated Apple at 70°C	56.5	6.8	24.8	32.11	74.6	25.68
	Raw apple	69.3	-2.2	52.8		92.4	52.86
	Dried Apple	61.7	9.6	28.5	28.12	71.3	30.06
2.2	Rehydrated Apple at 30°C	56.9	6.6	23.9	32.64	74.5	24.81
	Rehydrated Apple at 50°C	60.1	5.0	22.0	32.97	77.2	22.53
	Rehydrated Apple at 70°C	59.0	5.4	24.3	31.23	77.4	24.92
	Raw apple	69.27	-2.18	52.82		92.4	52.86
	Dried Apple	59.48	10.44	29.85	27.97	70.7	31.62
2.3	Rehydrated Apple at 30°C	60.18	5.72	21.89	33.19	75.3	22.62
	Rehydrated Apple at 50°C	57.73	5.95	23.25	32.77	75.7	23.99
	Rehydrated Apple at 70°C	59.12	3.80	19.88	34.98	79.2	20.24
	Raw apple	69.27	-2.18	52.82		92.36	52.86
	Dried Apple	58.77	11.12	32.52	26.44	71.13	34.37
3.1	Rehydrated Apple at 30°C	59.09	6.77	25.79	30.24	75.28	26.66
	Rehydrated Apple at 50°C	59.61	6.34	26.08	29.68	76.33	26.84
	Rehydrated Apple at 70°C	58.06	6.13	24.78	31.32	76.10	25.52
	Raw apple	69.27	-2.18	52.82		92.36	52.86
	Dried Apple	61.06	9.84	32.29	25.17	73.05	33.75
3.2	Rehydrated Apple at 30°C	57.83	4.73	24.30	31.49	78.98	24.76
	Rehydrated Apple at 50°C	62.88	3.21	22.75	31.21	81.98	22.97
	Rehydrated Apple at 70°C	59.44	5.22	26.01	29.49	78.66	26.53
	Raw apple	69.27	-2.18	52.82		92.36	52.86
	Dried Apple	60.45	12.77	30.43	28.32	67.24	33.00
3.3	Rehydrated Apple at 30°C	58.19	5.11	22.39	33.19	77.15	22.96
	Rehydrated Apple at 50°C	58.32	6.14	23.75	32.16	75.49	24.53
	Rehydrated Apple at 70°C	54.17	4.63	20.14	36.63	77.06	20.67

5.2 Influence of Velocity

Five experiments are conducted for the velocities of 1.1, 1.4, 1.9, 2.3 and 2.5 m/s**,** respectively, while the temperature and relative humidity of drying air is kept constant at 44.1^{o}C and 17.7% as given in Table 5.11.

Table 5.11. Experimental Conditions of Velocity Influence

Group No.	Exp No.	RH1 (%)	RH2 (%)	T1 (^{o}C)	T2 (^{o}C)	v (m/s)	Drying time (min)
	4.1	64.06		19.65		1.1	270
	4.2	62.4		22.6		1.4	290
4	4.3	56.34	17.7	20.78	44.1	1.9	270
	4.4	49.89		24.95		2.3	260
	4.5	61.66		21.53		2.5	250

Initial moisture content of apple cubes is determined as 4.73±1.46 g water/g dry matter. Drying time with respect to velocity is shown in Figure 5.21.

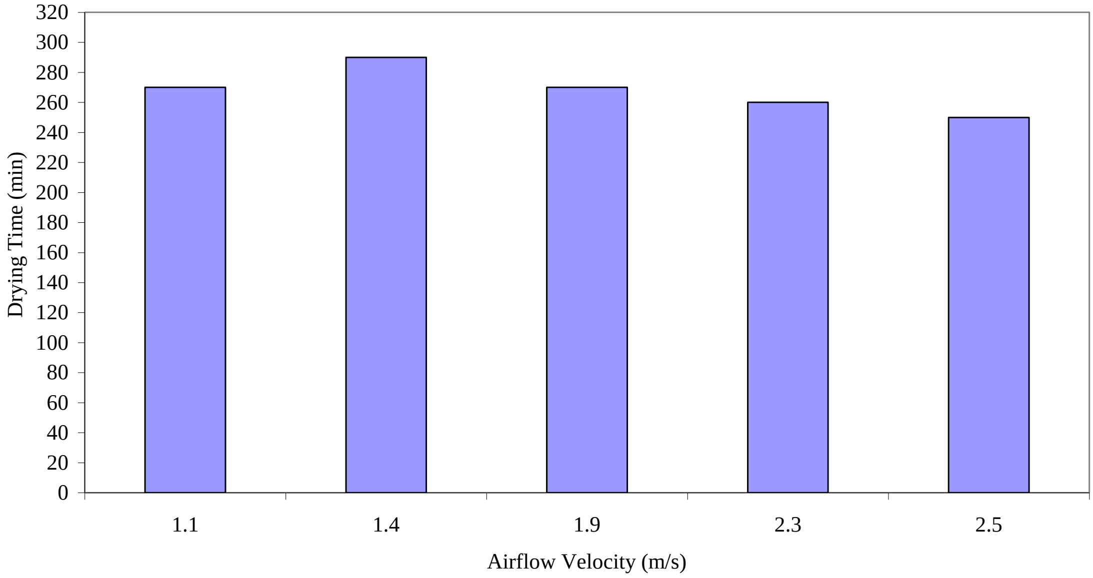

Figure 5.21. Drying Time versus Drying Air Velocity at 44.1^{o}C Drying Air Temperature and 17.7% Drying Air Relative Humidity

Figure 5.21 indicates that at constant temperature and relative humidity, increasing velocity decreases drying time as expected. Drying time is increased with a velocity increase of 0.4 m/s from Experiment 4.1 to 4.2. Further increase in the values for drying air velocity decreased the drying time.

The moisture content of the apple cubes as a function of time and drying rate with respect to moisture content are shown in Figures 5.22 and 5.23, respectively. Both exhibit the same trend and a short constant drying rate period is followed by falling rate period as observed in first 3 groups.

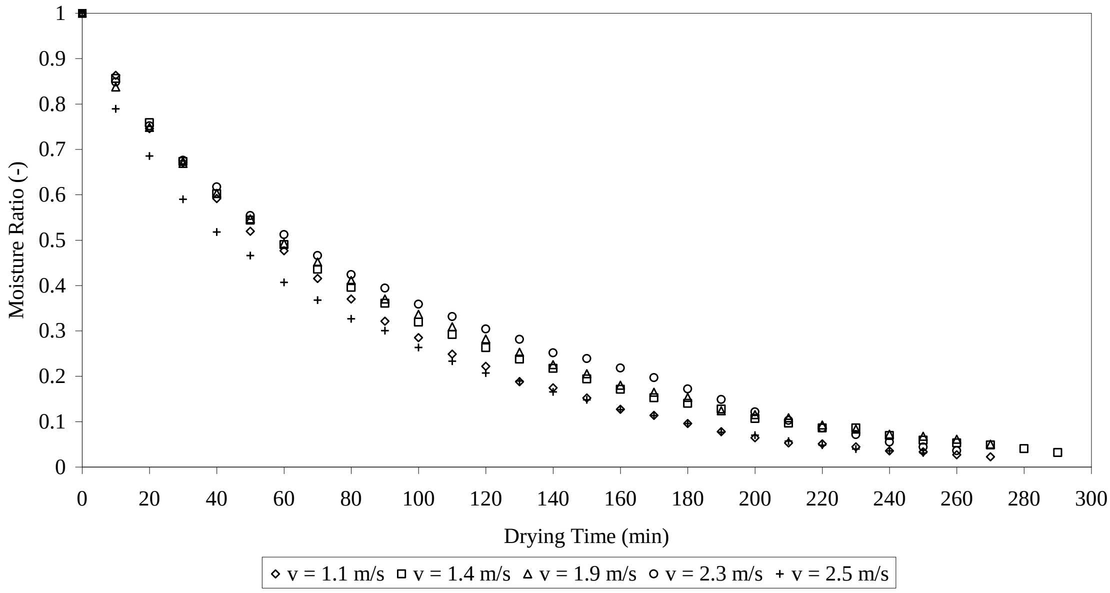

Figure 5.22. Moisture Ratio versus Drying Time at 44.1°C Temperature and 17.7% Relative Humidity and Different Velocities

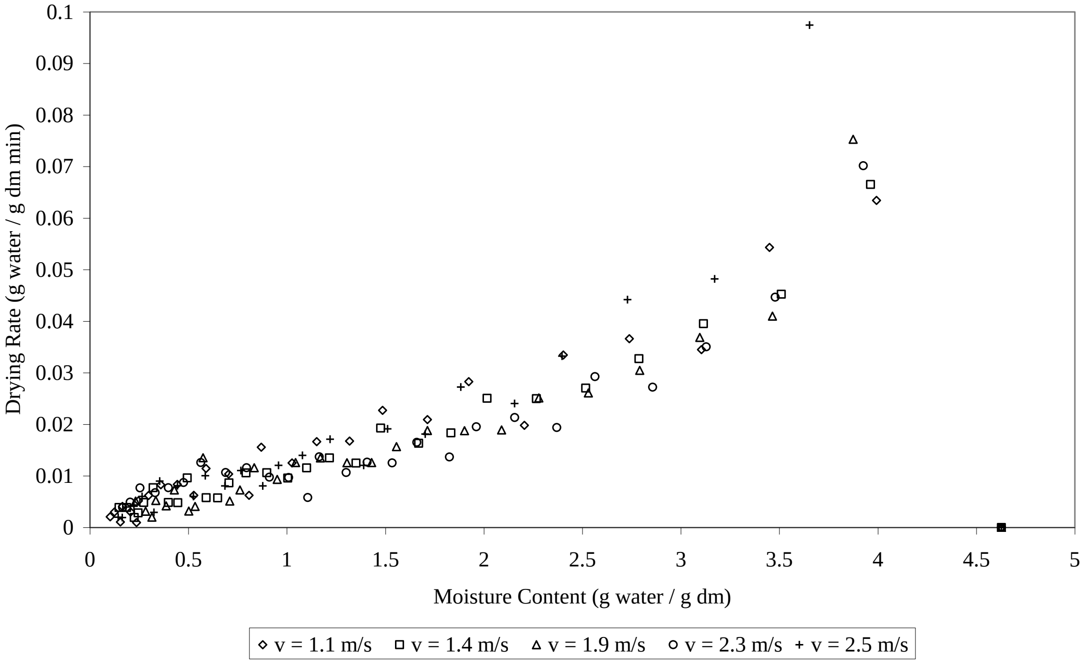

Figure 5.23. Drying Rate versus Moisture Content at 44.1^{o}C Temperature and 17.7% Relative Humidity and Different Velocities

The falling rate period can be divided into two parts. First falling rate period is continued till moisture content of apples reach to approximately 39% (w-b) which is longer than second falling rate period. Duration of the periods is given in Table 5.12.

Table 5.12. Duration of Drying Periods for the Group No.4

Velocity (v)	**1st Falling Rate (min)**	**2nd Falling Rate (min)**	**Total Drying Time (min)**
1.1	170	90	270
1.4	180	100	290
1.9	170	90	270
2.3	170	80	260
2.5	170	70	250

The calculated effective diffusion coefficients which are given in the Table 5.13, shows a decreasing trend with increasing drying air velocities lower than 2.3 m/s.

Table 5.13. Effective Diffusion Coefficient of Apple Cubes at 44.1°C Drying Air Temperature and 17.7% Drying Air Relative Humidity for Various Drying Air Velocities

Velocity (m/s)	Effective diffusion coefficient (m^2/s)	
	1st Falling Rate Period	**2nd Falling Rate Period**
1.1	$2.15x10^{-9}$	$2.58x10^{-9}$
1.4	$1.77x10^{-9}$	$2.19x10^{-9}$
1.9	$1.68x10^{-9}$	$1.95x10^{-9}$
2.3	$1.51x10^{-9}$	$3.34x10^{-9}$
2.5	$2x10^{-9}$	$2.75x10^{-9}$

The results of the thin layer models which are fitted to experimental results are given in Table A.10-A.14. The best fit for the five experiments is obtained by Midilli&Kucuk model. The results of the best fit model are given in Table 5.14.

Table 5.14. Results of Best Fitted Model of Group No.4

Group No.	Model No.	Model Constants	R^2	RMSE	χ^2
4.1	14	A=0.993926 k=0.015552 n=0.946653 b=-0.000110	0.9995	0.004004	0.0000187
4.2	14	A=0.998112 k=0.020103 n=0.869039 b=-0.000105	0.9999	0.002390	0.0000066
4.3	14	A=0.996316 k=0.024728 n=0.808218 b=-0.000224	0.9996	0.0044461	0.0000231
4.4	14	A=1.003597 k=0.033486 n=0.706251 b=-0.000586	0.9995	0.0048685	0.0000278
4.5	14	A=0.998414 k=0.040506 n=0.744268 b=-0.000253	0.9997	0.00315	0.0000117

Rehydration curves are plotted in Figures 5.24-5.26 and rehydration times are listed in Table 5.15. Rehydration time decreases with increasing rehydration temperature.

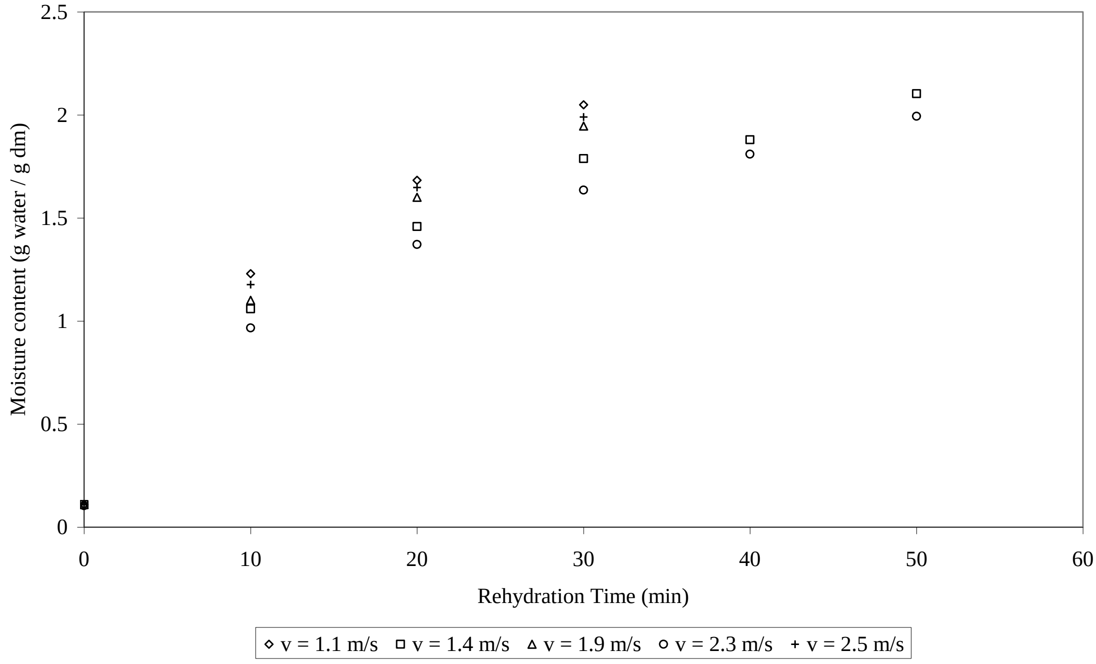

Figure 5.24. Rehydration Curve of Dried Apples for Rehydration Temperatures of 30^{o}C for Group No.4

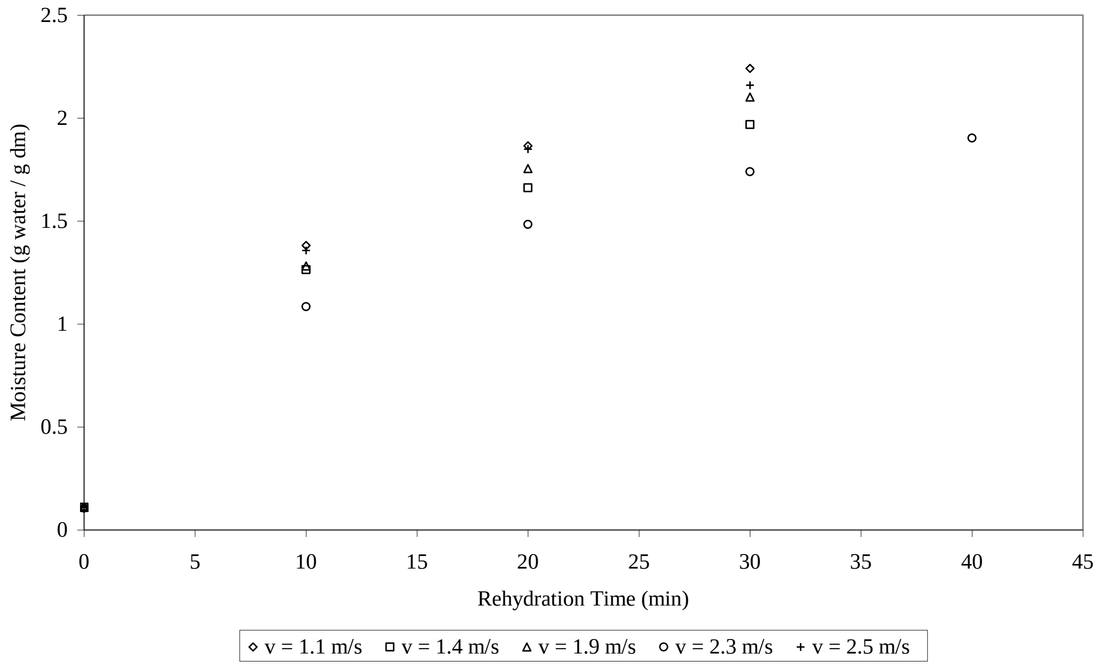

Figure 5.25. Rehydration Curve of Dried Apples for Rehydration Temperatures of 50^{o}C for Group No.4

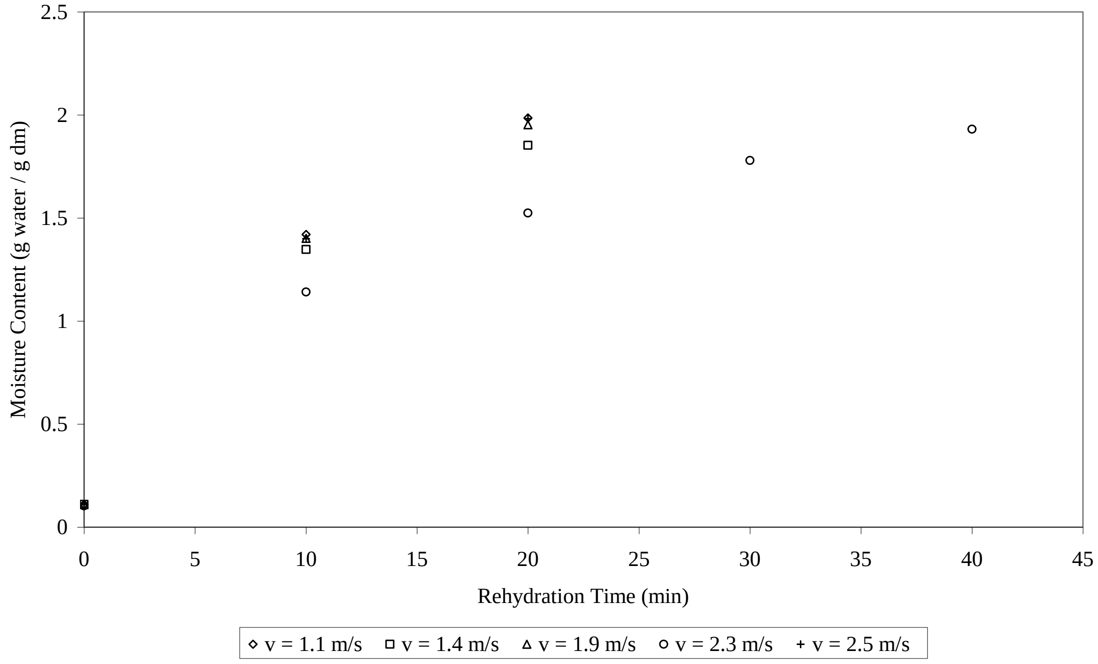

Figure 5.26. Rehydration Curve of Dried Apples for Rehydration Temperatures of 70°C for Group No.4

Table 5.15. Rehydration Time for Group No.4

Exp. No.	**Rehydration time (min)**		
	30°C	**50°C**	**70°C**
4.1	28.1	24.4	20.0
4.2	41.6	28.2	17.8
4.3	29.6	25.2	18.2
4.4	45.0	40.0	38.7
4.5	28.2	23.0	17.9

The colour change values are given in Table 5.16. Colour difference values increases at rehydration process comparing with dried apple. Colour saturation values decreases at drying and rehydration process comparing with raw apple.

Table 5.16. Colour Values of Apples for Different Drying Air Velocities

Exp No:		**L**	**a**	**B**	**ΔE**	**H°**	**C**
	Raw apple	69.27	-2.18	52.82		92.36	52.86
	Dried Apple	59.32	7.28	30.61	26.11	76.63	31.46
4.1	Rehydrated Apple at 30°C	43.56	11.84	26.43	39.42	65.86	28.96
	Rehydrated Apple at 50°C	51.32	8.22	26.85	33.24	72.98	28.08
	Rehydrated Apple at 70°C	50.95	7.46	26.91	33.16	74.50	27.93
	Raw apple	69.27	-2.18	52.82		92.36	52.86
	Dried Apple	60.00	5.38	33.78	22.48	80.95	34.20
4.2	Rehydrated Apple at 30°C	43.35	11.84	23.84	41.33	63.58	26.62
	Rehydrated Apple at 50°C	44.84	10.66	20.97	42.14	63.06	23.53
	Rehydrated Apple at 70°C	50.74	6.88	27.05	33.01	75.72	27.91
	Raw apple	69.27	-2.18	52.82		92.36	52.86
	Dried Apple	56.48	10.42	30.71	28.48	71.26	32.42
4.3	Rehydrated Apple at 30°C	45.35	10.20	27.38	37.05	69.57	29.21
	Rehydrated Apple at 50°C	50.67	9.86	28.87	32.62	71.14	30.51
	Rehydrated Apple at 70°C	48.05	8.24	27.53	34.62	73.34	28.73
	Raw apple	69.27	-2.18	52.82		92.36	52.86
	Dried Apple	54.35	8.04	25.43	32.82	72.45	26.67
4.4	Rehydrated Apple at 30°C	49.24	8.39	21.76	38.44	68.91	23.32
	Rehydrated Apple at 50°C	50.86	7.89	21.64	37.58	69.97	23.04
	Rehydrated Apple at 70°C	47.96	6.62	19.93	40.16	71.63	21.00
	Raw apple	69.27	-2.18	52.82		92.36	52.86
	Dried Apple	59.03	4.85	30.65	25.41	81.01	31.03
4.5	Rehydrated Apple at 30°C	51.05	9.86	26.43	34.25	69.55	28.21
	Rehydrated Apple at 50°C	48.97	9.14	27.17	34.61	71.41	28.66
	Rehydrated Apple at 70°C	54.27	5.76	24.67	32.87	76.86	25.33

5.3 Influence of Relative Humidity

Three sets of experiments are conducted for the relative humidities of 4.6%, 9.8% and 20.5%**,** respectively, while the temperature and velocity of drying air is kept constant at 59.8^{o}C and 0.8 m/s as given in Table 5.17.

Table 5.17. Experimental Conditions of Relative Humidity Influence

Group No.	Exp No.	RH1 (%)	T1 (^oC)	T2 (^oC)	v (m/s)	RH2 (%)	Drying time (min)
	5.1	32.21	19.47			4.6	180
5	5.2	66.23	23.17	59.8	0.8	9.8	140
	5.3	47.38	31.57			20.5	210

Initial moisture content of apple cubes is determined as in Section 5.2. Drying time change with relative humidity is shown in Figure 5.27.

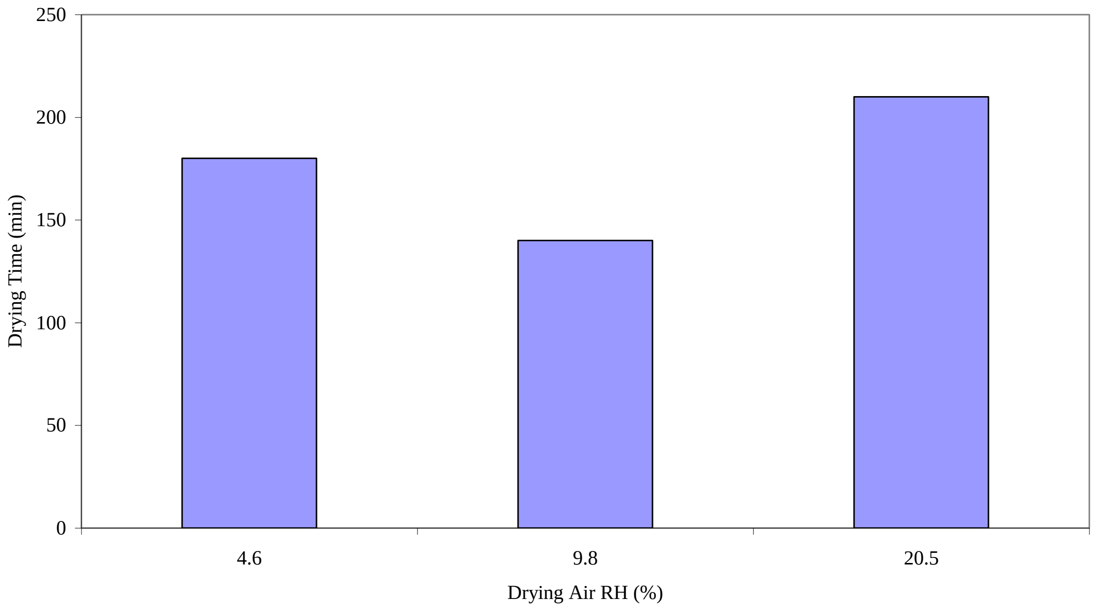

Figure 5.27. Drying Time versus Drying Air Relative Humidity at 59.8^{o}C Drying Air Temperature and 0.8 m/s Drying Air Velocity

Figure 5.27 shows a decrease then an increase with increasing relative humidity which is different than previous experiments. This may be due to a competition in the rates of evaporation and skin layer formation in the product. The relative humidity range should be extended to have a better sight.

The moisture ratio and drying rate is plotted in Figures 5.28 and 5.29, respectively. Both exhibit the same trend as the previous experiments showing a long falling rate period. Duration of the falling rate periods and effective diffusion coefficients are given in Tables 5.18 and 5.19, respectively.

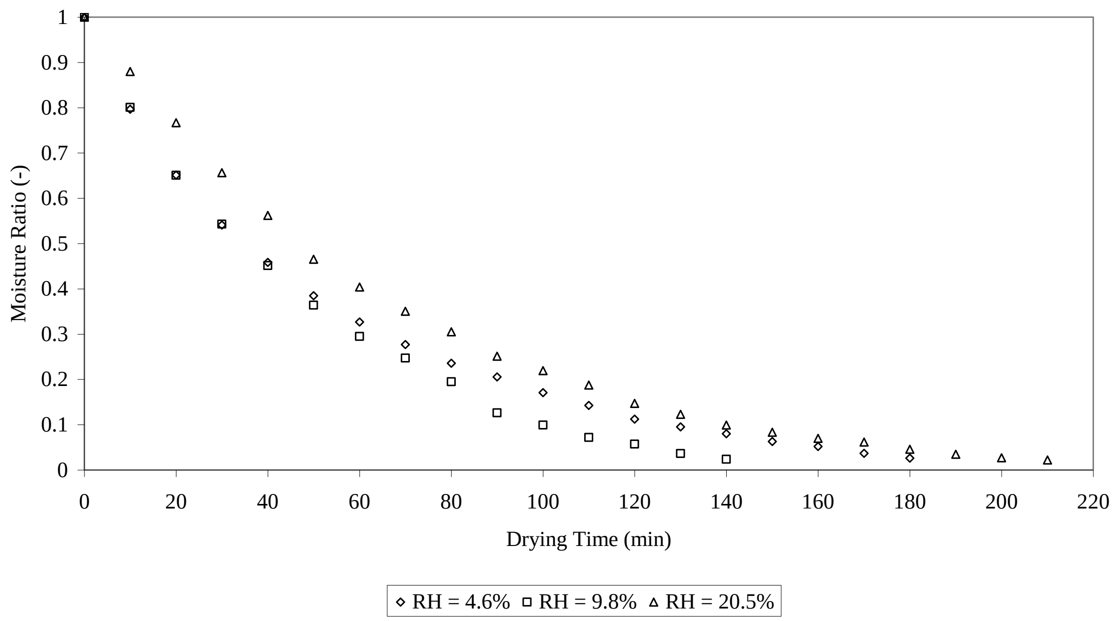

Figure 5.28. Moisture Ratio versus Drying Time at 59.8°C Temperature, 0.8 m/s Velocity and Different Relative Humidities

Table 5.18. Duration of Drying Periods for the Group No.5

RH (%)	**1st Falling Rate (min)**	**2nd Falling Rate (min)**	**Total Drying Time (min)**
4.6	100	70	180
9.8	70	60	140
20.5	160	40	210

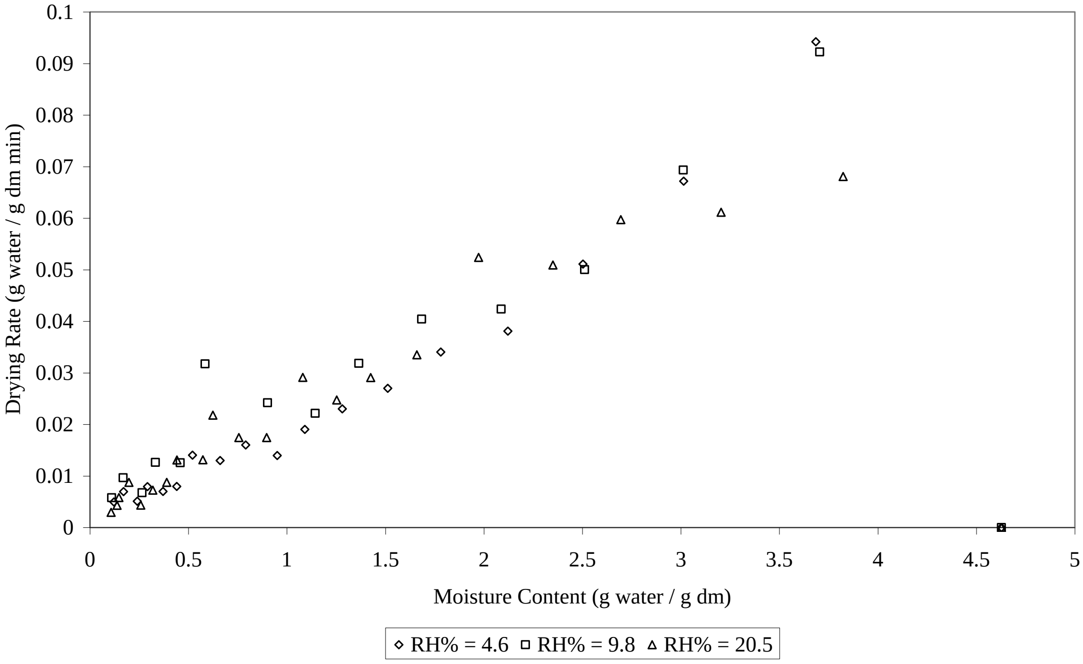

Figure 5.29. Drying Rate versus Moisture Content of Apple Cubes at 59.8°C Temperature, 0.8 m/s Velocity and Different Relative Humidities

Table 5.19. Effective Diffusion Coefficient of Apple Cubes at 59.8°C Drying Air Temperature and 0.8 m/s Drying air Velocity for Various Drying Air Relative Humidities

RH (%)	**Effective diffusion coefficient (m^2/s)**	
	1st Falling Rate Period	**2nd Falling Rate Period**
4.6	$2.84x10^{-9}$	$3.92x10^{-9}$
9.8	$3.37x10^{-9}$	$5.63x10^{-9}$
20.5	$2.85x10^{-9}$	$4.37x10^{-9}$

Similar to the minimum obtained in Figure 5.27, diffusion coefficients give a peak at 9.8% relative humidity.

The results of models applied to the experimental data are given in Table A.15, A.16 and A.17. The best fit obtained by Midilli & Kucuk model and the results are given in Table 5.20.

Table 5.20. Results of Best Fitted Model of Group No.5

Group No.	Model No.	Model Constants	R^2	RMSE	χ^2
5.1	14	a=1.001524 k=0.032611 n=0.855091 b=-0.000201	0.9998	0.0028044	9.962E-06
5.2	14	a=0.996846 k=0.023473 n=0.946054 b=-0.000483	0.9991	0.0087976	0.0001055
5.3	14	a=0.999325 k=0.015751 n=0.952684 b=0.000435	0.9997	0.0040944	0.0000205

Rehydration curves and rehydration times are given in Figures 5.30-5.32 and Table 5.21, respectively. Rehydration time decreases with increasing rehydration temperatures.

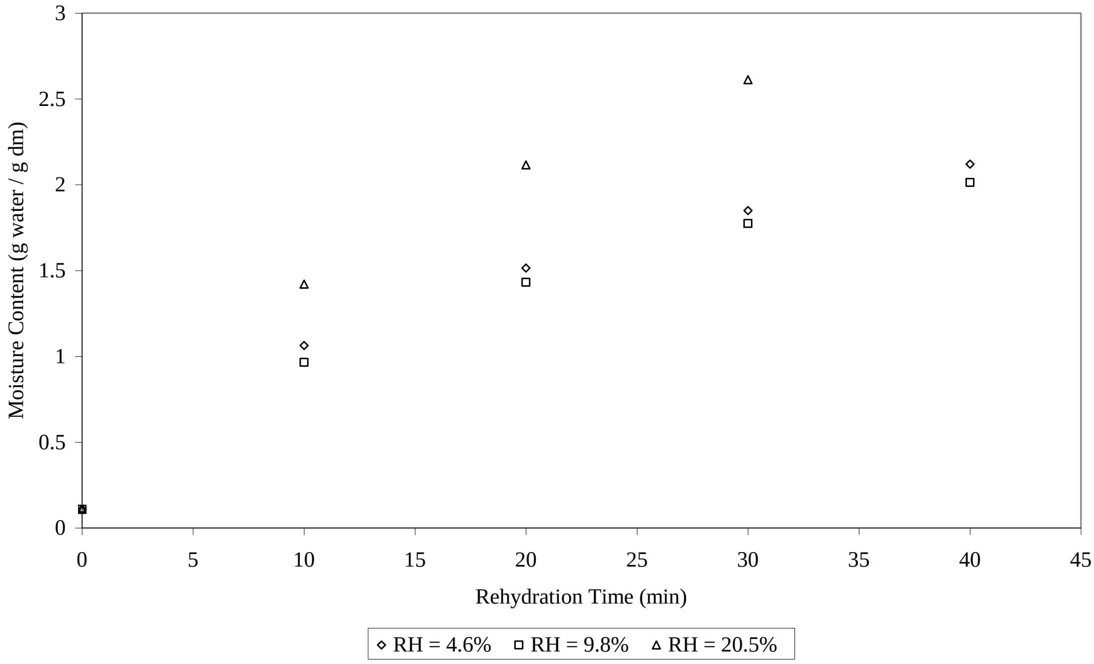

Figure 5.30. Rehydration Curve of Dried Apples for Rehydration Temperatures of 30°C for Group No.5

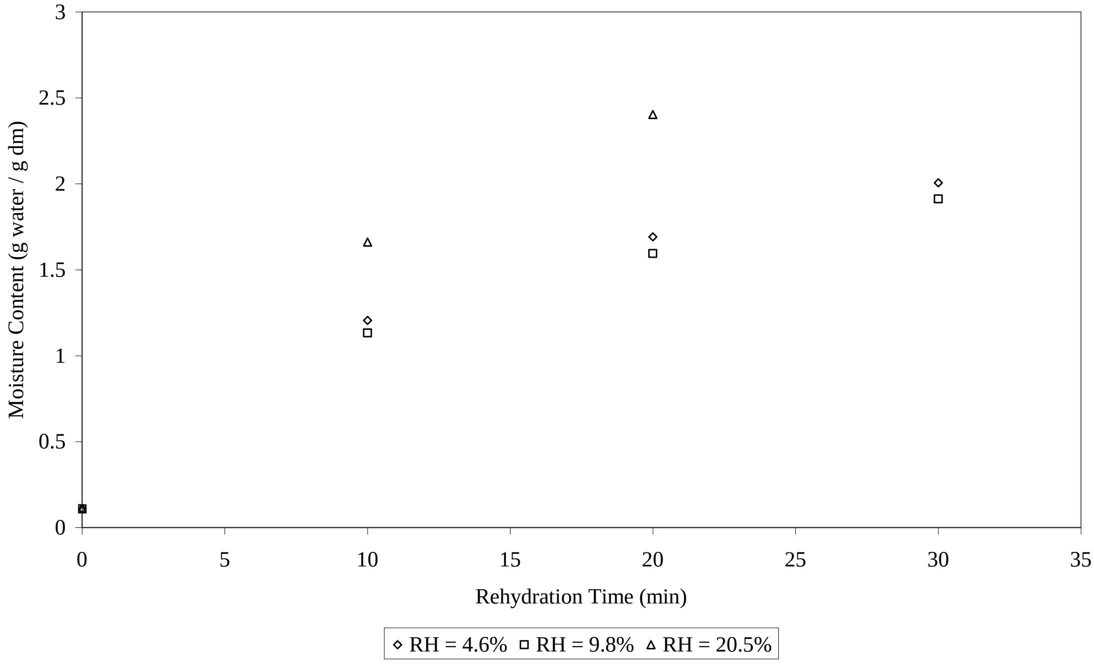

Figure 5.31. Rehydration Curve of Dried Apples for Rehydration Temperatures of 50^{o}C for Group No.5

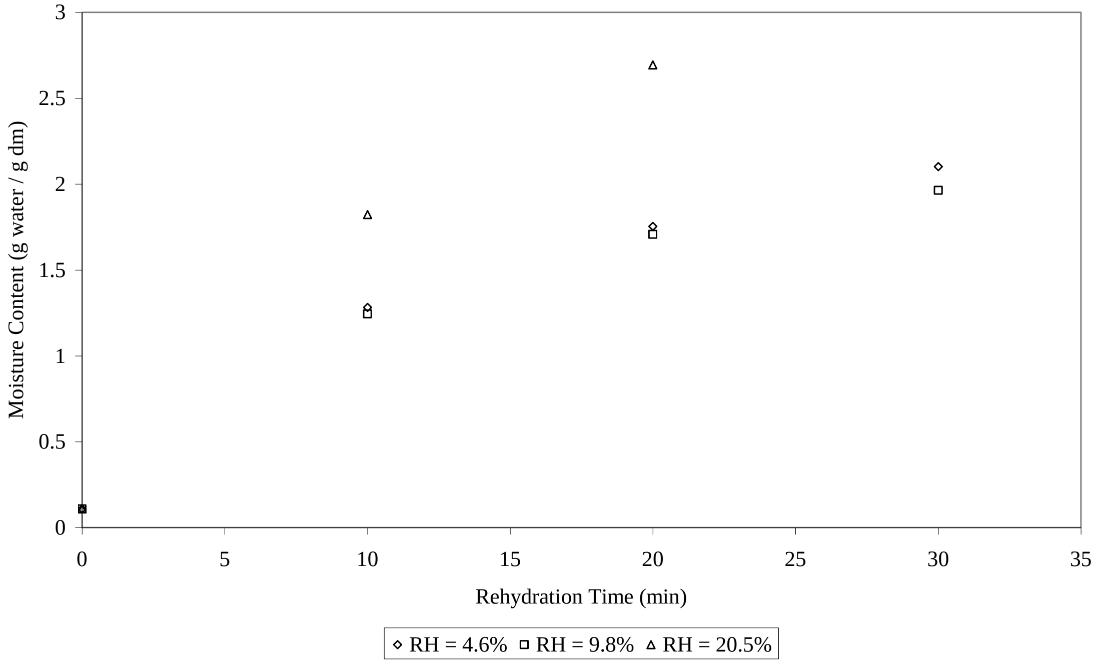

Figure 5.32. Rehydration Curve of Dried Apples for Rehydration Temperatures of 70^{o}C for Group No.5

Table 5.21. Rehydration Time for Group No.5

Exp. No.	**Rehydration time (min)**		
	30°C	**50°C**	**70°C**
5.1	33.0	27.0	24.5
5.2	34.6	29.3	26.5
5.3	24.4	18.7	15.9

The colour change values are given in Table 5.22. Colour difference values increases at rehydration process comparing with dried apple. Colour saturation values decreases at drying and rehydration process comparing with raw apple.

Table 5.22. Colour Values of Apples for Different Drying Air Relative Humidities

Exp No:		**L**	**a**	**b**	**ΔE**	**H°**	**C**
	Raw apple	69.27	-2.18	52.82		92.36	52.86
	Dried Apple	60.30	3.32	26.12	28.70	82.75	26.33
5.1	Rehydrated Apple at 30°C	50.22	8.59	23.30	36.74	69.76	24.84
	Rehydrated Apple at 50°C	52.37	6.57	23.76	34.74	74.55	24.65
	Rehydrated Apple at 70°C	57.24	1.87	23.28	32.15	85.41	23.35
	Raw apple	69.27	-2.18	52.82		92.36	52.86
	Dried Apple	61.64	4.39	28.37	26.44	81.20	28.70
5.2	Rehydrated Apple at 30°C	48.90	9.15	23.64	37.34	68.85	25.35
	Rehydrated Apple at 50°C	53.72	7.52	28.33	30.58	75.15	29.31
	Rehydrated Apple at 70°C	54.40	2.85	19.44	36.89	81.66	19.64
	Raw apple	69.27	-2.18	52.82		92.36	52.86
	Dried Apple	64.68	8.10	31.49	24.11	75.58	32.51
5.3	Rehydrated Apple at 30°C	57.72	5.59	24.13	31.89	76.95	24.76
	Rehydrated Apple at 50°C	62.81	4.24	24.67	29.58	80.26	25.03
	Rehydrated Apple at 70°C	60.16	2.90	21.48	33.02	82.31	21.68

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

Five groups of apple drying experiments are performed in a tunnel dryer to investigate the effects of temperature, velocity and relative humidity of air on the drying kinetics of apples. The first three groups are tested to investigate the effect of drying air temperature (40.1-65.3^{o}C), and the next two groups are conducted to evaluate the effect of drying air velocity (1.1-2.5 m/s) and relative humidity (4.6-20.5%), respectively.

The duration of the drying experiments are obtained between 140-290 min. The results indicate that increasing air temperature and velocity and decreasing relative humidity of air reduces drying time. This result is in agreement with the literature (Kaya, et al. 2007, Mandala, et al. 2005, Velić, et al. 2004, Akpınar and Bicer 2003).

Drying rate curves indicated that drying process takes place mostly in the falling rate period except very short unsteady-state initial and constant rate periods. Two well-defined falling rate periods are observed. When the temperature is increased and the velocity is decreased, effective diffusion coefficients generally increase. The range of effective diffusion coefficients is obtained as 0.486×10^{-9} to 5.63×10^{-9} m^2/s which is in agreement with the data in the literature (10^{-8}-10^{-11} m^2/s) (Kaya, et al. 2007, Akpınar and Bicer 2003, Srikiatden and Roberts 2005, Velić, et al. 2004).

With increasing drying air temperature and velocity; hue angle and colour saturation are decreased. Rehydration time is decreased with increasing drying air temperature or decreasing drying air velocity. Rehydration time, colour difference and hue angle are generally decreased with increasing relative humidity of air. On the contrary, color saturation is increased with increasing drying air relative humidity. As quality measures, lowest rehydration time and ΔE, highest hue angle and colour saturation is desired.

In consequence, with a view of drying time and product quality, drying air temperatures of 55.3-65.3^{o}C, velocity of 2.5 m/s and relative humidity of 20.5% are determined as the best experimental conditions among the others investigated in this study. It should be noticed that the best values obtained are the upper limits of the experimental conditions. To be able to evaluate the wider range, the upper limit should be extended for further experiments.

The moisture content data observed during the experiments are converted into the moisture ratio (MR) and fitted to the fourteen thin layer drying models listed in Table 3.1. The Midilli and Kucuk model is the best descriptive model, suggested by the highest value of R^2, the lowest value of RMSE and χ^2, namely, 0,9999, 2.39×10^{-3} and 6.6×10^{-6}, respectively. In order to take into account the effect of drying air temperature, velocity and relative humidity on constants of the Midilli and Kucuk model, the linear regression analysis is used.

$$MR = a * \exp(-k * t^{n}) + b * t$$

Where

a = 0.892822+0.001309*T+0.24266*RH+0.001885*v $R^2 = 0.8682$

k = 0.023789+0.000031*T-0.051162*RH+0.003042*v $R^2 = 0.8909$

n = 0.795895+0.001952*T+0.337614*RH-0.084011*v $R^2 = 0.9116$

b = 0.00365+0.000057*T-0.005423*RH-0.000232*v $R^2 = 0.9575$

The consistency of the model is evident but R^2 values for constants are low. The regression analysis of constants should be improved trying another regression methods and increasing the number of experiments.

During the experiments, it was difficult to keep the drying air conditions constant because of uncontrolled laboratory environment. For further experiments, control units should be included to the experimental set-up. In order to eliminate errors associated with moisture gain during the weight measurements outside the dryer, on extension of the set-up for online measurements should be considered.

Finally, to determine the optimum dryer length, the number of the tray should be increased.

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APPENDIX A

STATISTICAL RESULTS OBTAINED FROM DIFFERENT THIN LAYER DRYING MODELS

Table A.1. Results of Fitted Models for Experiment 1.1

Exp. No.	Model No.	Model Constants	R^2	RMSE	χ^2
1.1	1	k=0.008554	0.9513	0.0526864	0.0028869
	2	k=0.030778 n=0.736375	0.9964	0.0142361	0.0002196
	3	k=0.008852 n=0.736385	0.9964	0.0142361	0.0002196
	4	a=0.897733 k=0.007480	0.9737	0.0387589	0.0016274
	5	a=0.827331 k=0.012637 c=0.145606	0.9989	0.0078517	0.0000697
	6	a=0.297747 k0=0.002370, b=0.683962 k1=0.015475	0.9993	0.0065089	0.0000501
	7	a=0.222298 k=0.030117	0.9879	0.0262503	0.0007465
	8	a=-0.007519 b=0.000017	0.9550	0.0506867	0.0000000
	9	a=0.626699 k=0.017755 b=0.175695	0.9989	0.0078161	0.0000691
	10	a=0.624254 k=0.017817 g=0.003143	0.9989	0.0078165	0.0000691
	11	a=0.051264 k=0.398272 b=0.791639 g=0.012236 c=0.157377 h=0.000421	0.9999	0.0024311	0.0000077
	12	a=0.897715 c=0.039796 L=2.306639	0.9737	0.0387589	0.0016982
	13	c=0.000186 L=0.012178 n=0.636299	0.9872	0.0270796	0.0008290
	14	a=0.996915 k=0.019533 n=0.861378 b=0.000300	0.9999	0.0028697	0.0000097

Table A.2. Results of Fitted Models for Experiment 1.2

Exp. No.	Model No.	Model Constants	R^2	RMSE	χ^2
1.2	1	k=0.010073	0.9704	0.0402090	0.0016871
	2	k=0.027237 n=0.786561	0.9968	0.0132841	0.0001925
	3	k=0.010245 n=0.786562	0.9968	0.0132841	0.0001925
	4	a=0.926967 k=0.009196	0.9817	0.0316493	0.0010927
	5	a=0.848930 k=0.014130 c=0.136775	0.9994	0.0056073	0.0000359
	6	a=0.739624 k0=0.016173 b=0.251050 k1=0.002357	0.9995	0.0050453	0.0000305
	7	a=0.236082 k=0.032824	0.9951	0.0164224	0.0002942
	8	a=-0.009037 b=0.000025	0.9740	0.0376794	0.0015488
	9	a=0.692426 k=0.017543 b=0.177403	0.9994	0.0055271	0.0000349
	10	a=0.689466 k=0.017602 g=0.003151	0.9994	0.0055276	0.0000349
	11	a=0.011563 k=-0.008395 b=0.150377 g=0.042220 c=0.836498 h=0.009621	0.9998	0.0030616	0.0000125
	12	a=0.927067 c=0.000923 L=-0.316787	0.9817	0.0316493	0.0011448
	13	c=0.062312 L=1.692271 n=0.786561	0.9968	0.0132841	0.0002017
	14	a=0.999525 k=0.018040 n=0.905952 b=0.000368	0.9998	0.0031640	0.0000120

Table A.3. Results of Fitted Models for Experiment 1.3

Exp. No.	Model No.	Model Constants	R^2	RMSE	χ^2
1.3	1	k=0.010827	0.9787	0.0349382	0.0012788
	2	k=0.024794 n=0.819095	0.9962	0.0147234	0.0002385
	3	k=0.010958 n=0.819126	0.9962	0.0147234	0.0002385
	4	a=0.943395 k=0.010100	0.9853	0.0290082	0.0009256
	5	a=0.866791 k=0.014864 b=0.128195	0.9997	0.0043851	0.0000223
	6	a=0.136152 k0=0.00025 b=0.859189 k1=0.015004	0.9997	0.0043814	0.0000235
	7	a=0.263191 k=0.030954	0.9966	0.0138989	0.0002125
	8	a=-0.009709 b=0.000029	0.9818	0.0323290	0.0011497
	9	a=0.840452 k=0.015520 b=0.055734	0.9996	0.0045452	0.0000239
	10	a=0.838750 k=0.015547 g=0.000910	0.9996	0.0045455	0.0000239
	11	a=0.303005 k=0.023503 b=0.012740 g=-0.008155 c=0.681873 h=0.009340	0.9997	0.0041414	0.0000236
	12	a=0.943766 c=0.000984 L=-0.312028	0.9853	0.0290085	0.0009744
	13	c=0.943384 L=0.048424 n=2.189665	0.9853	0.0290082	0.0009743
	14	a=0.999325 k=0.015751 n=0.952684 b=0.000435	0.9997	0.0040944	0.0000205

Table A.4. Results of Fitted Models for Experiment 2.1

Exp. No.	Model No.	Model Constants	R^2	RMSE	χ^2
2.1	1	k=0.013235	0.9827	0.0317402	0.0010704
	2	k=0.028301 n=0.825455	0.9981	0.0106054	0.0001275
	3	k=0.013318 n=0.825458	0.9981	0.0106054	0.0001275
	4	a=0.947540 k=0.012400	0.9889	0.0254619	0.0007348
	5	a=0.863973 k=0.017644 b=0.124943	0.9994	0.0060660	0.0000447
	6	a=0.760738 k0=0.019702 b=0.230933 k1=0.003121	0.9994	0.0058417	0.0000446
	7	a=0.252071 k=0.039642	0.9981	0.0103965	0.0001225
	8	a=-0.012035 b=0.000045	0.9847	0.0298559	0.0010102
	9	a=0.689849 k=0.021668 b=0.209712	0.9993	0.0062479	0.0000474
	10	a=0.687707 k=0.021715 g=0.004580	0.9993	0.0062481	0.0000474
	11	a=0.327671 k=0.017067 b=0.228609 g=0.003179 c=0.435977 h=0.021748	0.9994	0.0058290	0.0000525
	12	a=0.947538 c=0.175205 L=3.758933	0.9889	0.0254619	0.0007872
	13	c=0.035484 L=1.146815 n=0.825453	0.9981	0.0106054	0.0001366
	14	a=0.997375 k=0.020498 n=0.927146 b=0.000443	0.9996	0.0046842	0.0000287

Table A.5. Results of Fitted Models for Experiment 2.2

Exp. No.	Model No.	Model Constants	R^2	RMSE	χ^2
2.2	1	k=0.013580	0.9740	0.0383712	0.0015644
	2	k=0.034124 n=0.787753	0.9983	0.0097346	0.0001074
	3	k=0.013735 n=0.787767	0.9983	0.0097346	0.0001074
	4	a=0.933666 k=0.012494	0.9840	0.0301233	0.0010284
	5	a=0.844864 k=0.018885 b=0.138773	0.9987	0.0087435	0.0000928
	6	a=0.507289 k0=0.007082 b=0.488171 k1=0.029910	0.9995	0.0053793	0.0000378
	7	a=0.222526 k=0.047320	0.9968	0.0133625	0.0002024
	8	a=-0.012320 b=0.000047	0.9739	0.0384088	0.0016719
	9	a=0.473961 k=0.031181 b=0.233825	0.9995	0.0055104	0.0000369
	10	a=0.526913 k=0.007303 g=0.031217	0.9995	0.0055104	0.0000369
	11	a=0.426265 k=0.006169 b=0.026533 g=0.198568 c=0.546518 h=0.025307	0.9996	0.0048133	0.0000358
	12	a=0.933660 c=0.766505 L=-7.83271	0.9840	0.0301233	0.0011019
	13	c=0.026593 L=-0.853636 n=0.787757	0.9983	0.0097346	0.0001151
	14	a=1.000542 k=0.026695 n=0.868224 b=0.000377	0.9995	0.0052510	0.0000361

Table A.6. Results of Fitted Models for Experiment 2.3

Exp. No.	Model No.	Model Constants	R^2	RMSE	χ^2
2.3	1	k=0.015636	0.9798	0.0348313	0.0012999
	2	k=0.034723 n=0.810210	0.9977	0.0118421	0.0001618
	3	k=0.015804 n=0.810218	0.9977	0.0118421	0.0001618
	4	a=0.946259 k=0.014633	0.9861	0.0288707	0.0009618
	5	a=0.860144 k=0.021506 b=0.131686	0.9997	0.0045546	0.0000259
	6	a=0.243975 k0=0.003738 b=0.751108 k1=0.024310	0.9997	0.0039533	0.0000213
	7	a=0.248721 k=0.047723	0.9975	0.0123672	0.0001765
	8	a=-0.014133 b=0.000061	0.9819	0.0329245	0.0012508
	9	a=0.723430 k=0.025390 b=0.175237	0.9997	0.0041892	0.0000219
	10	a=0.722081 k=0.025426 g=0.004479	0.9997	0.0041893	0.0000219
	11	a=0.369707 k=0.015885 b=0.469939 g=0.027958 c=0.155806 h=0.001842	0.9998	0.0039016	0.0000254
	12	a=0.946254 c=0.029948 L=-1.43058	0.9861	0.0288707	0.0010419
	13	c=0.009896 L=0.460812 n=0.810168	0.9977	0.0118421	0.0001753
	14	a=0.999056 k=0.024544 n=0.925582 b=0.000569	0.9998	0.0031221	0.0000133

Table A.7. Results of Fitted Models for Experiment 3.1

Exp. No.	Model No.	Model Constants	R^2	RMSE	χ^2
3.1	1	k=0.009851	0.9550	0.0501142	0.0026436
	2	k=0.032131 n=0.743278	0.9971	0.0127773	0.0001814
	3	k=0.009800 n=0.743283	0.9971	0.0127773	0.0001814
	4	a=0.911258 k=0.008688	0.9741	0.0380284	0.0016068
	5	a=0.817691 k=0.014447 b=0.159568	0.9987	0.0085841	0.0000867
	6	a=0.419282 k0=0.003846 b=0.570316 k1=0.020548	0.9995	0.0052413	0.0000343
	7	a=0.215269 k=0.035280	0.9903	0.0233359	0.0006051
	8	a=-0.008905 b=0.000024	0.9592	0.0477720	0.0025357
	9	a=0.542347 k=0.022311 b=0.188465	0.9994	0.0058925	0.0000408
	10	a=0.540757 k=0.022364 g=0.004221	0.9994	0.0058927	0.0000409
	11	a=0.680982 k=0.015899 b=0.043128 g=0.210691 c=0.275955 h=0.002282	0.9999	0.0026105	0.0000097
	12	a=0.911240 c=0.001171 L=-0.367195	0.9741	0.0380285	0.0017014
	13	c=0.006673 L=-0.347380 n=0.743276	0.9971	0.0127773	0.0001921
	14	a=1.000175 k=0.022344 n=0.850934 b=0.000351	0.9998	0.0034770	0.0000151

Table A.8. Results of Fitted Models for Experiment 3.2

Exp. No.	Model No.	Model Constants	R^2	RMSE	χ^2
3.2	1	k=0.010804	0.9512	0.0555698	0.0032505
	2	k=0.035984 n=0.739249	0.9942	0.0192279	0.0004108
	3	k=0.011138 n=0.739249	0.9942	0.0192279	0.0004108
	4	a=0.907398 k=0.009609	0.9690	0.0443083	0.0021814
	5	a=0.832873 k=0.016312 b=0.152391	0.9994	0.0059978	0.0000423
	6	a=0.264895 k0=0.002340 b=0.727209 k1=0.018996	0.9997	0.0043200	0.0000233
	7	a=0.235689 k=0.035397	0.9870	0.0287429	0.0009180
	8	a=-0.009581 b=0.000027	0.9576	0.0517856	0.0029797
	9	a=0.708917 k=0.019921 b=0.136642	0.9996	0.0047951	0.0000271
	10	a=0.291146 k=0.002723 g=0.019923	0.9996	0.0047951	0.0000271
	11	a=0.203864 k=0.001315 b=0.770087 g=0.017048 c=0.026050 h=2.166648	0.9999	0.0028552	0.0000116
	12	a=0.907427 c=0.001786 L=-0.431168	0.9690	0.0443083	0.0023097
	13	c=0.039834 L=-1.07117 n=0.739248	0.9942	0.0192279	0.0004350
	14	a=1.000707 k=0.021671 n=0.887668 b=0.000450	0.9998	0.0039072	0.0000191

Table A.9. Results of Fitted Models for Experiment 3.3

Exp. No.	Model No.	Model Constants	R^2	RMSE	χ^2
3.3	1	k=0.014666	0.9567	0.0488386	0.0025343
	2	k=0.045644 n=0.735725	0.9976	0.0114304	0.0001481
	3	k=0.015060 n=0.735725	0.9976	0.0114304	0.0001481
	4	a=0.913947 k=0.013151	0.9731	0.0384878	0.0016788
	5	a=0.826060 k=0.021842 b=0.153923	0.9984	0.0094827	0.0001092
	6	a=0.538386 k0=0.033479 b=0.455802 k1=0.006520	0.9996	0.0048334	0.0000306
	7	a=0.219328 k=0.052269	0.9905	0.0229189	0.0005953
	8	a=-0.013171 b=0.000052	0.9602	0.0468443	0.0024870
	9	a=0.526312 k=0.034929 b=0.193619	0.9995	0.0050563	0.0000310
	10	a=0.526284 k=0.034930 g=0.006763	0.9995	0.0050563	0.0000310
	11	a=0.728427 k=0.019678 b=0.174929 g=0.001495 c=0.096684 h=0.111054	0.9999	0.0022544	0.0000079
	12	a=0.913949 c=0.015652 L=-1.09096	0.9731	0.0384878	0.0017987
	13	c=0.038650 L=0.893119 n=0.735725	0.9976	0.0114304	0.0001587
	14	a=1.000772 k=0.033339 n=0.838954 b=0.000473	0.9999	0.0024400	0.0000078

Table A.10. Results of Fitted Models for Experiment 4.1

Exp. No.	**Model No.**	**Model Constants**	**R^2**	**RMSE**	**χ^2**
4.1	1	k=0.012859	0.9986	0.005932	0.0000365
	2	k=0.013344 n=0.991891	0.9987	0.006437	0.0000446
	3	k=0.012882 n=0.991949	0.9987	0.006431	0.0000445
	4	a=0.988229 k=0.012707	0.9988	0.006489	0.0000453
	5	a=0.997730 k=0.012030 c=-0.018215	0.9993	0.003161	0.0000112
	6	a=0.494108 k0=0.012707 b=0.494112 k1=0.012707	0.9988	0.006490	0.0000491
	7	a=0.019605 k=0.642972	0.9989	0.006922	0.0000516
	8	a=-0.009120 b=0.000021	0.9733	0.027140	0.0007932
	9	a=0.019607 k=0.632888 b=0.019917	0.9989	0.006922	0.0000537
	10	a=0.019590 k=42.96369 g=0.012606	0.9989	0.006921	0.0000537
	11	a=0.301929 k=0.012705 b=0.301991 g=0.012705 c=0.384301 h=0.012709	0.9988	0.006490	0.0000536
	12	a=0.988220 c=0.473561 L=6.104806	0.9988	0.006490	0.0000472
	13	c=0.038367 L=1.703141 n=0.991953	0.9987	0.006432	0.0000463
	14	a=0.993926 k=0.015552 n=0.946653 b=-0.000110	0.9995	0.004004	0.0000187

Table A.11. Results of Fitted Models for Experiment 4.2

Exp. No.	**Model No.**	**Model Constants**	**R^2**	**RMSE**	**χ^2**
4.2	1	k=0.011466	0.9964	0.007423	0.0000570
	2	k=0.016944 n=0.916406	0.9992	0.005778	0.0000358
	3	k=0.011681 n=0.916435	0.9992	0.005776	0.0000357
	4	a=0.961093 k=0,011000	0.9984	0.004614	0.0000228
	5	a=0.957254 k=0.011268 c=0.007670	0.9985	0.005263	0.0000308
	6	a=0.076186 k0=0.109823 b=0.923871 k1=0.010584	0.9997	0.004042	0.0000188
	7	a=0.071826 k=0.147881	0.9997	0.003970	0.0000169
	8	a=-0.008333 b=0.000018	0.9605	0.031024	0.0010312
	9	a=0.076135 k=0.109752 b=0.096438	0.9997	0.004042	0.0000182
	10	a=-0.014342 k=0.011466 g=0.011466	0.9964	0.007422	0.0000612
	11	a=0.789477 k=0.010584 b=0.134392 g=0.010584 c=0.076187 h=0.109817	0.9997	0.004042	0.0000204
	12	a=0.961080 c=0.053671 L=2.208913	0.9984	0.004612	0.0000236
	13	c=0.022310 L=1.162039 n=0.916441	0.9992	0.005776	0.0000371
	14	a=0.998112 k=0.020103 n=0.869039 b=-0.000105	0.9999	0.002390	0.0000066

Table A.12. Results of Fitted Models for Experiment 4.3

Exp. No.	Model No.	Model Constants	R^2	RMSE	χ^2
4.3	1	k=0.011128	0.9927	0.009070	0.0000853
	2	k=0.018442 n=0.892137	0.9977	0.008769	0.0000828
	3	k=0.011379 n=0.892200	0.9977	0.008765	0.0000827
	4	a=0.947645 k=0.010507	0.9968	0.006120	0.0000403
	5	a=0.944447 k=0.010683 c=0.005611	0.9968	0.006633	0.0000493
	6	a=0.089086 k0=0.167075 b=0.910913 k1=0.010088	0.9992	0.006391	0.0000476
	7	a=0.093476 k=0.107600	0.9991	0.006475	0.0000452
	8	a=-0.008417 b=0.000019	0.9614	0.028108	0.0008508
	9	a=0.089090 k=0.167060 b=0.060383	0.9992	0.006391	0.0000457
	10	a=0.089087 k=0.167077 g=0.010088	0.9992	0.006391	0.0000457
	11	a=0129080 k=0.089642 b=0.887623 g=0.009021 c=-0.017823 h=-0.002128	0.9997	0.003862	0.0000190
	12	a=0.947633 c=0.049094 L=2.161612	0.9968	0.006119	0.0000419
	13	c=0.001426 L=0.238402 n=0.892260	0.9977	0.008778	0.0000863
	14	a=0.996316 k=0.024728 n=0.808218 b=-0.000224	0.9996	0.004446	0.0000231

Table A.13. Results of Fitted Models for Experiment 4.4

Exp. No.	Model No.	Model Constants	R^2	RMSE	χ^2
4.4	1	k=0.010577	0.9883	0.017168	0.0003061
	2	k=0.016702 n=0.903174	0.9924	0.019319	0.0004031
	3	k=0.010770 n=0.903174	0.9924	0.019319	0.0004031
	4	a=0.948528 k=0.009993	0.9925	0.016711	0.0003016
	5	a=0.971343 k=0.009103 c=-0.035001	0.9933	0.013026	0.0001909
	6	a=0.475783 k0=0.009993 b=0.472745 k1=0.009993	0.9925	0.016711	0.0003278
	7	a=0.086718 k=0.110963	0.9947	0.017428	0.0003280
	8	a=-0.008083 b=0.000018	0.9590	0.029782	0.0009579
	9	a=0.084595 k=0.178978 b=0.053793	0.9949	0.017397	0.0003405
	10	a=0.084593 k=0.178995 g=0.009628	0.9949	0.017397	0.0003405
	11	a=0.361164 k=0.009993 b=0.360726 g=0.009993 c=0.226638 h=0.009993	0.9925	0.016711	0.0003591
	12	a=0.948541 c=0.001446 L=-0.380334	0.9925	0.016711	0.0003142
	13	c=0.002553 L=0.353428 n=0.903108	0.9924	0.019323	0.0004200
	14	a=1.003597 k=0.033486 n=0.706251 b=-0.000586	0.9995	0.004868	0.0000278

Table A.14. Results of Fitted Models for Experiment 4.5

Exp. No.	Model No.	Model Constants	R^2	RMSE	χ^2
4.5	1	k=0.014177	0.9851	0.012839	0.0001714
	2	k=0.029466 n=0.836971	0.9970	0.010172	0.0001121
	3	k=0.014831 n=0.836978	0.9970	0.010171	0.0001121
	4	a=0.925111 k=0.013050	0.9929	0.007502	0.0000610
	5	a=0.917297 k=0.013806 c=0.016642	0.9933	0.008989	0.0000913
	6	a=0.850600 k0=0.012007 b=0.149254 k1=0.139765	0.9990	0.006706	0.0000531
	7	a=0.152980 k=0.078981	0.9982	0.006634	0.0000477
	8	a=-0.009959 b=0.000026	0.9262	0.036631	0.0014536
	9	a=0.149395 k=0.139862 b=0.085848	0.9990	0.006706	0.0000508
	10	a=0.149394 k=0.139864 g=0.012007	0.9990	0.006706	0.0000508
	11	a=0.149258 k=0.139778 b=0.373121 g=0.012002 c=0.477473 h=0.012010	0.9990	0.006706	0.0000585
	12	a=0.925111 c=0.041440 L=1.781997	0.9929	0.007502	0.0000636
	13	c=0.079916 L=1.814955 n=0.836976	0.9970	0.010172	0.0001170
	14	a=0.998414 k=0.040506 n=0.744268 b=-0.000253	0.9997	0.003150	0.0000117

Table A.15. Results of Fitted Models for Experiment 5.1

Exp. No.	Model No.	Model Constants	R^2	RMSE	χ^2
5.1	1	k=0.018806	0.9965	0.0160432	0.0002717
	2	k=0.026658 n=0.916616	0.9990	0.0084996	0.0000807
	3	k=0.019170 n=0.916638	0.9990	0.0084996	0.0000807
	4	a=0.968849 k=0.018198	0.9978	0.0127311	0.0001811
	5	a=0.964292 k=0.018682 c=0.008419	0.9979	0.0124360	0.0001837
	6	a=0.912087 k0=0.017193 b=0.088424 k1=0.124999	0.9994	0.0064054	0.0000520
	7	a=0.074399 k=0.233604	0.9993	0.0069319	0.0000537
	8	a=-0.013457 b=0.000047	0.9595	0.0544932	0.0033189
	9	a=0.087930 k=0.124511 b=0.138083	0.9994	0.0064065	0.0000487
	10	a=0.087916 k=0.124523 g=0.017193	0.9994	0.0064065	0.0000487
	11	a=0.413701 k=0.017192 b=0.498377 g=0.017194 c=0.088430 h=0.124969	0.9994	0.0064054	0.0000600
	12	a=0.968847 c=4.078574 L=-14.9706	0.9978	0.0127311	0.0001925
	13	c=0.000301 L=-0.047156 n=0.807377	0.9937	0.0214531	0.0005465
	14	a=1.001524 k=0.032611 n=0.855091 b=-0.000201	0.9998	0.0028044	0.0000100

Table A.16. Results of Fitted Models for Experiment 5.2

Exp. No.	Model No.	Model Constants	R^2	RMSE	χ^2
5.2	1	k=0.021164	0.9958	0.0189416	0.0003844
	2	k=0.016860 n=1.056192	0.9967	0.0168101	0.0003261
	3	k=0.020950 n=1.056261	0.9967	0.0168100	0.0003261
	4	a=1.005566 k=0.021282	0.9958	0.0188462	0.0004098
	5	a=1.049156 k=0.018152 c=-0.062953	0.9989	0.0098573	0.0001215
	6	a=0.363830 k0=0.021282 b=0.641735 k1=0.021282	0.9958	0.0188462	0.0004843
	7	a=0.005394 k=3.901124	0.9957	0.0191642	0.0004238
	8	a=-0.015597 b=0.000064	0.9887	0.0309943	0.0011084
	9	a=-146.570 k=0.028855 b=0.997699	0.9972	0.0153939	0.0002962
	10	a=0.067813 k=0.021163 g=0.021165	0.9958	0.0189416	0.0004485
	11	a=0.335189 k=0.021281 b=0.335188 g=0.021282 c=0.335187 h=0.021282	0.9958	0.0188462	0.0005920
	12	a=1.005564 c=3.902765 L=-13.5421	0.9958	0.0188462	0.0004440
	13	c=0.107780 L=-2.40682 n=1.056261	0.9967	0.0168100	0.0003532
	14	a=0.996846 k=0.023473 n=0.946054 b=-0.000483	0.9991	0.0087976	0.0001055

Table A.17. Results of Fitted Models for Experiment 5.3

Exp. No.	Model No.	Model Constants	R^2	RMSE	χ^2
5.3	1	k=0.010827	0.9787	0.0349382	0.0012788
	2	k=0.024794 n=0.819095	0.9962	0.0147234	0.0002385
	3	k=0.010958 n=0.819126	0.9962	0.0147234	0.0002385
	4	a=0.943395 k=0.010100	0.9853	0.0290082	0.0009256
	5	a=0.866791 k=0.014864 b=0.128195	0.9997	0.0043851	0.0000223
	6	a=0.136152 k0=0.00025 b=0.859189 k1=0.015004	0.9997	0.0043814	0.0000235
	7	a=0.263191 k=0.030954	0.9966	0.0138989	0.0002125
	8	a=-0.009709 b=0.000029	0.9818	0.0323290	0.0011497
	9	a=0.840452 k=0.015520 b=0.055734	0.9996	0.0045452	0.0000239
	10	a=0.838750 k=0.015547 g=0.000910	0.9996	0.0045455	0.0000239
	11	a=0.303005 k=0.023503 b=0.012740 g=-0.008155 c=0.681873 h=0.009340	0.9997	0.0041414	0.0000236
	12	a=0.943766 c=0.000984 L=-0.312028	0.9853	0.0290085	0.0009744
	13	c=0.943384 L=0.048424 n=2.189665	0.9853	0.0290082	0.0009743
	14	a=0.999325 k=0.015751 n=0.952684 b=0.000435	0.9997	0.0040944	0.0000205