# DESIGN AND TESTS OF A GEOTHERMAL DRYER AND DETERMINATION OF QUALITY PARAMETERS OF DRIED PRODUCT

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# ABSTRACT

## DESIGN AND TESTS OF A GEOTHERMAL DRYER AND DETERMINATION OF QUALITY PARAMETERS OF DRIED PRODUCT

Drying which is a heat and mass transfer process between the product surface and its surrounding medium and within the product is practised to enhance the storage life and reduce transportation costs of products. Olive leaves are the plants which have been used for medicinal purposes are often dried before use. Renewable energy sources such as geothermal energy can be used in drying processes as heat source besides fossil fuels. The temperature and the thermal potential of geothermal resources in Turkey is high enough to be used in drying process. In this thesis, a geothermal cabinet type drier was constructed and placed in Balcova-Narlidere geothermal field. To be able to determine drying parameters (temperature and velocity) and whose effects on drying kinetics of olive leaves and on the quality parameters of dried olive leaves (antioxidant content and phenolic content), drying experiments were carried out at three different air temperatures (40, 50 and 60 °C) and at three air velocities (0.5, 1, 1.5 m/s). During the experiments temperature, relative humidity and velocity of drying air was measured and recorded. Then, using the measured data drying time, drying rate, moisture ratio and effective diffusivity was determined and moisture ratio was modelled using thin-layer models. The quality parameters which are total antioxidant activity and total phenolic content were determined using spectrophotometric techniques. To evaluate the performance of the dryer, energy and exergy analyses were conducted. The drying time was determined as 240 – 555 min. (4 – 10) hour which is quite short comparing with open air sun drying. Optimum drying air temperature and velocity which gives the minimum total phenolic content and antioxidant loss value were determined by response surface methodology as 50 °C and 1 m/s, respectively. The energy utilization was found 0.3316 kW and the energy utilization ratios were found 50.36% and 7.96% for the case at drying air is re-circulated and the case at drying air was no re-circulated, respectively.

# ÖZET

## BİR JEOTERMAL KURUTUCUSUNUN TASARIMI VE TESTLERİ İLE KURUTULMUŞ ÜRÜNÜN KALİTE PARAMETRELERİNİN BELİRLENMESİ

Kurutma, ürünün iç kısmı, yüzeyi ve onu çevreleyen ortam arasında meydana gelen ısı ve kütle transferi olup, ürünün depolama ömrünü artırmak ve taşıma maliyetini azaltmak için kullanılan bir yöntemdir. Zeytin yaprağı, genellikle kullanımından önce kurutulan ve asırlardır tedavi amacı ile kullanılan bir bitkidir. Jeotermal enerji gibi, yenilenebilir enerji kaynakları kurutma işleminde ısı kaynağı olarak kullanılabilir. Türkiye'de mevcut olan jeotermal kaynaklar, kurutma işleminde kullanılmak için uygun bir potansiyele sahiptir. Bu tez çalışmasında, kabin tipi jeotermal kurutucusun imalatı yapılarak, Balçova-Narlıdere jeotermal sahasına yerleştirilmiştir. Sıcaklık ve hava hızı gibi etkin kuruma parametrelerinin, zeytin yaprağının kuruma kinetiği ve kurutulmuş zeytin yapraklarının (antioksidan ve fenolik madde) gibi kalite parametreleri üzerindeki etkilerini incelemek amacı ile (40, 50 ve 60 °C) hava sıcaklıklarında ve (0,5, 1, 1,5 m/s) hava hızlarında deneyler gerçekleştirilmiştir. Deneyler sırasında, hava sıcakılığı, bağıl nemi ve hava hızı ölçülmüş ve kaydedilmiştir. Daha sonra, ölçülen değerler kullanılarak kuruma süresi, kuruma hızı, boyutsuz nem oranı, efektif diffüzivite belirlenmiş ve ince tabaka modelleri kullanılarak boyutsuz nem oranı modellenmiştir. Antioksidan ve fenolik madde gibi kalite parametreleri, spektrometrik teknik ile belirlenmiştir. Enerji ve exerji yöntemleri kullanılarak kurutucunun performansı incelenmiştir. 240-555 dakika (4 - 10) saat ile, açık havada güneş altında kurutmaya göre oldukça kısa bir kurutma süresi gözlemlenmişir. Minimum antioksidan ve fenolik madde kaybını veren optimum kuruma havası sıcaklığı cevap yüzey yöntemi kullanılarak 50 °C ve 1 m/s bulunmuştur. Enerji kullanımı 0,3316 kW ve enerji kullanım oranı havanın sirküle edildiği durumda % 50,36, edilmediği durumda ise % 7,96 bulunmuştur.

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# LIST OF SYMBOLS

| | |
|---|---|
| a,b,c,g,h, L,$k_0$,$k_1$ | Model constant |
| A | Area, $m^2$ |
| AC | Total antioxidant activity loss, % |
| $c_p$ | Specific heat, kJ $kg^{-1}$ $K^{-1}$ |
| D | Diffusion coefficient, $m^2$ $s^{-1}$ |
| DR | Drying rate, g water $g^{-1}$ dm $s^{-1}$ |
| EU | Energy utilization, kJ $s^{-1}$ |
| EUR | Energy utilization ratio, % |
| Ex | Exergy, kJ $s^{-1}$ |
| h | Enthalpy, kJ $kg^{-1}$ |
| L | Thickness of product, mm |
| M | Moisture content, g water $g^{-1}$ dm |
| m | Mass, kg |
| $\dot{m}$ | Mass flow rate, kg $s^{-1}$ |
| MR | Moisture ratio, |
| P | Pressure, kPa |
| PC | Total phenolic content loss, % |
| Q | Heat, kJ $s^{-1}$ |
| r | Re-circulation |
| RH | Relative humidity, % |
| RMSE | Root mean square error |
| s | Specific entropy, (kJ $kg^{-1}$ $K^{-1}$) |
| SEE | Standard error of estimate |
| t | Time, min |
| T | Temperature, (°C) |
| TAC | Total antioxidant capacity |
| TPC | Total phenolic content |
| V | Velocity m $s^{-1}$ |
| W | Work, kJ $s^{-1}$ |

## Greek Symbols

| | |
|---|---|
| $\varepsilon$ | Exergetic efficiency |
| $\theta$ | Relative humidity (%) |
| $\omega$ | Absolute humidity (kg water $kg^{-1}$) |
| $\psi$ | Specific exergy, (kJ/kg) |

## Subscripts

| | |
|---|---|
| *cr* | Cross-sectional |
| *da* | Drying air |
| *dest* | Destruction |
| *e* | Equilibrium |
| *eff* | Effective |
| *env* | Environment |
| *exp* | Experimental |
| *f* | Final |
| *he* | Heat exchanger |
| *i* | Initial |
| *in* | Inlet, inflow |
| *0* | Dead (reference) state |
| *out* | Outlet, outflow |
| *sat* | Saturated |
| *t* | At time t |
| $\Delta t$ | Time interval |

# CHAPTER 1

# INTRODUCTION

Herbal, medicinal and aromatic plants have been widely used for preventing and treating specific ailments and diseases provide the raw material for the food, cosmetic and pharmaceutical industries to produce spice, essential oils and drugs (Öztekin et al., 1999; Öztekin and Martinov, 2007).

Antioxidants are the substances which have the capability of delaying of inhibiting oxidation of the substrate. Oxidants which cause the oxidation of the substrate are formed as a normal product of aerobic metabolism. Antioxidant functionality can be evaluated under three classes: prevention, interception and repair. Besides giving colour and sensory characteristics to the plant, they are more importantly responsible for the antioxidant activity of many plant components and extracts. The main dietary sources of phenolic compounds which are fruits, vegetables and beverages show a wide range of beneficial biological effects such as antioxidant, anti-inflammatory, antiproliferative, anti-atherogenic properties, antihypertensive and cholesterol lowering effect (Shaidi et al., 2010; Nadour et al., 2012).

Furthermore, antioxidant additives are very important tools in food processing and food preservation methods. Although synthetic antioxidant compounds are cheap and effective, due to their suspected carcinogenesis effect, the importance of the natural antioxidant has increased as bioactive components of foods (Farag et al., 2003).

Olive tree leaves have beneficial effect on human metabolism such as combating fevers and other diseases which are attributed to the phenolic compounds structure (Benavente - Garcia et al., 2000; Bouaziz and Sayadi, 2005). The most abundant phenolic compounds present in olive leaves are oleuropein and hydroxytyrosol. Oleuropein which presents in high amounts in unprocessed olive fruit and olive leaves has an antimicrobial activity and it also prevents from cardiac disease by protecting membrane lipid oxidation and by affecting coronary blood vessel dilation. Hydroxytyrosol which is more abundant in the processed olive fruit and olive oil also prevents cardiac and tumoral diseases and prevent diabetic neuropathy (Somova et al., 2003; Tan et al., 2003; Ferreira et al., 2007; Sato et al., 2007; Sing et al., 2008).

Olive leaves are used as raw materials for therapeutic and cosmetic purposes by the extraction of active phenolic compounds which have antioxidant activity. Many homoeopathic remedies are sold as capsules containing the dried olive leaves. Drying of olive leaves is the most important process prior to consumption and extraction by reducing moisture content and avoiding the interference of water to the process (Soysal and Öztekin, 2001; Bahloul et al., 2009a).

Although conventional drying methods such as open air sun drying is still the most common method in the World, is not suitable for drying of herbs and spices due to contamination with dust, soil and insects. Furthermore, unmanageable drying parameters such as temperature and velocity which causes over drying results in loss of quality of dried product. Therefore, the drying process should be undertaken in closed and controlled environment such as hot air dying in a tunnel or cabinet dryer. An improvement in the quality of dried product and decrease in time necessitates better technical drying process which results in a huge amount of thermal and electrical energy use. Therefore, use of renewable energy sources such as solar and geothermal energy plays an important role in the utilization of controlled conventional drying methods (Garg et al., 2001; Fargali 2008).

Exports of dried fruit in Turkey reaches a worth of 100 million US dollars that account for 1.01 percent of Turkey's overall export (Figure 1.1) (iib, 2012).

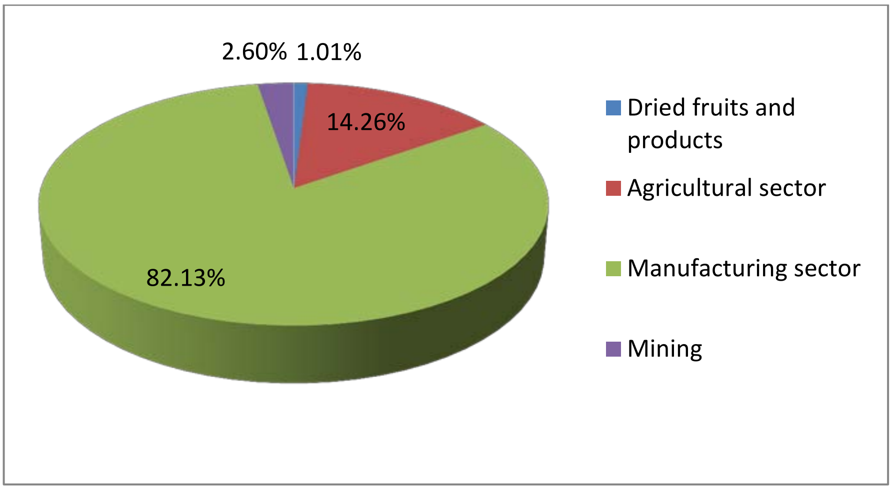


Figure 1.1. Portion of dried fruits and products exports into the overall exports in Turkey (Source: iib, 2012)

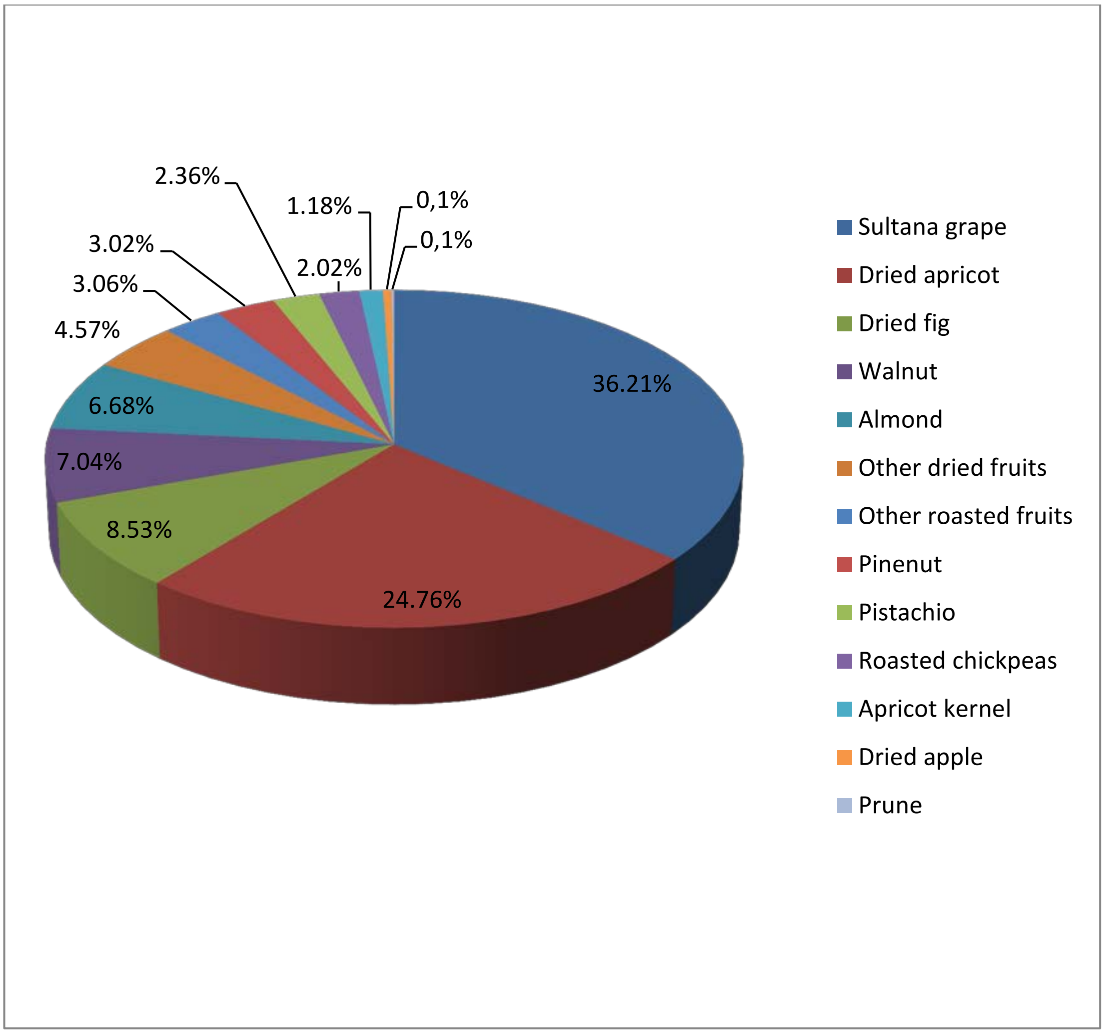


Figure 1.2. Various exported fruits and products in Turkey
(Source: iib, 2012)

The various dried fruits and products being exported were represented in Figure 1.2. Sultana grape and dried apricot have a significant share in the exported dried fruit products of Turkey. Furthermore, tomato, mushroom, aubergine, squash, leek, okra and onion are the vegetables being exported in Turkey. There is no information related with the exportation of herbal and medicinal plants were found.

Geothermal energy which is known as the thermal energy of the earth is one of the renewable energy sources. With respect to the temperature of heat source, geothermal energy can be used for electricity generation or direct use applications (Figure 1.3) (Lund et al., 2010).

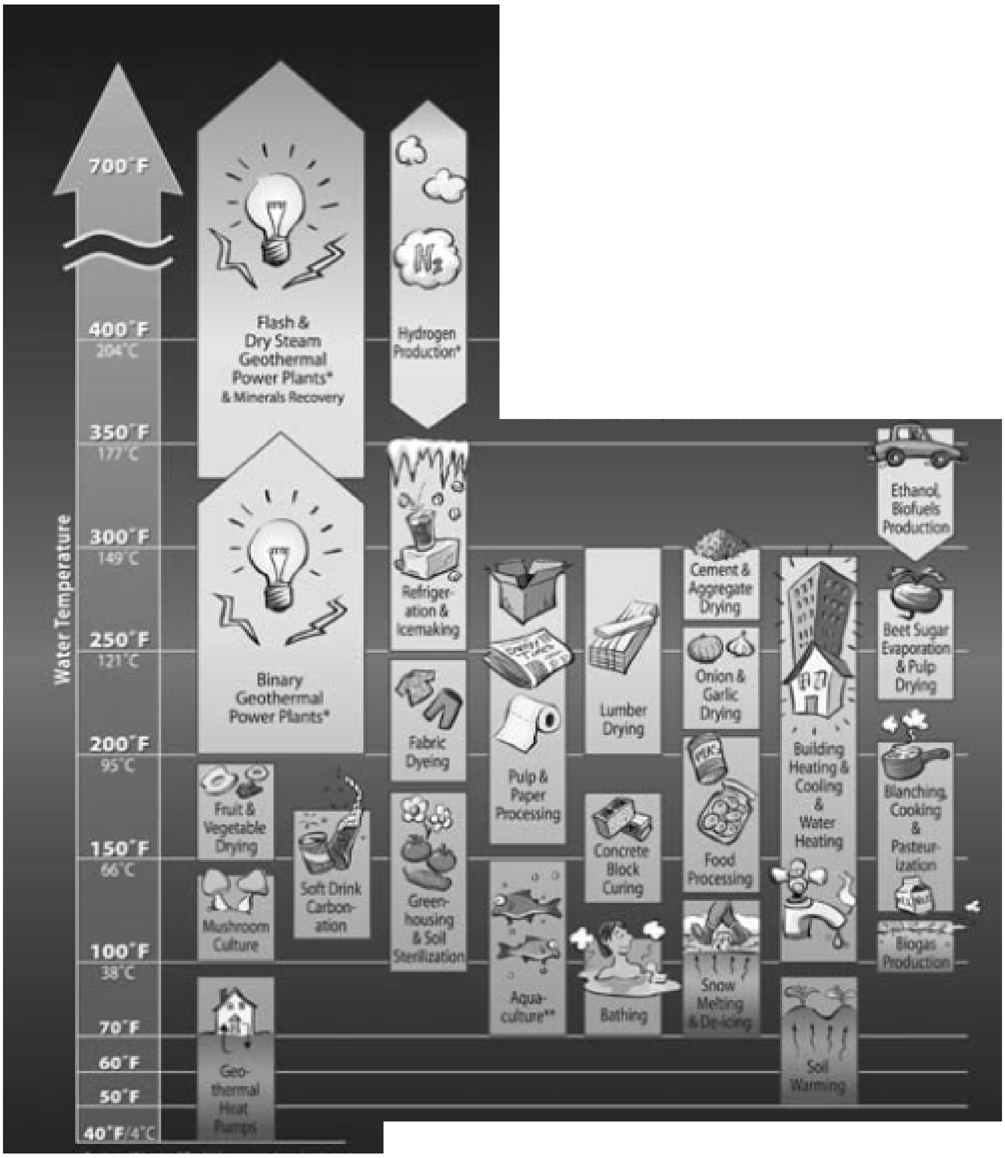


Figure 1.3. Geothermal energy uses based on the temperatures
(Source: Lund, 2010)

As it can be seen from the Figure 1.3, the temperature of various drying applications range from 60 °C to 150 °C depending upon the product to be dried. According to the Lund et al. (2010) space heating, geothermal heat pumps, greenhouse heating, cooling/snow melting, bathing and swimming, agricultural drying, industrial uses, and aquaculture are the types of direct use applications of geothermal energy being used worldwide. The total installed direct use capacity and total energy direct use breakdown of the World are shown in Figure 1.4 and Figure 1.5, respectively.

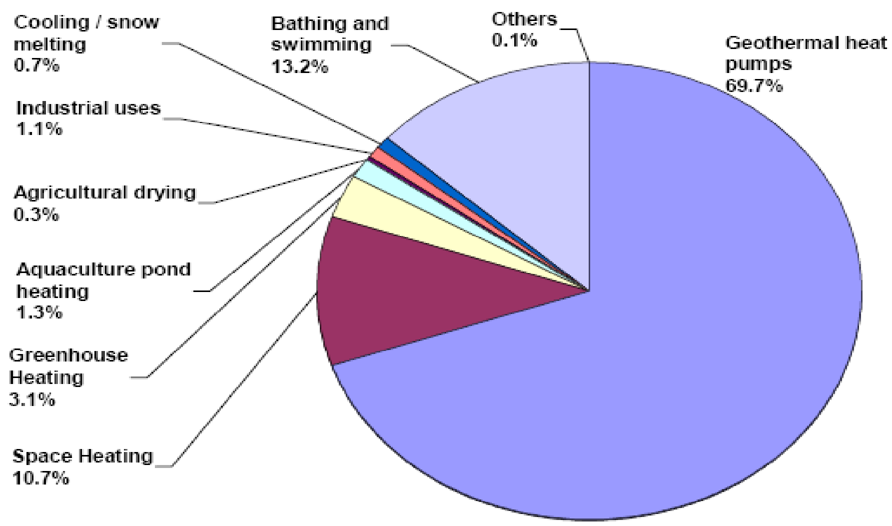


Figure 1.4. Total geothermal direct use installed capacity breakdown of the World (Source: Lund et al., 2010)

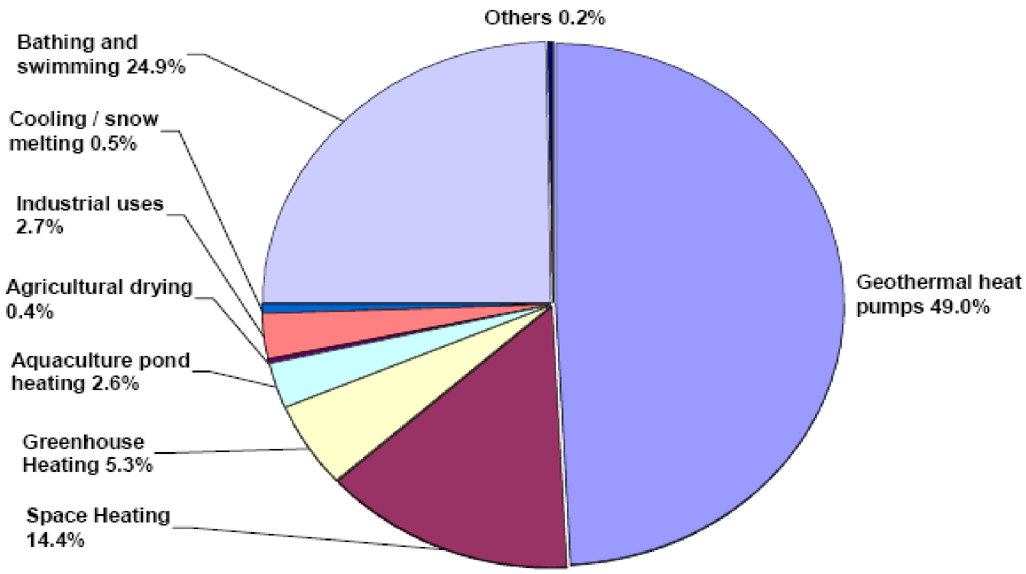


Figure 1.5. Total geothermal direct use breakdown of the World (Source: Lund et al., 2010)

Figure 1.4 and Figure 1.5 indicates that agricultural drying has a small share in both total energy use (0.4%) and total installed capacity (0.3%) of the World.

Turkey is ranked in 5$^{th}$ place in the World with 2084 $MW_t$ geothermal direct use installed capacity. District and individual space heating, thermal facilities (bathing, swimming, SPAs), greenhouse heating and geothermal heat pumps are the main geothermal direct use application in Turkey (Figure 1.6).

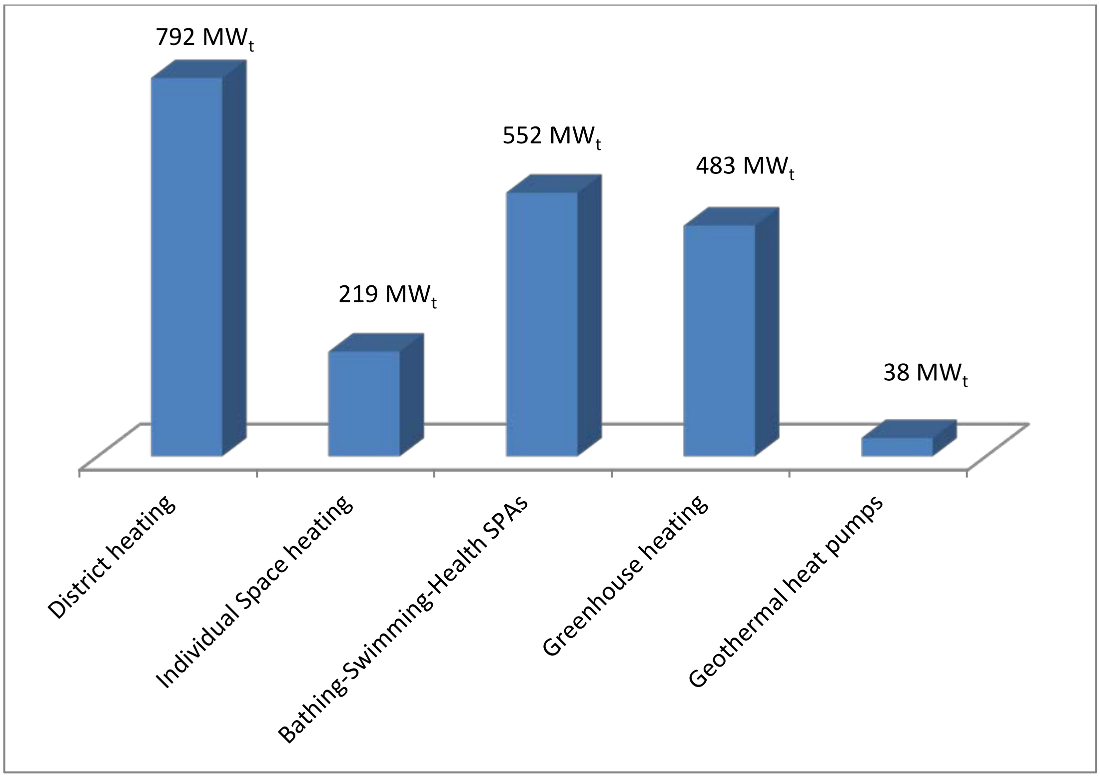


Figure 1.6. Geothermal direct use applications in Turkey
(Source: Satman et al., 2010)

Although the thermal potential of geothermal resources in Turkey is high enough to be used in drying process, there has not any company, using geothermal energy for drying process, established yet except for Taze Kuru Gida Company in Kizilcahamam, Turkey.

In this study, geothermal cabinet type drier was constructed and placed in Balçova-Narlıdere geothermal field. To determine drying parameters (temperature and velocity) and observe the effects of these parameters on drying kinetics of olive leaves and on the quality parameters of dried olive leaves, drying experiments were carried out.

*Balçova-Narlıdere Geothermal Field*

Balçova-Narlıdere geothermal field is located 7 km west from the Izmir city centre and 1 km south from the Izmir - Çesme highway. The system is the largest district heating application in Turkey with a heating capacity of 159 $MW_t$ including 2,470,000 $m^2$ heating capacity and 15,660 subscribers. The district heating system is fed by 13 production wells with a temperature of 85 - 44 °C. The geothermal fluid is injected back to the reservoir after use by 6 injections wells.

Balcova-Narlidere district heating system consists of a geothermal fluid production cycle, a closed loop cycle where the clean city water flows through the infrastructure and a distribution cycle to the end users (Figure 1.7).

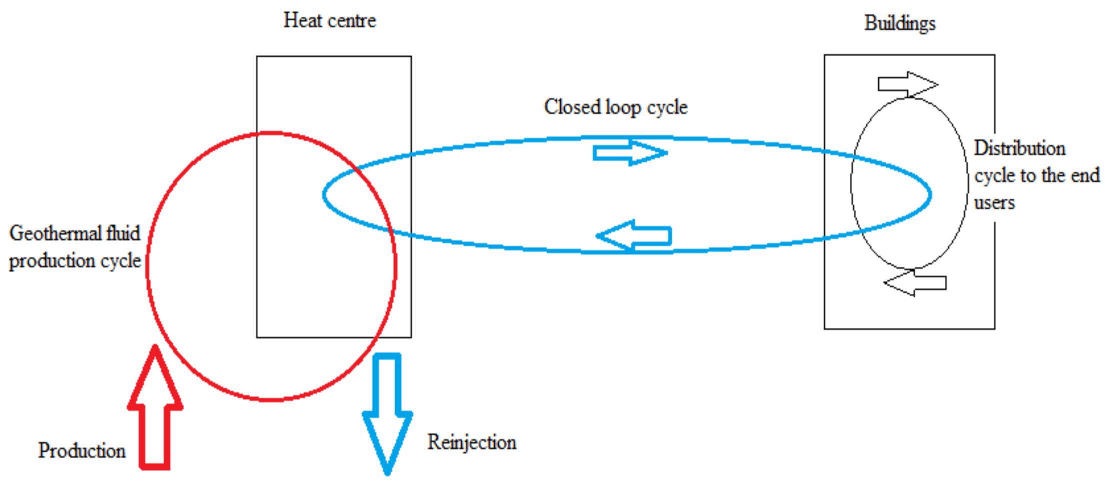


Figure 1.7. District heating system process
(Source: Özdiler and Sayik, 2011)

The system is operated by 14 heat centres and two pump stations. The geothermal fluid gathered from the 13 production wells first mixed in the mixing chamber in order to bring the temperature of mixture from 120 °C down to 99 °C. Then the fluid is transmitted to the heat exchangers where the heat is transferred to the clean city water. The geothermal fluid exits the heat exchangers at a temperature of approximately 60 - 62 °C where a portion is blended with the incoming geothermal brine and the rest is injected back into the reservoir. The heated water is distributed by a pipe network to the heat exchangers located at each building. Temperature gauges and control valves at each building are utilized to monitor and control the amount of water needed to heat the building. Figure 1.8 provides a schematic diagram for the Balcova-Narlidere district heating system (Çelen, 2012).

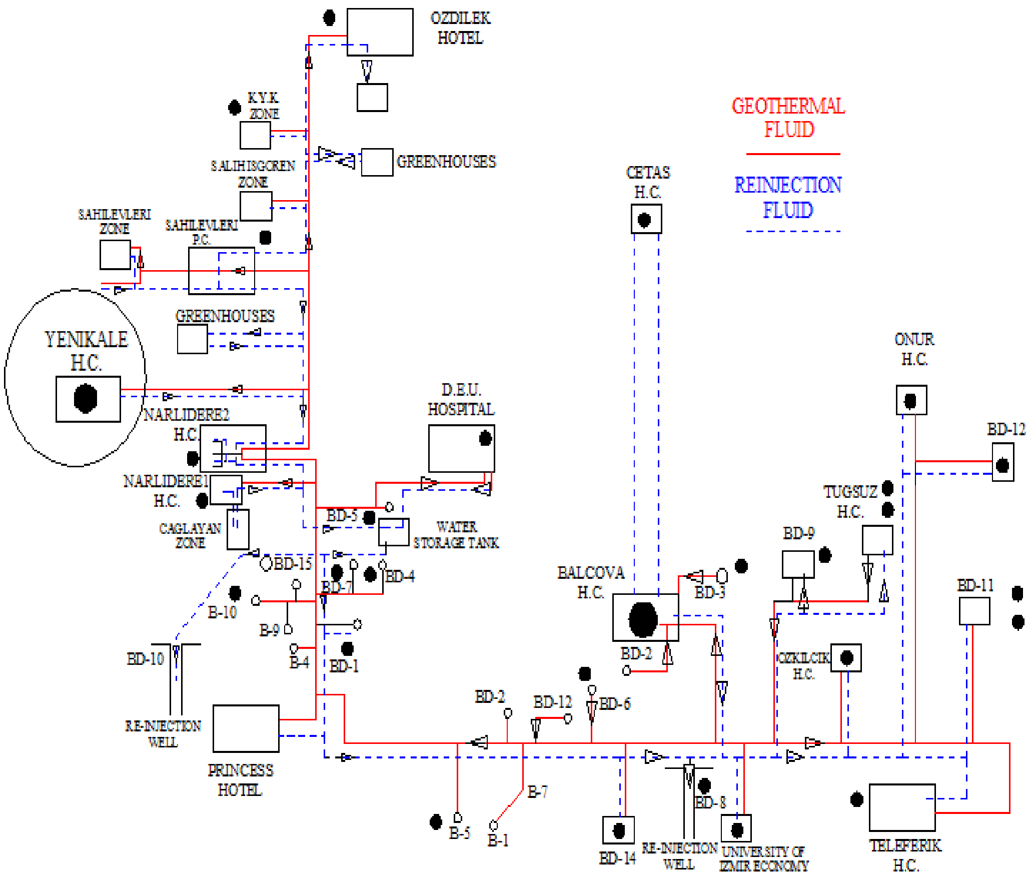


Figure 1.8. A schematic diagram of Balcova-Narlidere geothermal district heating system (Source: Çelen, 2012).

To fulfil the objectives were mentioned above

Chapter 2, deals with a literature survey on drying of herbal and medicinal plants and types of renewable energy sources that used in drying applications.

In Chapter 3, the principles of drying, drying mechanism, drying methods and types of dryers were explained.

Chapter 4, describes the experimental unit and procedure of the experiments to determine the drying characteristics of olive leaves. Quality parameters of dried olive leaves were defined and to evaluate the performance of the dryer energy and exergy analysis methods were also represented in Chapter 4.

In Chapter 5, the results gathered from the experiments, for the drying characteristics of olive leaves and quality of dried olive leaves and energy and exergy analysis were discussed.

In Chapter 6, the conclusions are stated.

# CHAPTER 2

# LITERATURE REVIEW

Drying which is a heat and mass transfer process between the product surface and its surrounding medium and within the product is practised to enhance the storage life and to reduce transportation costs of products (Dutta et al., 1998; Leon et al., 2002). Drying processes range from the open air sun drying to industrial (mechanized) drying.

Open air sun drying of products which is used to denote the exposure of a commodity to direct solar radiation and convective power of wind has been practised since ancient times (Best, 1978). Most of the studies conducted under open air were aimed to determine the drying kinetics of products (Doymaz, 2005; Akpınar, 2006; Jain and Pathare, 2007) while Njie and Rumsey (1997) compared the drying rates of cassava chips in sheet-metal trays and in wire mesh. Open air sun drying has many disadvantages such as spoilt products due to the rain, loss of product due to the birds and animals, high labour costs, large area and time requirement. Therefore, in industrialized regions open air sun drying has been replaced by mechanized drying which uses much less land, gives a better quality of product and less drying time. On the other hand, these drying equipment require considerable quantities of fuel to operate. Environmental pollution caused by the emission effects of $CO_2$ and high energy costs are the main drawbacks of fuels which provide thermal energy required to heat incoming drying air (Imre, 2006; Sharma et al., 2009).

Alternatively, renewable energy sources such as solar and geothermal energy can be used in drying processes as heat source. Solar dryers differ from the open air sun drying in which a simple construction of a structure is often used to enhance the insulation effect of the sun and minimizes losses of the collected energy to the surrounding (Boonthunjindal, 1980). Solar drying has advantages on traditional open air sun drying such as enhancing drying times, requiring smaller surface for the same quantity of product, increasing the productivity loading the dryer within few hours, being hygienic since the products are dried in a controlled environment. Many researchers compared the drying characteristics of drying products under open air and solar dryer and concluded that solar drying reduce the drying time considerably (Akpınar et al., 2006; Akpınar, 2010; Tunde – Akintunde, 2011).

Solar driers can be categorized into direct and indirect solar driers. In direct solar driers, the material to be dried is directly exposed to the solar radiation. Guine et al. (2007), investigated the drying of four cultivars of pears in a direct solar drier. The study showed that if the drying process is carried out inside the drier there is no need to interrupt it when adverse atmospheric conditions arise like night moist and rainfall event. Gbaha et al. (2007), designed a direct type solar drier then tested experimentally to analyze the behaviour of the dryer. The influence of the significant parameters such as solar incident radiation and drying air mass flow was analyzed in order to evaluate the dryer thermal performance for cassava, banana and mango drying. The results showed that drying air temperature was the main factor influencing the drying kinetics. The drying rate increased with drying air temperature and drying air mass flow. In indirect solar driers, solar radiation is not directly incident on the material. Yaldız and Ertekin (2001), investigated thin layer solar drying of various vegetables such as pumpkin, green pepper, stuffed pepper, green bean and onion and determined the mathematical models for drying curves of each vegetable with the effect of drying air velocity using an indirect solar drier. As a result of this study the approximation of diffusion model for pumpkin and green pepper drying, the two-term model for stuffed pepper and onion drying and lastly Page model for green bean drying was found the best fitted models of solar drying behaviours of examined products. Sreekumar et al. (2008), described the development and testing of an indirect type solar drier, particularly meant for drying vegetables and fruits and investigated its performance so as to optimize the design parameters. They had reported that the developed dryer could be well utilized in the domestic sector, and small farmer can also derive benefit from it. Furthermore to optimize energy use in solar driers several studies reported on energy and exergy analysis of solar drying (Midilli and Kucuk, 2003; Akpinar, 2010; Chowdury et al., 2011).

Heat pumps are the devices that use air, ground or water as heat source, increase the temperature of the heat source by adding work and use this higher temperature source where it is necessary. Heat pumps became popular for space heating and cooling and are also used for drying purposes since 1990s.

Solar assisted heat pump systems where the solar collectors are used to increase the heat source temperature to possess a higher coefficient of performance (Best et al., 1994;

Hawlader et al., 2003; Hawlader and Jahangeer, 2006). Li et al. (2011), tested a solar assisted heat pump dryer combined with energy storage system and conducted the performance analysis of the system.

The daily and seasonal changes of solar intensity, limited time that sun is available during the day make the drying process intermittent for solar drying. Geothermal resources can be used directly or indirectly, are good alternatives to the solar energy. As stated by Lund et al. (2010), the use of geothermal energy for drying several grains, vegetables and fruit crops was reported by fourteen countries. Examples include: seaweed (Iceland), onion (USA), wheat and other cereals (Serbia), fruit (El Salvador, Guatemala and Mexico), Lucerne or alfalfa (New Zealand), coconut meat (Philippines) and timber (Mexico, New Zealand and Romania).

Geothermal fluids can be directly used spraying steam over the dried products or indirectly by a heat exchanger or heat pumps. Kumoro and Kristano (2003), conducted a research into the drying of tobacco leaves using geothermal steam as a heat source. Also effect of the steam velocity on the drying rate of tobacco leaves was investigated. Results showed that the increase of steam flow rate can improve the drying performance. Andiritsos et al. (2003), investigated a tomato drying system in Greece where the geothermal water enters to the water-air heat exchanger to heat the drying air and discussed the possibilities of using geothermal energy for drying traditional agricultural products in the Aegean islands. As a result of this study such a geothermal drying unit seemed to be quite flexible regarding to the product to be dried and low-temperature geothermal energy can be used efficiently to dry many agricultural products. Hirunlabh et al. (2004), designed an industrial dryer and found out the appropriate drying conditions using geothermal hot water from the geothermal power plant in Thailand.  Also, cost analysis of the drying system was conducted. The air circulated through the drying installation at a constant rate. By altering the flow rate of the incoming geothermal hot water which enters to the water to air heat exchanger temperature of the drying air was controlled. As a result of this study such dryers offer an alternative for drying as the resulting costs are reasonable and the system operation is independent from weather conditions. Tesha (2006), designed and constructed a geothermal tray dryer and placed Lahendong geothermal field. Fluid-air heat exchanger was used to transfer the energy from brine water to air. Experimental results showed that, utilizing the energy from brine water, large number of products can be dried continuously indoors throughout the whole year. Sumotarto (2007), investigated a simulation study of beans and grains drying by using a geothermal dryer which would be implemented and technically feasible in Kamojang geothermal field, Indonesia.

A ground source heat pump which absorbs heat from the ground and uses it to heat working fluid then working fluid transfers its heat to drying air. Hancıoglu and Hepbaslı (2007), presented exergetic assessment of a ground source heat pump drying system which was designed, constructed and tested in the Solar Energy Institute of Ege University, Izmir,Turkey. Kuzgunkaya and Hepbaslı (2007), studied the exergy analysis of drying process of laurel leaves and the effects of drying air temperature on exergy losses and exergetic efficiencies were examined. Colak et al. (2008), investigated an exergy analysis of a a single layer drying process of a mint leaves in a ground source heat pump.

Medicinal and aromatic plants which provide raw materials for the food, cosmetic and pharmaceutical industries to produce spice, essential oils and drugs necessitate drying process for the preservation and avoid quality losses (Muller et al., 1989; Soysal and Oztekin, 2001). Many researchers determined the drying kinetics and investigated the effects of drying air conditions such as temperature, velocity and relative humidity on the drying behaviour of the various medicinal and aromatic plants such as mint leaves (Akpınar, 2006; Ozbek and Dadalı, 2007; Colak et al., 2008; Therdthai and Zhou, 2009), parsley leaves (Berset and Caniaux, 1983; Soysal, 2004; Akpınar et al., 2006), purslane (Kashaninejad and Tabil, 2004), basil (Ozcan et al., 2005), bay leaves (Demier et al., 2004; Gunhan et al., 2005). On the other hand, studies on olive leaves drying are limited and reported since 2000’s.

Lebert et al. (1992), conducted the drying of mint leaves and the effect of drying air conditions such as temperature, velocity and relative humidity on the drying kinetics of mint leaves were presented. Yagcıoglu et al. (1999), investigated the effects of drying air temperature and drying air velocity on drying behaviours of bay leaves. It was found that air velocity had significance effect on the drying of bay leaves. Park et al. (2002), dried mint leaves at various drying air velocity and various drying air temperature and investigated the effects of these conditions on the effective diffusivity. It was found that the effective diffusivity increased as air temperature and air velocity increased. Doymaz (2005), observed the effect of drying air temperature on the drying time of drying mint leaves. His results demonstrated that drying time reduced as the drying air temperature increased. Doymaz et al. (2006), determined the effect of drying air temperature on drying time and colour of dried dill and parsley leaves. They showed that drying air temperature was an effective parameter for the drying of dill and parsley leaves.

Olive leaves are the medicinal plants which have been used for medicinal purposes for centuries are often dried before use. Bahloul et al. (2008), studied solar drying characteristics of four varieties of olive leaves and the effective moisture diffusivity of the olive leaves were determined. Erbay and Icier (2009a), investigated the main effects of drying air temperature, drying air velocity and drying time on the product quality during hot air drying of olive leaves and determined the optimum process conditions for drying of olive leaves in a tray drier. Erbay and Icier (2009b), studied the main effects of same process variables on product quality during heat pump drying of olive leaves and optimisation study was conducted to determine optimum process conditions. Bahloul et al. (2009b), investigated the effects of solar drying conditions (drying air temperature and velocity) on drying time and on quality parameters such as colour, total phenols and radical scavenging activity of four varieties of olive leaves. The results verified that the total phenols and radical scavenging activity influenced mainly by drying conditions and tended to decrease with increased drying time. Erbay and Icier (2010a), discussed the importance of olive leaves and its major phenolic compounds on human health. They had reported that phenolic compounds in olive leaves may have many beneficial effects on human health because of their high antioxidant capacity. Erbay and Icier (2010b), determined the effects of drying air temperature and air velocity on the drying behaviours of olive leaves. It was found that drying rate of olive leaves was influenced mainly by drying air temperature. Finally, Erbay and Icier (2010c), investigated the energy utilization of the drying of olive leaves in a tray drier and evaluated the performance of tray drying process by exergy analysis depending upon drying air temperature and velocity. As a result of this study, lower drying air temperature and higher air velocity led to higher exergetic efficiencies. Medicinal plants are dried mostly in open air and solar type driers. Since the range of drying temperature is between 30 °C and 50 °C, low temperature geothermal resources and the waste water of direct use applications can be used to operate dryers. Although, geothermal resources of Turkey is mostly low to medium temperature range (40 – 100 °C) which are quite suitable for drying applications, only a few commercial applications is in the knowledge of the author but no research has been reported.

The main objective of the Thesis is to test a cabinet type drier in a geothermal field where the waste water of a district heating system is the energy source for the drier. Waste water of a district heating system is the energy source for the dryer. Waste water transfers its heat to the drying air in a heat exchanger. Olive leaves are chosen as the product to be dried because of its increasing popularity in various industries. To be able to preserve quality parameters (total phenolic content and total antioxidant activity) the two variables of drying process, temperature and velocity were optimised, effective diffusivity was determined. Furthermore, energetic and exergetic efficiency of the dryer was evaluated for two different dryer configuration.

# CHAPTER 3

# DRYING

## 3.1. Fundamentals of Drying

Drying which can be described as the removal of liquid from a solid involves simultaneous heat and mass transfer. The heat which is transferred from a heating medium to material in the course of convection, conduction, radiation or any combinations of these mechanisms increases the temperature of wet solid and supplies the required latent heat of vaporisation for both the surface water and the water inside the product. Heat transfer which occurs inside the product structure is related to the temperature gradient between the product surface and the water surface at some location within the product. Mass transfer, mainly the movement of internal moisture to the surface of the product, is a function of pressure differential between the vapour in the product and the vapour in the surrounding atmosphere (Figure 3.1).

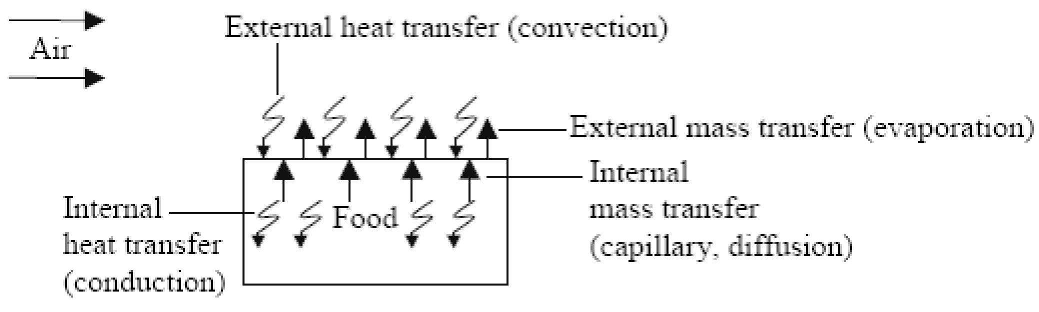


Figure 3.1. Heat and mass transfer in drying process
(Source: Aguilera and Stanley, 1990; Heldman and Hartel, 1997)

The transfer of energy (mainly as heat) from the air to the product and the transfer of vapour from the product surface to the air is a function of the existing vapour pressure, temperature gradients and the superiority of the convective coefficients at the product surface. While the heat transfer is limited by thermal conductivity of the product structure, mass transfer is proportional to the molecular diffusion of water vapour in air and both occurs at the molecular level within the product structure (Andales, 1981; Singh and Heldman, 2009). Various changes in product can take place due to the physical or chemical transformation during the drying process. Physical changes occur include colour, texture, and deterioration of aroma compounds or degradation of nutritional substances of the product. Thus, drying method and physiochemical changes which occur during the dehydration process affect the quality of the dried product (Achanta and Okos 1995).

### 3.1.1. Conditions Affecting the Rate of Moisture Removal

There are many factors which affects the rate of moisture removal during the dehydration process can be grouped into two categories: factors depending on the process conditions and depending on the food sample conditions.

***Process Conditions***

Temperature, relative humidity and the velocity are the essential factors depend on the process conditions. As the temperature difference between the drying air and the product increases, driving force for moisture removal which can be described as water-vapour pressure gradient between the product surface and the drying air will increase. Although this results in shorten overall drying time, extremely high drying air temperatures may cause quality loss such as colour. Relative humidity, mainly the amount of moisture in the air influence the moisture removal from the product though its effect on external mass transfer. As the relative humidity of drying air increases, the vapour pressure or water concentration gradient between the food surface and its surrounding air decreases then this results in a lessen the rate of external mass transfer. On the other hand, a decrease on the relative humidity of drying air enhances the rate of mass transfer. Another factor which effects the moisture removal is the velocity of drying air. The greater velocity of drying air will take greater amounts of moisture away from the drying surface of the food (Hallstrom, 1992; Young, 1996; Heldman and Hartel, 1997).

***Food Sample Conditions***

Smaller thickness of the product means a shorter distance for moisture migration to the surface before evaporating and also slight pieces have a larger surface area available for evaporation relative to their volume. Thus slicing or dicing into smaller pieces with high surface area will ease drying. Moisture may migrate on different directions depending upon the food microstructure. For example, moisture is removed more easily from intercellular spaces than from within the cells since there is an additional resistance to water migration across the cell boundary (Heldman and Hartel, 1997; Fellows, 2000).

## 3.2. Drying Mechanism

To determine the drying rate, Moisture Ratio, (MR) at specific temperatures plays a key role to understand mechanism of moisture loss during the drying of any product. This 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 Figure 3.2, the moisture content is plotted over the drying time. Starting from the left-hand side, the points A and A' represents the initial conditions for a cold and hot material at zero time. In the beginning, if the solid is at a colder temperature than its ultimate temperature, the rate may start at point A. On the other hand, if it is quite hot to start with, the rate may start at point A'. Section AB represents the transition period during which the solid surface conditions come into equilibrium with the drying air. This period usually is quite short and it is often neglected in the analysis of times of drying. The second section BC, is known as the *constant-rate period*. In this period, the surface of the product is very wet and saturated with free water and this result in the removal of free water from the surface. This water is entirely unbound water which can be described as the moisture in excess of the equilibrium moisture content corresponding to saturation humidity. In constant-rate period the rate of moisture migration from the interior to the surface under the given air conditions is independent of the solid and at least as high as the evaporation rate at the surface. This fast liquid migration to the surface is attributed to the capillary transport of water, which is more rapid than diffusion. Point C where the constant-rate period ends is known as critical moisture content. The drying period beyond this point is termed as *falling-rate period*, can be divided into different two sub-periods. Section CD represents the first falling rate period where the moisture migration from the interior of the product to the surface is less than the rate of evaporation from the surface. The surface of the product in no longer wetted, and wetted are continually decrease until point D. Surface of the product is completely dry at point D where the second falling rate period starts. This periods ends at the equilibrium point where the vapour pressure of the food and partial vapour pressure of the drying air becomes equal. This stage represents the level which product can be dried under given drying conditions. The same points are marked up in Figure 3.3, where the drying rate is plotted against the moisture contents (Geankoplis, 1993; Rizvi, 1995; Heldman and Hartel, 1997; Fellows, 2000; Saravakos and Kostaropoulos, 2002)

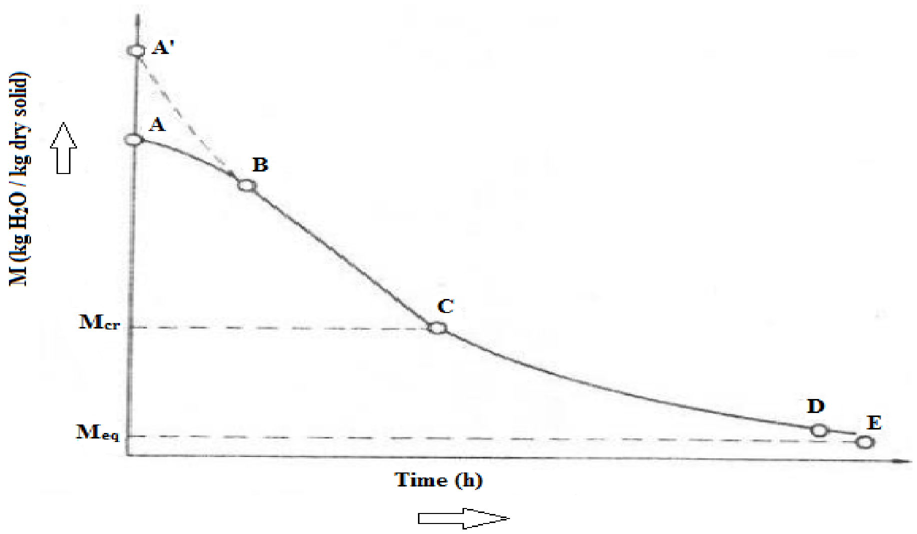


Figure 3.2. Moisture content versus drying time
(Source: Rizvi 1995 and Geankoplis 1993)

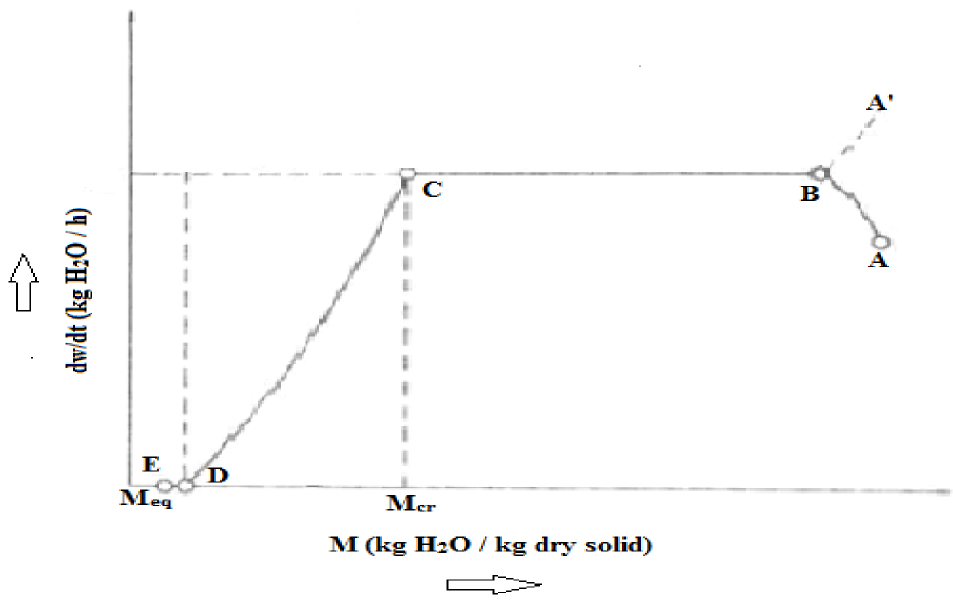


Figure 3.3. Drying rate versus moisture content
(Source: Rizvi 1995 and Geankoplis 1993)

## 3.3. Drying Technology

Many different types of drying methods and drying equipment were developed due to the diversity of food products in drying technology. Drying techniques including sun drying, osmotic drying, microwave drying and hot air drying are as follows;

### 3.3.1. Sun and Solar Drying

In this method the term *sun drying* is used to describe the process where the energy for drying of foods is supplied by direct radiation from the sun. On the other hand, the term *solar drying* is used to describe the process where the solar collectors are used to heat air to dry the food by convection.

Sun drying is used to dry fruits, vegetables, meat and fish for centuries in which the fruit or vegetable pieces are spread on the ground while strips of meat and fish are hung on racks. Although sun drying has the advantages of simplicity and the small capital investment, contamination by insects, birds and animals, uncertainty of the weather like rain, requiring large areas, and long drying time are the main drawbacks of this method.

### 3.3.2. Hot Air Drying

Hot air drying which is one of the simplest and most economical methods is used to dry most of the fruits and vegetables. In addition, it is easy to set and control the optimum drying conditions in this method. Different types of driers such as tunnel, cabinet, kiln, bin and conveyor have been designed, made and commercially used based on this technique. In this method wet material which is placed in a chamber of dryer is brought into contact with the heated air. Electricity, fossil fuels or renewable energy resources such as solar and geothermal energy are the main sources to heat the drying air (Jayaraman and Das Gupta, 2006).

### 3.3.3. Microwave Drying

Microwave drying uses radio frequency energy and interactions of chemical constituents of food to generate the heat inside the food materials. Penetrating quality which affects a uniform heating of materials upon which radiation impinges is one of advantages of microwave drying. Selective absorption of the radiation by liquid and capacity for easy control are the other advantages (Jayaraman and Das Gupta, 2006).

### 3.3.4. Spray Drying

Spray drying which means the transformation of a feed from a fluid state into a dried form by spraying into a hot, dry medium is the most important method for drying liquid food products. The applications of spray drying to fruit and vegetable products are very limited. Fruit juices, pulps, and pastes can be spray dried with additives (Jayaraman and Das Gupta, 2006).

## 3.3.5. Freeze Drying

Freeze drying provides an alternative approach for moisture removal when the product quality is an important factor for consumer acceptance. Freeze drying is carried through reducing the product temperature so that most of the product moisture is in solid state, and by decreasing the pressure around the product, sublimation of ice can be achieved (Singh and Heldman, 2009).

## 3.3.6. Tray or Cabinet Dryers

Trays or similar product holders are used to expose the product to heated air in an enclosed space. Heated air is brought into contact with the product which is placed inside a cabinet or similar enclosure to facilitate dehydration. Small size and versatility are the main features of these dryers. On the other hand, non-uniform drying of a product at different locations within the system are main disadvantages. The schematic illustration of a cabinet type tray dryer is shown in Figure 3.4 (Sokhansanj and Jayas, 2006).

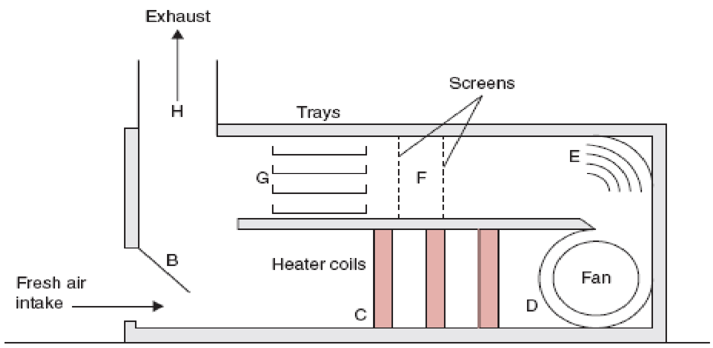


Figure 3.4. Schematic illustration of a cabinet type tray dryer
(Source: Singh and Heldman, 2009).

## 3.3.7. Tunnel Dryer

In tunnel dryers, the heated drying air is introduced at one end of the tunnel and moves at an established velocity through trays of products being carried on trucks (Figure 3.5). The product trucks are moved through the tunnel at a rate required to ensure the residence time needed for drying. The drying characteristic of these dryers depends on the movement of airflow relative to the movements of truck, which may move parallel to each other either concurrently or counter currently. Compared to the others tunnel dryers are more simple and versatile (Singh and Heldman, 2009).

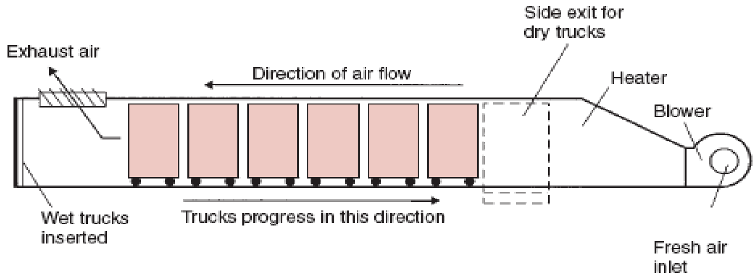


Figure 3.5. Schematic illustration of a tunnel dryer
(Source: Singh and Heldman, 2009)

### 3.3.8. Fluidized Bed Dryer

Fluidized bed dryers are used extensively for the drying of wet particulate and granular materials in which the product pieces are suspended in the heated air throughout the required for drying (Figure 3.6). The principle of the movement of product relies on the change in mass of individual particles as moisture is evaporated. Good solids mixing, high rates of heat and mass transfer and easily material transport are the advantages of Fluidized Bed Dryer. Conversely, the size of particles that will allow efficient drying is the primary limitation.

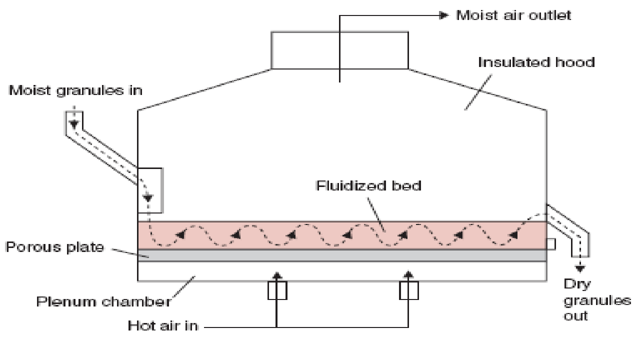


Figure 3.6. Schematic illustration of fluidized bed dryer
(Source: Singh and Heldman, 2009)

## 3.3.9. Rotary Dryer

Rotary dryers are grouped as direct, indirect-direct, indirect basing on the method of heat transfer. Direct rotary dryer which is the most common design, consist of a cylindrical shell, set an angle to the horizontal. Direct rotary dryers are suitable for low- and medium- temperature operations which are limited by the strength characteristics of the metal and the feed material must consist of relatively small particles (Brennan, 2006).

# CHAPTER 4

# MATERIALS AND METHODS

A cabinet type dryer was constructed to test in a geothermal field. Drier includes a water-to-air heat exchanger where the energy of geothermal fluid or waste of district heating system is transferred to the drying air. The geothermal fluid is chosen as Balçova-Narlıdere geothermal field where the geothermal district hating system exists. Since geothermal fluid temperatures are much higher than necessary for a drier, waste water from district heating system was decided to be used. The dryer was placed one of the heat centres, Yenikale heat centre. A schematic diagram of the heat centre and the connection of the drier to the waste water line were shown in Figure 4.1. Heat centres are the stations where geothermal fluid (1) transfers its heat by primary plate type heat exchangers (2), to the clean city water (3) which circulates through the city and provides heat to the buildings. Besides heat exchangers, heat centre houses circulations pumps for both city water and geothermal fluid. In Yenikale heat centre, the clean city water returns to the heat exchanger (4) at a temperature of 62-65 °C where the dryer heat input is supplied (5). The drier is called ‘‘geothermal drier’’ because of its energy source.

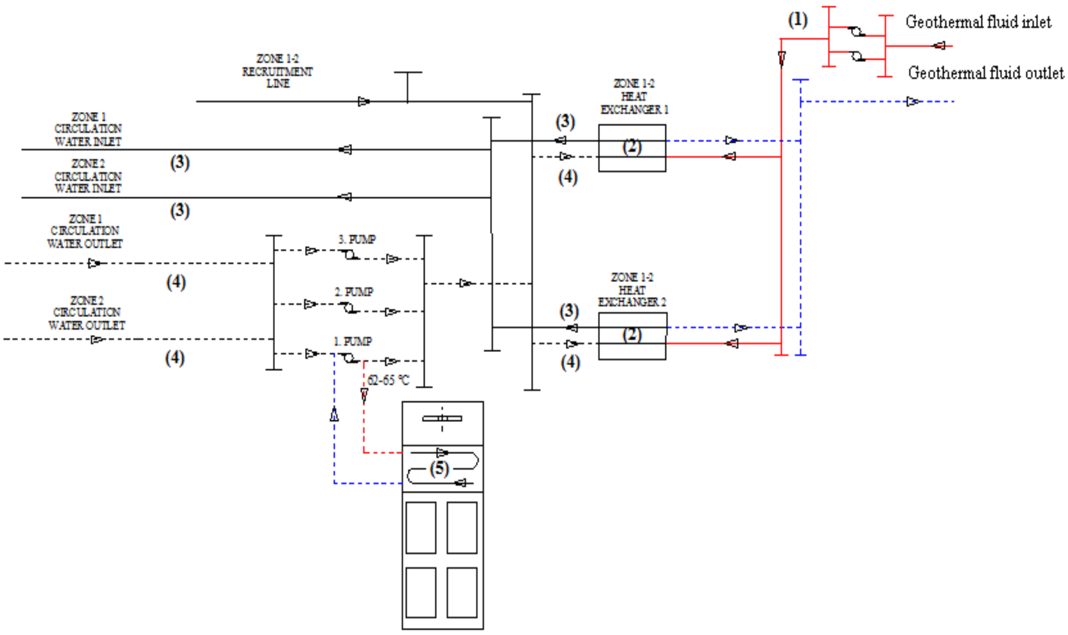


Figure 4.1. A schematic diagram of geothermal dryer at Yenikale Heat Centre
(Source: Çelen, 2012)

Olive leaves (Olea europaea L.) which were dried in the dryer were collected from the trees in the Izmir Institute of Technology Campus area (Figure 4.2). Drying experiments were carried out with a drying temperature range of (40-60 °C) and a drying air velocity range of (0.5 - 1.5 m/s). Under defined drying air conditions, effects of temperature and velocity of drying air on drying kinetics of olive leaves were determined. Effective moisture diffusivity was calculated by taking account of temperature and air velocity. The moisture ratio values were fitted to 13 thin layer drying models and the models constants were obtained. Thereafter, total phenolic content loss and total antioxidant loss were computed to determine the quality of dried product. In the course of the experiments, drying air temperature and relative humidity inside and outside of the drier and drying air velocity were measured and recorded to evaluate the performance of the drying process using energy and exergy analyses.

Figure 4.2. Olive trees in the Izmir Institute of Technology Campus area

## 4.1. Experimental Set-up

The geothermal dryer (Figure 4.3 - 4.4) is a cabinet dryer, consists of three sections; the fan unit, heating unit and drying tunnel sections. A schematic diagram and 3D view of the dryer were given in (Figure 4.5 - 4.6), respectively.

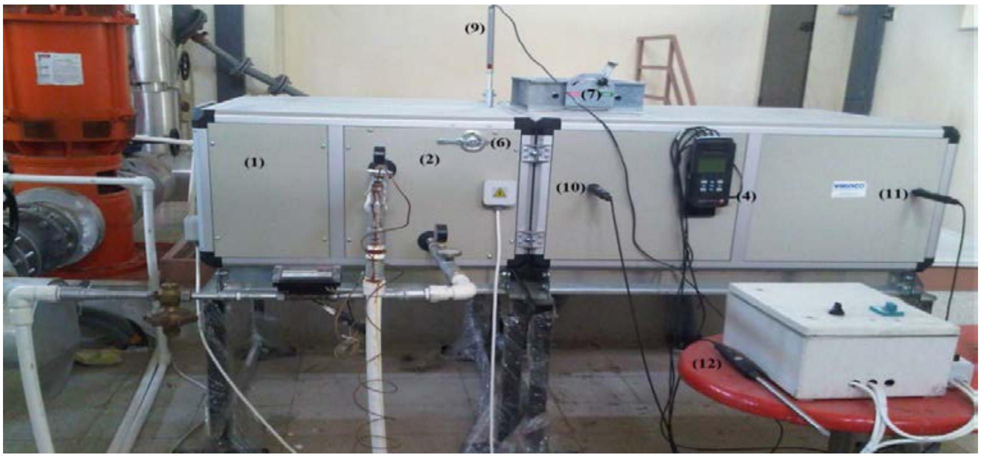


Figure 4.3. A view of geothermal drier


Figure 4.4. A view of drying trays

As seen in Figure 4.5, drying air is regulated by centrifugal fan (1) which draws the ambient into the dryer. The ambient air is mixed with re-cycled air before entering the water –to-air heat exchanger (2). The heated air leaving the heat exchanger reaches tot he drying chamber (4) which was made of approximately 1’’ plywood.

The inner surface of the dryer is insulated by fibber glass and covered with an aluminium sheet in order to reduce heat losses. The dryer contains 6 trays (3) which are 600 mm in length and 500 mm in width and there is an air re-circulating unit (5) to recover the exhaust air. The clean water returning to the primary heat exchanger in the Yenikale heat centre is directed to the dryer heat exchanger (Figure 4.1) as a heat source.

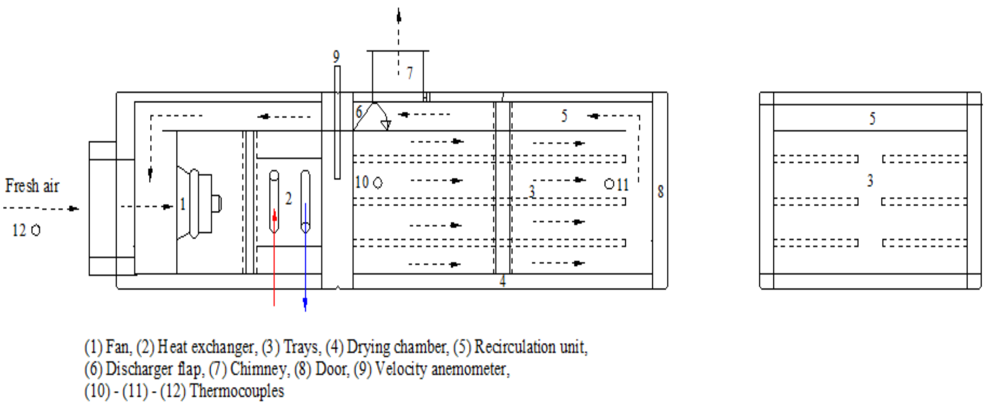


Figure 4.5. Schematic view of geothermal dryer

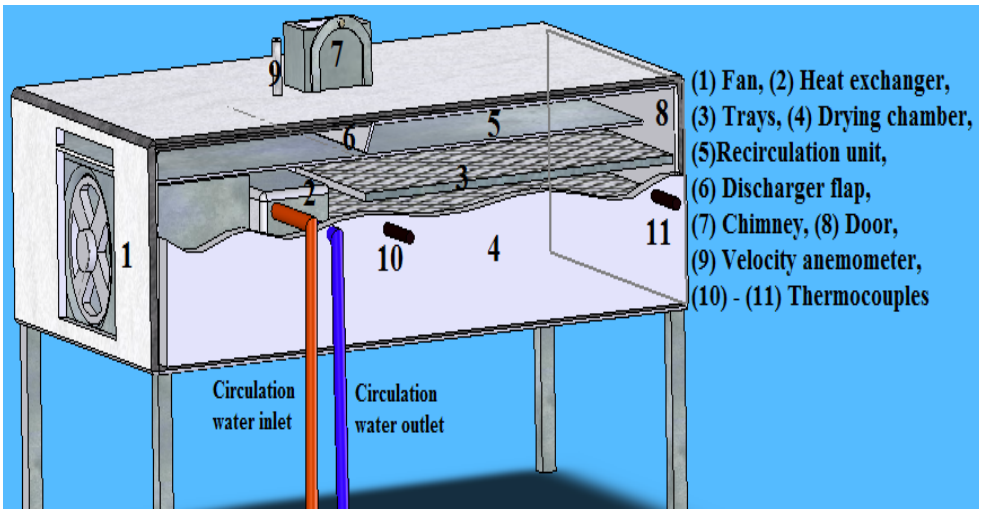


Figure 4.6. 3D view of the geothermal dryer

The finned coil water to air heat exchanger which has a total heating capacity of 24.26 kW consists of copper tubes with a high density of aluminium fins. The heat from the clean city water was dispersed through the copper tube walls via the aluminium fins which were attached to the copper tube coils so air temperature rises and the heat is transferred to the drying air (Figure 4.7). To be able to set various drying air temperatures (40, 50, 60 °C) during the experiments, mass flow rate of the clean city water is regulated by a globe valve. After use, clean city water is directed back to the heat exchanger (4).

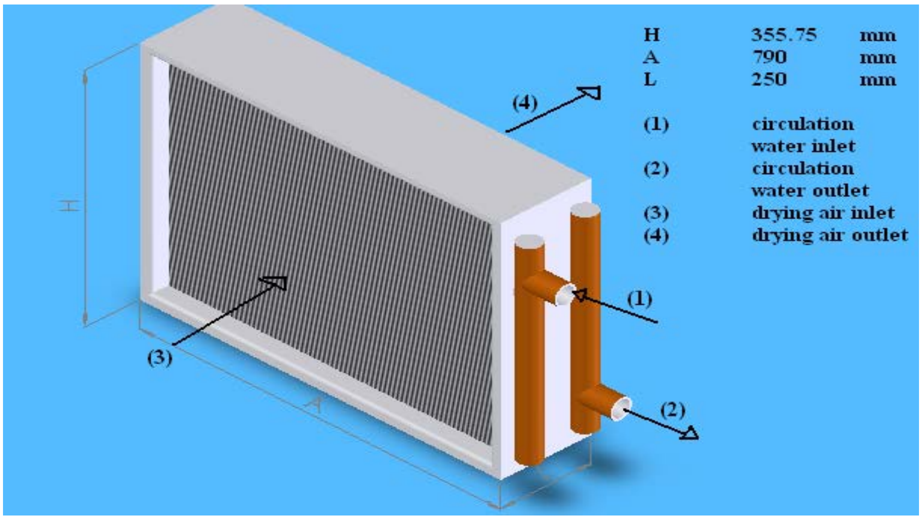


Figure 4.7. Detail of finned coil water to air heat exchanger

The basic technical data for the geothermal drier and geothermal fluid are listed in Table 4.1 and Table 4.2, respectively.

Table 4.1. Technical data for clean city water

| | | |
|---|---|---|
| Height of drier | mm | 554 |
| Width of drier | mm | 1100 |
| Length of drier | mm | 2000 |
| Width of tray | mm | 500 |
| Length of tray | mm | 600 |
| Thickness of each tray | mm | 20 |
| Distance between each tray | mm | 100 |
| Space of re-circulating unit | mm | 210 |
| Tray height from the floor | mm | 720 |
| Number of trays | | 6 |
| Critical area of dryer | $m^2$ | 0,3474 |

Table 4.2. Technical data for circulation water

| **Properties** | **Unit** | **Range** |
|---|---|---|
| Temperature | °C | 62-65 |
| Volumetric flow rate | $m^3$/min | 0.12-0.23 |

During the experiments, temperature [ambient (12), tray inlet (10), tray exit (11)], relative humidity [ambient (12), tray inlet (10), tray exit (11)] and velocity [tray inlet (9)] data were measured and recorded by a data logger. The locations of the sensors are shown in (Figure 4.3) and technical data of the measurement devices are given in (Table 4.3 and 4.4).

Table 4.3. Specification of measuring devices

| Dryer components | | |
|---|---|---|
| Instrument | Make | Model |
| Heat Exchanger | Termokar | 32×28 -1/2” 9T 6NR 790A 2,3P 3NC |
| Fan | ebmpapst | R2E 280 AE-52 -05 |
| | | Sheet aluminium |
| **Temperature and relative humidity measurements** | | |
| Instrument | Make | Model |
| Temperature and relative humidity probes | Testo | 350 M/XL |

Table 4.4. Specification of laboratory devices

| Quality measurements | | |
|---|---|---|
| Instrument | Make | Model |
| Shaking water bath | Memmert | |
| Spectro | Shimadzu | UV-Vis-2450 |
| **Weight measurements** | | |
| Instrument | Make | Model |
| Digital balance | Denver Instrument | SI-234 |

## 4.2. Experimental Procedure

### 4.2.1. Raw Material

Olive leaves (Olea europaea L.) were collected from the olive trees grown in the IZTECH campus (Izmir, Turkey), (Figure 4.8) and were stored for 3-5 days in the air proof plastic tubes at 4 °C.

Figure 4.8. Collection of olive leaves which were collected from the trees

Before conducting each experiment, collected leaves were washed (Figure 4.9) with tab water and filtered through a filter paper to remove the excess water on the surface.

Figure 4.9. Cleaning of olive leaves

### 4.2.2. Initial Moisture Content

The samples were dried in a drying oven at 105 °C until constant weight in order to determine the initial moisture content (AOAC, 1999). The sample weight was measured by analytical balance with a precision of ± 0.001 gr. The amount of moisture content was calculated using the Equation 4.1, given below

$$M_i = \frac{m_i - m_f}{m_i} \times 100 \tag{4.1}$$

$m_i$ and $m_f$ represents the weight of samples before and after the drying in the oven respectively. Moisture content was reported as wet-basis (w-b) percentages.

### 4.2.3. Drying Experiments

Drying experiments were conducted in March, April and May, 2012. Collected leaves were spread on to the trays as a thin layer (Figure 4.10). Approximately a mass of 150 g fresh olive leaves was used for each drying experiment. To determine the effects of drying air temperature and drying air velocity, drying experiments were carried out at 3 different drying air temperatures of 40-50-60 °C and 3 different drying air velocities of 0.5 - 1 - 1.5 m/s.

Figure 4.10. Distribution of olive leaves on a tray

The leaves were dried until the drying rate reached zero when the moisture content of the leaves were about 4-6% (w-b). Each experiment repeated twice for the reliability of the results. To determine changes in weight of leaves, a digital weighing apparatus (±0,01 g) was used during the drying process (Figure 4.11).


Figure 4.11. Weighing of olive leaves

### 4.2.4. Modelling of Thin Layer Drying Curves

To investigate the drying characteristic of olive leaves at different drying air temperatures and drying air velocities, dimensionless moisture ratio (MR) is modelled by thin layer modes exist in the literature (Table 4.5).

$$MR = \frac{M - M_e}{M_i - M_e} \quad (4.2)$$

where M, $M_e$, $M_0$ indicates the moisture content of product at each moment (t), equilibrium moisture content and initial moisture content of the product, respectively. The values of $M_e$ are relatively small when compared to M or $M_i$ for long drying times. Thus, Equation 4.2 can be simplified as;

$$MR = \frac{M}{M_i} \quad (4.3)$$

Table 4.5. Thin layer drying models

| No | Model Name | Model | Reference |
|---|---|---|---|
| 1 | Lewis | MR= exp(-k*t) | Wang et al., 2007a |
| 2 | Page | MR= exp(-k*(t^n)) | Diamente and Bruno, 1993 |
| 3 | Modified Page | MR= exp(-(k*t)^n) | Wang et al., 2007b |
| 4 | Henderson & Pabis | MR= a*exp(-k*t) | Ertekin and Yaldiz, 2004 |
| 5 | Logarithmic | MR= a*exp(-k*t)+c | Togrul and Pehlivan, 2002 |
| 6 | Two Term | MR= a*exp(-k0*t)+b*exp(-k1*t) | Akpinar and Bicer, 2003 |
| 7 | Two Term Exponential | MR= a*exp(-k*t)+(1-a)*exp(-k*a*t) | Ertekin and Yaldiz, 2004 |
| 8 | Wang & Singh | MR=1+a*t+b*(t^2) | Togrul and Pehlivan, 2002 |
| 9 | Approximation of Diffusion | MR= a*exp(-k*t)+(1-a)*exp(-k*b*t) | Akpinar and Bicer, 2003 |
| 10 | Verma *et al.* | MR= a*exp(-k*t)+(1-a)*exp(-g*t) | Akpinar et al., 2003 |
| 11 | Modified Henderson & Pabis | MR= a*exp(-k*t)+b*exp (-g*t)+c*exp(-h*t) | Ertekin and Yaldiz, 2004 |
| 12 | Modified Page 2 | MR= exp(-k*(t/(L^2)^n)) | Togrul and Pehlivan, 2002 |
| 13 | Midili & Kucuk | MR= a*exp(-k*(t^n))+b*t | Midilli et al., 2002 |

To test the validity of the mathematical models to experimental data, the correlation coefficient ($R^2$) is one of the most convenient criteria. In addition to $R^2$ (Equation 4.4), root mean square error (RMSE) (Equation 4.5) and Standard error of estimate (SEE) (Equation 4.6) were used to determine the quality of the fit.

$$R^2 = 1 - \frac{\sum_{i=1}^{N}(MR_{pred} - MR_{exp})^2}{\sum_{i=1}^{N}(\overline{MR}_{pred} - MR_{pred})^2} \tag{4.4}$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}|MR_{pred} - MR_{exp}|^2} \tag{4.5}$$

$$SSE = \sqrt{\frac{\sum_{i=1}^{N}(MR_{exp} - MR_{pred})\,2}{N-n}} \tag{4.6}$$

## 4.3. Determination of Effective Moisture Diffusivity

Drying characteristic of products in the falling rate period can be described by using Fick's diffusion equation. The solution of Fick's equation for the products with slab geometry is shown in Equation 4.7.

$$MR = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left(-\frac{(2n+1)^2\pi^2 D_{eff}t}{4L^2}\right) \tag{4.7}$$

Equation 4.7 may further be simplified to Equation 4.8 by considering only the first term of the series solution.

$$MR = \frac{8}{\pi^2}\exp\left(-\frac{\pi^2 D_{eff}t}{4L^2}\right) \tag{4.8}$$

Taking the natural logarithm of both side of the Equation 4.8 yield a linear function;

$$\ln MR = \ln\frac{8}{\pi^2} - \left(\frac{\pi^2 D_{eff}t}{4L^2}\right) \tag{4.9}$$

Therefore, $D_{eff}$ can be obtained from the slope of the graph of ln MR versus drying time;

$$Slope = \frac{\pi^2 D_{eff}}{4L^2} \tag{4.10}$$

## 4.4. Quality Measurements

The quality parameters of the dried olive leaves were indicated by determining the total phenolic content (TPC) and total antioxidant capacity (TAC) of olive leaves.

### 4.4.1. Total Phenolic Content

The dried samples collected at the end of each experiment were stored for 2-3 days in the air proof plastic tubes at 4°C. To extract phenolics the conventional extraction procedure was used. 4:1 vol/vol, ethanol-water mixture were placed and left to the stand for 24 h under agitation at 40°C in a shaking water bath in the dark (Bouaziz and Sayadi ,2005). The total phenolic content loss of olive leaves extracts was determined at 765 nm using the Folin-Ciocalteu method of Singleton and Rossi (1965). The average of the three-replicate measurements was calculated and by using these results the total phenolic content loss (PC) relative to raw olive leaves was calculated.

$$PC = \frac{TPC_{raw} - TPC_{dried}}{TPC_{raw}} \times 100 \quad (\%) \qquad (4.11)$$

### 4.4.2. Total Antioxidant Capacity

Improved ABTS radical cation decolorization assay was conducted using the ABTS radical by the method given in Re et al. (1999). The ABTS free radical cation was obtained by treating 7 mM ABTS solution with 2.45 mM potassium persulfate. The radical solution was diluted with 5 mM pH 7.4 phosphate buffer containing 150 mM NaCl (PBS) until its absorbance reached 0.700 units at 734 nm. The reaction mixture was prepared by mixing 20 µl of olive leave extract with 2 ml of ABTS radical cation solution. The absorbance of each reaction mixture was then monitored and recorded for 6 minutes. To calculate the AUC, the percent inhibition / concentration values for the extracts and trolox were plotted separately against test periods. The division of the areas of curves for each legume water extract to that of trolox was used to calculate the AUC value. All measurements were repeated three times and and total antioxidant activity loss (AC) according to raw olive leaves were calculated.

$$AC = \frac{TAC_{raw} - TAC_{dried}}{TAC_{raw}} \times 100 \qquad (\%) \qquad (4.12)$$

## 4.5. Energy and Exergy Analyses

Energy and exergy analysis were conducted by Engineering Equation Solver (EES) software (EES, Inc. 2012), using measured temperature, relative humidity and velocity data at tray inlet, outlet and environment. Figure 4.12 shows the flow diagram of energy and exergy analysis.

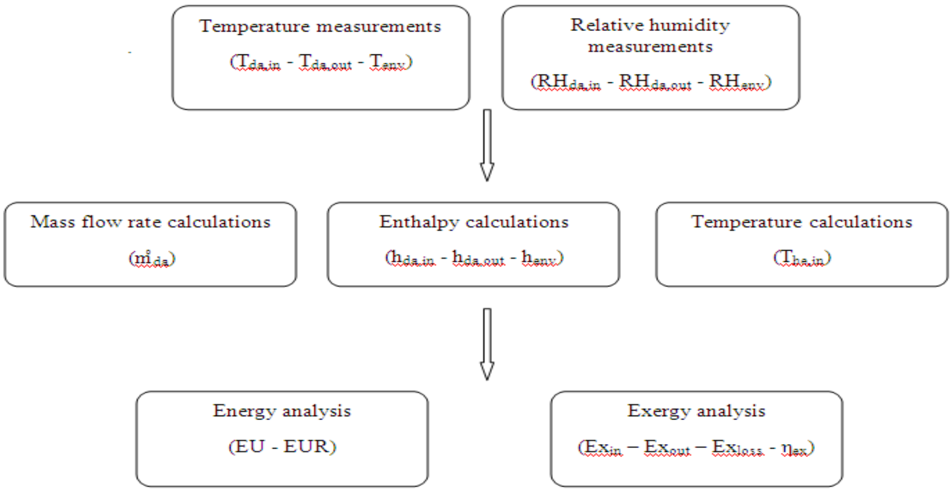


Figure 4.12. Energy and exergy analysis process

Energy and exergy analysis were conducted for two cases.

- Case 1 with air re-circulation,
- Case 2 without air re-circulation

### 4.5.1. Energy Analysis

Drying process was considered as a steady-state, steady-flow process in the analysis of conservation of mass (air, water) and energy.

Case 1: With air re-circulation

To investigate the effect of air recycling on the performance and energy consumption of the drier, exhaust air was partially re-circulated and mixed with the fresh air.

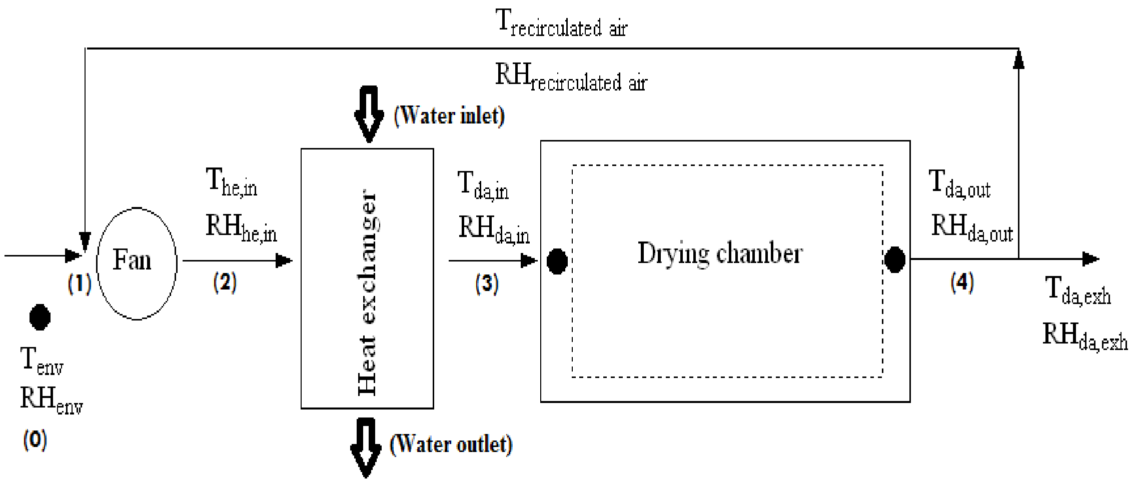


Figure 4.13. Schematic illustration of drying system with recirculation

$$\dot{m}_{da} = \dot{m}_{da,env} + \dot{m}_{recir,air} \qquad (kg/s) \qquad (4.13)$$

$$\dot{m}_{da,env} \times (1\text{-}r) + \dot{m}_{recir,air} \times (r) = \dot{m}_{air,(1)} \qquad (kg/s) \qquad (4.14)$$

$$\dot{m}_{da,env} \times h_{da,env} \times (1\text{-}r) + \dot{m}_{recir,air} \times h_{recir,air} \times (r) = \dot{m}_{air,(1)} \times h_{air,(1)} \qquad (4.15)$$

Case 2: Without re-circulation

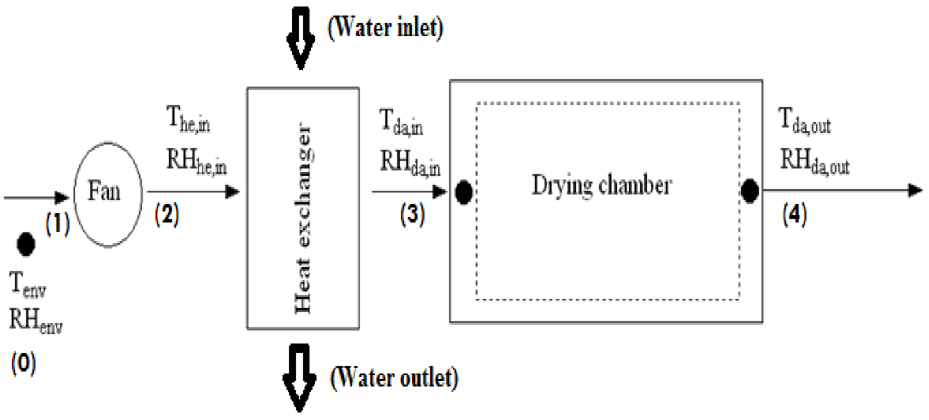


Figure 4.14. Schematic illustration of drying system without recirculation

$$\dot{m}_{da,env} = \dot{m}_{air,(1)} \qquad \text{(kg/s)} \tag{4.16}$$

$$\dot{m}_{da,env} \times h_{da,env} = \dot{m}_{air,(1)} \times h_{air,(1)} \tag{4.17}$$

Fan

The general equation of mass conservation is

$$\dot{m}_{air,(1)} = \dot{m}_{air,(2)} = \dot{m}_{da} \qquad \text{(kg/s)} \tag{4.18}$$

The general equation of energy conservation can be expressed as

$$Q - W = \sum(\dot{m}_{\ da})_{in}\ (h_{out} + \frac{Vout^2}{2}\ ) - \sum\ (\dot{m}_{\ da})_{out}\ (h_{out} + \frac{Vin^2}{2}) \tag{4.19}$$

$$W_{fan} = \dot{m}_{air} \times (h_2 - h_1 + \frac{v_{exit}^2}{2}) \qquad \text{(kW)} \tag{4.20}$$

Heat Exchanger

a) Water

$$\dot{m}_{water,inlet} = \dot{m}_{water,outlet} \qquad \text{(kg/s)} \qquad (4.21)$$

$$\dot{Q}_{water,inlet} = \dot{m}_{water} \times (h_{water,inlet} = h_{water,outlet}) \quad \text{(kW)} \qquad (4.22)$$

b) Air

$$\dot{m}_{air,(2)} = \dot{m}_{air,(3)} = \dot{m}_{da} \qquad \text{(kg/s)} \qquad (4.23)$$

$$\dot{Q}_{air} = \dot{m}_{da} \times (h_3 - h_2) \qquad \text{(kW)} \qquad (4.24)$$

Drying Chamber

A simplified schematic diagram o drying chamber is given Figure 4.15.

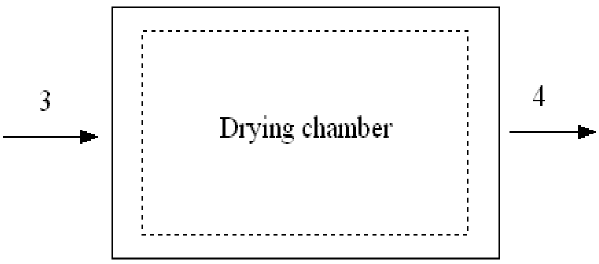


Figure 4.15. Schematic illustration of drying chamber

General equation of mass conservation of drying air for drying chamber

$$\sum \dot{m}_{da,(3)} = \sum \dot{m}_{da,(4)} = \dot{m}_{da} \quad (kg/s) \qquad (4.25)$$

General equation of mass conservation of moisture

$$\sum(\dot{m}_{w})_{in} + (\dot{m}_{w})_{product} = \sum(\dot{m}_{w})_{out} \quad (kg/s) \qquad (4.26)$$

or

$$\sum(\omega_{da})_{in} \times \dot{m}_{da,(3)} + (\dot{m}_{w})_{product} = \sum(\omega_{da})_{out} \times \dot{m}_{da,(4)} \quad (kg/s) \qquad (4.27)$$

Equation 4.29 is generally used to transform the relative humidity to humidity ratio of the air (kg water/kg dry air) at inlet and outlet of the drying chamber

$$\omega = \frac{\text{Ø Psat@T}}{\text{P}- \text{Psat@T}} \quad (kg/kg) \qquad (4.28)$$

Total mass flow of air needed for drying process was calculated using Equation 4.29

$$\dot{m}_{da} = \rho_{da} \times V_{da} \times A_{cr} \quad (kg/s) \qquad (4.29)$$

The enthalpy of drying air

$$h = (c_p)_{da}\, T_{da} + w.h_{sat"T} \quad (kJ/kg) \qquad (4.30)$$

The energy utilization (EU) which can be expressed as the amount of energy employed during moisture removal of the product was calculated using Equation 4.32

$$EU = \dot{m}_{da} \, . \, [h_{da,(3)} - ( h_{da,(4)}] \quad (kW) \qquad (4.31)$$

The energy utilization ratio (EUR) was defined as the ratio of the energy utilization to the energy given from the heat exchangers of dryer.

$$EUR = \frac{\dot{m}_{da}(h_{da,3} - h_{da,4})}{\dot{m}_{da}\,(h_3 - h_2)} \times 100 \qquad (4.32)$$

## 4.5.2. Exergy Analysis

The specific exergy is determined as

$$\psi = (h-h_0) - T_0 (s-s_0) \qquad \text{(kJ/kg)} \qquad (4.33)$$

Exergy rate

$$\dot{E}x = \dot{m}\psi \qquad \text{(kW)} \qquad (4.34)$$

or

$$\dot{E}x = \dot{m}_{da} c_{pda} [(T- T_0) - T_0 \ln\frac{T}{T_0}] \qquad \text{(kW)} \qquad (4.35)$$

The dead state temperature ($T_0$) was taken as the measured environment temperature ($T_{env}$) at each experiment.

Exergy destructions as well as exergetic efficiencies were obtained by exergy balances for each component.

<u>Fan</u>

$$\dot{E}x_{dest,fan} = \dot{W}_{fan} + \dot{m}_{da} \times (\psi_2 - \psi_1) \qquad \text{(kW)} \qquad (4.36)$$

$$\varepsilon_{fan} = \frac{\dot{m}_{da} \times (\psi_2 - \psi_1)}{\dot{W}_{fan}} \qquad (4.37)$$

<u>Heat Exchanger</u>

a) <u>Water</u>

$$\dot{E}x_{dest,water} = \dot{m}_{water} \times (\psi_{water,in} - \psi_{water,out}) \qquad \text{(kW)} \qquad (4.38)$$

b) Air

$$\dot{Ex}_{dest,air} = \dot{m}_{da} \times (\psi_3 - \psi_2) \qquad \text{(kW)} \qquad (4.39)$$

$$\varepsilon_{he} = \frac{\dot{m}_{da} \times (\psi_3 - \psi_2)}{\dot{m}_{water,in} \times (\psi_{water,in} - \psi_{water,out})} \qquad (4.40)$$

Drying Chamber

$$\dot{Ex}_{dest,dc} = \dot{m}_{da} \times \left(\psi_3 - \psi_4\right) \qquad \text{(kW)} \qquad (4.41)$$

$$\varepsilon_{dc} = \frac{\text{(Exergy inflow} - \text{Exergy outflow)}}{\text{Exergy inflow}} \qquad (4.42)$$

or

$$\varepsilon_{dc} = 1 - \frac{\dot{m}_{da} \times (\psi_3 - \psi_4)}{\dot{m}_{da} \times \psi_3} \qquad (4.43)$$

**Assumptions**

The following assumptions were used;

(1) All the process was taken as a steady state and steady flow.
(2) Heat transfer to the system and work transfer from the system are positive.
(3) Potential and kinetic energy effects were neglected.
(4) Air is an ideal gas with constant specific heat.

## 4.6. Experimental Design and Statistical Analyses

Two factor, face centred central composite design was applied and response surface methodology was used to determine the main and interaction effects of drying air temperature and drying air velocity on quality parameters of dried olive leaves. Statistical models with interaction terms were derived to examine the relative significance of the two variables, drying air temperature ($X_1$) and drying air velocity ($X_2$) and their interactions on the responses, Total Phenolic content loss ($Y_1$) and total antioxidant activity loss ($Y_2$). The independent factors, their levels and dependent responses are shown in (Table 4.6).

Table 4.6. Variables in $3^2$ central composite design

| Independent Variables (coded) | -1 | 0 | 1 |
|---|---|---|---|
| $X_1$ = Temperature (C) | 40 | 50 | 60 |
| $X_2$ = Air velocity (m/s) | 0,5 | 1 | 1,5 |
| **Dependent Variables** | | | |
| $Y_1$ = Total Phenolic content loss | | | |
| $Y_2$ = Total antioxidant activity loss | | | |

The matrix of face-centred central composite design (CCD) is shown in (Table 4.7). Each row demonstrates an experiment with coded levels.

Table 4.7. Matrix of $3^2$ Central composite designs

| Run | Drying air temperature (T) | Drying air velocity (v) |
|---|---|---|
| 1 | (0) | (1) |
| 2 | (1) | (0) |
| 3 | (-1) | (1) |
| 4 | (-1) | (0) |
| 5 | (-1) | (-1) |
| 6 | (0) | (-1) |
| 7 | (1) | (1) |
| 8 | (0) | (0) |
| 9 | (1) | (-1) |

Statistical analysis was performed using Minitab 15® software (Minitab, Inc. 2007). Significance terms in the model for each response were found by analyses of variance test (ANOVA-test) and p value of less than 0.05 ($p<0.05$) was considered statistically significant.

# CHAPTER 5

# RESULTS AND DISCUSSION

Olive leaves were collected and dried in geothermal dryer at different drying air properties to determine the influence of drying air temperature and velocity on the drying kinetics of olive leaves. The effective moisture diffusivity was also calculated. Under each drying air condition, moisture ratio was identified depending upon drying time. According to the moisture ratio curves, thin layer drying models were fitted. The correlation coefficient ($R^2$), root mean square error (RMSE) and standard error of estimate (SSE) for each model were selected as the statistical criteria parameters for model comparison. Quality parameters of dried product i.e. total phenolic content loss (PC) and total antioxidant activity loss (AC) were analysed using Minitab 16® software (Minitab 16 Statistical Software 2010 State College, PA : Minitab, Inc.) to obtain the effects of drying air temperature and velocity. Response surface methodology was used to examine the optimal drying air properties. To evaluate the performance of the drying process, energy and exergy analyses methods were used.

## 5.1. Moisture Content

Prior to experiments, the olive leaves samples were dried in a drying oven at 105 °C for 24 hours to determine the initial moisture content. Analytical balance with a precision of ± 0,001 g was used to weight the samples and initial moisture content of olive leaves was about 40 ± 2 % (w-b). Since dried products should have the moisture content of 4-6 % the amount of moisture to be removed from the product is 35 ±1 %.

## 5.2. Drying Characteristic

This section presents the results obtained from the experiments. Drying time, moisture ratio versus drying time, drying rate and diffusion coefficient have been studied under different specified temperatures (40, 50, 60 °C) and velocities (0.5, 1, 1.5 m/s).

### 5.2.1. Effect of Drying Air Temperature

**Drying time**

For the first set of experiments, drying air velocity was kept constant at 0.5, 1 and 1.5 m/s where the drying air temperature varied from 40 to 60 °C at 10 °C intervals and drying time was determined Table 5.1 and Figure 5.1. Table 5.1 and Figure 5.1 indicate that constant air velocity, increasing temperature decreases drying time.

Table 5.1. Drying time depending on air temperature at constant air velocities

| Velocity (m/s) | Temperature (°C) | Drying time (min) |
|---|---|---|
| **0.5** | 40 | 555 |
| | 50 | 390 |
| | 60 | 255 |
| **1** | 40 | 540 |
| | 50 | 300 |
| | 60 | 240 |
| **1.5** | 40 | 495 |
| | 50 | 285 |
| | 60 | 240 |

Furthermore, at 0.5 m/s, decrease in drying time is almost linear while at higher velocities there is a sudden decrease between 40 to 50 °C, and the slope of the line decreases between 50 to 60 °C. Increasing temperature further has an insignificant effect on drying time. The relation between the temperature and drying time is not linear and proves the exponential characteristic of drying curves (Mujumdar, 2006).

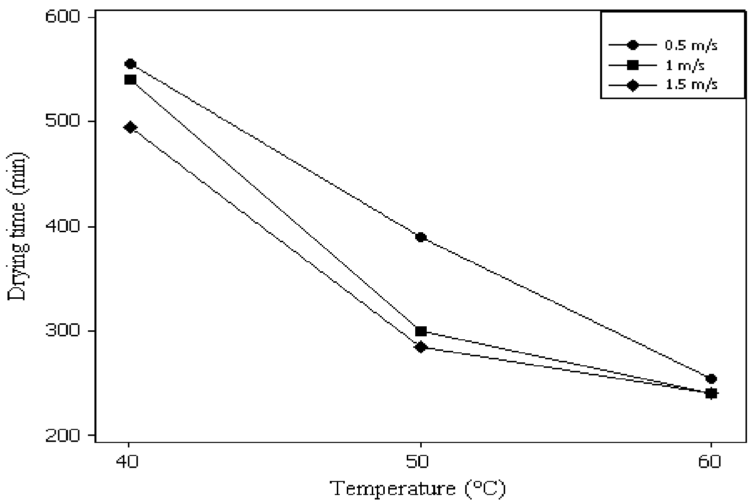


Figure 5.1. Influence of drying air temperature on the drying time

**Moisture Ratio**

Moisture ratio is a function of drying time was given in Figure 5.2. It decreases with increasing drying time and increasing temperature at constant velocities.

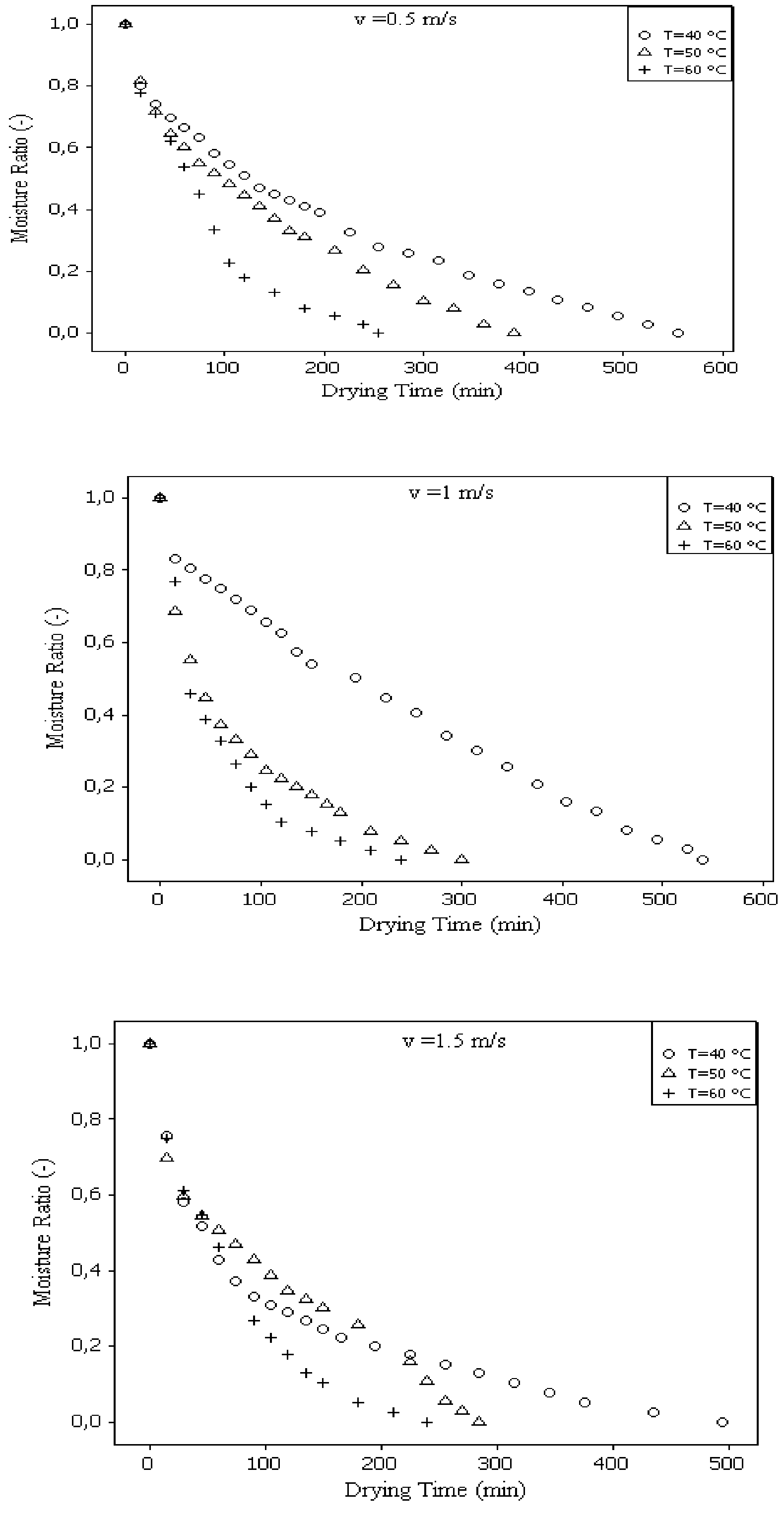


Figure 5.2. Moisture ratio versus drying time at different air velocities

## **Drying Rate**

Change in drying rate with moisture ratio depending on drying air temperatures at constant velocities are plotted in Figure 5.3.

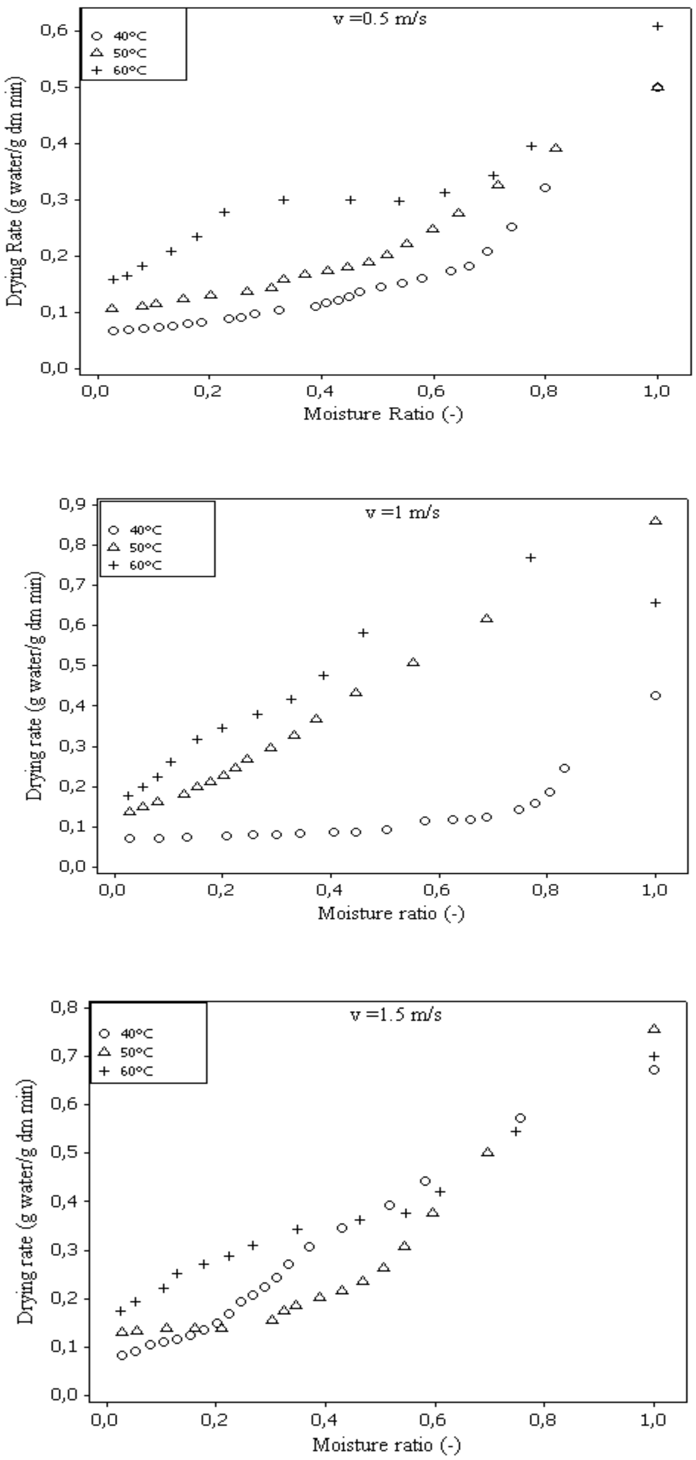


Figure 5.3. Drying rate versus moisture ratio at different air velocities

Figure 5.3 indicates that drying process occurred mainly in the falling rate period. Moreover, an important influence of drying air temperature on the moisture removal could be observed in these curves. As indicated by Prabhanjan et al. (1995), one of the driving forces for the outward moisture diffusion process is the differences between the saturate water vapour pressure and partial pressure of water vapour in air at a given temperature. High temperature provides a larger water vapour pressure dearth which results in the acceleration of water migration from inside of the product. At constant drying air velocity, higher drying air temperature produces higher drying rate and consequently, drying time decreased. The results were generally in agreement with several studies on drying of various products (Doymaz and Pala, 2002; Akpınar et al., 2003; Ertekin and Yaldız, 2004).

### 5.2.2. Effect of Drying Air Velocity

**Drying Time**

For the second set of experiments, drying air temperature was kept constant at 40, 50, 60 °C while drying air velocity varied from 0.5 to 1.5 m/s at a 0.5 m/s intervals and drying time was determined as given in Table 5.2 and Figure 5.4

Table 5.2. Drying time depending on air velocities at constant air temperatures

| Temperature (°C) | Velocity (m/s) | Drying time (min) |
|---|---|---|
| **40** | 0.5 | 555 |
| | 1 | 540 |
| | 1.5 | 495 |
| **50** | 0.5 | 390 |
| | 1 | 300 |
| | 1.5 | 285 |
| **60** | 0.5 | 255 |
| | 1 | 240 |
| | 1.5 | 240 |

The effect of drying air velocity on drying time for a temperature range of (40 – 60 °C) and velocity range of (0.5 – 1.5 m/s) is represented in Figure 5.4.

Figure 5.4 indicates that at constant temperature, increasing velocity decreases drying time. Drying time did not change with the increasing velocity from 1 m/s to 1.5 m/s at 60 °C. Further increase in air velocity decreased the drying time.

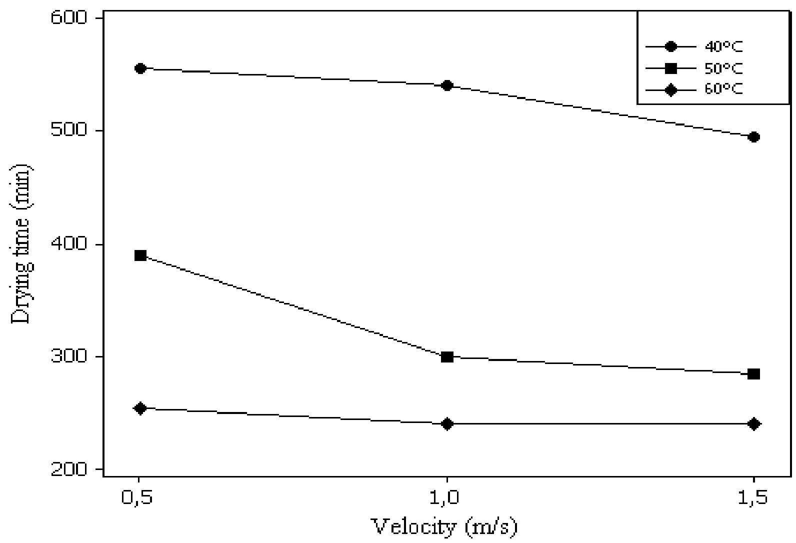


Figure 5.4. Influence of drying air velocity on the drying time

**Moisture Ratio**

Moisture ratio is a function of drying time was given in Figure 5.5. It decreases with increasing drying time.

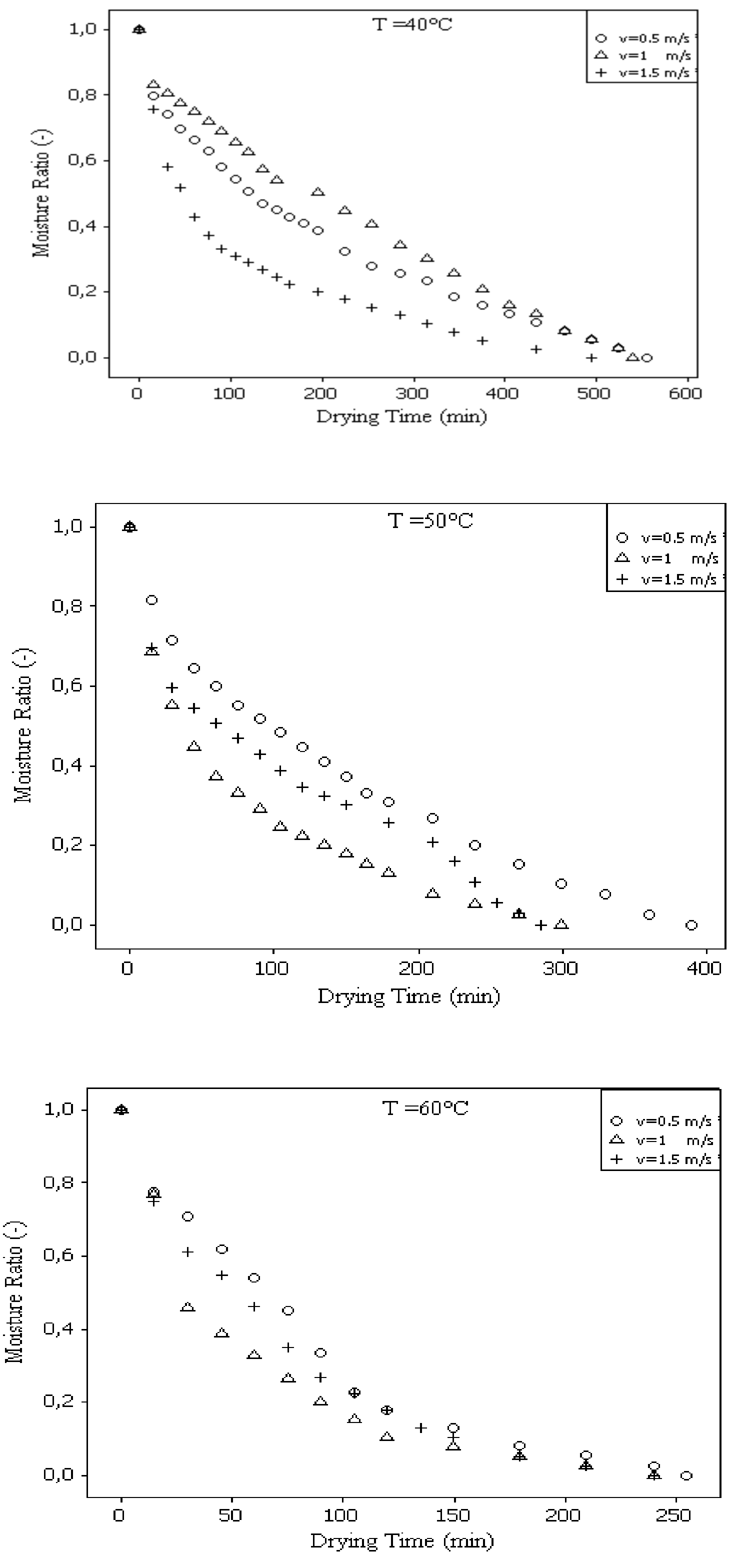


Figure 5.5. Moisture ratio versus drying time at different air temperatures

**Drying Rate**

Changes in drying rate with moisture ratio depending on drying air temperature at constant velocities are plotted in Figure 5.6.

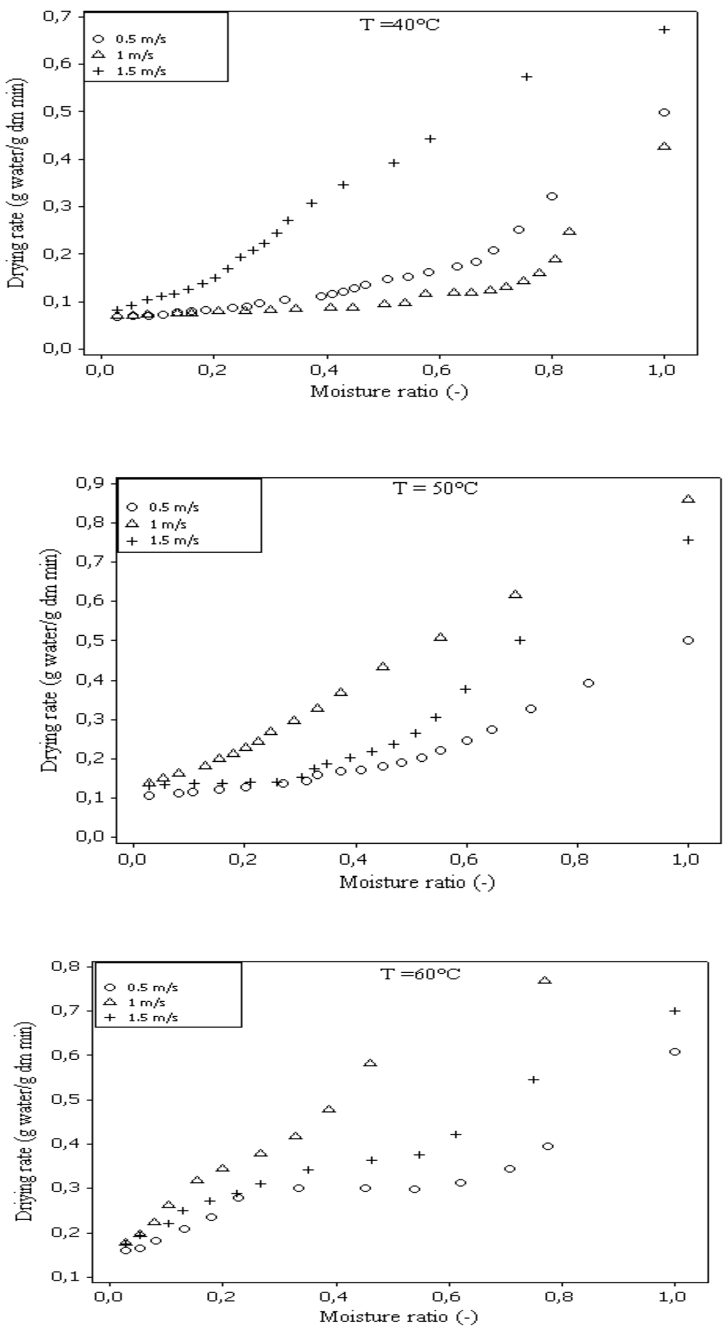


Figure 5.6. Drying rate versus moisture ratio at different air temperatures

Figure 5.6 indicates that drying process occurred mainly in the falling rate period. Drying rate shows a decreasing trend throughout the drying process. At 40 drying rate at the velocity of 1.5 m/s was higher than other velocities but at 50 °C and 60 °C, the drying rate at the velocity of 1 m/s was higher than it. The most effective drying was obtained at drying air temperature of 60 °C and air velocity of 1 m/s. It can be deduced that the interaction effect of temperature and was the reason for this (Erbay and Icier, 2008).

## 5.3. Effective Moisture Diffusivity

Since the falling rate period presence due to the internal mass transfer resistance, the effective diffusion coefficients ($D_{eff}$) are obtained by using the slopes of ln (MR) versus time Figure 5.7 and displaced in Table 5.3

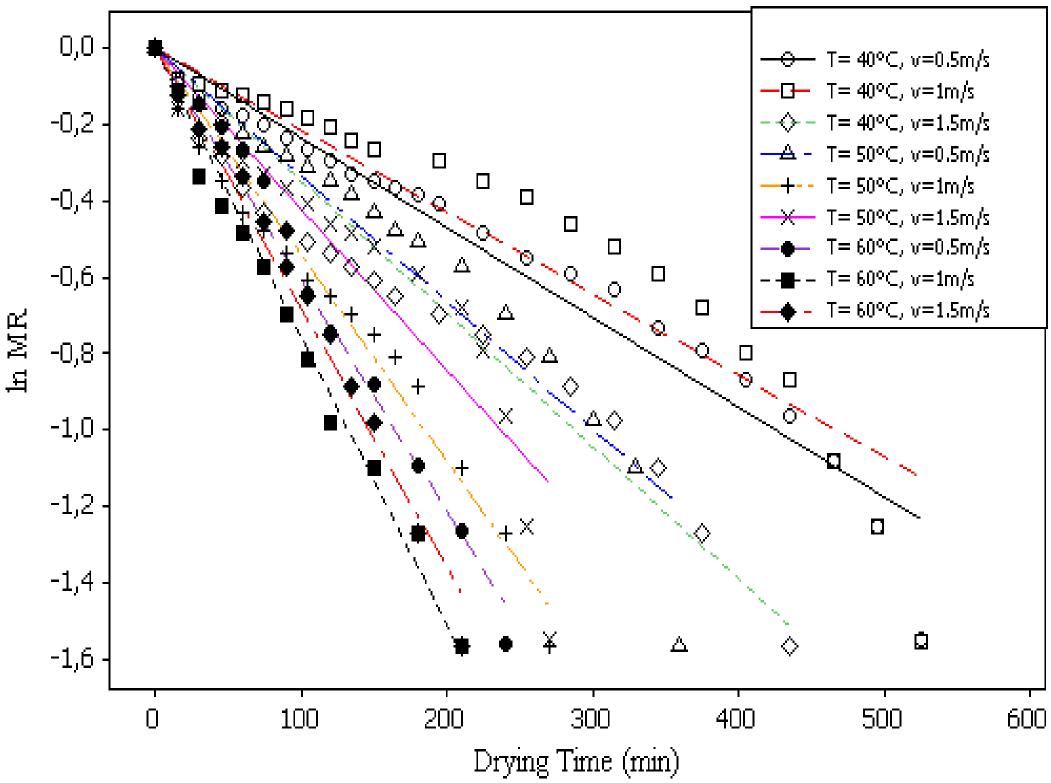


Figure 5.7. Ln (MR) versus drying time

Table 5.3 exhibits that, the effective diffusion coefficients increases with increasing drying air temperature and velocity, but temperature dominates the velocity.

Table 5.3. Effective diffusion coefficient of olive leaves under experimental conditions

| Temperature (°C) | Velocity (m/s) | $D_{eff}$ ($m^2/s$) |
|---|---|---|
| 40 | 0.5 | $2.03\times10^{-10}$ |
| | 1 | $2.31\times10^{-10}$ |
| | 1.5 | $2.91\times10^{-10}$ |
| 50 | 0.5 | $3.42\times10^{-10}$ |
| | 1 | $4.94\times10^{-10}$ |
| | 1.5 | $4.18\times10^{-10}$ |
| 60 | 0.5 | $6.34\times10^{-10}$ |
| | 1 | $7.03\times10^{-10}$ |
| | 1.5 | $7.05\times10^{-10}$ |

## 5.4. Modelling of Thin Layer Drying Curves

Moisture content data (M) were converted to the more useful dimensionless moisture ratio (MR) based on the Equation 4.3. The moisture ratio (MR) values are fitted to 13 various thin-layer models by applying the nonlinear regression analyses and the results are listed in Table 5.4. The model constants and comparison criteria for experimental conditions are given in Appendix (Table A1 - A.11). Three criteria for adequacy of the model fit namely coefficient of determination ($R^2$), root means square error (RMSE) and standard error of the estimate (SEE) were used to evaluate the models. According to the results of the comparison criteria the best fit is obtained by two-term model (Table 5.4) and Modified Henderson and Pabis model (Table 5.4).

Table 5.4. Results of Two-term model at experimental conditions

| Model | Temperature (°C) | Velocity (m/s) | Coefficients | $R^2$ | SSE | RMSE |
|---|---|---|---|---|---|---|
| Two-term | 40 | 0.5 | a= 0.1129<br>b=0,8879<br>$k_0$=0.1385<br>$k_1$=0,0041 | 0.974 | 0.0428 | 0.0451 |
| | | 1 | a=0.856 b=0.144<br>$k_0$=0.004433<br>$k_1$=0.999 | 0.9838 | 0.02553 | 0.0357 |
| | | 1.5 | a=0.4519<br>b=0.5506<br>$k_0$=0.04195<br>$k_1$=0.005455 | 0.9966 | 0.004262 | 0.01583 |
| | 50 | 0.5 | a=0.1056<br>b=0.8944<br>$k_0$=0.7423<br>$k_1$=0.00629 | 0.9869 | 0.01838 | 0.0339 |
| | | 1 | a=0.3092<br>b=0.6909<br>$k_0$=0.0805<br>$k_1$=0.00971 | 0.9967 | 0.00354 | 0.01651 |
| | | 1.5 | a=0.07131<br>b=0.9287<br>$k_0$=0.8625<br>$k_1$=0.01113 | 0.9972 | 0.003431 | 0.01691 |
| | 60 | 0.5 | a=0.6233<br>b=0.7199<br>$k_0$=0.0211<br>$k_1$=0.01935 | 0.9902 | 0.01304 | 0.03611 |
| | | 1 | a=0.3102<br>b=0.7016<br>$k_0$=0.04798<br>$k_1$=0.0147 | 0.9914 | 0.009362 | 0.03725 |
| | | 1.5 | a=0.04464<br>b=0.9554<br>$k_0$=0.9994<br>$k_1$=0.01389 | 0.9934 | 0.0077 | 0.03785 |

Table 5.5. Results of Modified Henderson and Pabis model at experimental conditions

| **Model** | **Temperature (°C)** | **Velocity (m/s)** | **Coefficients** | **$R^2$** | **SSE** | **RMSE** |
|---|---|---|---|---|---|---|
| Modified Henderson and Pabis | 40 | 0.5 | a=08864<br>b=0.0294<br>c=008715<br>g=0.131<br>h=0.1337<br>k=0.004097 | 0.9748 | 0.0286 | 0.0449 |
| | | 1 | a=0.2717 b=1<br>c=0.2713<br>g=0.005037<br>h=0.118<br>k=0.01986 | 0.9891 | 0.01717 | 0.03006 |
| | | 1.5 | a=0.5576<br>b=0.1652<br>c=0.2789<br>g=0.04329<br>h=0.0425<br>k=0.0055 | 0.9966 | 0.00428 | 0.01689 |
| | 50 | 0.5 | a=0.8923<br>b=0.00033<br>c=0.1074 g=0.95<br>h=0.211<br>k=0.006277 | 0.9869 | 0.01836 | 0.03622 |
| | | 1 | a=0,6943<br>b=0,1253<br>c=0,1805<br>g=0,08489<br>h=0,07949<br>k=0,009756 | 0.9967 | 0.00354 | 0.01595 |
| | | 1.5 | a=0.9218<br>b=0.009253<br>c=0.06928<br>g=0.01194<br>h=0.3958<br>k=0.0111 | 0.9972 | 0.003442 | 0.01855 |
| | 60 | 0.5 | a=0.9242<br>b=0.08403<br>c=0.004311<br>g=0.0126<br>h=0.4639<br>k=0.01252 | 0,9839 | 0.02131 | 0.05161 |
| | | 1 | a=0.7519<br>b=0.1426<br>c=0.1527<br>g=0.04912<br>h=0.0491<br>k=0.01489 | 0,9914 | 0.009367 | 0.03658 |
| | | 1.5 | a=0.932<br>b=0.02022<br>c=0.04989<br>g=0.01388<br>h=0.644 k=0.0138 | 0.9934 | 0.0077 | 0.03116 |

Although, Two-term model gave slightly better fit for the data series of olive leaves at 60 °C and 0.5 m/s, Modified Henderson and Pabis model provided a good agreement between experimental and predicted moisture ratio for the most of the series.

Thus, Modified Henderson and Pabis model can be considered to describe the thin-layer drying behaviour of olive leaves. The Modified Henderson and Pabis model has also been applied to other products like apricot (Togrul and Pehlivan, 2004) and olive leaves (Erbay and Icier, 2008).

In order to take into account the air temperature and air velocity effects on model constants, linear regression analysis used.

$$MR = a \times \exp^{(-kt)} + b \times \exp^{(-gt)} + c \times \exp^{(-ht)}$$

$a=-0.9239+0.1135T-3.1767v-0.0012T^2+1.1190v^2+0.0168Tv$ $R^2=72.3$

$b=-0.1890-0.0062T+0.9625v+0.0002T^2-0.2315v^2-0.0100Tv$ $R^2=73.8$

$c=0.2487-0.0216T+1.2490v+0.0002T^2-0.4086v^2-0.0073Tv$ $R^2= 88.1$

$g=-6.1706+0.3003T-1.7435v-0.0031T^2+0.5897v^2+0.0044Tv$ $R^2= 75.2$

$h=1.2009-0.0123T-2.4506v+0.0001v^2+0.0001T^2+0.9318v^2+0.0136Tv$ $R^2= 72.1$

$k=0.0449-0.0025T+0.0504v+0.0000T^2-0.0238v^2-0.0000Tv$ $R^2= 77.6$

## 5.5. Quality Measurements

Experiments were conducted to determine the quality parameters of dried product such as total phenolic content loss (PC) and total antioxidant activity loss (AC) are shown in Table 5.6. Multiple regression analyses led us to predict PC and AC. ANOVA was carried out to verify significance effects of independent variables on each response variable. Coefficients of regression equation of the various models and statistical significance of all main effects were calculated for each response and were shown in Table 5.7.

Table 5.6. Values of each response variable from the experiments

| Run | T | v | PC(%) | AC(%) |
|---|---|---|---|---|
| 1 | 50(0) | 1.5(1) | 11.34 | 9.43 |
| 2 | 60(1) | 1(0) | 33.8 | 42.94 |
| 3 | 40(-1) | 1.5(1) | 18.55 | 35.54 |
| 4 | 40(-1) | 1(0) | 28.68 | 24.88 |
| 5 | 40(-1) | 0.5(-1) | 29.59 | 37.6 |
| 6 | 50(0) | 0.5(-1) | 13.32 | 8.82 |
| 7 | 60(1) | 1.5(1) | 49.22 | 55.69 |
| 8 | 50(0) | 1(0) | 11.22 | 4.72 |
| 9 | 60(1) | 0.5(-1) | 41.05 | 47.34 |

Table 5.7. The fitted models and parameter estimates

| | PC | | | AC | | |
|---|---|---|---|---|---|---|
| **Term** | **Coefficient** | **S.E. Coefficient** | **P value** | **Coefficient** | **S.E. Coefficient** | **P value** |
| T | 7.875 | 2.2 | 0.037 | 7.992 | 1.053 | 0.005 |
| V | -0.8083 | 2.2 | 0.738 | 1.15 | 1.053 | 0.355 |
| T×T | 21.5217 | 3.81 | 0.011 | 33.008 | 1.824 | 0.000 |
| V×V | 2.6117 | 3.81 | 0.542 | 8.223 | 1.824 | 0.02 |
| T×V | 4.8025 | 3.81 | 0.173 | 2.603 | 1.29 | 0.137 |
| For PC $R^2$ (Coefficient of determination) = 94.2 % Adj.$R^2$ 84.5%<br>For AC $R^2$ (Coefficient of determination) = 99.3 % Adj.$R^2$ 98.1% | | | | | | |

With elimination of insignificant variables ($p>0.5$), relationship between dependent variables; (PC) and (AC), the independent variables; temperature (T) and velocity (v), through the following regression Equations (5.1) - (5.2) were shown below.

$$PC = 10.2189 + 7.875\times T + 21.5217\times T^2 \quad (5.1)$$

$$AC = 2.174 + 7.992\times T + 33.008\times T^2 + 8.223\times v^2 \quad (5.2)$$

In Equation (5.1) and (5.2), factors at higher order such as $T^2$ and $v^2$ indicate quadratic relationship.

It was observed that temperature has a positive significance linear and quadratic effect on both PC and AC that means T and $T^2$ suggest an increase in PC and AC. However both PC and AC decreased to a minimum value while the temperature increased from 40 to 50 °C whereas they reached to maximum value while the temperature increased 50 to 60 °C.

The PC was not statistically influenced as drying air velocity changed from 0.5 to 1.5 (p= 0,738), although PC values varied at constant temperatures and for various velocities. There is no significant interaction effect observed between T and v on both PC and AC. Although there is no significant effect of v on AC, quadratic relationship of $v^2$ on AC was obtained. The relationship between dependent variables PC and AC, and independent variables T and v is demonstrated on the contour plots in Figure (5.8) and surface response plots in Figure (5.9). The plots also show the region of maxima (region in muddy) and minima (region in cast).

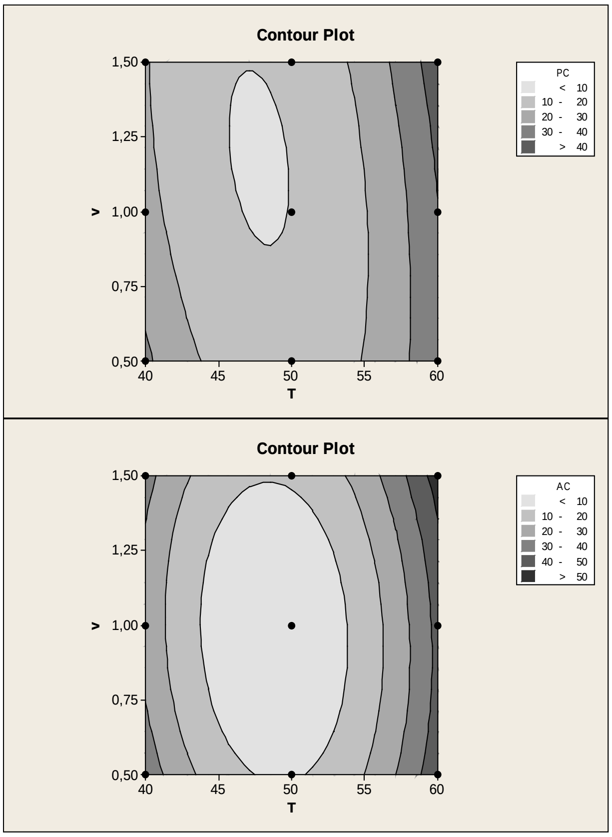


Figure 5.8. Contour plots for the effects of T and v on PC and AC

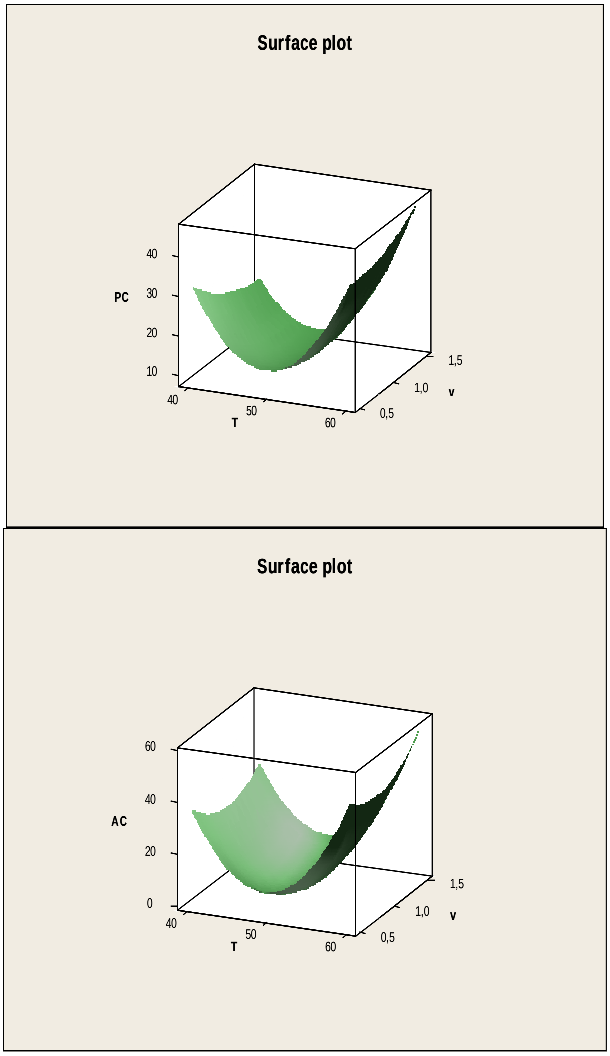


Figure 5.9. Surface response plots for the effects of T and v on PC and AC

Figure 5.8 and 5.9 demonstrate that the reduction in (TPC) values at various air temperatures and air velocities was accompanied by a reduction in the (TAC) values as well. The maximum (PC) and (AC) values were obtained at 60 °C for all air velocities. This is probably due to increase in temperature caused a degradation of polypehonlic compounds. However, (PC) and (AC) values were lower at 40 °C than 50 °C. The explanation could be that low drying air temperature resulted in a long drying period which might destroy the phenolic compounds and lower the antioxidant activity. Similar findings were reported by several researchers (Li et al., 2006; Erbay and Icier, 2009; Garau et al., 2007).

Figure (5.8 - 5.9) represents the optimal air conditions of olive leaves drying for minimum total phenolic content and antioxidant loss corresponded to air temperature of 50 °C and air velocity of 1 m/s in order to obtain (PC) of 11.22% and (AC) of 4.72%.

## 5.6. Energy and Exergy Analyses

Energy and exergy analysis of the drier was conducted using measured temperature, velocity and relative humidity data. Mass flow rates, enthalpy values and temperature of the air at inlet of the heat exchanger were calculated. Temperature, relative humidity, mass flow rate data, for the air and water are given in Table 5.8. Energy and exergy rates are also calculated for each state and represented in Table 5.8. In this study, the reference-dead state conditions were determined as $T_0 = T_{env}$, $RH_0 = RH_{env}$, $P_0 = 101.325$ kPa. The thermodynamic properties of air and water were obtained by using Engineering Equation Solver (EES, Inc. 2012) software package.

Table 5.9 presents exergy destruction and exergetic efficiencies for each component of drying system. Energy Utilization (EU) and Energy Utilization Ratio (EUR) values are also represented in Table 5.9.

The EU, which indicates the amount of energy employed for the reduction of moisture content of the product, was calculated as 0.3316 kW. Energy Utilization Ratios were obtained as 50.36 % and 7.96 % for both Case 1 and Case 2, respectively. The EUR indicates the ratio of the energy utilization to the amount of energy given from the heat exchangers of the dryer. The lower EUR values obtained from the experiments that air was not circulated compared to the experiments with air recirculation (Figure 5.10). This indicates that recycling the exhaust air allowed us to reuse the energy leaving the dryer which decreases the energy input from the heat exchanger and increases the energy efficiency (Corzo et al., 2008; Aghbashlo et al., 2008).

Table 5.8. Energy and exergy analysis data

| State No | Fluid | T (°C) | RH (%) | h (kJ/kg) | s (kJ/kgK) | ṁ kg/s | Specific Exergy (kJ/kg) | Exergy Rate (kW) | Energy rate (kW) |
|---|---|---|---|---|---|---|---|---|---|
| 0 | Air/Dead State | 22 | 42 | 39.67 | 5.75 | _ | _ | _ | _ |
| 1 | Air/Fan inlet | 37 | 19.4 | 56.79 | 5.8 | 0.20 | 0.3175 | 0.066 | 11.8 |
| 2 | Air/Fan outlet-HE inlet | 37.9 | 18.5 | 57.67 | 5.81 | 0.20 | 0.3615 | 0.076 | 11.97 |
| 3 | Air/HE outlet-Dryer inlet | 40.9 | 15.7 | 60.81 | 5.82 | 0.21 | 0.538 | 0.1128 | 12.78 |
| 4 | Air/Dryer outlet | 39.8 | 16.4 | 59.23 | 5.815 | 0.21 | 0.4823 | 0.1013 | 12.43 |
| $W_{in}$ | Water/ HE inlet | 62 | _ | 259.6 | 0.8562 | 0.03 | 63.11 | 2.272 | 9.34 |
| $W_{out}$ | Water/ HE outlet | 56.5 | _ | 236.5 | 0.7866 | 0.03 | 60.51 | 2.178 | 8.52 |

Table 5.9. Exergy destruction, exergetic efficiency, EU and EUR data of the dryer

| Component | Rate of Exergy Destruction $Ex_{destruction}$ (kW) | Exergetic efficiency ε (%) |
|---|---|---|
| Fan | 0.2913 | 3.08 |
| Heat exchanger | 0.05663 | 39.52 |
| Dryer | 0.0115 | 89.66 |
| EU = 0.3316 kW<br>EUR (Case 1) = 50.36 (%)<br>EUR (Case 2) = 7.96 (%) | | |

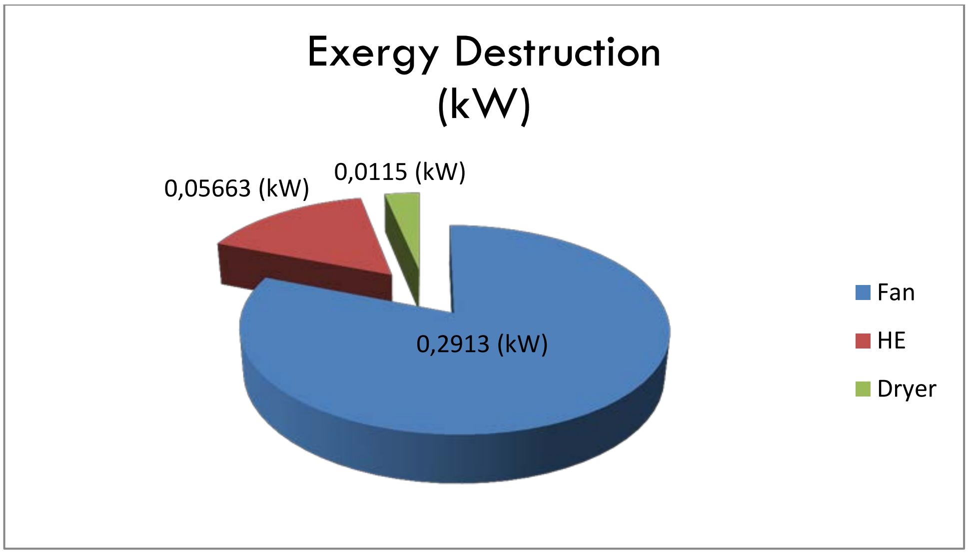


Figure 5.10. Exergy destruction values for each component of the drying system

It is clear from the Figure 5.10 that the greatest exergy destruction occurs in the fan, followed by heat exchanger and the dryer, accounting for 0.2913, 0.05663, 0.0115 kW. Exergetic efficiency can be defined as the ratio of exergy loss (exergy inflow – exergy outflow) to exergy inflow to the drying chamber. In this study exergetic efficiency of the drying cjamber was found 89.66 %. This result was similar with the results in the literature (Corzo et al. 2008; Çolak et al. 2008; Erbay and İçier, 2010c).

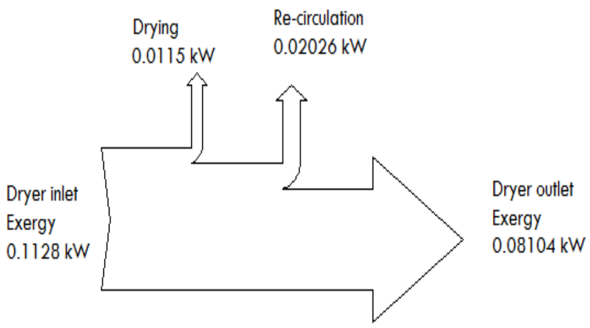


Figure 5.11. The exergy flow diagram for drying chamber (Case 1)

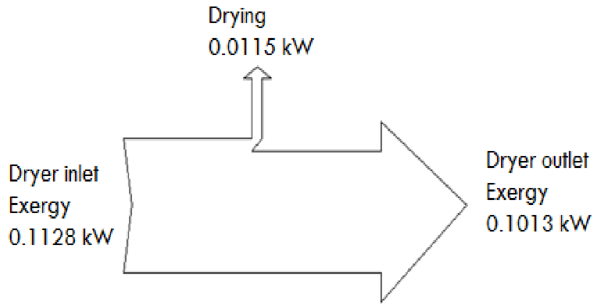


Figure 5.12. The exergy flow diagram for drying chamber (Case 2)

Figure (5.11 and 5.12) illustrates the exergy flow diagrams indicating exergy balance for drying chamber for both case 1 and case 2, respectively. It is shown that exergy loss accounted for 0.0115 kW for drying process. It is also clear from the Figures that exergy value at the outlet of the dryer decreased from 0.1013 kW to 0.08104 kW. That means re-circulating some portions of the exhaust air at the outlet of the dryer which still has availability.

# CHAPTER 6

# CONCLUSIONS

A geothermal drier was constructed and tested in Balcova-Narlıdere geothermal field, Izmir. The clean city water (62-65 °C) returns to the primary heat exchanger of the Balcova-Narlıdere district heating system was used as a heat supplier of the dryer. To evaluate the effects of drying air temperature and velocity on the drying process as well as on the product quality, a number of experiments have been conducted at drying air temperatures (40, 50 and 60 °C) and velocities (0.5, 1, 1.5 m/s). To estimate the performance of the drying process and dryer energy and exergy analyses methods were used.

Drying time for experiments was obtained as 240-555 min. The results indicated that as the drying air temperature and velocity increases, drying rate and correspondingly drying time decreases.

Drying rate curves indicates that, drying process takes place mainly in the falling rate period. The drying air temperature is the main factor influencing the drying kinetics of olive leaves. The effective moisture diffusivity values ranged from $2.03\times10^{-10}$ $m^2/s$ to $7.05\times10^{-10}$ $m^2/s$ which is in the range of the literature data ($10^{-8}$-$10^{-11}$ $m^2/s$).

Thin-layer models exist in the literature were applied to dimensionless moisture ratio data to describe the drying kinetics of olive leaves. The results of nonlinear regression analysis suggest that, the Modified Henderson and Pabis is the best model to describe the drying behaviour of olive leaves.

With the aim of investigating the effects of temperature and velocity on model constants, linear analysis was used. According to the results of linear regression analysis, $R^2$ values are relatively low. The number of experiments should be increased then multiple regression analysis method should be considered.

To investigate the optimal drying air conditions for minimum loss of quality of dried olive leaves, optimization study was carried out. Statistical results indicates that not only relatively high temperatures but also long drying periods has an important effects on total phenolic content and total antioxidant activity loss. Drying air temperature of 50 °C and air velocity of 1 m/s which corresponds to 300 min drying time was found the optimum drying air condition for minimal total pheonolic content and total antioxidant activity loss.

The results of the energy and exergy analysis showed that the greatest exergy destruction occurred in the fan. Re-circulating exhaust air increases EUR values by 42.4%, and decreases the exergy at the outlet of the dryer, means that re-using the air increases the performance of the dryer. An economical analysis should be conducted to show the viability of the recirculation for commercial drying facilities. In geothermal dryers, energy source (geothermal fluid) is almost free but if the energy source is a fossil fuel, drying process is more profitable.

One of the problems encountered during the experiments was stabilization of drying air parameters since the system controlled manually. The automation would improve the stability of the parameters. Furthermore, dryer length should be increased due to the difficulty of reaching the stable conditions at higher drying air velocities.

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# APPENDIX A

# RESULTS OF THE NONLINEAR REGRESSION ANALYSIS OBTAINED FROM DIFFERENT THIN LAYER DRYING MODELS

Table A.1. Results of Lewis model

| Model | Temperature (°C) | Velocity (m/s) | Coefficients | $R^2$ | SSE | RMSE |
|---|---|---|---|---|---|---|
| Lewis | 40 | 0.5 | k=0.004789 | 0.955 | 0.0758 | 0.05621 |
| | | 1 | k=0.00542 | 0.9502 | 0.0768 | 0.05849 |
| | | 1.5 | k=0.01099 | 0.9193 | 0.1005 | 0.07088 |
| | 50 | 0.5 | k=0.0072 | 0.9727 | 0.03823 | 0.04486 |
| | | 1 | k=0.01443 | 0.9537 | 0.05043 | 0.05614 |
| | | 1.5 | k=0.01207 | 0.9934 | 0.0082 | 0.02338 |
| | 60 | 0.5 | k=0.01242 | 0.9839 | 0.02137 | 0.0405 |
| | | 1 | k=0.01941 | 0.9863 | 0.01496 | 0.03531 |
| | | 1.5 | k=0.01456 | 0.9922 | 0.009192 | 0.0265 |

Table A.2. Results of Page model

| Model | Temperature (°C) | Velocity (m/s) | Coefficients | $R^2$ | SSE | RMSE |
|---|---|---|---|---|---|---|
| Page | 40 | 0.5 | k=0.0094 n=0.8727 | 0.963 | 0.0628 | 0.052 |
| | | 1 | k=0.01416 n=0.8174 | 0.9672 | 0.05186 | 0.04855 |
| | | 1.5 | k=0.0569 n=0.6451 | 0.9931 | 0.008551 | 0.02121 |
| | 50 | 0.5 | k=0.01037 n=0.8764 | 0.9794 | 0.02885 | 0.04303 |
| | | 1 | k= 0.05167 n=0.7133 | 0.9942 | 0.006296 | 0.02049 |
| | | 1.5 | k=0.01721 n=0.9223 | 0.9955 | 0.005556 | 0.001992 |
| | 60 | 0.5 | k=0.01242 n=1 | 0.9839 | 0.02137 | 0.04054 |
| | | 1 | k=0.03145 n=0.8823 | 0.9903 | 0.01053 | 0.03094 |
| | | 1.5 | k=0.01531 n=0.9888 | 0.9922 | 0.009149 | 0.02761 |

Table A.3. Results of Modified Page model

| Model | Temperature (°C) | Velocity (m/s) | Coefficients | $R^2$ | SSE | RMSE |
|---|---|---|---|---|---|---|
| Modified Page | 40 | 0.5 | k=0.0047 n=0.8727 | 0.9631 | 0.062 | 0.052 |
| | | 1 | k=0.0054 n=0.8174 | 0.9672 | 0.05186 | 0.04855 |
| | | 1.5 | k=0.01179 n=0.6451 | 0.9931 | 0.0085 | 0.02121 |
| | 50 | 0.5 | k=0.007273 n=0.8763 | 0.9794 | 0.02885 | 0.04003 |
| | | 1 | k=0.01571 n=0.7133 | 0.9942 | 0.006269 | 0.02049 |
| | | 1.5 | k=0.0122 n=0.9223 | 0.9955 | 0.005556 | 0.01992 |
| | 60 | 0.5 | k=0.01241 n=1 | 0.9839 | 0.02137 | 0.04054 |
| | | 1 | k=0.01983 n=0.8823 | 0.9903 | 0.01053 | 0.03094 |
| | | 1.5 | k=0.01459 n=0.9888 | 0.9922 | 0.009149 | 0.02761 |

Table A.4. Results of Henderson and Pabis model

| Model | Temperature (°C) | Velocity (m/s) | Coefficients | $R^2$ | SSE | RMSE |
|---|---|---|---|---|---|---|
| Henderson and Pabis | 40 | 0.5 | k=0.9199 n=0.004296 | 0.9696 | 0.0517 | 0.0474 |
| | | 1 | k=0.8948 n=0.004693 | 0.9742 | 0.0407 | 0.04303 |
| | | 1.5 | k=0.8578 n=0.00896 | 0.949 | 0.0632 | 0.05768 |
| | 50 | 0.5 | k=0.9318 n=0.0066 | 0.9817 | 0.02564 | 0.0377 |
| | | 1 | k=0.8935 n=0.01266 | 0.9708 | 0.03176 | 0.04601 |
| | | 1.5 | k=0.9653 n=0.01161 | 0.9952 | 0.005937 | 0.0205 |
| | 60 | 0.5 | k=1 n=0.01242 | 0.9839 | 0.02137 | 0.0422 |
| | | 1 | k=0.9789 n=0.01896 | 0.9868 | 0.01435 | 0.0361 |
| | | 1.5 | k=0.9813 n=0.01428 | 0.9927 | 0.008597 | 0.02677 |

Table A.5. Results of Logarithmic model

| Model | Temperature (°C) | Velocity (m/s) | Coefficients | $R^2$ | SSE | RMSE |
|---|---|---|---|---|---|---|
| Logarithmic | 40 | 0.5 | a=0.9198 c=0.004296 k= 2.004$e^{-9}$ | 0.9696 | 0.0517 | 0.0474 |
| | | 1 | a=0.8948 c=6.57$e^{-9}$ k=0.004693 | 0.9742 | 0.04074 | 0.04303 |
| | | 1.5 | a=0.8335 c=0.01261 k=0.0815 | 0.9676 | 0.0403 | 0.04732 |
| | 50 | 0.5 | a=0.9316 c=1.259$e^{-7}$ k=0.006615 | 0.9817 | 0.0256 | 0.03774 |
| | | 1 | a=0.8706 c=0.05119 k=0.01531 | 0.9759 | 0.02625 | 0.0433 |
| | | 1.5 | a=0.9653 c=1.82$e^{-9}$ k=0.01161 | 0.9952 | 0.005937 | 0.0205 |
| | 60 | 0.5 | a=1 c=7.586$e^{13}$ k=0.01242 | 0.9839 | 0.0213 | 0.0405 |
| | | 1 | a=0.9647 c=0.0246 k=0.03049 | 0.98882 | 0.01284 | 0.03583 |
| | | 1.5 | a=0.9813 c=1.909$e^{-8}$ k=0.01428 | 0.9927 | 0.00859 | 0.02796 |

Table A.6. Results of Two term exponential model

| Model | Temperature (°C) | Velocity (m/s) | Coefficients | $R^2$ | SSE | RMSE |
|---|---|---|---|---|---|---|
| Two term exponential | 40 | 0.5 | a=0.0881 k=0.0485 | 0.9706 | 0.0501 | 0.0466 |
| | | 1 | a=0.1041 k=0.04569 | 0.9718 | 0.04455 | 0.045 |
| | | 1.5 | a=0.2257 k=0.03762 | 0.9652 | 0.0433 | 0.0477 |
| | 50 | 0.5 | a=0.096 k=0.0668 | 0.9848 | 0.0213 | 0.0344 |
| | | 1 | a=0.8706 k=0.0554 | 0.9852 | 0.01613 | 0.03279 |
| | | 1.5 | a=0.0735 k=0.1512 | 0.9972 | 0.003533 | 0.01589 |
| | 60 | 0.5 | a=0.01225 k=1 | 0.9835 | 0.0219 | 0.04105 |
| | | 1 | a= 0.3277 k=0.0438 | 0.9913 | 0.009523 | 0.02942 |
| | | 1.5 | a= 0.04312 k=0.03226 | 0.9934 | 0.00778 | 0.02546 |

Table A.7. Results of Wang and Shing at model

| Model | Temperature (°C) | Velocity (m/s) | Coefficients | $R^2$ | SSE | RMSE |
|---|---|---|---|---|---|---|
| Wang and Shing | 40 | 0.5 | a = - 0.003709<br>b =3.711e$^{-006}$ | 0.9282 | 0.1223 | 0.729 |
| | | 1 | a = - 0.004165<br>b = 4.69e$^{-006}$ | 0.9668 | 0.1474 | 0.08184 |
| | | 1.5 | a = - 0.006221<br>b = 9.332e$^{-006}$ | 0.6545 | 0.4302 | 0.1505 |
| | 50 | 0.5 | a = - 0.005484<br>b = 7.978e$^{-006}$ | 0.9405 | 0.08331 | 0.06800 |
| | | 1 | a = - 0.009125<br>b = 2.073e$^{-005}$ | 0.8197 | 0.1926 | 0.1144 |
| | | 1.5 | a = - 0.008589<br>b = 1.882e$^{-005}$ | 0.9557 | 0.05496 | 0.06265 |
| | 60 | 0.5 | a = - 0.009213<br>b = 2.14e$^{-005}$ | 0.9853 | 0.01953 | 0.04034 |
| | | 1 | a = - 0.1208<br>b =3.497e$^{-005}$ | 0.899 | 0.11 | 0.1 |
| | | 1.5 | a = - 0.01028<br>b = 2.655e$^{-005}$ | 0.97 | 0.03527 | 0.05422 |

Table A.8. Results of App.of Diffusion model

| Model | Temperature (°C) | Velocity (m/s) | Coefficients | $R^2$ | SSE | RMSE |
|---|---|---|---|---|---|---|
| App.of Diffusion | 40 | 0.5 | a = 0.112<br>b= 0.0295<br>k = 0.1391 | 0.9749 | 0.0428 | 0.0441 |
| | | 1 | a = 0.144<br>b = 0.007717<br>k = 0.5743 | 0.9838 | 0.02553 | 0.03487 |
| | | 1.5 | a = 0.4502<br>b = 0.1309<br>k = 0.04164 | 0.9916 | 0.004269 | 0.0154 |
| | 50 | 0.5 | a = 0.1075<br>b = 0.02931<br>k =0.2142 | 0.9869 | 0.01836 | 0.03622 |
| | | 1 | a = 0.3393<br>b = 0.1208<br>k = 0.0804 | 0.9967 | 0.003542 | 0.01591 |
| | | 1.5 | a = 0.07181<br>b = 0.02426<br>k = 0.4588 | 0.9972 | 0.003402 | 0.01625 |
| | 60 | 0.5 | a = 1.512e$^{-008}$<br>b = 0.08336<br>k = 0.1489 | 0.9839 | 0.02137 | 0.04407 |
| | | 1 | a = 0.0301<br>b = 0.3214<br>k =0.04577 | 0.9910 | 0.00951 | 0.03084 |
| | | 1.5 | a = 0.0445<br>b = 0.03789<br>k = 0.3665 | 0.9934 | 0.007767 | 0.02657 |

Table A.9. Results of Varma et al. model

| Model | Temperature (°C) | Velocity (m/s) | Coefficients | $R^2$ | SSE | RMSE |
|---|---|---|---|---|---|---|
| Varma et al. | 40 | 0.5 | a = 0.112<br>g = 0.1394<br>k =0.004107 | 0.9747 | 0.0428 | 0.04413 |
| | | 1 | a = 0.8563<br>g =0.007717<br>k = 0.004435 | 0.9808 | 0.02553 | 0.03487 |
| | | 1.5 | a = 0.55<br>g = 0.04166<br>k = 0.04164 | 0.9966 | 0.00426 | 0.0154 |
| | 50 | 0.5 | a = 0.8924<br>g = 0.2139<br>k = 0.006278 | 0.9869 | 0.01806 | 0.03287 |
| | | 1 | a = 0.6906<br>g = 0.08036<br>k = 0.009708 | 0.9967 | 0.003542 | 0.01591 |
| | | 1.5 | a = 0.99282<br>g = 0.9552<br>k = 0.01113 | 0.9972 | 0.003431 | 0.01625 |
| | 60 | 0.5 | a = 1<br>g = 1<br>k = 0.1489 | 0.9839 | 0.02137 | 0.0422 |
| | | 1 | a = 0.7<br>g = 0.04588<br>k = 0.01472 | 0.9895 | 0.00951 | 0.0084 |
| | | 1.5 | a = 0.9554<br>g = 0.9984<br>k = 0.01389 | 0.0.9934 | 0.007758 | 0.02656 |

Table A.10. Results of Modified Page 2 model

| Model | Temperature (°C) | Velocity (m/s) | Coefficients | $R^2$ | SSE | RMSE |
|---|---|---|---|---|---|---|
| Modified Page 2 | 40 | 0.5 | L = 0.9962<br>k = 0.00478<br>n = 0.01 | 0.955 | 0.0758 | 0.0587 |
| | | 1 | L = 0.9965<br>k = 0.004224<br>n = 0.008845 | 0.9838 | 0.02564 | 0.03487 |
| | | 1.5 | L = 0.9913<br>k = 0.010099<br>n = 0.02293 | 0.9193 | 0.1005 | 0.07471 |
| | 50 | 0.5 | L = 0.9943<br>k = 0.007213<br>n = 0.01506 | 0.9727 | 0.01836 | 0.03622 |
| | | 1 | L = 0.9886<br>k = 0.01442<br>n = 0.0301 | 0.9537 | 0.05043 | 0.0602 |
| | | 1.5 | L = 0.9904<br>k = 0.01207<br>n = 0.0252 | 0.9934 | 0.0082 | 0.02511 |
| | 60 | 0.5 | L = 0.9901<br>k = 0.01241<br>n = 0.026 | 0.9839 | 0.02137 | 0.04407 |
| | | 1 | L = 0.9847<br>k = 0.01938<br>n = 0.04048 | 0.9863 | 0.01469 | 0.03868 |
| | | 1.5 | L = 0.9884<br>k = 0.01455<br>n = 0.0304 | 0.9922 | 0.009192 | 0.02891 |

Table A.11. Results of Midilli and Kucuk model

| Model | Temperature (°C) | Velocity (m/s) | Coefficients | $R^2$ | SSE | RMSE |
|---|---|---|---|---|---|---|
| Midilli and Kucuk | 40 | 0.5 | a = 0.9198<br>b = 2.248e-014<br>k = 0.004296<br>n = 1 | 0.9696 | 0.0517 | 0.04852 |
| | | 1 | a = 0.9742<br>b = 2.236e-014<br>k =0.005116<br>n = 0.9851 | 0.9742 | 0.0407 | 0.04402 |
| | | 1.5 | a = 1<br>b = 1,571e-0.12<br>k = 0.05699<br>n = 0.6451 | 0.9931 | 0.008551 | 0.0218 |
| | 50 | 0.5 | a =0.9435<br>b = 2.293e-014<br>k = 0.008053<br>n = 0.964 | 79819 | 0.02537 | 0.03863 |
| | | 1 | a = 0.9933<br>b = 6.78e-014<br>k = 0.05018<br>n = 0.7185 | 0.9943 | 0.00625 | 0.02113 |
| | | 1.5 | a = 0.9822<br>b = 4.165e-014<br>k = 0.01522<br>n = 0.945 | 0.9958 | 0.005215 | 0.02003 |
| | 60 | 0.5 | a = 1<br>b = 2.221e-014<br>k = 0.01242<br>n = 1 | 0.7839 | 0.02137 | 0.04054 |
| | | 1 | a = 1<br>b = 9.53e-010<br>k = 0.03146<br>n = 0.8823 | 0.9903 | 0.01053 | 0.3094 |
| | | 1.5 | a = 0.9813<br>b = 2.27e-14<br>k = 0.01428<br>n = 1 | 0.9927 | 0.008597 | 0.02677 |

# APPENDIX B

# TOTAL PHENOLIC CONTENT AND TOTAL ANTIOXIDANT CAPACITY DATA

Table B.1. Total Phenolic Content for raw and dried olive leaves

| TPC (raw) (μg gallic acid/g) | TPC (dried) (μg gallic acid/g) | | |
|---|---|---|---|
| | Temperature (°C) | Velocity (m/s) | TPC |
| 22669.88 | 40 | 0.5 | 15000.15 |
| 22669.88 | | 1 | 17295.32 |
| 22669.88 | | 1.5 | 17055.7 |
| 29271.93 | 50 | 0.5 | 24482.46 |
| 27262.5 | | 1 | 23207.16 |
| 28489.04 | | 1.5 | 26196.64 |
| 27262.5 | 60 | 0.5 | 15131.14 |
| 28489.04 | | 1 | 17548.61 |
| 28489.04 | | 1.5 | 13718.2 |

Table B.2. Total Antioxidant Capacity for raw and dried olive leaves

| TAC (raw) (μmol trolox/g) | TAC (dried) (μmol trolox/g) | | |
|---|---|---|---|
| | Temperature (°C) | Velocity (m/s) | TAC |
| 302.3 | 40 | 0.5 | 188.62 |
| 302.3 | | 1 | 227.07 |
| 302.3 | | 1.5 | 194.86 |
| 148.28 | 50 | 0.5 | 135.2 |
| 148.28 | | 1 | 141.28 |
| 346.95 | | 1.5 | 314.21 |
| 299.56 | 60 | 0.5 | 157.74 |
| 346.95 | | 1 | 197.96 |
| 346.95 | | 1.5 | 153.72 |