DRYING CHARACTERISTICS AND QUALITY OF LEMON SLICES DRIED UNDERGONE COULOMB FORCE ASSISTED HEAT PUMP DRYING

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DRYING CHARACTERISTICS AND QUALITY OF LEMON SLICES DRIED UNDERGONE COULOMB FORCE ASSISTED HEAT PUMP DRYING

By

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DEDICATION

Specially dedicated to my beloved family

ABSTRACT

DRYING CHARACTERISTICS AND QUALITY OF LEMON SLICES DRIED UNDERGONE COULOMB FORCE ASSISTED HEAT PUMP DRYING

LEE YONG HONG

In this research, a Coulomb force assisted heat pump (CF-HP) dryer was fabricated for the purpose of improving the drying characteristics and product quality of biomaterials such as lemon fruit slices during heat pump drying process. Interaction between the lemon slices with the high voltage wire mesh (15000V, 50Hz) in the drying chamber generated a positive net force (Coulomb force) which successfully enhanced the moisture diffusion from core towards the surface of the lemon slices and subsequently evaporated by convective air flow generated by heat pump dryer at mild temperature (22 ℃) and low relative humidity (34%).

The research results show that the drying rates of Coulomb force assisted heat pump dried lemon slices were up to 25.1% higher than the drying rates of heat pump dried slices. On the other hand, the drying rates of these hybrid heat pump dried slices were also found to be comparable to oven drying at elevated temperature (40 ℃ – 50 ℃). This indicates that assistance of Coulomb force in heat pump drying enhanced the drying rate by stimulating the moisture transportation through the semi-permeable membrane of the lemon slices. Eventually, the effective moisture diffusivity

was found to improve by up to 26.4%, and the total drying time required by CF-HP drying method was shortened by up to 39.9%, as compared to heat pump (HP) drying alone. It reduced the total energy consumption by 31.5% with the assistance of Coulomb force.

In terms of product quality, CF-HP dried slices were found to retain up to 116.7% higher vitamin C than other dried products. Mild temperature drying condition and high drying rate in hybrid heat pump (CF-HP) drying minimized the deterioration of ascorbic acid which could otherwise attributed to thermal degradation and enzymatic oxidation. However, the total phenolics content (TPC) amount of CF-HP dried slices was found to be slightly lower than CF-HP with heater (CF-HT-HP) and oven dried slices. Fast drying and short drying time of the lemon slices during CF-HT-HP and oven drying prevented the degradation of TPC due to volatilization, oxidation and heat destruction processes.

Meanwhile, the physical quality analysis of the lemon slices showed that area shrinkage of HP, CF-HP, and CF-HT-HP dried slices was lesser than oven dried slices. CF-HP drying which was conducted at mild temperature and high drying rate minimized the moisture concentration gradient within the lemon slices and thus reduced the area shrinkage of the dried products by up to 21.11% compared to oven dried slices. In term of colour assessment of dried product, both CF-HP and CF-HT-HP dried lemons slices showed minimum browning compared to oven and commercial dried slices. In fact, their colour was not much different from the fresh and freeze dried lemon slices. This indicated that zero heat generation from the Coulomb force during CF-HP and CF-HT-HP drying prevented the heat destruction processes such as enzymatic and non-enzymatic reactions.

The findings in this work showed that Coulomb force assisted heat pump drying reduced the energy consumption, intensified the drying rates, enhanced the moisture diffusivity and consequently shortened the total drying time of lemon slices compared to conventional heat pump drying method. On the product quality, it appears that CF-HP drying is a highly recommended drying method for the preservation of antioxidants and physical properties of dried lemon slices. Hence, other than foods and agricultural products, the potential of this drying method can also be extended to drying of materials with poor heat-transfer characteristics, which are difficult to dry with convection heating.

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Finally, I would like to thank my beloved family members for their continued support.

APPROVAL SHEET

This dissertation entitled "**DRYING CHARACTERISTICS AND QUALITY OF LEMON SLICES DRIED UNDERGONE COULOMB FORCE ASSISTED HEAT PUMP DRYING**" was prepared by LEE YONG HONG and submitted as partial fulfillment of the requirements for the degree of Master of Engineering Science at Universiti Tunku Abdul Rahman.

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SUBMISSION OF DISSERTATION

It is hereby certified that **Lee Yong Hong** (ID No: **12UEM07907**) has completed this dissertation entitled "DRYING CHARACTERISTICS AND QUALITY OF LEMON SLICES DRIED UNDERGONE COULOMB FORCE ASSISTED HEAT PUMP DRYING" under the supervision of Dr. Chin Siew Kian (Supervisor) from the Department of Chemical Engineering, Lee Kong Chian Faculty of Engineering and Science, and Dr. Chung Boon Kuan (Co-Supervisor) from the Department of Electrical and Electronic Engineering, Lee Kong Chian Faculty of Engineering and Science.

I understand that University will upload softcopy of my dissertation in pdf format into UTAR Institutional Repository, which may be made accessible to UTAR community and public.

Yours truly,

____
(Lee Yong Hong)

DECLARATION

I hereby declare that the dissertation is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at UTAR or other institutions.

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Date _______________________________

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LIST OF SYMBOLS / ABBREVIATIONS

A	Absorbance of the extract
$D_{eff,ave}$	Average effective diffusivity (m^2s^{-1})
V_a	Amount of of ascorbic acid solutions used (ℓ)
T_B	Boiling point of the water (K)
r	Coefficient of correlation
C_{AAS}	Concentrations of Ascorbic acid solutions (kg of AA / l of extracting solution)
C_{GA}	Concentration of Gallic acid solutions (kg of GA / l of extracting solution)
D_f	Dilution factor
x	Distance in the direction of moisture transfer (m)
W_d	Dry weight of the sample (kg)
R	Drying rate (kg H_2O / $m^2 \bullet s^1$)
t	Drying time (h)
D_{eff}	Effective moisture diffusivity (m^2s^{-1})
ΔH	Enthalpy of vaporization ($4.066 \times 10^4 Jmol^{-1}$)
M_{eq}	Equilibrium moisture content (kg H_2O / kg dry weight)
W_{eq}	Equilibrium weight of the sample (kg)
MR_{exp}	Experimentally obtained moisture ratio
F_t	Free moisture content at time t (kg H_2O / kg dry weight)
R	Ideal gas constant ($8.314 Jmol^{-1}K^{-1}$)
M_0	Initial moisture content (kg H_2O / kg dry weight)

W_0	Initial weight of the sample (kg)
L	Length (m)
$E(\%)$	Mean relative error (%)
M_t	Moisture content at time t (kg H_2O / kg dry weight)
M	Moisture content of the product (kg H_2O / kg dry weight)
MR	Moisture ratio
MR_t	Moisture ratio at time t
n	Numerical constants
MR_{pre}	Predicted moisture ratio
P_V	Pressure inside the vacuum chamber (Pa)
R_c	Radius of cylindrical (m)
r	Radius of sphere (m)
χ^2	Reduced chi-square
α_i	Roots of Bessel function of Zeroth order
T_0	Specific temperature (373K)
P_0	Specific vapour pressure (101,325Pa)
A_F	Surface area of lemon slices after drying process (m^2)
A_0	Surface area of lemon slices before drying process (m^2)
A_s	Surface area of the sample (m^2)
T	Temperature (K)
MR_{theo}	Theoretical moisture ratio
l	Thickness of the samples (m)
N	Total number of data points
P	Vapour pressure (Pa)
V	Volume of the extracting solution used (ℓ)

V_s	Volume of supernatants (ℓ)
W_t	Weight of the sample at time *t* (kg)

ANOVA	Analysis of variance
AA	Ascorbic acid
AAS	Ascorbic acid solutions
COP	Coefficient of performance
CF-HP	Coulomb force assisted heat pump
CF-HT-HP	Coulomb force assisted heat pump with heater
d.b.	Dry basis
EMC	Equilibrium moisture content
EHD	Electrohydrodynamic
GA	Gallic acid
HP	Heat pump
HPD	Heat pump drying
IS	Indophenols standard
PPO	Polyphenol oxidase
RH	Relative humidity
RMSE	Root mean square error
SEM	Scanning electron microscope
TPC	Total phenolics content
w.b.	Wet basis

CHAPTER 1

INTRODUCTION

1.1 Research Background

Drying process is required in almost all material processing industries, ranging from agriculture to pharmaceuticals. In most cases, it is the most energy-hungry unit operation of the whole material processing system. Drying technology deals not only with removal of liquid to a produce solid product but also with the post drying properties of the dried material. Some conventional drying technologies may provide high drying rate, but required a great amount of energy and give rise to degradation of the product quality (in terms of nutrients, flavour, mechanical strength, volume and surface structures, colour, heat conductivity and specific heat capacity) due to heating, while others have a moderate drying rate but offer better quality control that is desirable for certain products (Chin et al., 2011). Hence, many advanced drying technologies have been developed in the past decades to address the drying efficiency aspect without affecting the quality of the dried product. These advanced drying technologies include inert particles drying (Kutsakova, 2007), impinging stream drying (Wang and Mujumdar, 2007), superheated steam drying (Haque and Sergeant, 2008), vacu jet drying (Maekawa, 1994), contact-sorption drying (Ye et al., 2007), ultrasound-assisted drying (Carcel et al., 2002), pulse combustion drying (Kudra, 2008), atmospheric freeze-drying (Alves-Filho et al., 2007), refractance window drying (Nindo and Tang, 2007), and microwave-vacuum drying (Cui et al., 2004). However, these technologies could be expensive to implement in terms of equipment cost and operating cost.

Heat pump drying (HPD) is one of the advanced drying methods that have been used for drying of many agriculture products (Pal et al., 2008; Aktaş et al., 2009; Ayub Hossain et al., 2013; Shi et al., 2013). It is known as an energy efficient drying method with higher coefficient of performance (COP) and produces relatively good product quality as drying was conducted at mild temperature and low relative humidity (Fatouh et al., 2005; Chua et al., 2010; Marnoto et al., 2012). However, it usually requires relatively long drying time as this drying method is conducted at mild drying temperature, which in turn limits the moisture diffusion in the drying materials.

During drying process, moisture diffusion is driven by mass concentration gradient between the core and the surface of the material being dried. Slow process of moisture diffusion due to mild temperature heat pump drying eventually limits the drying rate, which consequently prolong the drying time. Hybrid drying involving heat pump combined with other methods such as ultrasound assisted, radio frequency / microwave heating, infrared heating, solar heating, and hot air also been studied by a number of researchers with the purpose to stimulate the drying rates and moisture diffusivity of the drying materials during heat pump drying (Kudra and Mujumdar, 2002; Goh et al., 2011; Mujumdar and Jangam, 2011; Patel and Kar, 2012; Sevik et al., 2013; Mohanraj, 2014; Sun, 2014). The application of ultrasound energy is limited by the inefficient transmission of ultrasonic energy in the air to the drying material which is insignificant for the improvement of drying rate due to the acoustic impedance mismatch (Gallego-Juarez, 2010; Cárcel et al., 2012; Sun, 2014). Volumetric heating from radio frequency / microwave drying allows the transmitted heat energy to be absorbed by the whole drying samples instead of the surface of drying samples. This causes the great improvement in drying rate and effective moisture diffusivity and thus, shortens the total drying time (Bradshaw et al., 1998; Darvishi et al., 2012; Ghanem et al., 2012). However, there is a limit on the amount of drying rate enhancement achievable. For example, the applied microwave power must not be too high such that it overheats and destroys the desired properties of the material due to volumetric heating (Bantle et al., 2013; Jaroenkit et al., 2013). Other hybrid drying methods which involved heating also not suitable for drying of heat sensitive materials (Kaya et al., 2010; Sun, 2014; Barzegar et al., 2015). Hence, a major breakthrough will be made if an efficient method to move moisture from the core to the material surface during heat pump drying is found.

1.2 Problem Statement

As drying process is energy intensive, the desired drying process is preferable low energy consumption, short drying time and preserves maximally the physical and chemical quality of dried products. In order to improve the product quality while increase the energy efficiency of the drying process; heat pump drying has been adopted for the drying of heat sensitive materials. However, heat pump drying with mild drying temperature tends to prolong the drying process, especially at the late phase of drying process, due to slow diffusion of moisture in the drying materials which limits the drying rate (Patel and Kar, 2012; Yang et al., 2013; Closas and Villanueva, 2014; Kivevele and Huan, 2014). Hybrid heat pump drying method by integrating the heat source such as heating coils, infrared heater, solar radiation, radio frequency and microwave into the heat pump dryer could shorten the drying duration of heat pump drying. However, heating coil assisted heat pump drying and infrared assisted heap pump drying are energy intensive and it usually involves high temperature drying whereas solar assisted heat pump drying method tends to heat up the drying materials and resulted in uneven temperature distribution of the drying materials. Meanwhile, radio frequency / microwave assisted heat pump drying is not suitable for drying materials with poor dielectric properties. Furthermore, volumetric heating which resulted in rapid increases of inner temperature of food materials also produces adverse effects on the bioactive ingredients of dried products. Hence, these drying technologies are lack of practical application for drying of heat sensitive materials.

In this research, Coulomb force assisted heat pump (CF-HP) drying has been proposed as an alternative drying technology to enhance the moisture diffusivity, without the need to heat up the drying material. Not only it will save energy, the desired properties of the dried material can be preserved as it is non-thermal drying. In CF-HP drying, a high voltage wire mesh (15000V, 50Hz) is incorporated in the drying chamber of the heat pump dryer in order to enhance the removal rate of bound moisture in the drying material, which in turn counteracts the long drying time required in a conventional heat pump dryer due to mild temperature drying. The working principle of the microwave drying shows that water dipoles are capable to re-orient themselves in the rapid reversal of electromagnetic field (the frequency of electromagnetic field can be ranged from 3 to 30 $\times 10^8$Hz) (Bradshaw et al., 1998; Bantle et al., 2013; Hemis et al., 2015). As CF-HP drying is conducted at low frequency (50Hz); water molecules can be polarized without heat generation found in microwave heating. Owing to the bipolar property of moisture content in the drying samples, a positive net force (Coulomb force) can be induced when the samples are placed near to the high voltage (15000V), but low frequency wire mesh. Moreover, using alternating current in high voltage power supply can avoid the used of inefficient AC – DC converter, a common issue reported by researchers when assessing an energy efficiency of electrohydrodynamic drying methods (Martynenko & Zheng, 2016). Unlike electrohydrodynamic drying which uses high voltage (DC) needle-like electrodes that cause localized drying; a low frequency (large wavelength) electric field radiated from high voltage wire mesh is approximately a plane wave and capable to provide uniform drying rate enhancement across the surface of drying materials (Li, Li, Sun, & Tatsumi, 2006; Martynenko & Kudra, 2016). The electromagnetic force stimulates the moisture diffusion from the core to the surface of the samples which consequently evaporated by convective air flow produced by heat pump system at mild temperature and low relative humidity. The quality of the drying material can be preserved as CF-HP drying technique operates at mild drying temperature, low relative humidity and high drying rate. In the current work, lemon fruit slices were used as drying material. CF-HP drying is envisaged to enhance the overall drying kinetics of lemon slices as compared to heat pump drying alone, at the same time, producing dried lemon slices with high retention of antioxidants, low area shrinkage and less browning in terms of optical quality of dried product.

1.3 Research Objectives

The objectives of this research were

- **i.** To fabricate the Coulomb force assisted heat pump (CF-HP) drying system.
- **ii.** To investigate the effect of Coulomb force on the drying characteristics of lemon slices during Coulomb force assisted heat pump (CF-HP) drying as compared to heat pump drying alone.
- **iii.** To determine the quality of Coulomb force assisted heat pump (CF-HP) dried lemon slices in terms of vitamin C and total phenolics content (TPC), and also the effect of CF-HP drying on shrinkage and browning of dried products.

1.4 Research Scopes

(I) To fabricate the drying system.

A heat pump drying chamber was designed and constructed. The principle of the heat pump is similar to the thermodynamic cycle that used in the refrigeration system. Firstly, humid air leaving the drying chamber is cooled in an evaporator. Consequently, condensation of the moisture from the air stream occurs and the heat released is absorbed by the working fluid and causing it to boil in the evaporator. The temperature of the vaporised working fluid is increased as it passes through a compressor. It is then condensed in a condenser; thus, releasing sensible heat to the cold dry air that is blown into the drying chamber for drying purposes. Hence, energy can be recovered from the exhaust air when the latent heat of vapour condensation is converted into a sensible heat of an air stream. The drying performance of the heat pump dryer was evaluated before it was integrated with high voltage wire mesh to form a hybrid drying system. The high voltage wire mesh created Coulomb force which enhanced the diffusivity of moisture to the surface of the drying materials. Subsequently, the moisture was removed by the convective air flow generated by the heat pump system.

(II) To investigate the effect of Coulomb force on the drying characteristics of lemon slices during Coulomb force assisted heat pump (CF-HP) drying.

The drying characteristics of lemon slices were investigated by using heat pump drying with and without integration of Coulomb force. Heat pump drying was operating at 22.0 ℃, relative humidity of 34.0% and air velocity of 1.1ms^{-1} when the auxiliary heater was switched off. Whereas, when the auxiliary heater was switched on, the operating condition was recorded as 31.0 ℃, relative humidity of 24.0% with air velocity remained the same. Coulomb force assisted heat pump (CF-HP) drying was conducted by incorporating a high voltage wire mesh into the drying chamber of heat pump dryer. Lemon slices were loaded on the high voltage wire mesh with a determined effective distance between the wire mesh and drying samples (3×10^{-3}m). The reductions of moisture content in the lemon slices were recorded throughout the whole process for both drying methods. The drying curves and effective moisture diffusivity were obtained from the recorded experimental data. The drying characteristics of CF-HP drying were also compared with heat pump and conventional drying method of lemon slices which was oven drying.

(III) To investigate the effect of Coulomb force assisted heat pump (CF-HP) drying on the quality of lemon slices.

The content of vitamin C and TPC, area shrinkage, and browning effect of Coulomb force assisted heat pump dried lemon slices were determined and compared with heat pump, conventional (oven dried), freeze dried and commercial dried products. In this research, quality of freeze dried lemon slices was used as a reference for comparison purpose.

1.5 Significance of Research

This research will be a major breakthrough in drying technology, especially in hybrid drying technique. It is energy saving (energy consumption for heating element can be reduced), time saving and the quality of dried products can be preserved since it foster the drying rates and it does not involve heating of the drying samples. Dried products with lower cost of production but relatively good quality could improve the sales and increase the profitability of products. Furthermore, this drying technique is potential for drying of material with poor heat-transfer characteristics, such as glass fibres and ceramics that are difficult to dry with convective hot air drying. The outcomes of this research are essential for knowledge enhancement in drying technology, especially in the current industry which involved drying process.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction to Drying

Drying is the most general and diverse unit operation in industrial sectors such as agriculture, chemical, biotechnology, food, ceramics, polymer, paper, wood processing, mineral processing, pharmaceuticals and etc. Nevertheless, phase change of moisture content and production of dry solid as the end product during drying process necessitate huge amount of energy for the high latent heat of vaporization. In addition, an intrinsic ineffectiveness of commonly used hot air as the drying medium makes it as an energy-intensive unit operation (Barba et al., 2013; Zielinska et al., 2013; Closas and Villanueva, 2014). Energy consumption in drying process ranges from around 5% for some chemical processing industries to around 40% for the paper processing industries. Thus, this shows that the major costs are falling under the drying operation (Mujumdar and Devahastin, 2000). Despite that, drying is still an essential unit operation in the production line as it helps to reduce the cost of packaging, transportation and storing by reducing the weight and size of the end products, at the same time, achieve the desired quality of dried product for the preservation purposes. Nevertheless, It has been well known that improper drying may cause irreversible damage to either physical or chemical properties of the dried product and hence a non-saleable product (Zhang et al., 2006; Vega-Gálveza et al., 2009; Djendoubi Mrad et al., 2012).

Removal of moisture from the moist material is a complex unit operation which involves simultaneous heat and mass transfer along with various processes like physical or chemical transformations of the dried product. Physical changes, for example, shrinkage, puffing, crystallization, phase change and glass transitions may occur during the drying process (Le and Jittanit, 2015). Occasionally, undesirable chemical reactions may occur and cause the changes in physical appearance, texture, and other properties of the dried product (Wu et al., 2007; Koné et al., 2013; Paengkanya et al., 2015; Taghian Dinani and Havet, 2015). During drying, there are several ways to deliver the heat required for the vaporization of the water content inside the moist material, for example, conduction, convection, radiation like microwave or radio frequency fields, and combined mode. Yet, most of the industrial dryers are convection dryer that uses hot air (Barba et al., 2013; Bardy et al., 2015).

2.2 Drying Technology

Drying technology unites the knowledge of transport phenomena and material science as it deals not only with the removal of moisture content of drying material, but it also ensures the quality of dried product meets the requirement. Removing the water from drying material, which can be in the form of solid, semi-solid, or liquid, to its final dried product, can lengthen the commercial life of the said product as this limits the microbial growth and retards the deteriorating chemical reactions.

As compared to others, demand of food drying for the preparation of convenience food as well as nutraceutical products is rapidly increasing in both domestic and international markets. Several drying methods are available for food drying; yet, solar drying and hot air convection drying are the most popular drying methods which have been used since historic times.

2.2.1 Solar Drying

Solar drying is one of the drying methods that has been broadly used in drying of fruits and vegetables. This drying method can be divided into two main categories, which are direct or indirect exposure of drying materials to the sun. Direct solar drying involves the spread out of the drying materials in the thin layer form on the large outdoor free threshing surface (Belessiotis and Delyannis, 2011; Chaudhari and Salve, 2014; Sontakke and Salve, 2015). This traditional drying method is usually called as open sun drying and it is in practice for fruits and vegetables preservation since time immemorial (VijayaVenkataRaman et al., 2012; Toshniwal and Karale, 2013). Else, some may also apply passive solar dryer, where the products in the hot closed chamber are exposed to the solar energy through the transparent plastic or glass covers (Figure 2.1). Conversely, for indirect solar drying, drying materials are not directly exposed to the sun; instead, thermal energy collecting devices such as concentrated type solar collector is used to collect the thermal energy from solar radiation in order to heat up the air which later flows through the materials to be dried with either natural convection or force convection (Figure 2.2) (Toshniwal and Karale, 2013; Phadke et al., 2015).

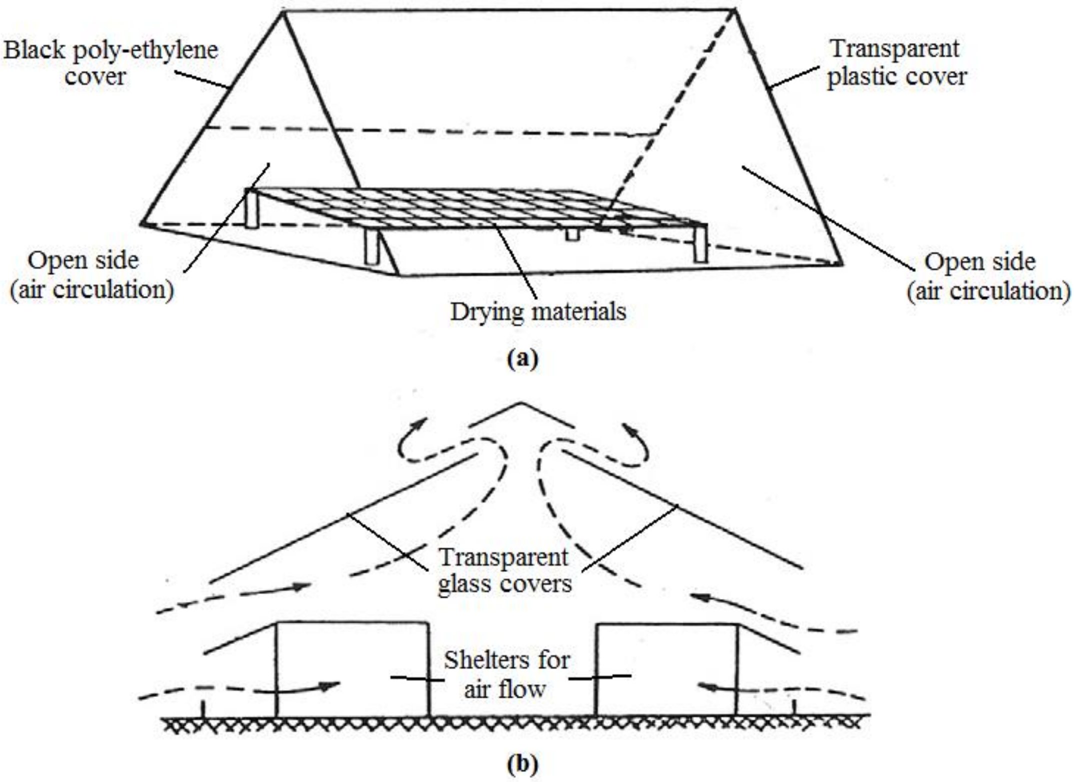

Figure 2.1: Direct solar dryer. (a) Passive solar dryer covered by transparent plastic material. (b) Passive solar dryer with glass covers (Belessiotis and Delyannis, 2011).

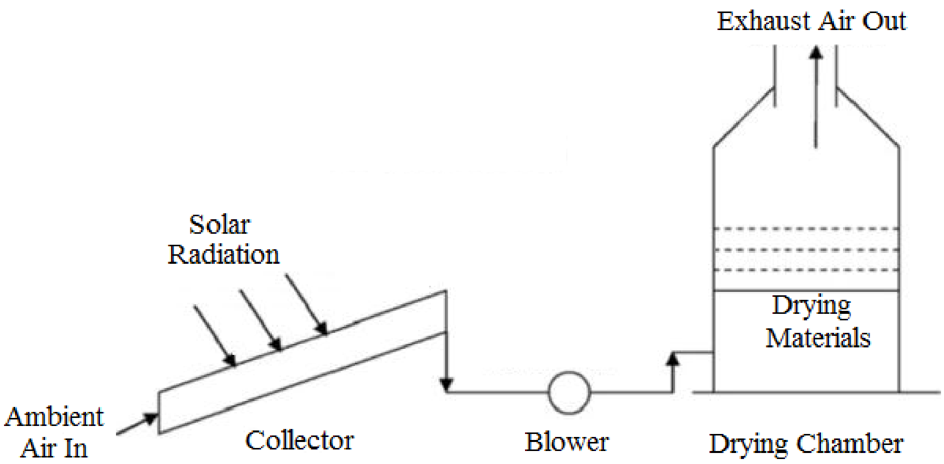

Figure 2.2: Indirect solar dryer (Toshniwal and Karale, 2013).

However, this drying method is accompanied by a multitude of drawbacks that greatly reduce its functionality. In direct solar drying process, drying materials have to be flipped over or stirred frequently as to provide an even drying process, until the materials have been dried up. Thus, scientific control of equilibrium moisture content (EMC) is not possible as it is up to the personnel's experience to decide whether the materials have been dried or not (Ndukwu et al., 2011; Chaudhari and Salve, 2014; Jain and Tewari, 2015). Moreover, the portion of solar energy that can be absorbed by the materials is depends on the absorptivity of the materials (Ramos et al., 2015). Materials with darker surface can be heated up to higher temperature which will cause case hardening on the exposed surface as well as reduce the quality of the products especially in terms of heat sensitive bioactive ingredients (Mustayen et al., 2014). Similarly, deterioration of sugars content and vitamin C due to elevated temperature also has been reported by Chen et al. (2005) during solar drying of lemon slices. In addition, shrinkage, loss of rehydration ability, and surface browning of solar dried products also become prominent (Abano and Sam-Amoah, 2011; Finck-Pastrana, 2014; Phadke et al., 2015).

During open sun dying, materials that remain outdoor for long period of time are easily contaminated by dirt or dust as well as subjected to climate changes and natural attacks such as insect infestation, hail, and etc., which can destroy the drying materials (López-Vidaña et al., 2013; Toshniwal and Karale, 2013; Sontakke and Salve, 2015). As the drying process is relatively slow, enzymatic reactions, growth of microorganisms, and augmentation of mycotoxin will also lead to considerable reduction in quality of dried products (Mustayen et al., 2014). According to Kouchakzadeh (2013), it was found that longer drying time of pistachios at open environment (sun drying) will promote the growth of aflatoxin on pistachios and thus cause huge losses in production. On the other hand, Aritesty and Wulandani (2014) have shown that moisture content of wild ginger dropped noticeably only for the first six hours of open sun drying from 80% w.b. to 40% w.b.. However, there was a great reduction of drying rate in the following 14 hours. This shows that the drying process was hardly to proceed after daily sunshine hours. This also promotes the growth of unwanted microbes that will destroy the drying materials. Furthermore, huge variation in moisture content reduction also reveals the unsteady drying condition of open sun drying. Thus, large dependence on the availability of the solar radiation has greatly reduced the functionality of this drying method. In other words, this drying method can only be practical in Sun Belt, regions where solar radiation is sufficient and sunshine duration is long (Belessiotis and Delyannis, 2011).

Indirect solar drying is a new drying method which is yet to be standardized and widely commercialized. The type and size of the constructed dryer can be customized to suit the drying requirements of food products. However, this could increase the initial capital cost of the dryer (Mustayen et al., 2014). Furthermore, routine maintenance cost especially for equipments such as collector, thermal energy storage system, convective air control system, and skilful personnel to operate drying process also enhance the overall operating cost of this drying method (Kalogirou, 2013; Ramos et al., 2015). Hence, with these hindrances, majority of the solar dryers are used mainly for small scale drying of foods (López-Vidaña et al., 2013). Solar energy will only serve as a secondary energy sources to facilitate the whole drying process in larger food processing industries.

2.2.2 Hot Air Convection Drying

Hot air convection drying is another frequently used drying method for industrial food drying. In this drying method, the drying kinetics are greatly affected by drying temperature and characteristics of drying materials, while all other process factors have negligible influence (Haghi and Ghanadzadeh, 2005). Several types of hot air dryer such as cabinet / tray dryer and tunnel dryer which usually used for different food drying requirements are shown in Figure 2.3. In fact, the basic configuration of hot air dryer is similar to solar dryer with its heating element being replaced by either electrical coil or combustion gas (Bardy et al., 2015). Inside the drying chamber, a mechanical blower provides the circulation of hot convective air stream through the drying materials to facilitate the evaporation of moisture content on the surface of drying materials as well as to expel vaporized moisture from drying chamber. Relative movement of air stream over the product surface is at high velocity to ensure that heat and mass transfer proceed in an efficient manner (Ibarz and Barbosa-Cánovas, 2003; Paul Singh and Heldman, 2009).

Hot air drying is a “simple and fast drying method”; yet, this drying method requires huge amount of energy in processing line. Great amount of energy is required to raise up the temperature of the convective air to enhance the drying rate (Pati et al., 2015). Also, a significant amount of energy is needed to maintain the high temperature inside the drying chamber as well as to provide high convective air velocity in the rapid drying process. Nevertheless, energy and exergetic analyses show that energy utilization drops when drying rate increases by increasing the drying temperature or convective air velocity (Sekone et al., 2015). Besides, low thermal conductivity of drying materials will limit the heat transfer to the interior parts of drying materials during falling rate period. As the heat energy of the hot air convection dryers is not conserved in the drying chamber, a great deal of thermal energy (35 – 45%) will be wasted with the exhaust air (Motevali et al., 2014). In addition, hot air drying at elevated temperature inevitably produces adverse effects on the quality of dried products. As reported by Timoumia et al. (2007), drying of apple slices at elevated temperature (40 to 70 ℃) enhanced the degradation of vitamin C as well as the aroma compounds in dried products. Similar finding was reported by Moraes et al. (2013) during the investigation on the effect of drying temperature (55 to 75 ℃) on vitamin C, TPC and colour of hot air dried pepper. Other than deterioration of bioactive ingredients, several undesirable attributes such as shrinkage, case hardening and browning of dried product were also caused by hot air convection drying (Jiao et al., 2014). The product discolouration and case hardening of hot air dried banana foam mat were found significant due to high temperature drying (Thuwapanichayanan et al., 2008).

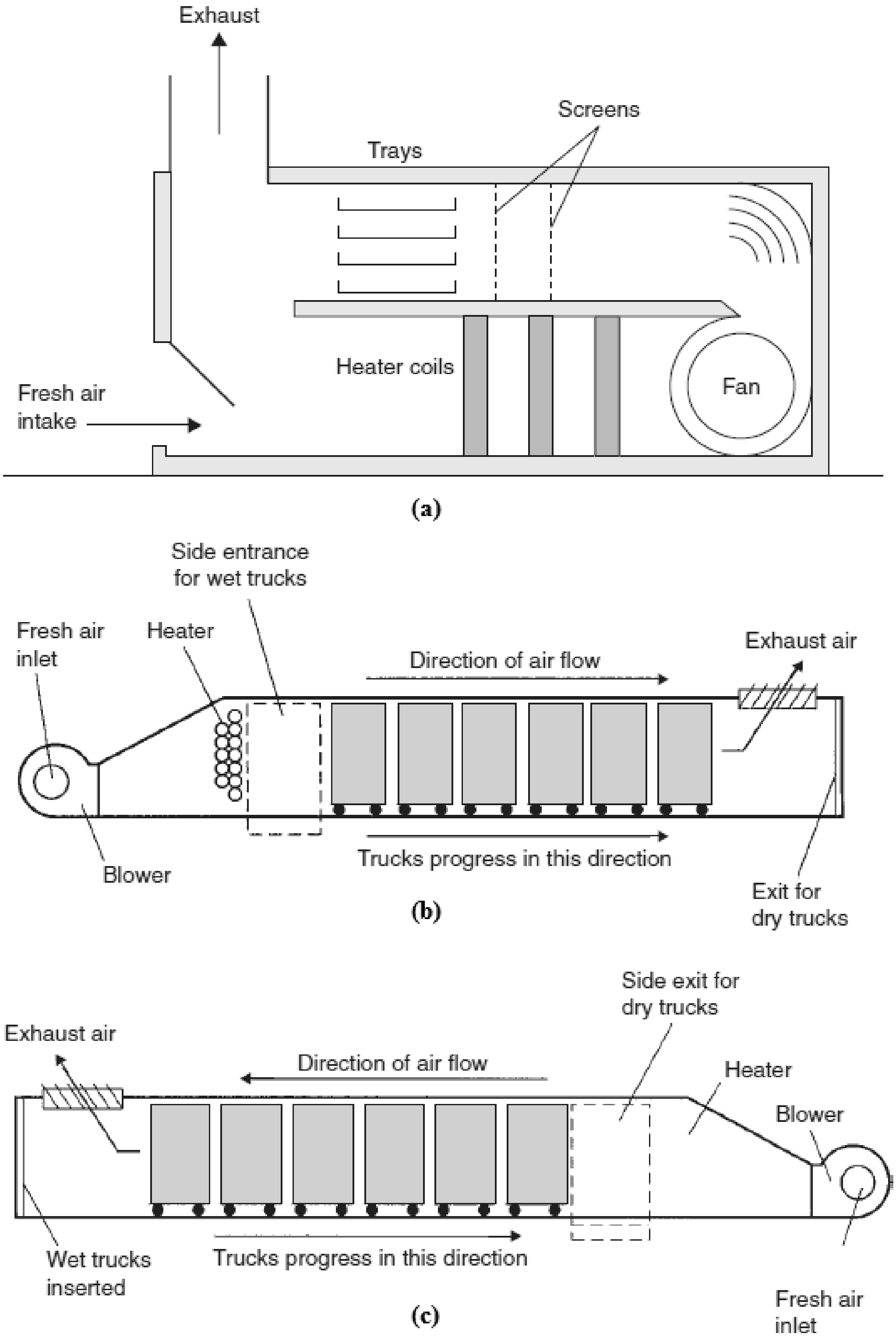

Figure 2.3: (a) Cabinet-type tray dryer. (b) Concurrent-flow tunnel dryer. (c) Countercurrent-flow tunnel dryer (Paul Singh and Heldman, 2009).

2.3 Advanced Drying Methods

Conventional dryers such as hot air dryers with great established records of performance may have become the first choice of consideration. Yet, not all of the dryers are necessarily superlative regarding of energy efficiency, quality of dried products, ability to manipulate drying conditions during drying process, and minimal environmental impact. Thus, advanced drying methods are sought to intensify the drying rate as well as to overcome the drawbacks of conventional drying methods (Kivevele and Huan, 2014).

During drying process, the rate at which wet surface being dried is depends solely on the external heat and mass transfer. Consequently, enhancing the rate of heat and mass transfer by increasing the convective air velocity, drying temperature, or reducing convective air humidity will lead to increased drying rate for conventional dryers (Babalis and Belessiotis, 2004; Fatouh et al., 2005; Zarein et al., 2015). Implementing the mechanical vibrator in advanced drying technologies which generated free-stream turbulence or oscillation of the flow will give rise to higher drying rate. Also, increasing the effective interfacial areas during impinging stream drying can intensify the drying rate (Kudra and Mujumdar, 2002; Nikolopoulos et al., 2015). However, drying rate drops when slow moisture diffusion is taken place during falling rate period. Enhancement of drying rate at this stage requires fast heat and mass transfer through the material (Bantle et al., 2013; Başlar et al., 2014). For that reason, advanced drying technologies must capable to provide an efficient method to move water droplets from the core to the material surface.

2.3.1 Microwave Drying

Microwave has similar properties with visible light (its frequency ranges from 3×10^8 Hz to 3×10^{11} Hz). Depending on the dielectric properties of a material, it may be reflected or absorbed by the material (Barba et al., 2013). As microwave radiation is a form of field energy, it can penetrate a food, and heating occurs within the entire food material (Kudra and Mujumdar, 2002). Thus, heat drying with microwave energy has become an eye-catching solution to many problems in conventional drying process. Major components in a typical microwave dryer are shown in Figure 2.4.

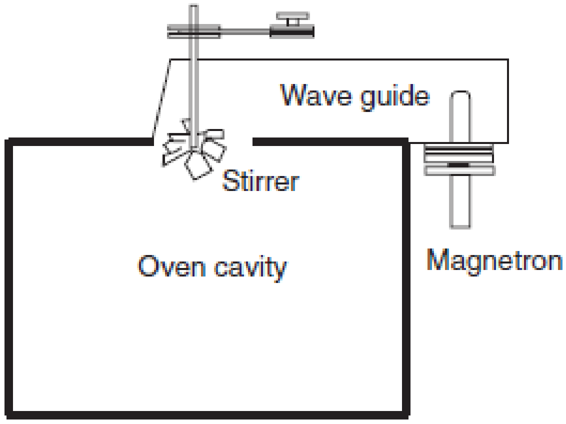

Figure 2.4: Basic composition of microwave dryer (Paul Singh and Heldman, 2009).

Unlike those ionizing radiations such as X-rays and gamma rays, microwave itself is non-ionizing radiation. When food is exposed to microwave radiation, absorption of microwave energy leads to the ionic polarization and dipole rotation of hydronium ions, hydroxide ions, and polar water molecules (Feng et al., 2012). Polarized ions will accelerate and collide with each other, which will cause the conversion of kinetic energy into thermal energy. Meanwhile, bipolar water molecules which initially have a random orientation will orient themselves in accordance with the polarity of the applied electric field. High frequency alternating of microwave's polarity causes fast rotation of the water molecules. While these molecules rotate continuously to align with oscillating field, friction between water molecules and surrounding medium generates heat energy and eventually increases the temperature of the drying material (Kaasová et al., 2002; Zhang et al., 2006). In view of the fact that microwave isn't a thermal energy, therefore heat drying can take place only when there is an interaction between the microwave and drying material. Thus, electrical properties of the material being heated, as well as size, shape and state of the material must be taken into the account when applying microwave drying (Berteli et al., 2009).

Microwave drying offers several advantages over the conventional drying methods. Increasing microwave field strength has a dramatic effect on the power density and thus boosts up the heating speed. As microwave is in the form of field energy and is independent of heat transfer by conduction or convection; therefore it can penetrate the drying materials and heat up within the materials. Consequently, dramatic improvement in drying rate can be seen in materials with poor thermal conductivity since the microwave energy is dissipated towards the wet regions of the materials being dried (Ibarz and Barbosa-Cánovas, 2003). This volumetric heating crafts a temperature gradient within the drying materials and gives rise to a greater partial pressure that drives moisture content to the surface for convective evaporation. As a result, "case hardening" due to rapid drying at high temperature will not occur; instead, the surface remains permeable for moisture content to diffuse out from the interior part (Feng et al., 2012). Paengkanya et al. (2015) found that high microwave power could produce dried durian chips with low shrinkage and hardness values. Similar results were reported by Talens et al. (2015) during microwave drying of orange peel. It was found that dissipation of microwave energy inside the orange peel caused internal evaporation and thus induced an internal swelling which would lessen the shrinkage of dried product (Talens et al., 2015). Moreover, microwave drying is an energy efficient drying method because its energy consumption is much lesser as compared to conventional dryers as only the drying materials are heated during drying process. Hence, thermal energy loss through the heating of the surrounding media such as air, drying chamber, trays and etc. can be eliminated. Further heating of the materials also can be avoided once the materials are totally dried since dry solids are more “transparent” to microwave radiation than water molecules.

Nevertheless, there are few features of microwave heating that will affect the feasibility of this drying method in drying process. Although wave energy transfer in microwave drying improves drying rate of low thermal conductivity materials; yet, not every material can be dried with this drying method. The amount of the energy can be delivered is determined by the loss factor and depth of penetration of drying materials (Paul Singh and Heldman, 2009). The higher the loss factor, the greater the amount of heat can be absorbed by the drying materials for the drying purposes. Meanwhile, the penetration depth also has to be in the correct range to allow the microwave to penetrate to the center of the drying materials but not passing through it. Else, these drying materials will become “transparent” to the microwave generated.

Inability to provide uniform energy distribution inside the drying chamber has also marked down the outstanding of microwave drying. This inherent non-uniformity of the electromagnetic field has assembled several "hot" and "cold" spots inside the microwave cavity (Kaasová et al., 2001). Though, rotation of drying trays and implementation of waveguides can improve the energy distribution, but it can't solve this problem completely (Zhang et al., 2006). Thus, materials to be dried have to be in constant motion inside the drying chamber to avoid any "hot" spots. Non-uniform shapes, sharp edges and corners of the food materials also contribute to the localized heating, causing certain regions to be underexposed and other regions to be overexposed (Paul Singh and Heldman, 2009). The excessive temperature build up along the edges and corners of the materials may lead to the scorching and development of off-flavours (Le and Jittanit, 2015; Pu and Sun, 2015). In addition, dielectric and thermophysical properties of drying materials can result in uneven heating and its effect is more prominent when processing at low frequencies (Jiao et al., 2014). Rapid rise of relative temperature gradient also has an adverse effect on the quality and texture of the dried product (Koné et al., 2013; Zielinska et al., 2013). This thermal process initiates further degradation of heat sensitive bioactive ingredients such as vitamin C and total phenolics content of dried product, decomposition of the high-sugar food product, as well as leads to severe damage to the physical properties of drying material (Nollet and Toldra, 2008; Kaya et al., 2010; Moraes et al., 2013).

Meanwhile, microwave drying is also expensive despite the high capital and operating costs. It may not be economical if microwave energy acts as a sole source of power, especially for drying materials with high moisture content and long constant rate period (Kudra and Mujumdar, 2002). In addition, microwave radiation itself poses a safety hazard. Hence, it is essential to ensure integrity of all the microwave joints and doors. Extra care must be taken to shield the operators from the microwave radiation power. A radiation flux of $100W / m^2$ at a distance 0.05m from the dryer is the acceptable limit (Bradshaw et al., 1998).

2.3.2 Electrohydrodynamic (EHD) Drying

EHD drying is rather a new drying method whereby its drying mechanism involved the production of corona wind by high voltage needle-like electrodes (Cao et al., 2004; Singh et al., 2012). This corona wind perturbs the boundary layer above the grounded surface on which the drying materials are placed, hence amplifying the mass transfer between the surface of materials and the ambient air. A typical EHD drying system is shown in Figure 2.5. The EHD system consisted of multiple vertically mounted high voltage needle-like electrodes pointed toward the grounded drying materials (Lai, 2010; Yang and Ding, 2016). A direct current high voltage of either polarity is chosen as it is substantially better than alternating current (Li et al., 2006).

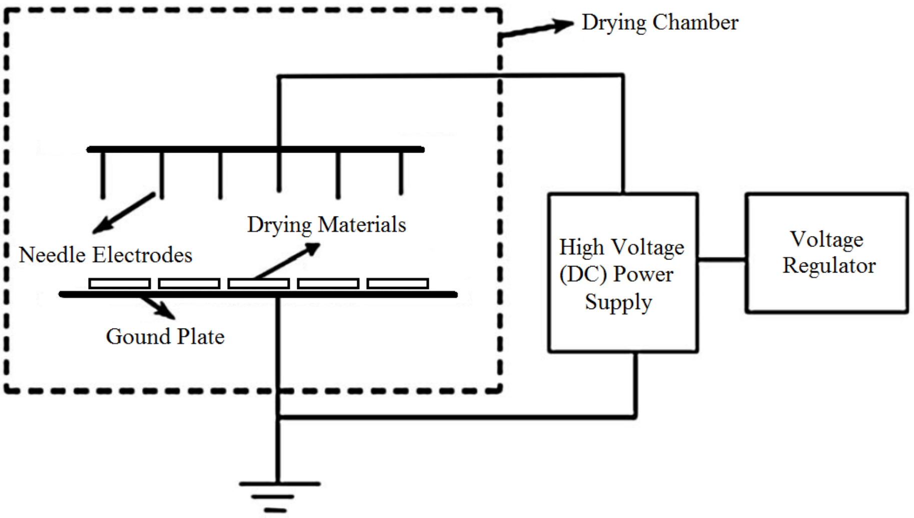

Figure 2.5: Electrohydrodynamic dryer.

High electric field between the electrodes and grounded drying materials accelerates the gaseous ions, causing them to collide with non-charged molecules, which results in an ion-drag phenomenon commonly known as ionic wind (Hashinaga et al., 2007). The generated corona wind impinges on the moist materials, produces turbulent, vortex-like motions which lead to the evaporation enhancement (Basiry and Esehaghbeygi, 2010; Bai and Sun, 2011). Pirnazari et al. (2014) found that increasing electric field strength from 4.5 to 8.5 $\times 10^5 Vm^{-1}$ could increase the drying rate, reduce the total drying time by 19.2%, and produce dried banana slices with low shrinkage. Similarly, high drying rate, porosity, and rehydration ratio are the advantages concluded by Taghian Dinani and Havet (2015) during EHD drying of mushroom slices with applied voltage up to 30000V. In addition, high electric field causes the electrical polarization of water molecules inside the drying materials, leading to decreasing of the entropy and thus lowering the temperature of the materials being dried. Therefore, this drying method is useful for drying of heat sensitive materials (Pirnazari et al., 2014).

The enhancement of mass transfer inside the drying materials during EHD drying depends on the strength of the corona wind. Therefore, sole EHD drying is less efficient and takes longer time to complete if without the convective air flow, which responsible for mass transfer outside the drying materials (Bai et al., 2013). Moreover, the generated electric wind velocity has a limitation. It cannot be increased beyond the breakdown voltage of the electric field, which is $6 \times 10^6 Vm^{-1}$ (Singh et al., 2012). Although EHD drying consumes small amount of energy as compared to the conventional drying methods, inefficient of high voltage AC – DC converter has pulled down the energy efficiency of the whole EHD drying process (Martynenko and Zheng, 2016). On the other hand, intense electric field right under the needle electrodes causes moisture diffusion rate at the area pointed by needle electrodes to be higher than other part of the same drying material. Consequently, parts that pointed by needle electrodes will be over dried and thus led to the localized discolouration of that drying material (Li et al., 2006).

2.3.3 Vacuum Drying

Vacuum drying is another alternative drying method which enables the water contain inside the food to be evaporated in the low temperature more easily than the atmospheric conditions. Low air density around the food will cause rapid evaporation of water inside the food in ambient air temperature. Since air is removed during the drying process, oxidation reactions of food can be reduced. Thus, colour, taste, aroma and nutritional value of the food can be preserved (Wu et al., 2007; Çelen et al., 2013). As shown in Figure 2.6, vacuum dryer is similar with tray dryer, except that it is operated under vacuum condition. The trays are enclosed in a vacuum chamber which connected to a mechanical pump with gauge and valves. Usually, vacuum chamber is equipped with airtight front doors that having vacuum grease on a rubber gasket (Nollet and Toldra, 2008). A condenser with freezing coil will be employed to trap the evaporated moisture from ingested into the mechanical pump.

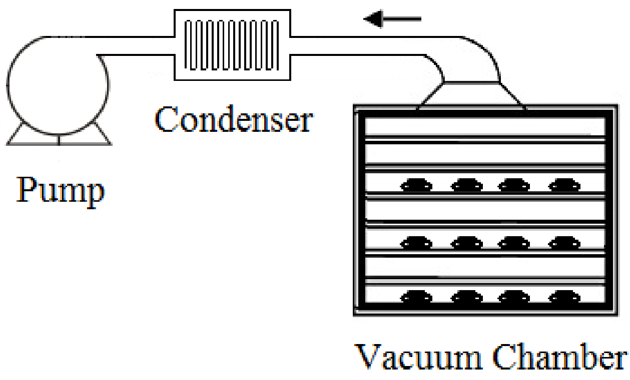

Figure 2.6: Composition of vacuum dryer.

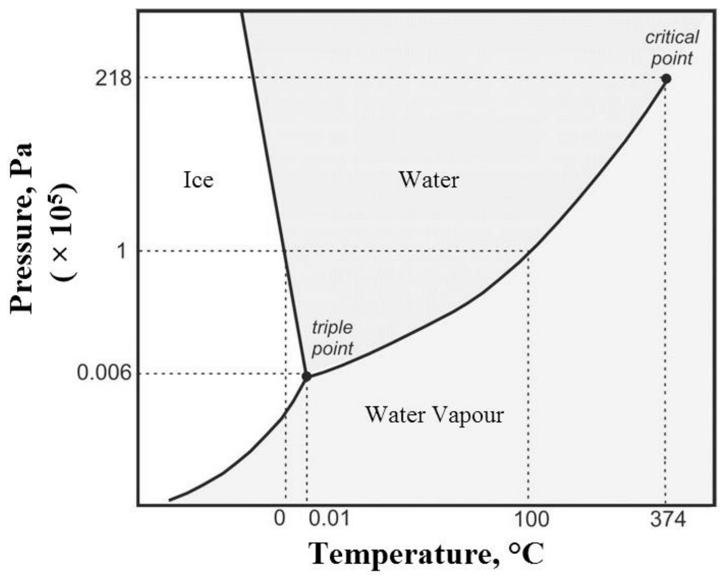

Figure 2.7: Phase diagram of water.

As illustrated in Figure 2.7, water will change phase when its temperature is raised above 373K at 1.01 $\times 10^5$Pa. However, this phenomenon will occur at lower temperature if the surrounding pressure drops below 1.01×10^5Pa and it can be easily proved by the Clausius-Clapeyron equation (equation 2.1).

$$ln\left(\frac{P}{P_0}\right) = \frac{\Delta H}{R}\left(\frac{1}{T_0} - \frac{1}{T}\right) \tag{2.1}$$

Where P is vapour pressure of water at a specific temperature, T, ΔH is enthalpy of vaporization (4.066×10^4Jmol^{-1}), R is the ideal gas constant (8.314Jmol^{-1}K^{-1}). Usually, the known values of pressure and temperature will be used as P_0 and T_0, such as 1.01×10^5Pa and 373K respectively. Given that the vapour pressure of the water will equal to the surrounding environmental pressure when its temperature reaches the boiling point. Hence, equation 2.1 can be modified to determine the boiling point of the water, T_B contained by the food material with the given value of pressure, P_V inside the vacuum chamber.

$$T_B = \left[\frac{1}{T_0} - \frac{R}{\Delta H} ln\left(\frac{P_V}{P_0}\right)\right]^{-1} \tag{2.2}$$

During vacuum drying, the pressure inside the chamber is reduced below atmospheric pressure, which ranges from 6 to 25×10^3Pa (Mitra et al., 2011). Low pressure around the food materials will trim down the boiling point of the moisture below 373K (or 100 ℃), which then allows moisture to evaporate without elevating the temperature. Obtaining a higher degree of dryness at low drying temperature has become a promising factor for this drying method. Drying at lower temperature not only can yield superior quality of dried products, it can also lessen the energy consumption and minimize the air pollution due to combustion fuels used. Additionally, drying under a vacuum condition can prevent oxidation degradation of sensitive product that cannot be dried with the presence of convective air (Çelen et al., 2013). Better final product quality such as flavour, texture, colour and retention of bioactive ingredients can also be achieved. Hence, vacuum drying is competent to provide fast and effective drying of high-value products that are likely to be heat sensitive (Mitra et al., 2011).

Nevertheless, vacuum drying comes along with several drawbacks. This drying method has higher initial and operating costs as compared to the hot air convection dryer (Kivevele and Huan, 2014). This is due to the need for construction of airtight vacuum chamber and an expensive vacuum pumping system which need to be replaced regularly. Low efficiency of the equipments and small production capacity have also offset its advantage in low energy consumption. Moreover, it is not convenient to access the drying materials during vacuum drying until the whole drying process has been completed. This in turn reduced the flexibility of this drying method. In terms of quality preservation, vacuum condition of this drying method will cause more losses in volatile organic compounds such as acetic acid, phenolic compounds and alcohols in the dried products (Nollet and Toldra, 2008).

Besides, the use of a vacuum alone is not effective for rapid drying of food materials as vacuum condition has lesser beneficial effect on the drying rate as compared to the drying temperature. This result was found by Wu et al. (2007) during their research on the vacuum drying of eggplants. In fact, reducing the pressure inside the chamber will bring down the temperature around the food materials, causing these food materials to loss heat energy to the surrounding (Piotrowski et al., 2007; Zakipour and Hamidi, 2011; Mitra et al., 2011). Evaporation of the moisture will further devour the remaining energy, causing the remaining moisture to freeze. Without the supplementary heat sources, drying process becomes dawdling as the frozen moisture need to acquire enough energy to liquefy and then vaporize (Wu et al., 2007). As there is no air inside the chamber, heat energy can only be supplied in the form of radiation (for example, infrared and microwave radiation) or conduction (for example, heating up the trays which contain the food materials). In addition, drying efficiency will be further reduced when drying materials contain high amount of moisture as more energy has to be supplied to complete the drying process under vacuum condition (Richter Reis, 2014). Therefore, this drying method is often used as a secondary dryer, to reduce the moisture of hot air dried product from 20 – 25% to 1 – 3% (Mujumdar, 2014).

2.3.4 Freeze Drying

Freeze drying (technically known as lyophilisation) is well known as the best drying method for preserving the freshness and textural quality of the food materials such as coffee, strawberries, sliced mushrooms, steaks and chops. This drying method is accomplished by reducing the pressure and temperature of the drying chamber in order to facilitate the sublimation of ice crystals inside the frozen food materials (Adams, 2007; Paul Singh and Heldman, 2009; Nireesha et al., 2013). Figure 2.8 shows the sublimation of ice crystals inside the food materials into water vapour which later been collected at freezing condenser.

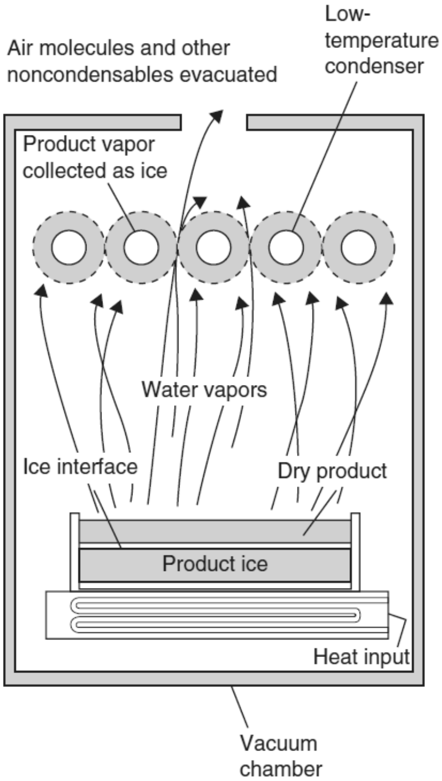

Figure 2.8: Freeze drying process (Paul Singh and Heldman, 2009).

Freeze drying and vacuum drying having a similar working principle, yet these two drying methods are exploiting different regime of pressures and temperatures. Vacuum drying is taken place at pressure and temperature beyond the triple point of water (600Pa, 0.01 ℃); however, freeze drying works at pressure and temperature below the triple point of water. Prior to freeze drying, food materials need to undergo a quick freezing stage in order to obtain small ice crystals which are in an amorphous state. Formation of these amorphous ice crystals can enhance the thermal conductivity of food materials by increase the porosity of food matrix (Xiao Dong and Mujumdar, 2009). Subsequently, low pressure and temperature inside the chamber allow the ice crystals to undergo sublimation and leave the food materials as water vapour whereas pores inside the food materials where the crystals of pure ice had been will be maintained (Nollet and Toldra, 2008). Since sublimation is a much faster process as compared to the vaporization, there will be a quick reduction in the moisture content of the drying materials before reaching as low as 5% of equilibrium moisture content. Heat energy required to enhance the sublimation rate can be supplied by either radiation or conduction (Ibarz and Barbosa-Cánovas, 2003).

Freeze drying is remarkable in yielding superior product quality which cannot be well preserved by any other drying methods. Drying process which conducted at low temperature and vacuum condition can prevent deterioration due to oxidation, enzymatic and non-enzymatic browning reactions of the food products (Antal, 2015; Rudy et al., 2015). As a result, colour, intense flavour, aroma, and bioactive ingredients of the food products remain unaltered. Hence, freeze drying is always recommended for drying materials that contain heat sensitive bioactive ingredients (Rudy et al., 2015). With the adequate packages, greatly reduced water content in freeze dried products can be kept for unlimited time, maintaining most of the physical and chemical properties of the fresh products (Nireesha et al., 2013). Thus, freeze dried product which has the best dried product quality is often used as a benchmark for assessing the quality of food products dried by other drying methods (Asami et al., 2003; Stawczyk et al., 2004). Furthermore, drying by means of rapid sublimation of frozen moisture will not cause shrinkage or toughening of the drying material (Paul Singh and Heldman, 2009; Antal, 2015). High porosity constitution of freeze dried products allows rapid rehydration to recuperate their original shape and structure.

Nevertheless, the advantages of freeze drying are compromised by the energy intensive aspects especially for rapid freezing and vacuum requirements (Paul Singh and Heldman, 2009; Zielinska et al., 2013). Drying at very low temperature and pressure requires the employ of heavy duty freezing and vacuum pumping systems; consequently, its operating cost can easily boost up to 2 to 5 times greater than other drying methods (Ibarz and Barbosa-Cánovas, 2003; Antal, 2015). For this reason, food materials with high moisture content can only be cost effectively dried by using the combination of freeze drying and other drying methods (Antal, 2015). Similar to vacuum drying, low temperature and pressure drying in this drying method prolongs the total drying time and promote greater losses in volatile organic compounds (Nollet and Toldra, 2008; Antal, 2015). Pei et al. (2014) found that the level of compounds such as soluble sugar, free amino acids, 5'-nucleotides and organic acids dropped significantly during freeze drying of button mushroom slices.

2.3.5 Other Advanced Drying Methods

There are other advanced drying methods such as pulse combustion drying, fluidized bed drying, impinging stream drying, inert particle drying, super heated steam drying, ultrasound-assisted drying and etc. Some of the drying methods have evolved and demonstrated their potential to compete with the conventional drying methods as they improve the drying rate and are capable to produce superb quality of dried product in terms of flavour, aroma, texture, colour and precious nutrients (Kudra and Mujumdar, 2002). However, these advanced drying methods are usually cost intensive due to high equipment and operating costs. Hence, there is a preference to employ conventional drying methods in industry due to their mature status and lower initial cost. More R&Ds have to be done to improve the drying performance and reduce the operating costs concurrently, before it will readily replace the conventional drying methods for industrial acceptance.

2.4 Heat Pump Drying

With lifting in the cost of fuel and global warming issues, it is crucial to improve overall energy efficiency of the drying process, which has been proven to be an energy intensive process (Chua et al., 2010). Literally, masses of technical papers of archival interest are published as researchers are seeking for a desire drying technology which has low energy consumption, short drying time and preserves maximally the physical and chemical properties of the dried products. Among the advanced drying technologies, heat pump drying has become a mature drying technology over the past two decades owing to its energy efficient and environmental friendly capability. Its ability to recuperate and convert environmental and waste energy such as latent heat of vaporization to sensible heat of an air stream that passing through the drying materials make it attractive in drying applications.

The operating principle of heat pump system is the same thermodynamic cycle that employed in the refrigeration system. As illustrated in Figure 2.9, inlet drying air (hot dried air) enters the drying chamber from point A and vaporizes the moisture from the moist samples. Then, the humid air (point B) is directed to the evaporator coil for cooling and dehumidification as low temperature refrigerant entering the evaporator will be vaporized by thermal input from convective air. During the dehumidification process at evaporator, the air stream is first cooled down to its dew point. Further cooling process will cause the water vapour being condensed from the air stream and the released latent heat is absorbed by the evaporator for the boiling of refrigerant. Subsequently, the refrigerant enters the compressor (point C) in saturated vapour state and it is compressed to high pressure and temperature. The hot, compressed refrigerant vapour enters the condenser that uses surrounding air to cool the superheated refrigerant vapour to its saturation temperature before fully condense into a liquid state. At the condenser (point D), the refrigerant experiences two-phase condensation. During this process, heat is released by the condenser to heat up the cooled and dehumidified air. Subsequently, hot and dehumidified air is diverted to drying chamber for drying purposes. A throttling device like expansion valve is used to reduce the pressure of liquid refrigerant. After the abrupt reduction in pressure, the refrigerant is heading to the evaporator in a two-phase state and the cycle will repeat until the drying process stops (Kudra and Mujumdar, 2002; Chua et al., 2010).

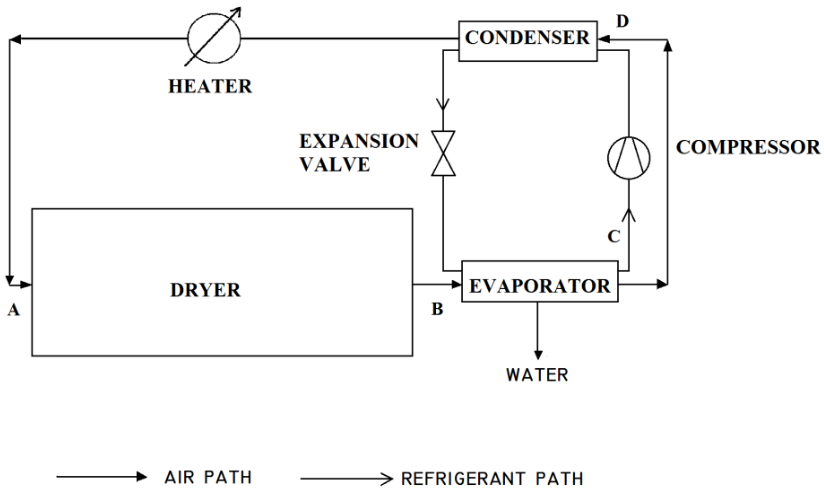

Figure 2.9: Schematic representation of the heat pump drying system.

Heat pump dryer has many advantages over conventional dryers that using electric heaters for food drying. It is capable to recover the latent heat by condensing water vapour from the convective air. The recovered heat energy is then recycling back to the dryer through heating up the dehumidified drying air. With this drying method, 40% of heat energy required by food drying can be reused for whole drying process, leading to a substantial energy saving (Goh et al., 2011; Patel and Kar, 2012). Thus, a net reduction in total energy consumption and decreased of the emission of greenhouse gases. High coefficient of performance (COP) and well controlled drying conditions which lead to possibility of a wide range of operating conditions have further increased its competency as the best drying method (Fatouh et al., 2005; Marnoto et al., 2012). In addition, heat pump drying which uses cool dry air as the convective drying medium is capable to produce a relatively good quality of dried products as compared to conventional hot air drying (Chua et al., 2010; Shi et al., 2013). This is because drying of heat sensitive food materials requires huge amount of low temperature heat energy (Somogyi et al., 1996; Chua et al., 2010). The closed system of heat pump is also very useful for retention of volatile bioactive ingredients of the drying materials which otherwise are vanished using the common convective dryers.

Although heat pump drying offers a simple way of energy efficient drying method; this drying method requires relatively long drying time due to ambient drying temperature. As discussed in the previous section, mild temperature drying will lead to slow moisture diffusion between the core and the surface of the material being dried. Eventually, slow process of moisture diffusion will limit the drying rate and prolong the total drying time especially at the late phase of the drying process. In consequence, it will be a common practice by combining heat pump system with other drying methods in order to enhance the moisture transfer mechanism. Such combined drying system is called hybrid drying methods. Wide range of successful drying methods fall in this category as they have been developed based on an adequate combination of conventional drying methods (Kudra and Mujumdar, 2002).

2.5 Hybrid Heat Pump Drying

Numerous hybrid heat pump drying have been introduced to enhance the drying rate during heat pump drying of food materials. The limitation of relatively low heat and mass transfer rates in heat pump drying during falling rate period can be solved by integrating the heating elements into the conventional heat pump dryer. Several heating modes such as radio frequency / microwave heating, solar heating and infrared heating as well as non-heating mode such as power ultrasound have been used along with convective heating during heat pump drying in order to enhance the drying rates, particularly during final stages of drying (Goh et al., 2011; Kouchakzadeh, 2013). Various attempts have been made and the suitability of the hybrid heat pump systems in food drying operation has been discussed in literatures.

In radio frequency / microwave assisted heat pump drying, both electromagnetic fields are capable to volumetrically heat up the food material by the combined mechanism of dipole rotation and ionic conduction (Kudra and Mujumdar, 2002). Such internal heat generation can speed up the drying process because of the development of unidirectional temperature, internal pressure and moisture concentration gradients (Kudra and Mujumdar, 2002). Thus, materials that are difficult to dry with a convection dryer can be good candidates for radio frequency / microwave assisted heat pump drying. However, this hybrid drying system may not suitable for drying materials that have poor dielectric properties. Though increasing the field energy can enhance the drying rate by increasing the internal temperature of food materials; precautions are needed to confine the high energy electromagnetic fields inside the dryer. Furthermore, rapid rise of internal temperature will have a propensity for degradation of heat sensitive nutrients in drying materials (Kudra and Mujumdar, 2002).

On the other hand, performance of conventional heat pump dryer can be enhanced through the incorporation of sustainable energy sources such as solar energy (Mortezapour et al., 2012; Mohanraj, 2014). The integration of a heat pump drying with solar system appears to be more efficient than heat pump drying and solar drying alone (Sevik et al., 2013). While solar system can supply thermal energy at temperatures higher than surrounding temperature, this energy can be utilized for auxiliary heating either by direct heat transfers through solar radiation or heating up the convective air by using the stored solar energy. Thus, external auxiliary load requirement would be lessened and this hybrid system will be operated more economically (Sevik et al., 2013). Nevertheless, it is difficult to control the amount of heat energy to be transferred to food materials when direct solar radiation is utilized as a heat source as it will lead to uneven temperature distribution of the drying materials. Several factors such as weather conditions, absorptivity of food material and intensity of solar radiation will affect the amount of heat delivered to food materials (Chaudhari and Salve, 2014). Meanwhile, indirect solar system can have better distribution of heat energy, yet it requires much higher start-up cost for building up the thermal energy storage system (Chaudhari and Salve, 2014).

Alternatively, infrared heater can also be used as an auxiliary energy source for heat pump drying (Song, 2013). The heater transfers its energy to food materials to a certain depth via infrared light radiation (Antal, 2015). Therefore, it can raise the temperature of food materials without heating up the convective air. Yet, similar to coil heating, infrared heating is energy intensive process. Rapid rise of temperature on heat-irradiated surface of drying materials tends to cause shrinkage and discolouration of dried products, as well as thermal degradation of heat sensitive phytochemicals (Vega-Gálveza et al., 2009; Chong et al., 2013). According to Kammoun Bejar et al. (2011), the thickness of orange peels shrank significantly at elevated temperature (70 °C) due to the large quantity of evaporated moisture during drying. On the other hand, Gabel et al. (2006) also found that long exposure of higher surface heat flux could lead to greater browning of infrared dried onion. Similar findings were reported by Barzegar et al. (2015) who found that colour of infrared dried green peas turned reddish brown as infrared intensity increased to $9000 Wm^{-2}$.

Other than incorporation of heating element, the drying rates of low temperature heat pump drying can also be enhanced by supplying the non-thermal vibrational energy such as power ultrasound to the drying materials. By varying the intensity of the applied ultrasound, the internal moisture diffusivity especially at the late phase of the drying process can be accelerated. During this period of time, heat transfer from the convective air to the material which exposed to ultrasonic field can be increased by approximately 30 – 60% (Povey and Mason, 1998; Proctor, 2011). However, the mechanism of rapid compressions and rarefactions induced by ultrasound is only feasible on the materials with high porosity due to the "sponge effect". Meanwhile, for materials with low porosity, its high structural resistance to the mechanical stress will lead to the serious ruptures leading to undesirable texture damage (Feng et al., 2010; Sun, 2014). Moreover, the acoustic impedance mismatch will reduce the efficiency of ultrasound energy transmission to the drying material and thus minimize the improvement of drying rate (Gallego-Juarez, 2010; Cárcel et al., 2012; Sun, 2014).

Review of hybrid heat pump drying shows that the mainstream of drying rate improvement is incorporating of heating elements, which has been proven undesirable on heat sensitive bioactive ingredients. In addition, these methods are relatively expensive due to high initial and operating costs. For that reason, a novel hybrid heat pump drying method with minimum heating and high drying rate has to be developed for drying of heat-labile bioactive materials or material with poor heat transfer properties. This is not limited to all kinds of agriculture products only, but also the materials such as bricks, ceramic, fibers and etc.

2.6 Drying Characteristics of Food Material

Drying characteristics are determined by how the moisture is stored inside the material. In the first instance, heat and mass transfer occurs simultaneously on the product surface. The moisture adhering to the product surface can be removed by the vaporisation or evaporation which is controlled by convective process. Once this moisture has been removed, drying of the water content stored within the capillaries and pores begins. Thermal drying requires a sufficient amount of heat to remove water content within the material; however, all heating modes except for the microwave and radio frequency are supplying the energy at the boundaries of the drying material (Thirumaleshwar, 2009). As consequences, heat must be transferred into the interior part primarily by conduction, which being confined by the thermal conductivity of the product structure. When sufficient thermal energy is provided to cause the evaporation of water, the vapours are transported from the water surface within the product to the product surface before it can be transported away by the convective hot drying air or by the application of low pressure vacuum condition for non-convective dryers (Adams, 2007; Mitra et al., 2011; Zakipour and Hamidi, 2011). This moisture-vapour diffusion is very much influenced by the vapour pressure gradient between the interior and outer surface of the drying product. The drying speed will be reduced as moisture-vapour need to overcome the diffusion resistance as well as capillary forces (Thuwapanichayanan et al., 2008; Berk, 2013). Moreover, crystal water which is kept inside the drying material only can be removed by intensive heating in addition to low drying speed. For most products, heat and mass transfer inside the product structure will be rate-limiting processes.

There are several mass transfer mechanisms being used for the transportation of moisture within the drying sample, as shown in Table 2.1 (Mujumdar and Devahastin, 2000). Since the physical structure of the drying material is subjected to change during drying, the mechanisms of mass transfer may also vary with drying time.

Table 2.1: Mass transfer mechanisms during drying process.

Mechanism of Mass Transfer	Condition
Liquid diffusion	• Moist sample is at a temperature lower than the 100 ℃. • Due to capillary forces and concentration gradients.
Vapour diffusion	• Liquid vaporises within material. • Diffusion in pores filled with air.
Knudsen diffusion	• Drying at very low temperatures and pressures, for example, freeze drying.
Hydrostatic pressure differences	• Vaporisation rate of interior moisture exceeds the rate of vapour being removed from the drying sample.

The moisture transfer of the material during the drying process is usually described by the drying curve, as shown in Figure 2.10 (a) and (b). As both of these are used to explain the drying mechanism of food material during the drying process, they can be varied according to the drying method, drying conditions and type of drying material.

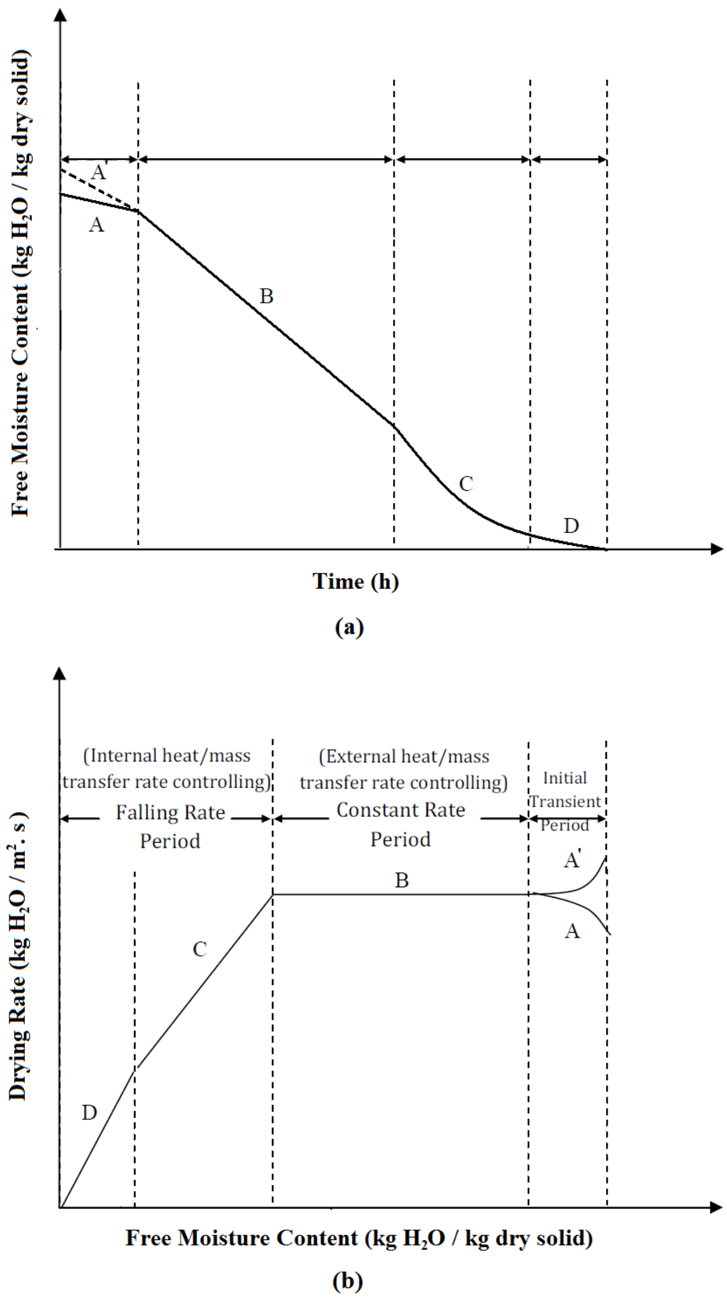

Figure 2.10: Drying curve (Geankoplis, 2003).

Generally, a typical drying rate curve can be divided into initial, constant rate and falling rate periods. From region A to region B, the drying material is being heated up slowly from inlet condition to process condition and sensible heat is transferred into the drying material. At this phase, the drying rate increases dramatically as heat supplied promotes greater rate of evaporation of the free moisture content on the surface of material. Alternatively, region A' will be obtained if the initial temperature of the product is higher than the drying temperature in the drying chamber. Given that the elapsed time from the initial transient period to constant rate period is short, therefore, regions A and A' tend to be neglected in the calculation of drying time (Ibarz and Barbosa-Cánovas, 2003).

As the surface temperature of drying material is in equilibrium with drying temperature, drying rate becomes constant (region B). In this constant rate period, the rate of mass transfer is associated with the removal of free water in the drying material. This period continuously occurs even though the surface is wet. The water vaporized from the surface is then compensated by the water diffused out from the interior of the material, which then causing the rate of evaporation to be close to the rate of moisture transfer from core to the surface of material. In this section, the rate of evaporation has reached its maximum value and it alters very little as the moisture content reduces (Paul Singh and Heldman, 2009; Jangam and Mujumdar, 2011).

When the surface is deficient of water to maintain surface evaporation process, transition of high constant drying rate to falling rate period at the so-called critical moisture content (a turning point between region B and region C) will occur. Usually, falling rate period can be separated into two regions, which are regions C and D or known as first falling rate and second falling rate, respectively. During first falling rate period (region C), interior moisture needs to diffuse out to the surface in order to maintain the moisture vaporization. As a result, the rate of evaporation will be controlled by the rate of internal moisture transfer (or known as diffusion controlled) and this process will continue until the wetted surface of the drying material is completely dry. After that, the second falling rate period (region D) begins. The zone of vaporization recedes slowly below the surface and the remaining water inside the drying material vaporizes by the heat conducted through the material and diffuses into the air stream. Sometimes, the change between the falling rate periods is undetectable (Geankoplis, 2003). Finally, the drying process terminates when free moisture content of the product approaches zero and equilibrium moisture content is achieved.

2.7 Effective Moisture Diffusivity

Moisture diffusivity is an important criterion in drying process, it describes the transportation of water from the interior to the external surface of drying material. Movement of water through the drying material is dependent on the product texture as well as the interactions of bound water inside the product matrix and it can be explained by different mechanisms such as diffusion of liquid which caused by concentration gradients, partial vapour pressure, capillary forces, gravity forces, or surface diffusion (Dak and Pareek, 2014). For drying of heat sensitive material which should be conducted at mild temperature condition, most of the drying technologies will rely on mass transfer (eg. moisture diffusion) driven by mass concentration gradient between the core and the surface of material being dried. Moisture transfer is a slow process and it essentially limits the drying rate.

Fick's second law of diffusion is commonly used in describing the drying process of drying material during falling rate period. According to Fick’s second law of diffusion, assuming constant effective moisture diffusivity, rate of change of moisture content can be expressed as in equation 2.3:

$$\frac{\partial M}{\partial t} = D_{eff}\,\frac{\partial^2 M}{\partial x^2} \tag{2.3}$$

In this equation, M is the moisture content of the drying material, t is the drying time, x is the distance in the direction of moisture transfer, and D_{eff} is the effective moisture diffusivity (Crank, 1975; Miller et al., 2009).

Depending on the geometry of drying material, the analytical solution to Fick's second law of diffusion takes different forms. Few assumptions were made for the analytical solution of drying material such as uniform initial moisture distribution, constant diffusivity, insignificant of shrinkage effect, mass transfer is symmetrical, and resistance of surface mass transfer is insignificant as compared to resistance of internal mass transfer. The solutions for simple geometry like slab, cylinder, and sphere are shown in equations 2.4, 2.5, and 2.6 (Ibarz and Barbosa-Cánovas, 2003).

Slab geometry:

$$MR = \frac{M_t - M_{eq}}{M_0 - M_{eq}} = \frac{8}{\pi^2}\left[\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left(\frac{-(2n+1)^2\pi^2 D_{eff}\,t}{L^2}\right)\right] \tag{2.4}$$

Spherical geometry:

$$MR = \frac{M_t - M_{eq}}{M_0 - M_{eq}} = \frac{6}{\pi^2}[\sum_{n=1}^{\infty} \frac{1}{n^2} \exp\left(\frac{-n^2\pi^2 D_{eff}\, t}{r^2}\right)]$$

(2.5)

Cylindrical geometry:

$$MR = \frac{M_t - M_{eq}}{M_0 - M_{eq}} = \frac{8{R_c}^2}{L^2}[\sum_{i=1}^{\infty}\sum_{j=1}^{\infty} \frac{1}{\alpha_i^2 \beta_j^2} \exp -\left(\alpha_i^2 + \beta_j^2\right)\left(\frac{D_{eff}\, t}{r^2}\right)]$$

(2.6)

Where MR = Moisture ratio

M_t = Moisture content at time t, kg H_2O / kg dry weight

M_0 = Initial moisture content, kg H_2O / kg dry weight

M_{eq} = Equilibrium moisture content, kg H_2O / kg dry weight

r = Radius of sphere, m

L = Length, m

R_c = Radius of cylindrical, m

α_i = Roots of Bessel function of Zeroth order

$\beta_j = \frac{(2j-1)\pi R}{2L}$

However, equations 2.4 and 2.5 can be simplified into equations 2.7 and 2.8 by neglecting the higher order terms, for long drying time, $tD_{eff} / L^2 > 0.2$, or $MR > 0.6$, the equations become:

Slab geometry:

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

(2.7)

Spherical geometry:

$$MR = \frac{6}{\pi^2} \exp\left(-\frac{\pi^2 D_{eff}\, t}{r^2}\right)$$

(2.8)

Subsequently, taking logarithmic on both sides, equations 2.7 and 2.8 will become equations 2.9 and 2.10, respectively. The constant effective diffusivity can be obtained from the gradient of the straight line of graph ln(*MR*) against *t*.

Slab geometry:

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

(2.9)

Spherical geometry:

$$\ln(MR) = \left(-\frac{\pi^2 D_{eff}}{r^2}\right) t + \ln\left(\frac{6}{\pi^2}\right)$$

(2.10)

However, effective diffusivity could be varied with moisture content as in Figure 2.11. Region A represents the monomolecular adsorption on the surface of the drying material and also the movement of water via vapour phase diffusion. Region B includes multi-molecular desorption in which moisture moves in the liquid phase. Both regions A and B exhibits a maximum diffusivity at low moisture content. At high moisture content region, liquid phase diffusion coefficient governs the mechanism of diffusion. Microcapillarity is influential in region C, the period where moisture can easily emigrate from pores structure. In region D, unbound moisture exerts its maximum vapour pressure and the mobility of moisture is mainly due to the capillarity. Generally, different materials do exhibit different behaviour of diffusivity with the decline in moisture content during drying process. The effective diffusivity values for some food products are given in Table 2.2.

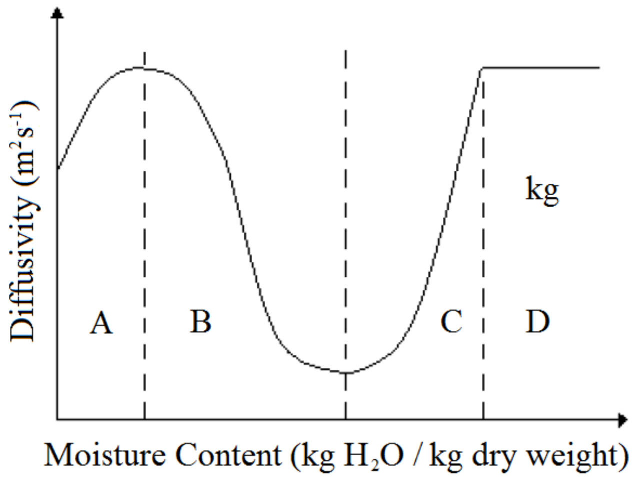

Figure 2.11: Profile of the variation of effective diffusivity with moisture content (Ibarz and Barbosa-Cánovas, 2003).

Table 2.2: Effective diffusivity of some food products (Mujumdar and Devahastin, 2000; Ibarz and Barbosa-Cánovas, 2003).

Food	Moisture Content (kg H_2O / kg dry weight, d.b.)	T (°C)	D_{eff} (m^2s^{-1})
Apple	0.10 – 0.15	30 – 70	$1.0 \times 10^{-11} - 6.4 \times 10^{-9}$
Banana	0.01 – 3.50	20 – 40	$3.0 \times 10^{-13} - 2.1 \times 10^{-10}$
Biscuit	0.10 – 0.60	20 – 100	$8.6 \times 10^{-10} - 9.4 \times 10^{-8}$
Carrot	0.01 – 5.00	30 – 70	$1.2 \times 10^{-9} - 5.9 \times 10^{-9}$
Carrot cube	–	40 – 100	$6.8 \times 10^{-11} - 2.4 \times 10^{-10}$
Egg liquid	–	85 – 105	$1.0 \times 10^{-11} - 1.5 \times 10^{-11}$
Glucose	0.08 – 1.50	30 – 70	$4.5 \times 10^{-12} - 6.5 \times 10^{-10}$
Freeze-dried apple	–	25	2.4×10^{-10}
Muffin	0.10 – 0.95	20 – 100	$8.5 \times 10^{-10} - 1.6 \times 10^{-7}$
Pears (slabs)	–	66	9.6×10^{-10}
Pepperoni	0.16	12	$4.7 \times 10^{-11} - 5.7 \times 10^{-11}$
Potato	–	54 – 68.8	$2.6 \times 10^{-11} - 6.4 \times 10^{-11}$
Raisins	0.15 – 2.40	25 – 60	$4.2 \times 10^{-11} - 2.5 \times 10^{-10}$
Rice	0.10 – 0.25	30 – 50	$3.8 \times 10^{-8} - 2.5 \times 10^{-7}$
Soybeans	0.07	30	$7.5 \times 10^{-13} - 5.4 \times 10^{-12}$
Starch gel	0.20 – 3.00	30 – 50	$1.0 \times 10^{-10} - 1.2 \times 10^{-9}$
Wheat	0.12 – 0.30	21 – 80	$6.9 \times 10^{-12} - 2.8 \times 10^{-10}$
Whole milk, foam	–	35 – 50	$8.5 \times 10^{-10} - 2.0 \times 10^{-9}$

Although D_{eff} varies according to the type of drying material; it should be noted that D_{eff} is not an actual property of the materials. Thus, extra care should be taken when applying D_{eff} obtained with simple geometric shapes to the more complex shapes as it will lead to incorrect calculated results (Bakalis et al., 2005). Other than being dependent on geometric shapes, D_{eff} is also dependent on the drying conditions. At high water activity, there might be no differences in terms of D_{eff}; but at lower water activity levels, D_{eff} can differ significantly owing to the inherent physical structure of the dried product. Furthermore, D_{eff} will show remarkable variations if the material experiences glass transition during the drying process (Mujumdar and Devahastin, 2000).

The average effective diffusivity along the drying process can be calculated by equation 2.11.

$$D_{eff,ave} = \frac{\int_{M_o}^{M_f} D_{eff}(M)\, dM}{\int_{M_o}^{M_f} dM} \tag{2.11}$$

However average effective diffusivity also can be determined by dividing the total sum of effective diffusivity at different moisture content with the total number of data point, *N*.

$$D_{eff,ave} = \sum_{i=0}^{N} \frac{D_{eff}(M_i)}{N} \tag{2.12}$$

Both, equations 2.11 and 2.12 are often used to describe the drying characteristics of food material as it varies considerably with moisture content and drying temperature (Panda, 2013; Chin and Law, 2014).

CHAPTER 3

METHODOLOGY

3.1 Sample Preparation

Fresh Eureka lemons (Figure 3.1) which used as drying samples in this project were purchased from Aeon Hypermarket at Wangsa Maju, Setapak, Kuala Lumpur. Ripe lemon fruits were chosen as they contain high antioxidant capability. Lemon fruits with diameters of $5.5 \pm 1.0 \times 10^{-2}$m were washed thoroughly with tap water before they were sliced crosswise into circular slices. The average thickness of slices was measured as $3.0 \pm 0.5 \times 10^{-3}$m, using vernier calliper (MarCal-16 EXV, range $0 - 2 \times 10^{-1}$m, with an accuracy of $\pm 3 \times 10^{-5}$m). The seeds were removed and the initial weight of each slice was recorded as $8.20 \pm 0.05 \times 10^{-3}$kg, using precision balance (A&D-GX1000, capacity up to 1.1kg with an accuracy of $\pm 1 \times 10^{-6}$kg). Average surface area of the slices was calculated as 2.38×10^{-3}m^2.

Figure 3.1: Fresh lemon slices prior to the drying process.

3.2 Drying Methods

Drying of lemon slices was conducted using various drying methods. The drying methods included heat pump drying, hybrid heat pump drying, hot air circulation oven drying, and freeze drying.

3.2.1 Heat Pump Drying

In this research, a laboratory scale heat pump dryer was designed and fabricated by I-Lab Sdn. Bhd., Selangor, Malaysia (Figure 3.2). The heat pump dryer consists of a drying chamber of dimensions 0.8m × 0.6m × 0.6m and a heat pump system is comprised of an expansion valve, two heat exchangers (condenser and evaporator) and a compressor (415 AC, 1120W). The refrigerant used in the heat pump system is R22 Freon gas. Mild temperature dehumidified air produced by the heat pump system is used as a drying medium and forced circulation of convective air is done by a blower (fan diameter: 0.15m, speed: 5 – 950 × $10^{-4} m^3 s^{-1}$). The schematic diagram of the heat pump dryer is shown in Figure 3.3.

Heat pump dryer was switched on for 30 minutes prior to the start of the experiments to produce drying air with stable drying condition. During drying, lemon slices were placed on a string mesh (0.08m × 0.08m) before being rested on the wire mesh with size of 0.2m × 0.3m in the drying chamber. The dryer was operated at drying temperature of 22.0 ± 1.0 ℃ and 34.0 ± 0.5% relative humidity (RH) when the auxiliary heater was turned off, whereas the drying temperature was 31.0 ± 1.0 ℃ and 24.0 ± 0.5% RH when the auxiliary heater was on. The average air velocity in the chamber was maintained at 1.1 ± $0.1 ms^{-1}$.

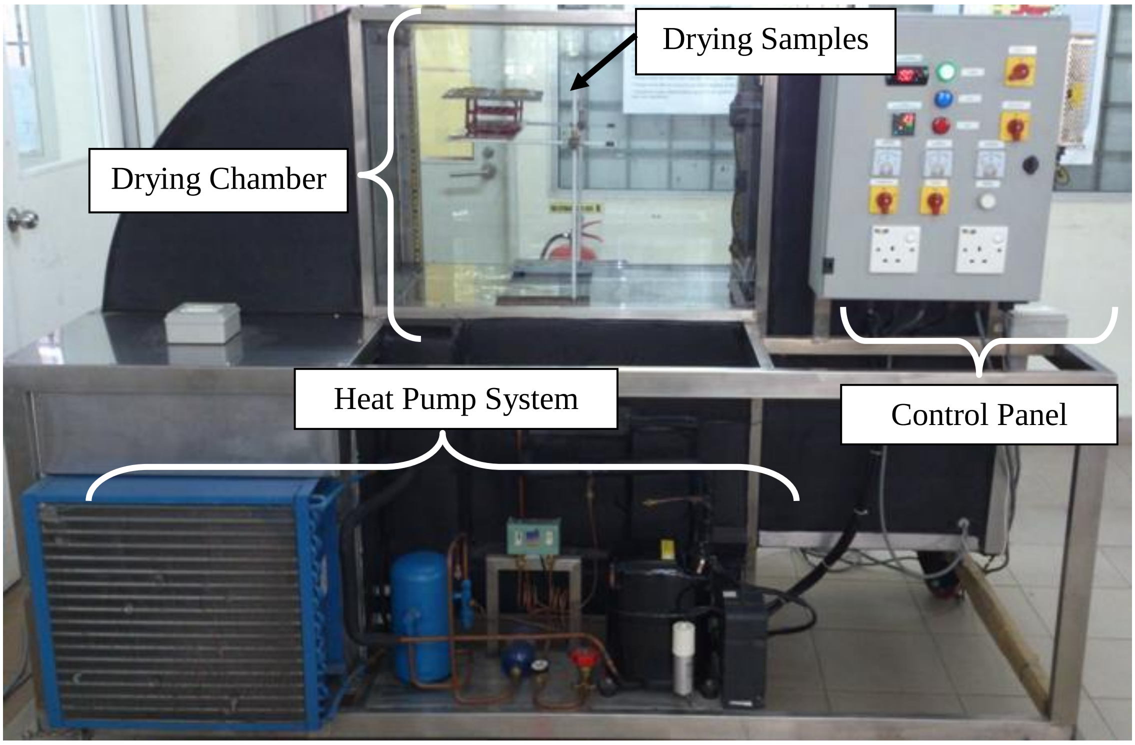

Figure 3.2: Laboratory scale heat pump dryer.

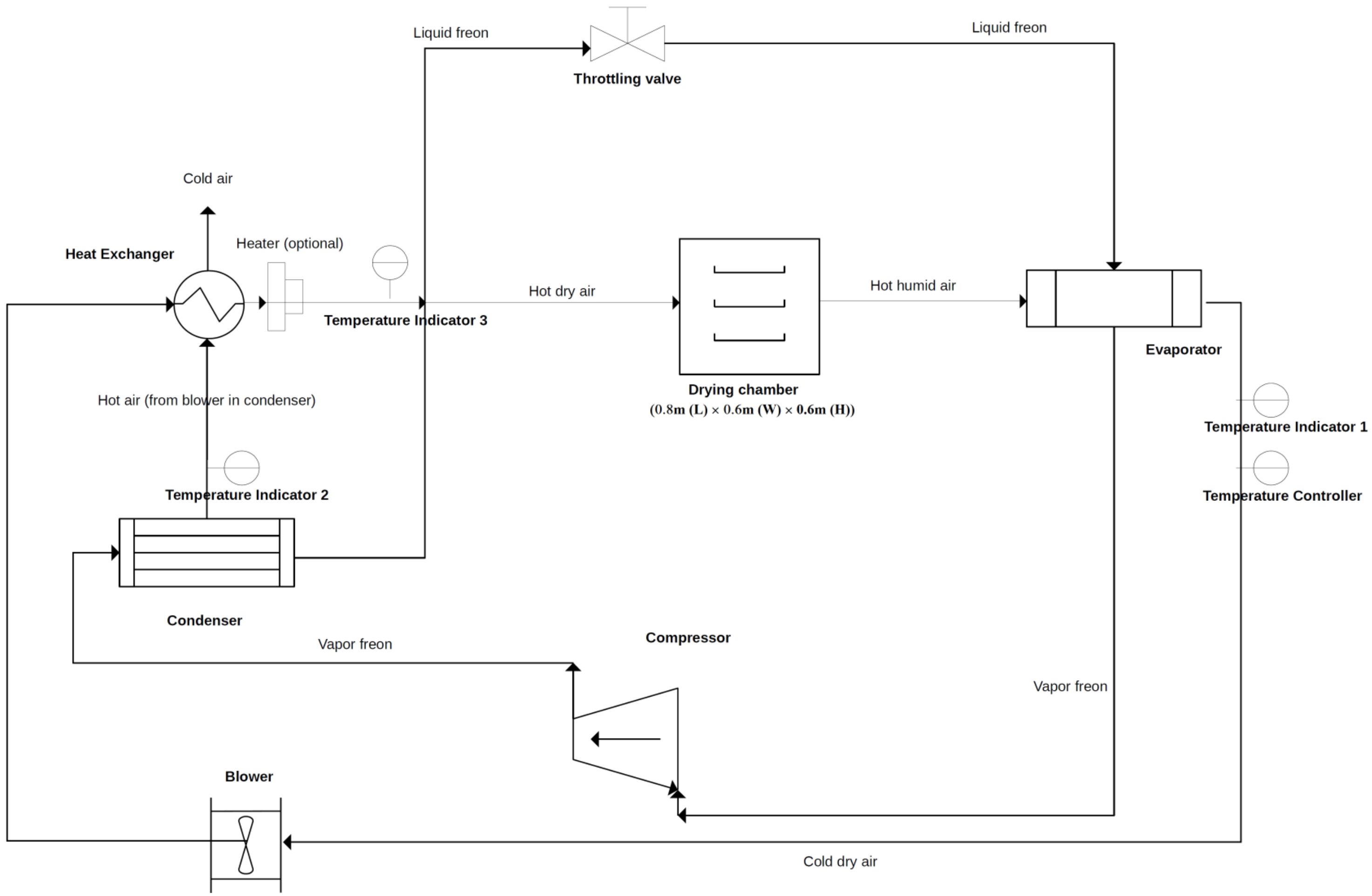

Figure 3.3: Schematic diagram of the heat pump (HP) dryer.

3.2.2 Hybrid Heat Pump Drying

For hybrid heat pump drying, a high voltage system was incorporated inside the drying chamber, as shown in Figure 3.4. The high voltage source which determined to be 15000V and 50Hz, was generated by using a Neon Transformer FART (RESINBLOCK 2000). The output of the transformer was connected to the wire mesh, where the string meshes and lemon slices were being loaded on. The distance between the slices and wire mesh was varied from $1 – 5 \times 10^{-3}$m during preliminary drying in order to determine the effective distance. Water droplets on the bottom surface were attracted to high voltage wire mesh and a water bridge was formed between the wire mesh and slices when the distance was less than 3×10^{-3}m. Meanwhile, drying rate enhancement was not significant when the distance was more than 3×10^{-3}m. Hence, the effective distance was determined to be 3×10^{-3}m and it was used for henceforward drying processes. The drying condition of the hybrid heat pump dryer is similar to the heat pump dryer during drying process.

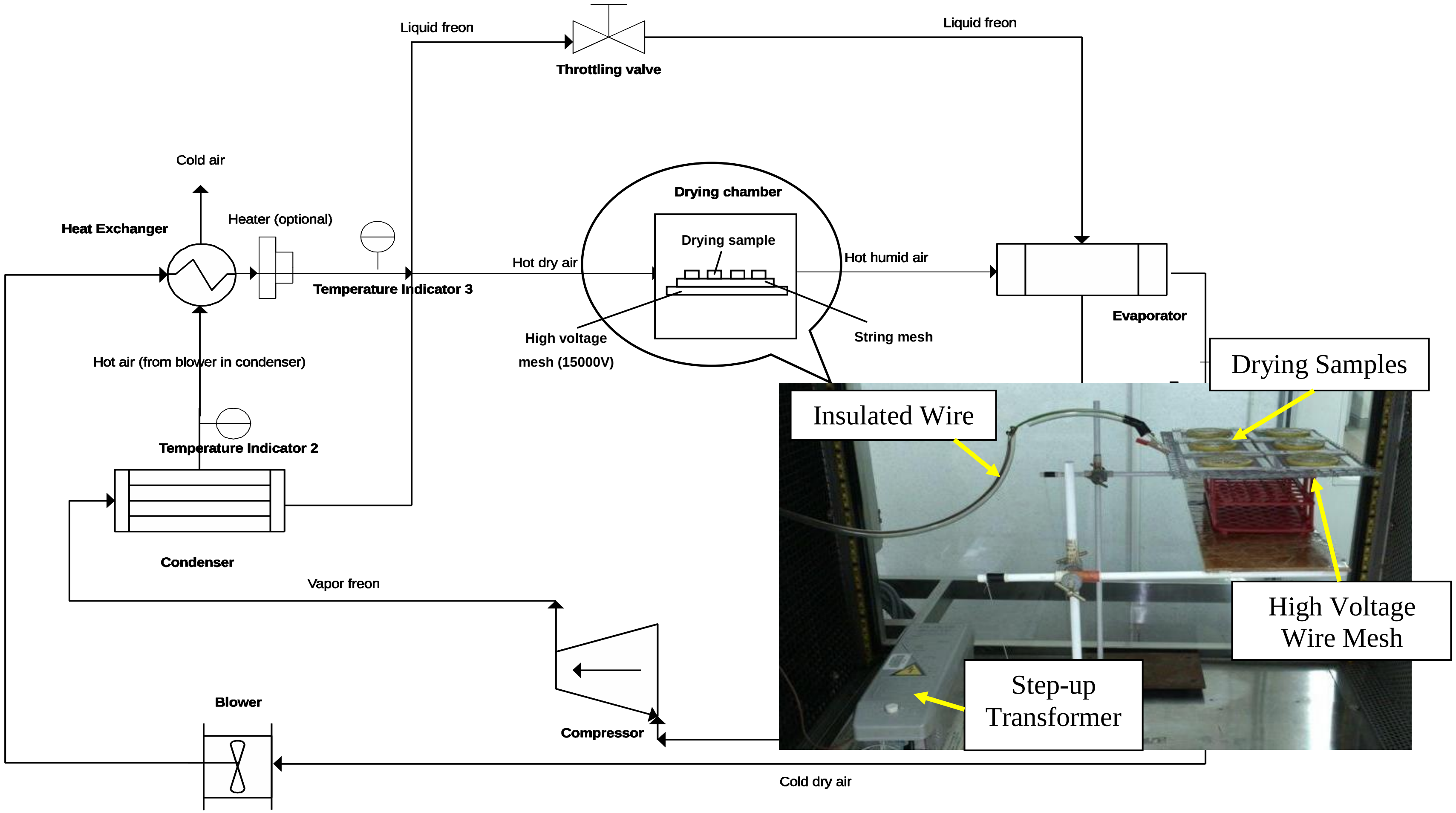

Figure 3.4: Schematic diagram of Coulomb force assisted heat pump (CF-HP) dryer.

3.2.3 Oven Drying

A laboratory scale hot air convection oven (Memmert 100–800, temperature range 5 ℃ above room temperature up to 250 ℃, with an accuracy of ± 0.5 ℃) was used to study the drying process of lemon slices. The lemon slices were dried at three different temperatures which were 40.0 ℃, 50.0 ℃, and 60.0 ℃, at the corresponding relative humidity (RH) of 33.4%, 20.2% and 12.6%, respectively. The average air velocity inside the chamber was determined as $0.6 ms^{-1}$. Prior to drying experiments, the hot air oven was turned on under selected operating condition for approximately 30 minutes to allow it to achieve steady-state condition. Lemon slices were placed on aluminium foil before being loaded into the oven for drying purpose (Figure 3.5).

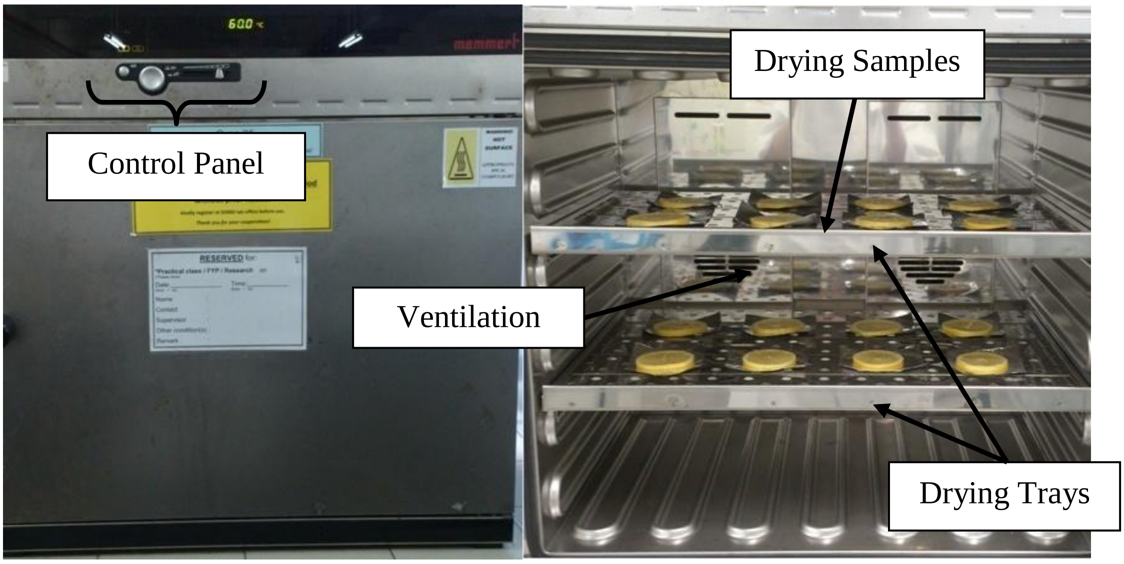

Figure 3.5: Laboratory scale hot air circulation oven.

Incoming air is warmed in a preheated chamber before entering the chamber through ventilation slots; the ventilation fan located at the back of the drying chamber wall can produce a larger air throughput and forced circulation of convective air to dry the samples on the drying tray with natural convection. Lemon slices dried by oven drying were used as reference samples which meant for the comparison with samples dried by heat pump and hybrid heat pump drying in term of drying kinetics, vitamin C and TPC analysis, area shrinkage and browning effect of dried lemon slices.

3.2.4 Freeze Drying

Lemon slices were pre-frozen in a deep freezer (ARDO-CV382 Upright Freezer) at –40 ℃ for 24 hours, before freeze dried in a laboratory scale freeze dryer (Labconco FreeZone-7670530), as shown in Figure 3.6. Pre-freezing temperature was typically set at about 15 ℃ below the eutectic temperature of lemon slices. Before loading the sample into the drying chamber, the water in the chamber was drained off to remove all the condensates that had been defrosted. The frozen slices were placed on drying trays in freeze dryer when the temperature of the freeze dryer reached –40 ℃. Thereafter, the vacuum pump was turned on until the pressure in the chamber achieved 13.3Pa. The samples were subsequently freeze dried under the designated temperature and pressure. The total drying time for freeze drying of lemon slices was set at 48 hours to obtain the optimum vitamin C and TPC retention in freeze dried lemon slices (Lai, 2014). The freeze dried slices were used as a benchmark regarding the retention of vitamin C and TPC in the dried slices subjected to different drying methods (Varzakas and Tzia, 2016).

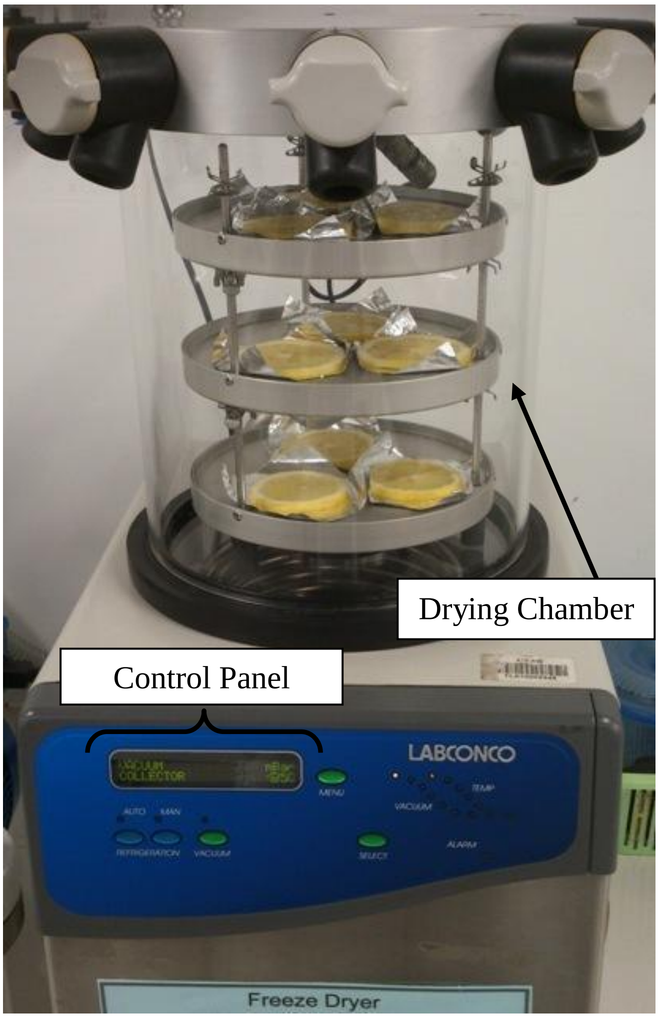

Figure 3.6: Laboratory scale freeze dryer.

3.2.5 Dryer Temperature, Relative Humidity and Air Velocity

The temperature and relative humidity inside the drying chamber were measured by hygrometer (Rotronic Hygrolog HL-NT2-D, range –30 – 70 ℃ / 0 – 100%RH with an accuracy of ± 0.2 ℃ / 1.5%RH) whereas the velocity of air circulation was measured using hot wire anemometer (LT Lutron YK-2005AH, range 0.2 – 20.0ms^{-1}, with an accuracy of ± 0.1ms^{-1}).

3.2.6 Energy Consumption

Total energy consumption for heat pump and hybrid heat pump drying was measured by the power meter (D02A, ± 1W) in order to study the energy efficiency of the newly developed Coulomb force assisted heat pump drying.

3.3 Drying Kinetics

3.3.1 Moisture Content

For each of the drying experiments, moisture content in the samples was determined in triplicate following the method prescribed by AOAC Official Method 934.06. The initial moisture content of the slices was 7.56 kg H_2O / kg dry weight. The weight of the slices was measured with precision balance (A&D-GX1000, capacity up to 1.1kg with an accuracy of $\pm 1 \times 10^{-6}$ kg) at 5 minutes interval for the first 30 minutes, 10 minutes interval for the next one hour, 30 minutes interval in the following 3 hours and 1 hour interval for the rest of drying period. The drying processes were terminated when the slices achieved equilibrium moisture content (EMC), which is indicated by the constant weight of the dried slices at a certain drying condition. The moisture content was expressed in bone dry basis (d.b.), a decimal ratio with the unit of kilogram H_2O per kilogram dry weight. The dry weight was acquired by subjecting the sample that reached EMC to the oven drying at 105 ℃ for 24 hours (AOAC, 1996).

The initial moisture content (M_o), moisture content at a given drying time t (M_t), and equilibrium moisture content (M_{eq}) of the lemon slices were calculated by equation 3.1, 3.2, and 3.3, respectively.

$$M_0 = \frac{W_0 - W_d}{W_d} \tag{3.1}$$

$$M_t = \frac{W_t - W_d}{W_d} \tag{3.2}$$

$$M_{eq} = \frac{W_{eq} - W_d}{W_d} \tag{3.3}$$

Where W_o, W_t, W_d, and W_{eq} refers to initial weight of the sample, weight of the sample in the middle of drying process at time t, bone dry weight of the sample, and equilibrium weight of the sample, respectively. Meanwhile, moisture ratio (MR) at a given drying time t can be evaluated by equation 3.4 below:

$$MR_t = \frac{M_t - M_{eq}}{M_0 - M_{eq}} \tag{3.4}$$

3.3.2 Mathematical Modeling

The drying kinetics of thin layer samples are often used to describe the heat and mass transfer during the drying process and it is affected by the drying conditions. Single layer semi-empirical expressions are sufficient to describe the drying kinetics when the resistance to the heat and mass transfers is minimum (Midilli et al., 2002; Rayaguru and Routray, 2012). In the current work, drying kinetics of lemon slices were modelled with few empirical equations tabulated in Table 3.1. The constants of tested models were determined by multiple regression technique.

Table 3.1: Mathematical models to describe thin-layer drying curve.

Model Name	Model Equation	Constants	References
Newton	$MR=\exp(-kt)$	k	(O'Callaghan et al., 1971)
Page	$MR=\exp(-kt^n)$	k, n	(Agrawal and Singh, 1977)
Modified Page	$MR=\exp(-(kt)^n)$	k, n	(White et al., 1981)
Henderson & Pabis	$MR=a\exp(-kt)$	a, k	(Cihan et al., 2006)
Logarithm	$MR=a\exp(-kt)+a_1$	a, k, a_1	(Artnaseaw et al., 2010)
Two-term	$MR=a\exp(-kt)+a_1\exp(-k_1t)$	a, k, a_1, k_1	(Henderson, 1974)
Two-term exponential	$MR=a\exp(-kt)+(1-a)\exp(-kat)$	a, k	(Midilli et al., 2002)
Wang and Singh	$MR=1+at+a_1t^2$	a, a_1	(Wang and Singh, 1978)
Approximation of Diffusion	$MR=a\exp(-kt)+(1-a)\exp(-kbt)$	a, k, b	(Sangamithra et al., 2014)

Non-linear regression analysis was executed to determine the constants of the models and to evaluate the validity of the models with the experimental drying kinetics. The fitness of each mathematical model to the experimental data was assessed by the statistical test methods such as root mean square error (RMSE), coefficient of correlation (r) and reduced chi-square (χ^2) as described by equations 3.5, 3.6, and 3.7.

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{N}\left(MR_{pre,i} - MR_{exp,i}\right)^2}{N}} \tag{3.5}$$

$$r = \frac{N\sum_{i=1}^{N}\left(MR_{pre,i}MR_{exp,i}\right) - \left(\sum_{i=1}^{N} MR_{pre,i}\right)\left(\sum_{i=1}^{N} MR_{exp,i}\right)}{\sqrt{N\sum_{i=1}^{N}\left(MR_{pre,i}\right)^2 - \left(\sum_{i=1}^{N} MR_{pre,i}\right)^2}\sqrt{N\sum_{i=1}^{N}\left(MR_{exp,i}\right)^2 - \left(\sum_{i=1}^{N} MR_{exp,i}\right)^2}} \tag{3.6}$$

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(MR_{pre,i} - MR_{exp,i}\right)^2}{N-n} \tag{3.7}$$

Where $MR_{exp,i}$ is the i-th experimentally obtained moisture ratio, $MR_{pre,i}$ the i-th predicted moisture ratio, N is the total number of data points and n is the numerical constants. The higher the r value and the lower the RMSE and χ^2 values indicated the better fitness of the curves (Midilli et al., 2002; Cihan et al., 2006; Rayaguru and Routray, 2012). The model which gave the best fitness was used to represent the drying kinetic of the lemon slices. The dimensionless predicted moisture ratios were used to plot the drying curve of the sample against the time.

3.3.3 Drying Rate

Drying rates of the samples were determined using equation 3.8 at constant drying condition (Geankoplis, 2003).

$$R = \frac{W_d}{A_s}\left|\frac{F_{t+1} - F_t}{t_{i+1} - t_i}\right| \tag{3.8}$$

Where W_d is bone dry weight of the sample, A_s is denoted as the surface area of the sample exposed to the drying condition. F_t is the free moisture content of the sample at time t (kg H_2O / kg dry weight), which is calculated from equation 3.9.

$$F_t = M_t - M_{eq} \tag{3.9}$$

Subsequently, equations 3.8 and 3.9 can be rewritten in terms of predicted moisture ratio at given drying time t ($MR_{pre,t}$), as shown in equations 3.10 and 3.11, respectively.

$$F_t = MR_{pre,t}(M_0 - M_{eq}) \tag{3.10}$$

$$R = \frac{W_d(M_0 - M_{eq})}{A_s}\left|\frac{MR_{pre,t+1} - MR_{pre,t}}{t_{i+1} - t_i}\right| \tag{3.11}$$

3.3.4 Effective Moisture Diffusivity

Effective moisture diffusivity, D_{eff} of the samples was obtained by assuming the lemon slices to be of the shape of slab. The first one hundred terms in the Fourier series of simplified mathematical Fick's second model (equation 3.12) (Reyes et al., 2013; Shi et al., 2013; Richter Reis, 2014) were taken into account to determine the D_{eff} of the lemon slices along the drying process.

$$MR_{theo} = \frac{8}{\pi^2}\left[\sum_{n=0}^{99}\frac{1}{(2n+1)^2}\exp\left(\frac{-(2n+1)^2\pi^2 D_{eff}\, t}{l^2}\right)\right] \tag{3.12}$$

Where l is the sample's thickness, t is the drying time, and n is the positive integer.

The values of D_{eff} at different moisture contents were determined by using Solver program in Microsoft Excel, by fitting each of the moisture ratio of the diffusion model, MR_{theo} to the predicted moisture ratio, MR_{pre}. Subsequently, the mean relative error, E(%), between MR_{theo} and MR_{pre} was determined by equation (3.13). Generally, E(%) less than 10% is considered as a good fit (Garau et al., 2006). However, smaller E(%) indicates a better precision of the predicted D_{eff} during the drying process. The average effective diffusivity, $D_{eff,ave}$, for each of the drying condition was determined based on equation 3.14 (Singh and Gupta, 2007).

$$E(\%) = \sum_{i=1}^{N} \left| \frac{MR_{pre,i} - MR_{theo,i}}{N \times MR_{pre,i}} \right| \times 100\% \tag{3.13}$$

$$D_{eff,ave} = \sum_{i=1}^{N} \frac{D_{eff}(M_i)}{N} \tag{3.14}$$

3.4 Quality Analysis

3.4.1 Vitamin C

For vitamin C analysis of dried lemon slices, metaphosphoric acid-acetic acid (HPO_3-CH_3COOH) extracting solution and indophenols standard solution (IS solution) were prepared as described in AOAC Official Method 967.21, 45.1.14. These solutions were prepared as follows:

Extracting solution: Metaphosphoric acid – acetic acid (HPO_3-CH_3COOH)
7.5×10^{-3}kg of HPO_3 pellets or freshly pulverized stick HPO_3 is dissolved, with shaking, in 0.02ℓ of CH_3COOH and 0.1ℓ of H_2O. Subsequently, it is diluted to 0.25ℓ as well as filtered rapidly through fluted paper into a glass-stopped bottle and then stored in the refrigerator.

Indophenols standard (IS) solution

5×10^{-5}kg of 2,6-dichloroindophenol Na salt is dissolved in 0.05ℓ of H_2O which has been added with 4.2×10^{-5}kg of $NaHCO_3$. Solution is shook vigorously and diluted to 0.2ℓ after the dye has dissolved. Then, solution is filtered through the fluted paper into a glass-stopped bottle and stored in refrigerator.

The steps performed for the determination of vitamin C content in dried lemon slices are summarized in Figure 3.7.

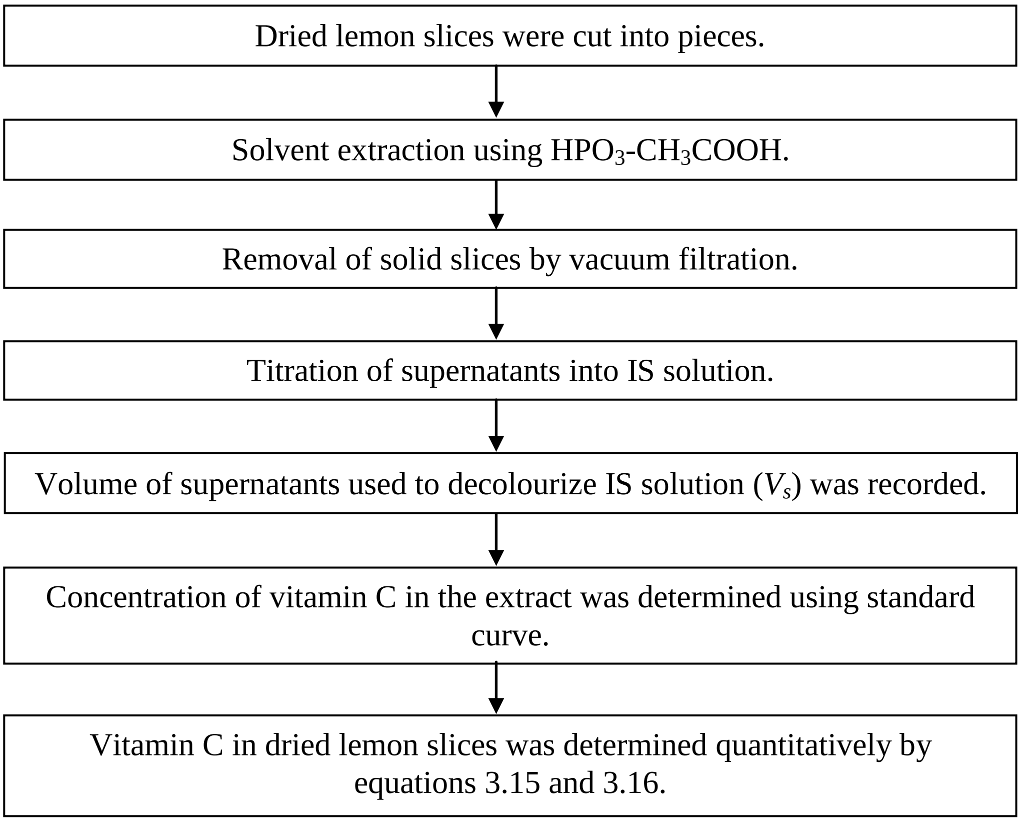

Figure 3.7: Flow chart of vitamin C analysis.

Dried lemon slices (at EMC) were cut into small pieces of equivalent size and subjected to the extraction process at 4℃ for 24 hours using 0.05ℓ of metaphosphoric acid-acetic acid (HPO_3-CH_3COOH) as extracting solvent. After removal of solid slices by vacuum filtration, the supernatants were titrated into $5 \times 10^{-3} \ell$ of IS solution. The amount of supernatants, V_s used to decolourize the IS solution was recorded.

The standard curve for quantitative analysis of vitamin C content in the dried lemon slices was obtained using Ascorbic acid as standard solution (Nielsen, 2010). Ascorbic acid solutions (AAS) were prepared by dissolving the L(+) – Ascorbic acid into extracting solution to obtain five solutions with different concentrations (C_{AAS}), which were 1, 2, 3, 4, and 5×10^{-4}kg of Ascorbic acid per ℓ of extracting solution. Subsequently, these solutions were titrated into $5 \times 10^{-3} \ell$ of IS solution. The amount of AAS used, V_a to decolourize the IS solution for each concentration was recorded. The graph of V_a against 1 / C_{AAS} was plotted and shown in Figure 3.8.

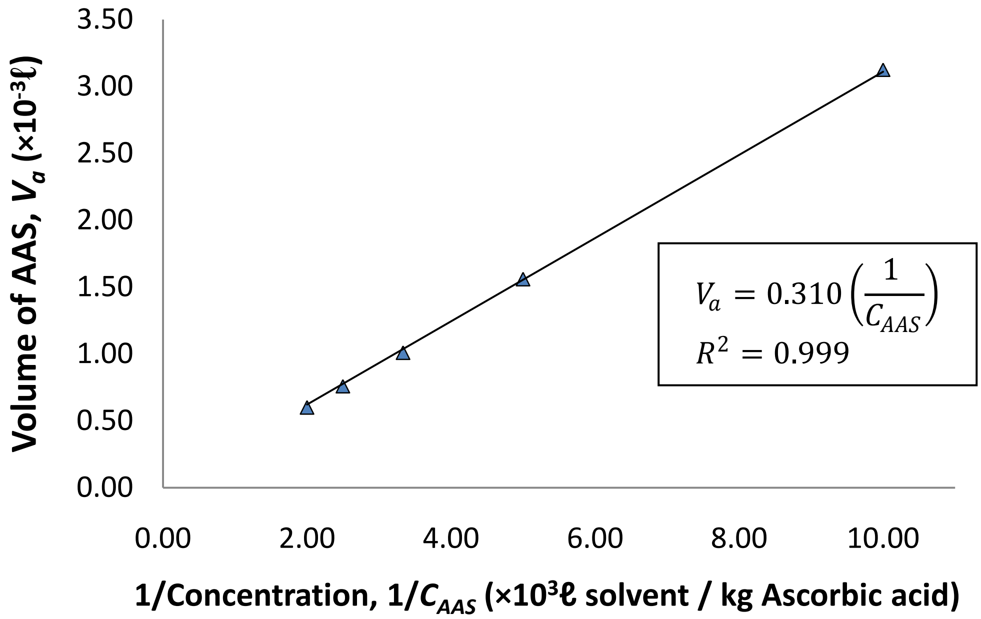

Figure 3.8: Standard curve of reciprocal of ascorbic acid concentration which varies linearly with V_a.

The concentration of vitamin C in each dried sample extract (C_{AAS}) can be determined based on the volume of supernatant (V_s) used to decolourize the IS solution (equation 3.15). Vitamin C of the dried samples was expressed in kg of Ascorbic acid / kg dry weight of dried sample according to equation 3.16.

$$C_{AAS} = \frac{0.310}{V_s} \tag{3.15}$$

$$\text{Vitamin C} = \left(\frac{C_{AAS} \times V}{W_d}\right) \tag{3.16}$$

Where V is the volume of the extracting solution used.

3.4.2 Total Phenolics Content (TPC)

The steps performed for the determination of TPC in dried lemon slices are summarized in Figure 3.9 (Genwali et al., 2013; Shirazi et al., 2014).

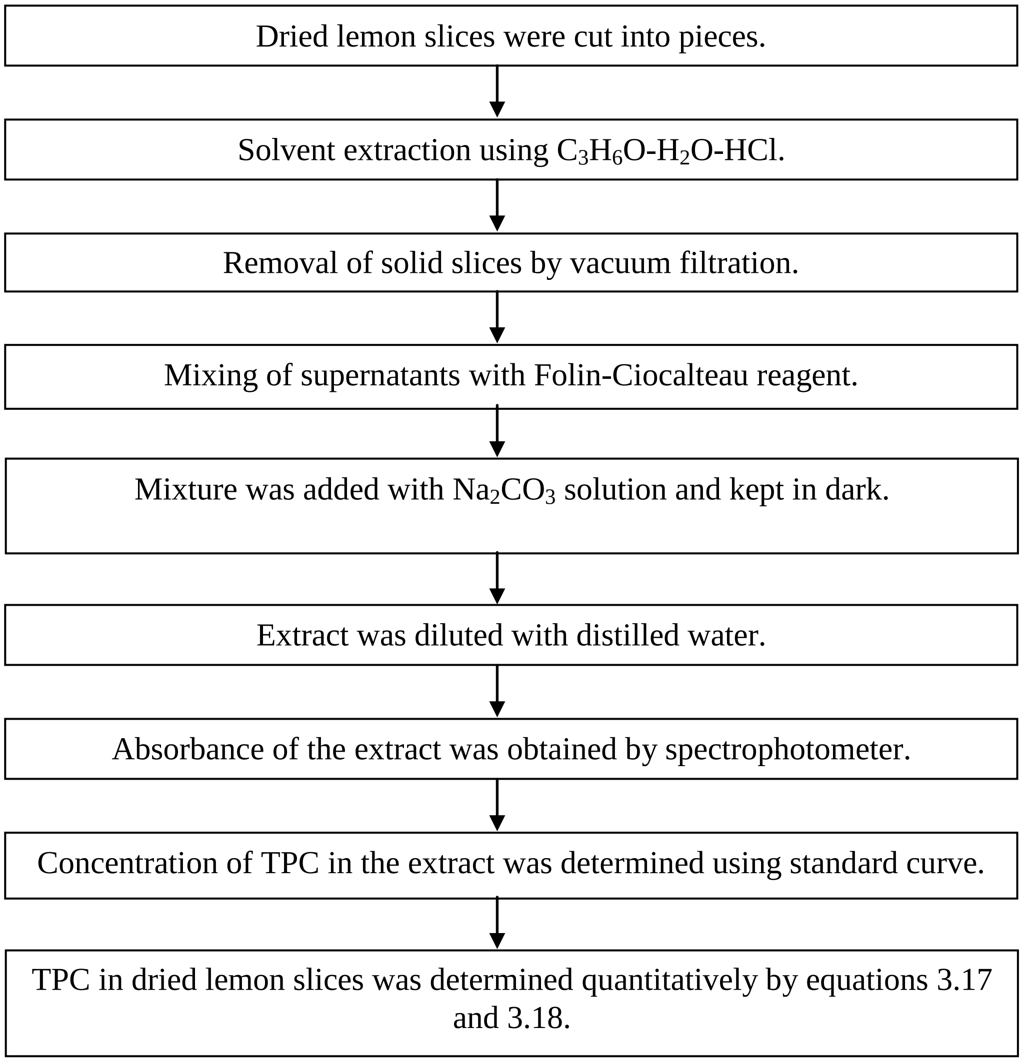

Figure 3.9: Flow chart of TPC analysis.

Similar to the vitamin C analysis, dried lemon slices (at EMC) were cut into small pieces of equivalent size and subjected to the extraction process at 4 ℃ for 24 hours using 0.05ℓ of solvent which made up of hydrochloric acid, distilled water and acetone in volume percentage of 3%, 22% and 75%, respectively. After removal of solid slices by vacuum filtration, 1×10^{-3}ℓ of supernatants were titrated into 5×10^{-3}ℓ of 0.2N Folin-Ciocalteau reagent and held for 3 minutes. Then, 4×10^{-3}ℓ of 7.5% sodium carbonate solution (Na_2CO_3) was added into the mixture and incubated in dark at room temperature for half an hour to allow colour development. Subsequently, the extract was adjusted with 0.04ℓ of distilled water and the absorbance (*A*) of the extract was measured at 7.65 $\times 10^{-7}$m in a single beam spectrophotometer (JENWAY 6320D, range 3.2 – 10 $\times 10^{-7}$m with an accuracy of ± 2 $\times 10^{-9}$m).

The standard curve for quantitative analysis of TPC in the dried lemon slices was obtained using Gallic acid (2 – 8 $\times 10^{-5}$kg / ℓ) as standard solution (Mukherjee et al., 2011; Saha et al., 2013). The standard curve is shown in Figure 3.10.

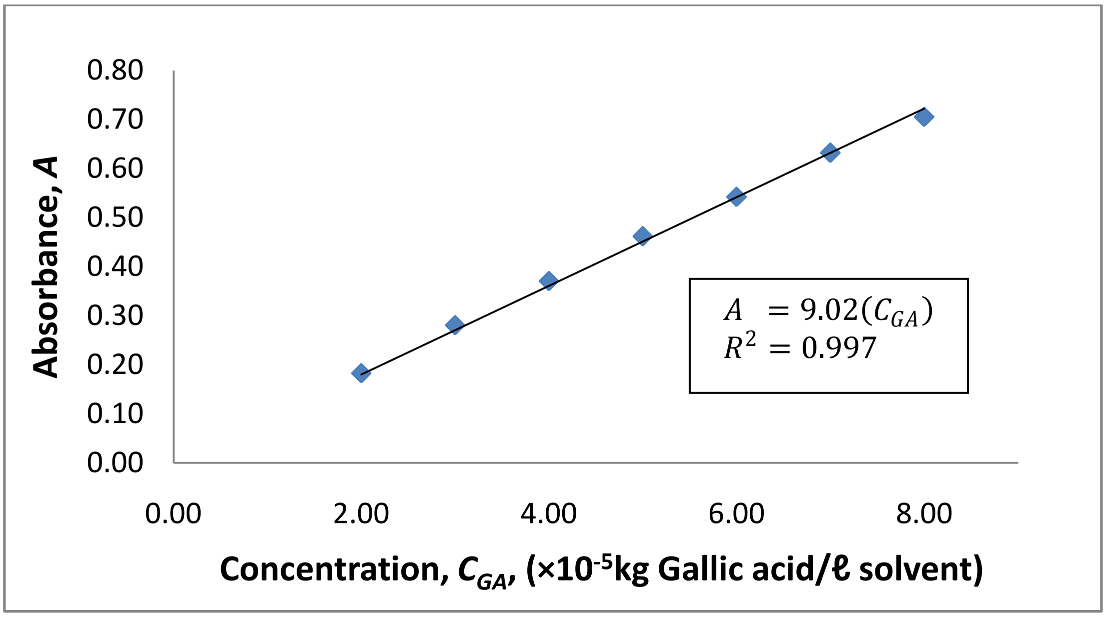

Figure 3.10: Standard curve of concentration of Gallic acid which varies linearly with absorbance at 7.65 $\times 10^{-7}$m.

TPC of the dried sample extract was determined in term of the concentration of Gallic acid (C_{GA}) based on equation 3.17 whereas the TPC of the dried sample was expressed quantitatively in kg of Gallic acid / kg dry weight of dried samples according to equation 3.18.

$$C_{GA} = \frac{A}{9.02} \tag{3.17}$$

$$\text{TPC} = \left(\frac{C_{GA} \times D_f \times V}{W_d}\right)$$

(3.18)

Where D_f is dilution factor and V is the volume of the extracting solution used.

3.4.3 Shrinkage

The internal and external diameters of lemon peels for both fresh and dried lemon slices were measured and applied in area calculation. Subsequently, the area shrinkage of lemon pulp cells and peels was calculated based on the percentage of area reduction as shown in equation 3.19.

$$\text{Shrinkage} = \frac{A_0 - A_F}{A_0} \times 100\%$$

(3.19)

Where A_0 and A_F are the surface area of the lemon slices before and after drying, respectively.

3.4.4 Colour Assessment

Visual evaluation of the fresh and dried lemon slices was conducted. The photos of fresh and dried lemon slices were captured and compared with freeze dried and commercial dried lemon slices in order to evaluate the browning effect of the dried lemon slices (Pathare et al., 2013).

3.5 Statistical Analysis

The results were analyzed with a completely randomized design in triplicate. Analysis of variance (ANOVA) was conducted by using SAS statistical analysis package (SAS Institute Inc, SAS / STAT 9.2, 2008). Means were compared with Tukey's Studentized Range test at 95% confidence level.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Energy Consumption

Table 4.1: Power and total energy consumption of heat pump and hybrid heat pump drying.

Drying Method	Power (W)	Total Energy Consumption ($\times 10^8$J)
HP	1723.07	9.20
CF-HP	1726.62	6.30
CF-HT-HP	3150.11	10.11

Experimental results in Table 4.1 indicate that CF-HP drying is more efficient in terms of energy saving as it required the least energy, which is only 68.5% and 62.3% of the total amount of energy required by HP and CF-HT-HP drying, respectively. Indeed, introducing the high voltage wire mesh to the heat pump dryer only raised the power consumption by 3.55W, which is only 0.2% of the power requirement for the heat pump dryer. During its unique drying mechanism, interaction between Coulomb force and moisture content caused a negligible amount of electrical energy of high voltage wire mesh to convert to the kinetic energy of moisture content. Consequently, it improved the moisture diffusion rate and thus shorten the total drying time. However, when the auxiliary heater was turned on (CF-HT-HP), power consumption of hybrid heat pump dryer was amplified by almost 83%. This is because vast amounts of energy was converted to thermal energy and subsequently latent heat for moisture vaporization. Eventually, it tumbled the energy efficiency of this drying method. This is in agreement with the analysis of energy efficiency reported by other researchers (Daghigh et al., 2010; Wankhade et al., 2012). The energy efficiency dropped with the increased of drying temperature.

4.2 Mathematical Modeling

Thin layer drying models were used to predict the drying kinetics of lemon slices at different drying conditions. According to Table 4.2 to 4.7, nine mathematical models were analyzed and the suitability of these models was evaluated according to the statistical analysis. The model parameters (e.g. k, a, and n) were determined by using non-linear regression analysis while the best fit model was chosen based on the goodness of fit between mathematical models and experimental data according to the coefficient of correlation (r), root mean square error (RMSE), and reduced chi-square (χ^2) parameters. Based on the statistical results showed in Table 4.2 to 4.7, Two-term model was found to adequately describe the drying kinetics of lemon slices at all drying condition of oven, HP, CF-HP, and CF-HT-HP with r, RMSE, and χ^2 ranged from 0.99315 to 0.99950, 0.01057 to 0.03637 and 0.00011 to 0.00134, respectively. For all drying methods, the drying constants, k and k_1 increase with increasing drying temperature, range from 3.358×10^{-4} to 5.729×10^{-2}. This is attributed to higher drying temperature enhances the driving force of heat transfer (Chin et al., 2009).

Table 4.2: Statistical analysis of mathematical models for 40 ℃ oven drying.

Model	Model Parameter	Value	Root Mean Square Error (RMSE)	Coefficient of Correlation (*r*)	Reduced Chi-square (χ^2)
Newton	k	4.484E-03	0.05871	0.99308	0.00349
Page	k	2.591E-02	0.01861	0.99850	0.00035
	n	6.570E-01			
Modified Page	k	3.848E-03	0.01861	0.99850	0.00035
	n	6.570E-01			
Henderson & Pabis	a	9.011E-01	0.04423	0.99309	0.00198
	k	3.646E-03			
Logarithm	a	3.743E-02	0.03725	0.99365	0.00141
	a_1	8.725E-01			
	k	4.045E-03			
Two-term	a	4.932E-01	0.01308	0.99922	0.00017
	k	1.463E-03			
	a_1	4.889E-01			
	k_1	1.253E-02			
Two-term Exponential	a	1.681E-01	0.04032	0.99661	0.00165
	k	2.062E-02			
Wang & Singh	a	-3.745E-04	0.36226	0.81181	0.13298
	a_1	-2.070E-08			
Approximation of Diffusion	a	4.908E-01	0.01380	0.99915	0.00019
	k	1.388E-02			
	b	1.080E-01			

Table 4.3: Statistical analysis of mathematical models for 50 ℃ oven drying.

Model	Model Parameter	Value	Root Mean Square Error (RMSE)	Coefficient of Correlation (*r*)	Reduced Chi-square (χ^2)
Newton	*k*	6.498E-03	0.06335	0.98677	0.00407
Page	*k*	2.358E-02	0.03721	0.99286	0.00140
	n	7.336E-01			
Modified Page	*k*	6.045E-03	0.03721	0.99286	0.00140
	n	7.336E-01			
Henderson & Pabis	*a*	9.090E-01	0.04907	0.98765	0.00244
	k	5.465E-03			
Logarithm	*a*	1.772E-02	0.04851	0.98778	0.00239
	a_1	8.951E-01			
	k	5.717E-03			
Two-term	*a*	7.176E-01	0.03637	0.99315	0.00134
	k	3.996E-03			
	a_1	2.777E-01			
	k_1	2.964E-02			
Two-term Exponential	*a*	1.686E-01	0.04335	0.99168	0.00191
	k	3.011E-02			
Wang & Singh	*a*	-1.591E-03	0.29014	0.85686	0.08533
	a_1	5.081E-07			
Approximation of Diffusion	a	2.771E-01	0.03639	0.99314	0.00134
	k	3.098E-02			
	b	1.299E-01			

Table 4.4: Statistical analysis of mathematical models for 60 ℃ oven drying.

Model	Model Parameter	Value	Root Mean Square Error (RMSE)	Coefficient of Correlation (*r*)	Reduced Chi-square (χ^2)
Newton	*k*	9.856E-03	0.04248	0.99381	0.00183
Page	*k*	2.035E-02	0.03022	0.99553	0.00093
	n	8.396E-01			
Modified Page	*k*	9.670E-03	0.03022	0.99553	0.00093
	n	8.396E-01			
Henderson & Pabis	*a*	9.373E-01	0.03491	0.99406	0.00124
	k	8.874E-03			
Logarithm	*a*	1.079E-02	0.03458	0.99412	0.00121
	a_1	9.303E-01			
	k	9.162E-03			
Two-term	*a*	8.394E-01	0.02916	0.99583	0.00086
	k	7.780E-03			
	a_1	1.648E-01			
	k_1	5.729E-02			
Two-term Exponential	*a*	1.561E-01	0.02936	0.99578	0.00087
	k	5.059E-02			
Wang & Singh	*a*	-3.858E-03	0.19521	0.92856	0.03863
	a_1	2.207E-06			
Approximation of Diffusion	*a*	1.618E-01	0.02917	0.99583	0.00086
	k	5.520E-02			
	b	1.408E-01			

Table 4.5: Statistical analysis of mathematical models for HP drying.

Model	Model Parameter	Value	Root Mean Square Error (RMSE)	Coefficient of Correlation (*r*)	Reduced Chi-square (χ^2)
Newton	k	5.233E-03	0.06569	0.99200	0.00434
Page	k	4.240E-02	0.04613	0.99114	0.00214
	n	5.384E-01			
Modified Page	k	4.542E-03	0.06378	0.99382	0.00409
	n	5.638E-01			
Henderson & Pabis	a	9.643E-01	0.06468	0.99145	0.00421
	k	4.815E-03			
Logarithm	a	6.228E-02	0.04171	0.99209	0.00175
	a_1	9.110E-01			
	k	5.493E-03			
Two-term	a	7.679E-01	0.01345	0.99919	0.00018
	k	7.525E-03			
	a_1	2.214E-01			
	k_1	3.358E-04			
Two-term Exponential	a	2.636E-01	0.06251	0.99227	0.00393
	k	1.321E-02			
Wang & Singh	a	-3.624E-04	0.26769	0.87936	0.07206
	a_1	2.975E-08			
Approximation of Diffusion	a	7.748E-01	0.01383	0.99916	0.00019
	k	7.767E-03			
	b	4.397E-02			

Table 4.6: Statistical analysis of mathematical models for CF-HP drying.

Model	Model Parameter	Value	Root Mean Square Error (RMSE)	Coefficient of Correlation (r)	Reduced Chi-square (χ^2)
Newton	k	5.685E-03	0.04381	0.99626	0.00193
Page	k	1.414E-02	0.03966	0.99622	0.00158
	n	8.013E-01			
Modified Page	k	4.916E-03	0.03966	0.99622	0.00158
	n	8.013E-01			
Henderson & Pabis	a	9.671E-01	0.04190	0.99605	0.00177
	k	5.271E-03			
Logarithm	a	3.843E-02	0.03160	0.99626	0.00100
	a_1	9.323E-01			
	k	5.661E-03			
Two-term	a	7.806E-01	0.01871	0.99869	0.00035
	k	7.698E-03			
	a_1	2.045E-01			
	k_1	4.569E-04			
Two-term Exponential	a	2.282E-01	0.04023	0.99649	0.00163
	k	1.731E-02			
Wang & Singh	a	-4.716E-04	0.27166	0.89887	0.07429
	a_1	4.409E-08			
Approximation of Diffusion	a	7.776E-01	0.01940	0.99862	0.00038
	k	8.282E-03			
	b	5.882E-02			

Table 4.7: Statistical analysis of mathematical models for CF-HT-HP drying.

Model	Model Parameter	Value	Root Mean Square Error (RMSE)	Coefficient of Correlation (*r*)	Reduced Chi-square (χ^2)
Newton	*k*	6.361E-03	0.04962	0.99504	0.00249
Page	*k*	1.491E-02	0.04573	0.99472	0.00212
	n	8.188E-01			
Modified Page	*k*	5.879E-03	0.04573	0.99472	0.00212
	n	8.188E-01			
Henderson & Pabis	*a*	9.687E-01	0.04846	0.99455	0.00238
	k	5.994E-03			
Logarithm	*a*	4.759E-02	0.03267	0.99518	0.00108
	a_1	9.298E-01			
	k	6.689E-03			
Two-term	*a*	7.993E-01	0.01057	0.99950	0.00011
	k	9.422E-03			
	a_1	2.028E-01			
	k_1	5.140E-04			
Two-term Exponential	*a*	2.757E-01	0.04564	0.99534	0.00211
	k	1.622E-02			
Wang & Singh	*a*	-2.816E-05	0.51115	0.63271	0.26458
	a_1	-3.033E-08			
Approximation of Diffusion	*a*	7.985E-01	0.01059	0.99950	0.00011
	k	9.361E-03			
	b	5.464E-02			

The Two-term model equations for drying of lemon slices at different drying conditions are expressed in Table 4.8.

Table 4.8: Two-term model equations for different drying methods.

Drying Method	Two-term Model Equation
HP Drying	$MR=7.679\times10^{-1}\exp(-7.525\times10^{-3}t)+2.214\times10^{-1}\exp(-3.358\times10^{-4}t)$
CF-HP Drying	$MR=7.806\times10^{-1}\exp(-7.698\times10^{-3}t)+2.045\times10^{-1}\exp(-4.569\times10^{-4}t)$
CF-HT-HP Drying	$MR=7.993\times10^{-1}\exp(-9.422\times10^{-3}t)+2.028\times10^{-1}\exp(-5.140\times10^{-4}t)$
Oven 40 ℃	$MR=4.932\times10^{-1}\exp(-1.463\times10^{-3}t)+4.889\times10^{-1}\exp(-1.253\times10^{-2}t)$
Oven 50 ℃	$MR=7.176\times10^{-1}\exp(-3.996\times10^{-3}t)+2.777\times10^{-1}\exp(-2.964\times10^{-2}t)$
Oven 60 ℃	$MR=8.394\times10^{-1}\exp(-7.780\times10^{-3}t)+1.648\times10^{-1}\exp(-5.729\times10^{-2}t)$

4.3 Drying Kinetics

Figure 4.1 shows the drying curves of lemon slices under different drying methods. Moisture content of lemon slices for all tested drying methods decreased exponentially and stopped when samples reached equilibrium moisture content (EMC). Among all tested drying methods, oven drying at 60 ℃ showed the highest drying rate with total drying time found to be up to 90.2% shorter as compared to those oven and heat pump dried slices at lower drying temperature. It is clearly observed that elevated drying temperature enhances the kinetics of water molecules and eventually excites the rate of evaporation of the free moisture content on the surface of lemon slices. Moreover, higher drying temperature intensifies the drying rate by enhancing the vapour pressure within the lemon slices which stimulates the diffusion of moisture to the product surface and consequently evaporated by convection. Hence, shorter total drying time is needed. However, drying of lemon slices at elevated temperature tends to impose a negative impact on the quality attributes of dried slices.

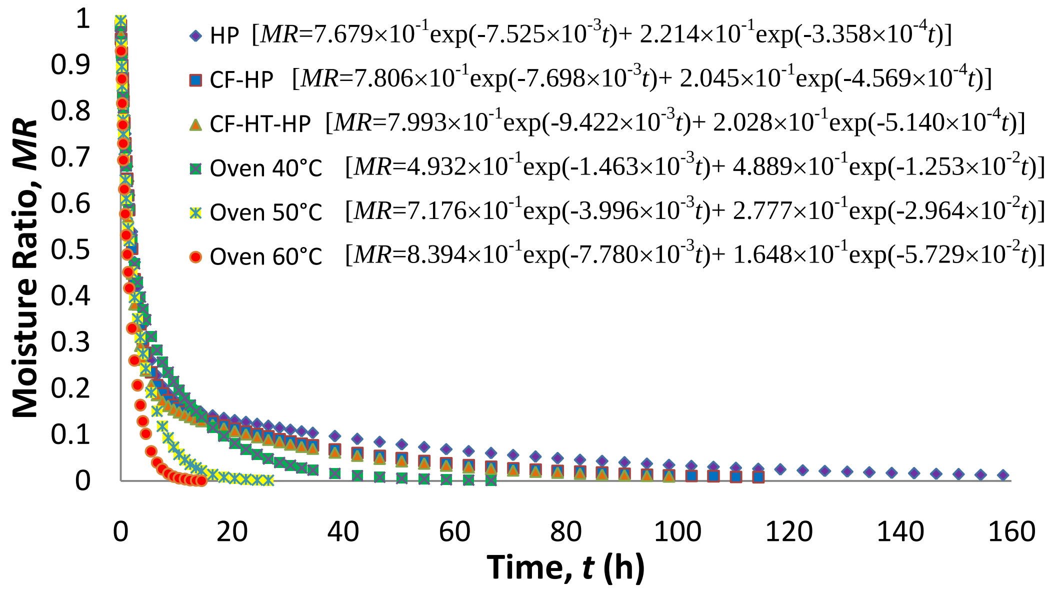

Figure 4.1: Drying curves for different drying methods.

On the other hand, moisture ratio declines rapidly on the beginning stage of drying process for all drying methods. This is due to the greater evaporation rate of the free moisture content on the product surface by convective process. However, the drying kinetics of Coulomb force assisted heat pump (CF-HP and CF-HT-HP) dried lemon slices which conducted at 22 ℃ and 31 ℃ respectively, are seen to be comparable with oven drying at elevated temperature (40 ℃ and 50 ℃) within the first 8.33 hours. Low relative humidity condition and the notable effect of Coulomb force in hybrid heat pump dryers enhance the moisture evaporation of the sample although it was conducted at mild drying temperature. The effect of low relative humidity which intensified the drying rate also has been observed by Pau et al. (2008) during drying of green sweet pepper with heat pump dryer.

Nevertheless, when moisture content of the sample further decreases along the drying process, drying temperature dominates the drying process and prolongs the total drying time required as compared to oven drying at elevated temperature. Mild temperature drying of heat pump and hybrid heat pump dryers required longer total drying time, especially at the late phase of drying process, due to slow internal diffusion of bound moisture in the lemon slices which limits the drying rate. Unlike other porous drying materials, the moisture content was encapsulated in the semi-permeable membrane of lemon pulp, which in turn resisted the diffusivity of moisture to the surface of the lemon slices through the semi-permeable membrane (Geankoplis, 2003). Similar behavior of drying process was reported by Chen et al. (2005) during drying process of lemon slices by using closed-type solar dryer.

Meanwhile, total drying time of CF-HP dried slices was shorter than HP dried slices by 31.6% even though both HP and CF-HP drying were conducted at same drying temperature. This could be explained as the Coulomb force generated by CF-HP drying excited the moisture diffusion from core to product surface and consequently offered a better mass transfer which led to the reduction of total drying time. Yet, among heat pump and hybrid heat pump drying, total drying time required for CF-HT-HP dried lemon slices was the shortest, which was found to be 12.1% and 39.9% shorter than CF-HP and HP dried lemon slices, respectively. The assistance of auxiliary heater during CF-HT-HP drying increased the drying temperature and consequently intensified the drying rate by stimulating the surface vaporization. Greater moisture content gradient produced a resultant driving force (Mujumdar, 2014) with Coulomb force which drove the moisture from the core to the surface of lemon slices. Hence, this eventually shortened the total drying time required by CF-

HT-HP drying as compared to CF-HP drying and HP drying alone. Likewise, total drying time was shortened by 72.5% as drying temperature increased from 40 ℃ to 60 ℃ during oven drying of lemon slices. It is clearly observed that higher drying temperature promoted greater heat transfer and eventually increased the rate of moisture vaporization (Gupta et al., 2011). Thus, shorter total drying time was required. The total drying time for lemon slices dried with heat pump, hybrid heat pump and oven drying methods is summarized in Table 4.9 and 4.10.

Table 4.9: Total drying time of heat pump and hybrid heat pump dried lemon slices.

Drying Method	Total Drying Time (h)	Reduction of Total Drying Time as Compared to HP Drying (%)
HP	148.27	–
CF-HP	101.40	31.6
CF-HT-HP	89.17	39.9

Table 4.10: Total drying time of oven dried lemon slices.

Drying Method	Total Drying Time (h)	Reduction of Total Drying Time as Compared to Oven Drying at 40 ℃ (%)
Oven 40 ℃	52.77	–
Oven 50 ℃	23.78	54.9
Oven 60 ℃	14.50	72.5

Table 4.11: Equilibrium moisture content of oven, heat pump and hybrid heat pump dried lemon slices.

Drying Method	Drying Temperature (°C)	Relative Humidity (%)	EMC (d.b.)*	EMC (w.b.)**
HP Drying	22.0	34.0	28.39	22.11
CF-HP Drying	22.0	34.0	27.58	21.62
CF-HT-HP Drying	31.0	24.0	25.84	20.53
Oven 40 °C	40.0	33.4	23.08	18.75
Oven 50 °C	50.0	20.2	20.17	16.79
Oven 60 °C	60.0	12.6	15.51	13.43

d.b.* = dry basis
w.b.** = wet basis

Table 4.11 shows the equilibrium moisture content of heat pump, hybrid heat pump and oven dried lemon slices. Based on Table 4.11, equilibrium moisture content of lemon slices dried by different drying methods was found in the range of 0.258 to 0.284 kg H_2O / kg dry weight for heat pump and hybrid pump drying, and 0.155 to 0.231 kg H_2O / kg dry weight for oven drying method. The EMC was found to decrease as drying temperature increased. This shows that EMC of the dried lemon slices is inversely proportional to the drying temperature (Ibrahim et al., 2009). Drying at elevated temperature promotes greater rate of moisture vaporization which consequently lead to a lower final moisture content of dried product. At the same drying condition, the EMC of CF-HP dried lemon slices is relatively lower than those HP dried lemon slices. This indicates that the assistance of Coulomb force at mild drying temperature stimulated the moisture diffusivity from the core to the product surface for vaporization process which in turn reduced the EMC of the dried product. Low relative humidity of heat pump and hybrid heat pump also contributed to lower EMC of dried lemon slices, although it was conducted at mild temperature (Sarker et al., 2015). As a result, EMC of heat pump and hybrid heat pump dried slices were found to be comparable to EMC of oven dried slices. However, the EMC of all dried lemon slices is within the food safety range, which is less than 25% (w.b.) (Salunkhe and Kadam, 1995; Kudra and Mujumdar, 2002).

4.4 Drying Rate

Variation of drying rate with free moisture content of lemon slices subjected to different drying methods is illustrated in Figure 4.2 whereas the average drying rate of heat pump, hybrid heat pump, and oven dried slices are tabulated in Table 4.12 and 4.13. Highest average drying rate was found for oven drying of lemon slices at 60 ℃, which recorded at 21.83 $\times 10^{-5}$kg H_2O / $m^2 \bullet s$, followed by oven drying at 50 ℃ and 40 ℃, CF-HT-HP, CF-HP and HP drying recorded at 14.00, 8.17, 6.67, 5.83, and 5.33 $\times 10^{-5}$kg H_2O / $m^2 \bullet s$, respectively. As expected, oven drying recorded the highest drying rate as drying was conducted at elevated temperatures. On the other hand, the effect of Coulomb force on hybrid heat pump drying significantly improved the average drying rate of lemon slices up to 25.1%. The induced Coulomb force in lemon slices during hybrid heat pump drying decreased external mass transfer resistance rendered by the high electric field, which consequently enhanced the moisture transportation through the semi-permeable membrane. As a result, there was an improvement in terms of average drying rate for CF-HP and CF-HT-HP drying of lemon slices as compared to heat pump drying alone, which in turn shortened the total drying time required as discussed in the previous section.

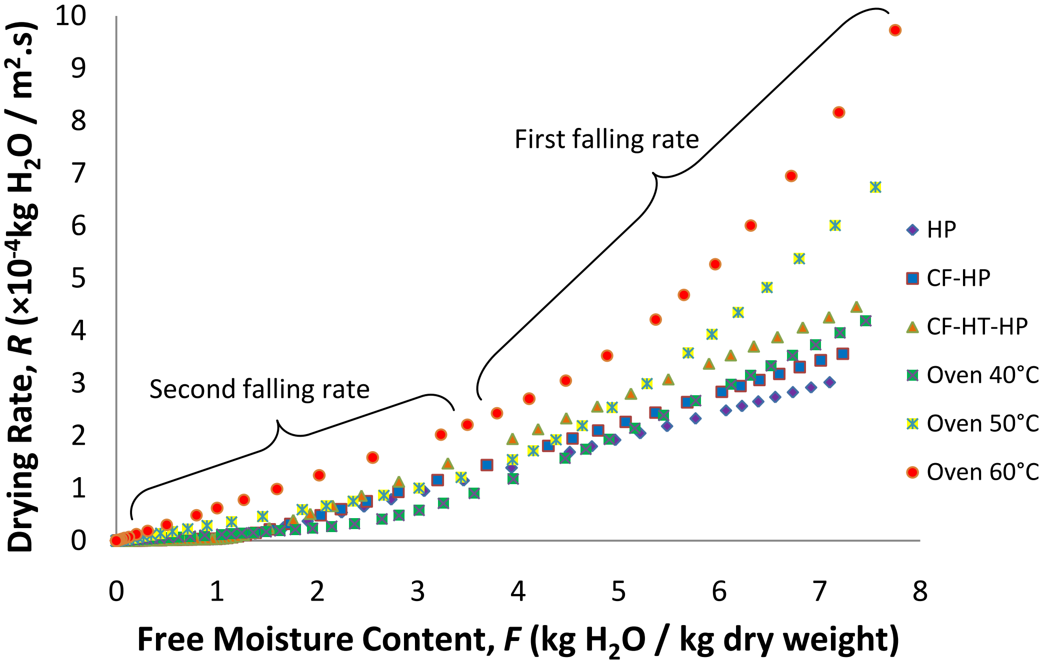

Figure 4.2: Graph of drying rate against free moisture content for different drying methods.

Table 4.12: Average drying rate of heat pump and hybrid heat pump dried lemon slices.

Drying Method	Average Drying Rate ($\times10^{-5}$kg H_2O / $m^2\bullet s$)	Increment of Average Drying Rate as Compared to HP Drying (%)
HP	5.33	–
CF-HP	5.83	9.4
CF-HT-HP	6.67	25.1

Table 4.13: Average drying rate of oven dried lemon slices.

Drying Method	Average Drying Rate ($\times10^{-5}$kg H_2O / $m^2\bullet s$)	Increment of Average Drying Rate as Compared to Oven Drying at 40 ℃ (%)
Oven 40 ℃	8.17	–
Oven 50 ℃	14.00	71.4
Oven 60 ℃	21.83	167.2

According to Figure 4.2, only two falling rate periods were found in the drying of lemon slices; first falling rate and second falling rate, which designates the entire drying process was dominated by the internal moisture diffusion. The absence of constant rate period for all tested drying methods implies that interior part of lemon slices could not maintain a constant supply of moisture to the surface for rapid thin layer drying process (Singh and Gupta, 2007). Turning point of the two falling rate periods for lemon slices dried with heat pump and hybrid heat pump is determined as 1.5 kg H_2O / kg dry weight, whereas for oven drying of the slices at 40^oC, 50^oC, and 60^oC, the turning points are recorded as 4.2, 5.0, and 5.6 kg H_2O / kg dry weight, respectively. The turning point of the first falling rate was found at high free moisture content of the lemon slices which dried at elevated drying temperatures, as high initial rate of unbound moisture evaporation of the slices occurred before the bound moisture vaporized at the later stage of drying. At free moisture content higher than 3.0 kg H_2O / kg dry weight, CF-HT-HP and CF-HP drying of lemon slices showed relatively high drying rate as it overtook the drying rate of oven dried slices at 40 ℃. Whereas, when the free moisture content of the slices reduced from 4.5 kg H_2O / kg dry weight to 2.0 kg H_2O / kg dry weight, the drying rate of hybrid heat pump dried slices was found to be comparable with the drying rate of oven dried slices at 50^oC. For free moisture content below 2.0 kg H_2O / kg dry weight, drying rate for each drying method was almost equal to each other, except for oven drying of the slices at 60^oC.

4.5 Effective Diffusivity

Generally, moisture diffusivity of drying material is affected by its moisture content, drying conditions, as well as its composition and porosity (Luikov, 1970; Chin et al., 2009). However, for drying of lemon slices, the effective moisture diffusivity was investigated based on the effect of drying conditions and its moisture content when dried under different drying methods. As shown in Table 4.14 and 4.15, the average effective diffusivity values were found in the range of 2.95 to 3.73 $\times$ $10^{-11}m^2s^{-1}$ for heat pump and hybrid heat pump drying and 3.52 to 10.63 $\times$ $10^{-11}m^2s^{-1}$ for oven drying of lemon slices. These values fall within the range of the reported moisture diffusivity values for most of the food and biological materials, which is in the range of 10^{-13} to $10^{-9}m^2s^{-1}$ (Madamba et al., 1996; Zogzas et al., 1996).

As compared among heat pump and hybrid heat pump drying methods, there is a significant increment in average effective diffusivity up to 26.4% and it is in accordance with the increment of drying rates of hybrid heat pump drying. The induced Coulomb force in lemon slices during CF-HP and CF-HT-HP drying provoked greater internal moisture diffusion through the semi-permeable membrane of the slices. On the other hand, increasing in drying temperature of oven drying also increased the average effective diffusivity of lemon slices. This is because drying at elevated temperature produced larger moisture concentration difference between the interior and surface of lemon slices which consequently intensified the rate of moisture diffusivity from the interior to the surface for evaporation.

Table 4.14: Average effective diffusivity of heat pump and hybrid heat pump dried lemon slices.

Drying Method	Average Effective Diffusivity ($\times 10^{-11} m^2 s^{-1}$)	Increment of Average Effective Diffusivity as Compared to HP Drying (%)
HP	2.95	–
CF-HP	3.25	10.2
CF-HT-HP	3.73	26.4

Table 4.15: Average effective diffusivity of oven dried lemon slices.

Drying Method	Average Effective Diffusivity ($\times 10^{-11} m^2 s^{-1}$)	Increment of Average Effective Diffusivity as Compared to Oven Drying at 40 ℃ (%)
Oven 40 ℃	3.52	–
Oven 50 ℃	6.35	80.6
Oven 60 ℃	10.63	202.0

Figure 4.3 shows the variation of effective diffusivity against moisture content for different drying methods.

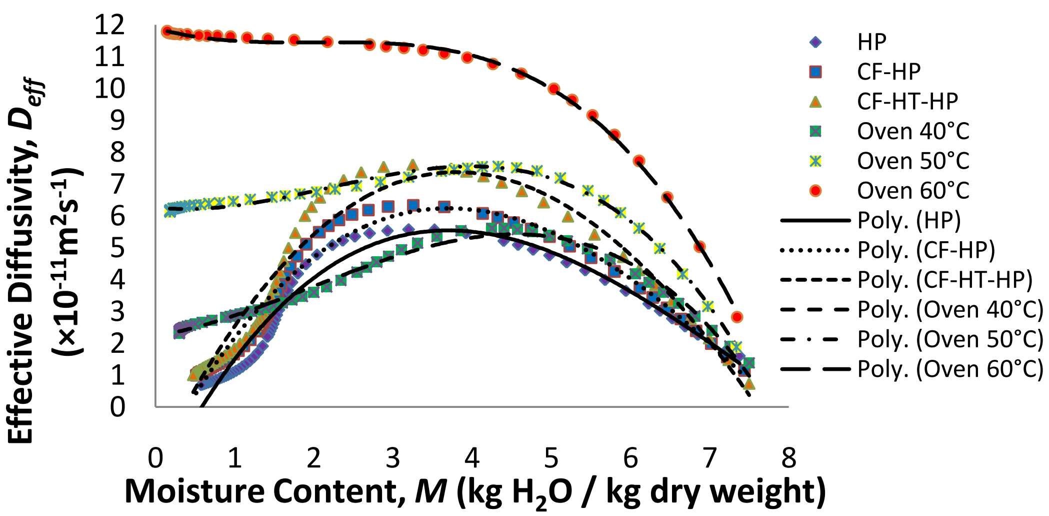

Figure 4.3: Variation of effective diffusivity with moisture content for different drying methods.

The effective diffusivity of each drying method was found to increase to maximum as moisture content decreased to about 3.0 kg H_2O / kg dry weight for heat pump and hybrid heat pump dried lemon slices and 4.6 kg H_2O / kg dry weight for oven dried lemon slices. In addition, the profile of effective diffusivity of all drying methods was similar to Region A and Region B of the diffusion model which was proposed by Luikov (1970) in Chapter 2, Section 7, which indicated that vapour phase diffusion dominated the mechanism of internal diffusion. During oven drying, as the temperature of the lemon slices rose at early stage of the drying process, the water vapour pressure inside the lemon slices increased. This resulted in rapid transportation of moisture content through the semi-permeable membrane and pressure induced opening of pores which in turn enhanced the moisture diffusivity of lemon slices (Darvishi et al., 2012). Whereas for mild temperature hybrid heat pump drying, induced Coulomb force and low relative humidity condition stimulated the moisture diffusion by “pulling out” the moisture towards the surface of lemon slices for vapour evaporation process. Furthermore, convective air which generated by the heat pump dryer also induced the moisture concentration difference between the core and surface of the lemon slices and thus facilitated the transportation of moisture to the surface of drying product.

Nevertheless, rapid declined in effective diffusivity was observed in both heat pump and hybrid heat pump drying methods when moisture content dropped below 3.0 kg H_2O / kg dry weight. This could be due to the shrinkage effect as the collapse of interior structure of lemon slices mitigated the moisture diffusion and only a small amount of moisture was able to diffuse out to the surface when the moisture content of the slices was near to EMC (Chin et al., 2009). Meanwhile, effective diffusivity was found to drop mildly in all oven dried slices. This showed that drying with sufficient heat energy promotes greater vapour pressure inside the lemon slices for a better vapour phase diffusion. However, drying at elevated temperature will induce prominent shrinkage effects on the dried slices.

A third order polynomial relationship (equation 4.1) was found to be well correlated with effective moisture diffusivity with the moisture content of lemon slices dried with different drying methods. The coefficients of the correlation for each drying methods were determined by non-linear regression method and they are tabulated in Table 4.16.

$$D_{eff} = \sum_{i=0}^{3} a_i M^i \tag{4.1}$$

Table 4.16: Coefficients of equation 4.1 for different drying methods.

Drying Method	a_0	a_1	a_2	a_3	R^2	$E(\%)$
HP Drying	-1.555E-3	2.961E-3	-5.301E-4	2.337E-5	0.946	0.30
CF-HP Drying	-1.068E-3	2.832E-3	-4.762E-4	1.682E-5	0.957	0.16
CF-HT-HP Drying	-1.062E-3	3.024E-3	-4.526E-4	9.635E-6	0.944	0.40
Oven 40 ℃	1.339E-3	2.458E-4	1.689E-4	-2.867E-5	0.986	0.37
Oven 50 ℃	3.760E-3	-1.621E-4	2.272E-4	-3.460E-5	0.992	0.10
Oven 60 ℃	7.136E-3	-4.111E-4	2.066E-4	-3.401E-5	0.998	0.65

4.6 Quality Analysis

Among the tested drying methods, quantitative determination of bioactive ingredients reveals that freeze dried lemon slices with total drying time of 48 hours possesses relatively high amount of vitamin C and TPC contents as compared to other drying methods. Freeze drying is widely known as the best drying method for food preservation seeing that it can yield dried products with good sensory quality and superior level of bioactive ingredients retention (Pei et al., 2014; Paengkanya et al., 2015). Therefore, it was used as control sample when analysing the quality of heat pump, hybrid heat pump, and oven dried lemon slices.

4.6.1 Vitamin C Content of Dried Lemon Slices

Vitamin C analysis of the oven and heat pump dried lemon slices at different drying conditions were conducted. The vitamin C content in lemon slices was calculated using the standard curve in Chapter 3, Section 4.1, Figure 3.8. Based on Figure 4.4, except for freeze dried samples, CF-HP dried lemon slices showed the highest amount of vitamin C among all samples with the value of 6.74×10^{-3}kg Ascorbic acid / kg dry weight. The vitamin C content of CF-HP dried slices is significantly higher ($p<0.05$) than oven dried slices due to mild temperature drying condition and relatively fast drying rate. Similar to this, the amount of vitamin C in heat pump and CF-HT-HP dried samples was found to be 2.5% to 93.2% higher than oven dried samples.

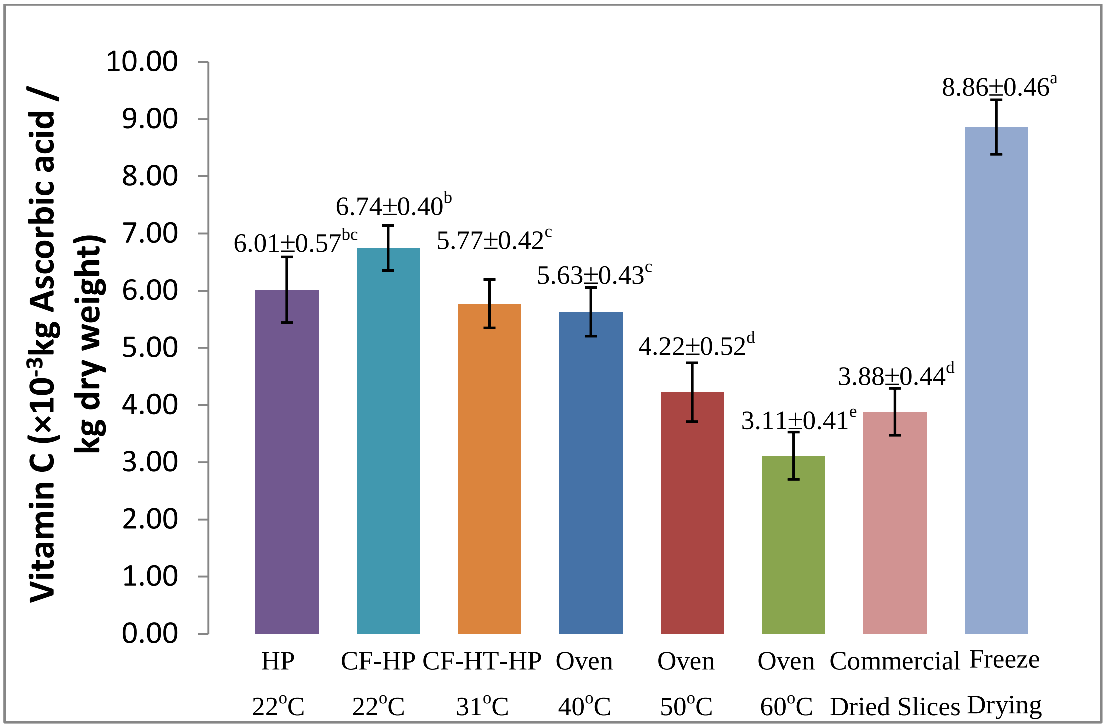

Figure 4.4: Comparison of vitamin C in lemon slices for different drying methods. Different superscript letters indicates there is a significant difference ($p<0.05$) of vitamin C content.

In other words, oven drying of lemon slices at elevated temperature degraded the vitamin C content drastically as compared to heat pump and hybrid heat pump drying of lemon slices at mild temperature. This indicates drying of lemon slices at mild temperature could retain high amount of vitamin C during the dying process. Similar results were concluded by Kaya et al. (2010) when study the effect of drying conditions on the retention of vitamin C in Hayward kiwifruits. Prominent degradation of vitamin C in 50°C and 60°C oven dried lemon slices could be due to combination of thermal degradation and enzymatic oxidation of vitamin C. Thus, heat pump and hybrid heat pump drying preserved most of the vitamin C content in the dried lemon slices as mild drying temperature with relatively high drying rate (especially CF-HP and CF-HT-HP drying) could minimize the deterioration of vitamin C which attributed to thermal degradation as well as enzymatic oxidation. In addition, integration of Coulomb force in heat pump drying (CF-HP) enhanced the drying rate and shortened the total drying time required compared to HP drying which lead to a better vitamin C retention in dried lemon slices. As compared with CF-HP and HP, the used of auxiliary heater in CF-HT-HP drying method which raised the temperature to 31^{o}C further reduced the vitamin C content of lemon slices to 5.77 $\times$ 10^{-3}kg Ascorbic acid / kg dry weight, which was insignificant difference ($p>0.05$) with the vitamin C content of lemon slices dried at 40^{o}C. This further proved the retention of vitamin C in lemon slices could significantly deteriorated by increased drying temperature. Meanwhile, the amount of vitamin C found in heat pump and hybrid heat pump dried lemon slices was lesser as compared to the freeze dried lemon slices. This could be due to the minimum oxidation degradation of vitamin C during freeze drying process which conducted at high vacuum condition. In addition, thin layer drying of lemon slices through the convective process will intensify the losses of vitamin C due to greater exposure of slices to the oxygen (Burg and Fraile, 1995; Hui, 2008). The retention of vitamin C in all tested drying methods is summarized in Table 4.17 with freeze dried lemon slices as control samples.

Generally, vitamin C of hybrid heat pump dried lemon slices was found to be up 73.7% higher than commercial dried lemon slices. Commercial dried products which commonly dried by solar drying or hot air drying method are found to produce dried slices with low content of vitamin C attributed to thermal degradation of this active ingredient. Likewise, longer exposure of commercial dried product to the high intensity solar radiation such as ultraviolet rays during solar drying process could also be the cause for prominent oxidative destruction of vitamin C (Ndawula et al., 2004).

Table 4.17: Retention of vitamin C of lemon slices dried with different drying methods.

Drying Method	Retention of Vitamin C as Compared to the Freeze Dried Slices (%)
HP Drying	67.8
CF-HP Drying	76.1
CF-HT-HP Drying	65.1
Oven 40 ℃	63.5
Oven 50 ℃	47.6
Oven 60 ℃	35.1
Commercial Dried Slices	43.8
Freeze Drying	–

4.6.2 TPC Content of Dried Lemon Slices

TPC analysis of lemon slices dried with different drying methods was conducted and the results were shown in Figure 4.5. In contrast to the results shown in Vitamin C analysis of dried lemon slices, oven dried slices at elevated temperature (50^{o}C) retained the highest amount of TPC, followed by oven dried slices at 60^{o}C and 40^{o}C, hybrid heat pump and heat pump dried slices. The result is in accordance with the findings of Vega-Galvez et al. (2009) and Moraes et al. (2013) for drying of peppers, where high retention of TPC in lemon slices dried at elevated temperature (50^{o}C and 60^{o}C) might be due to the conversion of phenolic molecules from other forms of phenolic compounds, which led to greater amount detected.

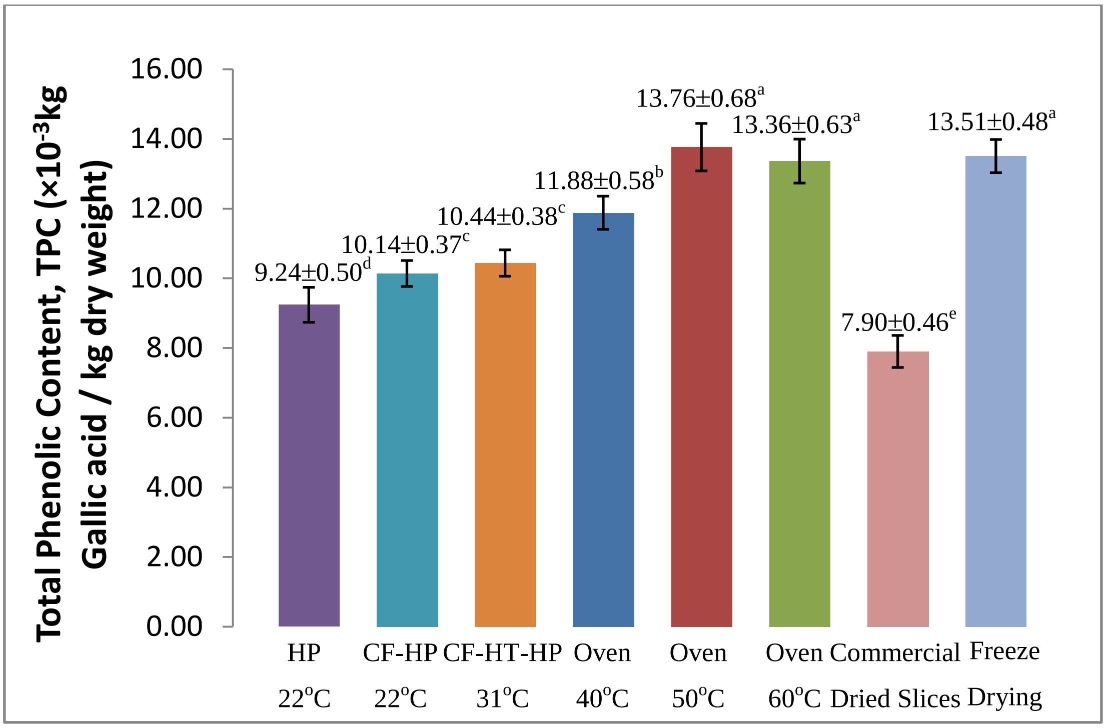

Figure 4.5: Comparison of total phenolics content (TPC) in lemon slices for different drying methods. Different superscript letters indicates there is a significant difference ($p<0.05$) of TPC.

Furthermore, fast drying rate of the lemon slices at 50°C and 60°C also prevents the degradation of TPC due to volatilization, oxidation and heat destruction process. The TPC found in freeze dried slices was slightly lower than those in oven dried slices at 50°C as a high vacuum condition in freeze drying can promote losses of volatile compounds (e.g. TPC) during the drying process (Nollet and Toldra, 2008). The amount of TPC in 50°C and 60°C oven dried samples was significantly higher ($p<0.05$) than those in 40°C oven dried slices and both heat pump and hybrid heat pump dried slices. The effect of drying rate and total drying time on the TPC of dried slices was further shown by the heat pump and hybrid heat pump dried slices. Among the heat pump and hybrid heat pump dried slices, the TPC in CF-HP and CF-HT-HP was insignificantly different ($p>0.05$), but they were significantly higher than the TPC of HP dried slices ($p<0.05$). This could be due to high drying rate and shorter total drying time required by hybrid heat pump drying as compared to heat pump drying of lemon slices which prevented the deterioration of TPC. The results also indicated that overall drying rate and drying duration significantly affected the TPC of lemon slices as compared to drying temperatures. This also contributed to a higher amount of TPC found in oven dried slices as compared to heat pump and hybrid heat pump dried slices. Similar to the results of vitamin C analysis, TPC in commercial dried lemon slices was the lowest among of all ($p<0.05$). Greater loss of TPC of commercial dried slices could be attributed to low drying rate and longer drying time of open sun drying or solar drying. The retention of TPC in all tested drying methods is tabulated in Table 4.18 with reference to the TPC content found in freeze dried lemon slices.

Table 4.18: Retention of TPC of lemon slices dried with different drying methods.

Drying Method	Retention of TPC as Compared to the Freeze Dried Slices (%)
HP Drying	68.4
CF-HP Drying	75.1
CF-HT-HP Drying	77.3
Oven 40 ℃	87.9
Oven 50 ℃	101.9
Oven 60 ℃	98.9
Commercial Dried Slices	58.5
Freeze Drying	–

4.6.3 Shrinkage

The area shrinkage of oven, heat pump and hybrid heat pump dried lemon slices has been determined experimentally and results are presented in Figure 4.6 below.

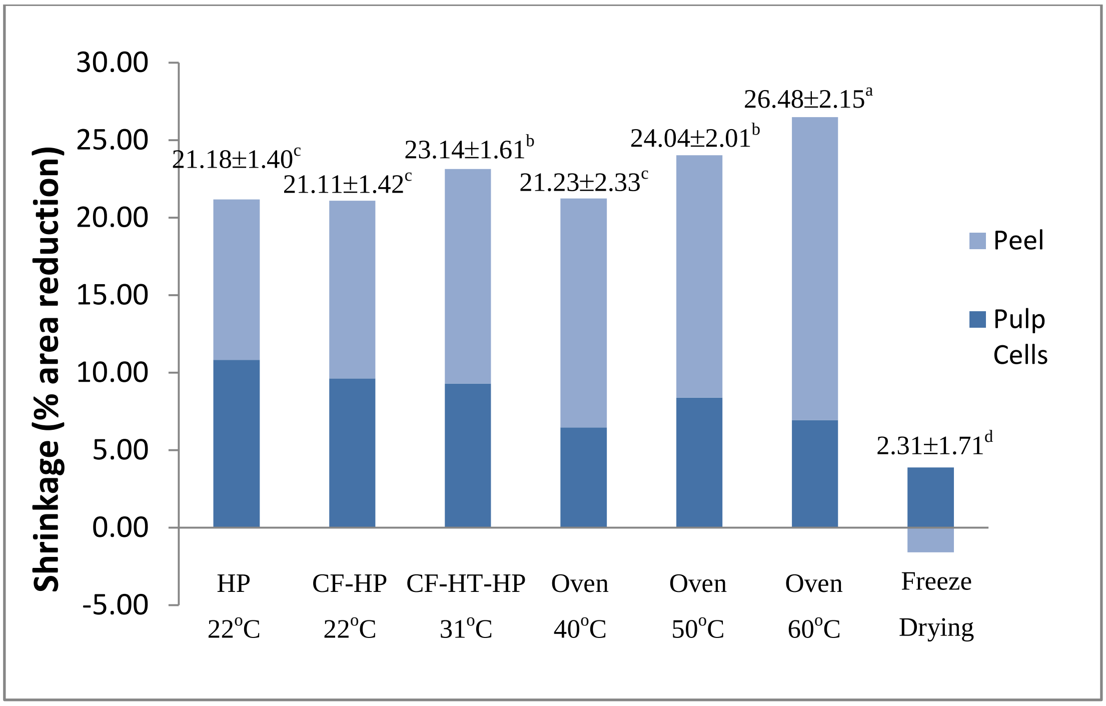

Figure 4.6: Area shrinkage of lemon slices for different drying methods.

According to Figure 4.6, shrinkage of heat pump and hybrid heat pump dried lemon slices was found lower than oven dried lemon slices at 50°C and 60°C. This is attributed to mild temperature drying which minimized the moisture concentration gradient within the slices during drying process and thus reduced the shrinkage of the dried product. Among of all, CF-HP drying method successfully retained the structure of the lemon slices with the lowest shrinkage (21.11% area reduction) as compared to other lemon slices dried at elevated temperature. Meanwhile, oven dried slices at 60^{o}C shrank significantly ($p<0.05$) as compared to slices dried by other methods. Since higher drying temperatures promote a greater rate of moisture lost through the vaporization; lemon slices which contain high initial moisture could suffer alternation from their original structure which lead to significant cell collapse (Thuwapanichayanan et al., 2008; Touil et al., 2014; Coradi et al., 2015). As expected, shrinkage of freeze dried lemon slices was found to be the lowest among the tested drying methods, which is less than 10% for freeze dried product (Ratti, 2008). Removal of moisture by lyophilization tends to prevent cell collapse and produces dried product with high porosity (Hui, 2008; Xiao Dong and Mujumdar, 2009).

Furthermore, the shrinkage of the different parts of lemon slices which subjected to oven, heat pump and hybrid heat pump drying also has been determined and tabulated in Table 4.19. As overall, the shrinkage of lemon peel was found higher than lemon pulp cells for all tested drying methods. This could be due to the greater loss of moisture in lemon peel than lemon pulp cells during drying, where higher porosity of lemon peel enhanced the moisture vaporization and caused greater shrinkage of lemon peel (Taylor, 2004; Manjarres-Pinzon et al., 2013). On the other hand, the rate of moisture vaporization of lemon pulp was essentially limited by the moisture diffusivity across the pulp membranes. Thus, lower rate of moisture lost prevented the collapse of cells which in turn reduced the shrinkage of lemon pulp. Instead, lemon pulp cells were deflated when dried.

Table 4.19: Shrinkage of the parts of lemon slices dried with different drying methods.

Drying Method	Shrinkage (% area reduction)		
	Peel	Pulp Cells	Total
Oven 40 ℃	14.77	6.46	21.23
Oven 50 ℃	15.65	8.39	24.04
Oven 60 ℃	19.54	6.94	26.48
HP Drying	10.36	10.82	21.18
CF-HP Drying	11.47	9.64	21.11
CF-HT-HP Drying	13.85	9.29	23.14
Freeze Drying	-1.58	3.89	2.31

In a nutshell, high shrinkage degrades quality, texture and rehydration properties of dried product and thus affects its marketability (Shekofteh et al., 2012).

4.6.4 Colour Assessment

Browning of biological material can be either caused by enzymatic or non-enzymatic (Caramelization or Maillard reaction) process (Gupta et al., 2011). Enzymatic browning occurs when oxidation of phenolic compounds in drying materials is catalyzed by polyphenol oxidase (PPO) to form quinones which consequently polymerized to form brown pigment (melanins). On the other hand, Caramelization occurs due to decomposition of carbohydrates or sugars in the drying material and form brown pigment, whereas Maillard reaction produces brown nitrogenous polymers and melanoidins from the reaction between amino acid and reducing sugar in the drying material. Both enzymatic and non-enzymatic browning reactions above involve the presence of heat during drying process (Berk, 2016).

Picture of fresh lemon slices before undergone drying process is illustrated in Figure 4.7 whereas pictures of dried lemon slices subjected to different drying methods are shown in Figure 4.8 to 4.14. Based on Figure 4.10 to 4.11, CF-HP and CF-HT-HP dried lemon slices showed bright yellowish colour with minimum browning at the outer part of lemon peel. Furthermore, the colour of lemon slices dried by hybrid heat pump drying method was found insignificantly different as compared to heat pump dried slices (Figure 4.9). This shows that both heat pump and hybrid heat pump drying at mild temperature could minimize enzymatic and non-enzymatic browning of lemon slices. Zero heat generation from the Coulomb force during CF-HP and CF-HT-HP drying also decelerated the enzymatic reaction of polyphenols to form brown pigments (melanin) with the presence of PPO (Bennett et al., 2011; Djendoubi Mrad et al., 2012; Chong et al., 2013). Moreover, the colour of hybrid heat pump dried lemon slices was also found insignificantly different with the fresh and freeze dried lemon slices (Figure 4.7 and 4.8). Thus, this also shows that the absence of heat in drying process minimizes the Maillard reaction and produces dried product with lower browning effect. However, when oven drying at elevated temperature from 40 ℃ to 60 ℃, the browning effect of the dried slices was prominent as the colour of dried lemon slices changed from light brown to dark brown (Figure 4.12 to 4.14). Thus, it demonstrated that elevated drying temperature is the main factor to exaggerate both enzymatic and non-enzymatic browning reactions in dried lemon slices. Likewise, prominent browning also found in commercial dried lemon slices which usually dried at elevated drying temperature or long drying time, as shown in Figure 4.15. On the other hand, it is also noticeable that the colour change mainly occurred on lemon pulp instead of lemon peel. This could be due to higher concentration of catalyst such as PPO in lemon pulp which had stimulated the enzymatic reactions (Santos and Silva, 2008; Bonazzi and Dumoulin, 2011).

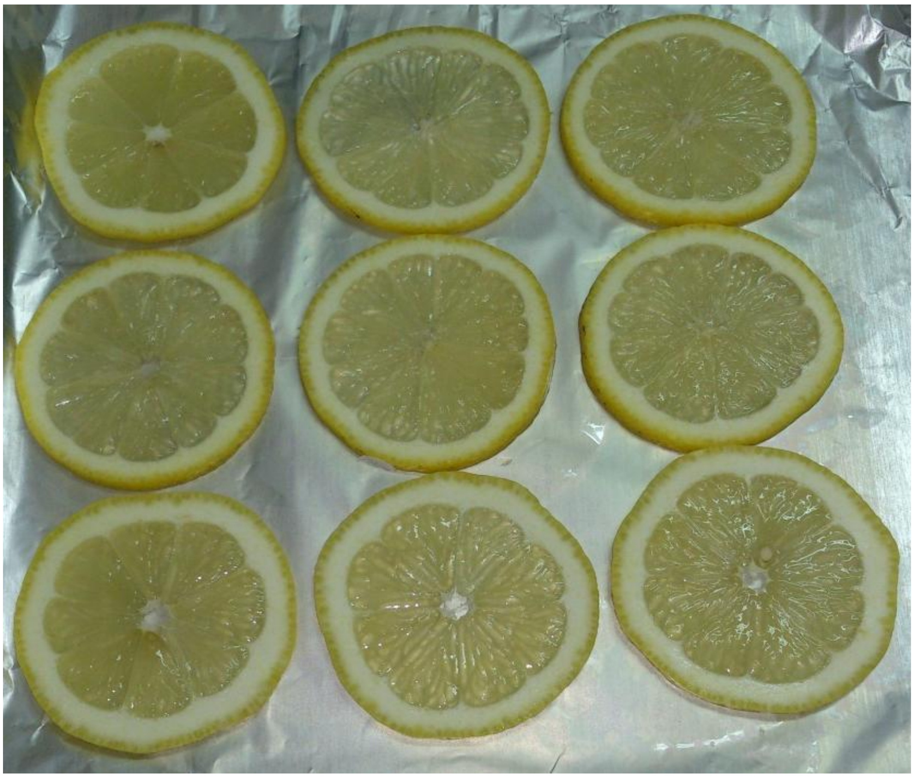

Figure 4.7: Fresh lemon slices.

Figure 4.8: Freeze dried lemon slices.

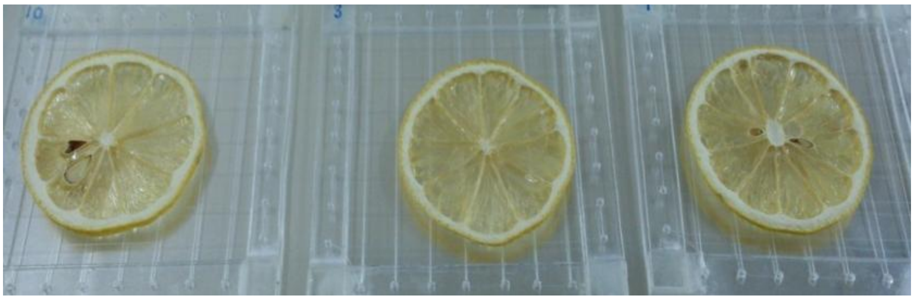

Figure 4.9: HP dried lemon slices.

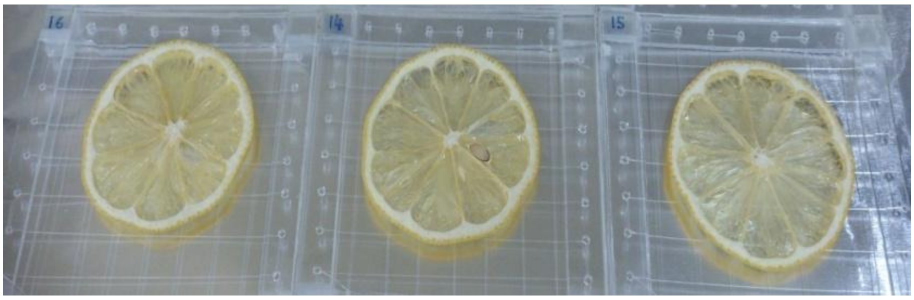

Figure 4.10: CF-HP dried lemon slices.

Figure 4.11: CF-HT-HP dried lemon slices.

Figure 4.12: Oven dried lemon slices at drying temperature of 40 ℃.

Figure 4.13: Oven dried lemon slices at drying temperature of 50 ℃.

Figure 4.14: Oven dried lemon slices at drying temperature of 60 ℃.

Figure 4.15: Commercial dried lemon slices.

CHAPTER 5

CONCLUSION AND FUTURE WORK

5.1 Conclusion

This thesis reports on the drying characteristics and quality of lemon slices dried by an advanced drying method called Coulomb force assisted heat pump drying. The drying characteristics of lemon slices showed that induced Coulomb force in the hybrid heat pump drying could decrease external mass transfer resistance rendered by the electric field. It stimulated greater rate of moisture diffusion from the core to the surface of lemon slices which was subsequently evaporated by the mild temperature and low relative humidity air generated within the heat pump system. Thus, greater rate of moisture evaporation and shorter total drying time were achieved during the drying process. This Coulomb force improved the drying rate by up to 25.1% and shortened the total drying time and energy consumption by 39.9% and 31.5%, respectively.

Meanwhile, vitamin C and TPC analyses of dried lemon slices revealed that Coulomb force assisted heat pump drying was suitable for drying of fruit slices with heat-labile antioxidants. Negligible amount of heat generated by the Coulomb force in hybrid heat pump drying minimized the thermal degradation of vitamin C and resulted in higher retention of vitamin C in Coulomb force assisted heat pump dried lemon slices (up to 116.7%) compared to other dried product. Furthermore, fast drying rate and shorter drying time of Coulomb force assisted heat pump drying also prevented the degradation of TPC due to volatilization, oxidation and heat destruction processes which eventually produced dried slices with relatively high retention of TPC (77.3%) as compared to heat pump dried slices (68.4%). With respect to the physical properties of dried lemon slices, it was found that Coulomb force assisted heat pump drying method which operated at mild drying temperature and relatively fast drying could minimize the shrinkage of dried slices by up to 21.11 % area reduction from original wet slices. On the other hand, minimum browning was observed for Coulomb force assisted heat pump dried slices and the colour of dried product was not much different from fresh and freeze dried slices.

From the findings, it is concluded that Coulomb force assisted heat pump drying is an effective drying method for heat sensitive biomaterials such as food products.

5.2 Future Work

The following are some of the recommendations for future work.

- To study the effects of Coulomb force on the retention of other active ingredients in lemon slices such as vitamin B, vitamin E, bioflavonoids, and essential volatile oils.
- To investigate the effect of Coulomb force on the morphology of dried lemon slices with the application of scanning electron microscope (SEM). Understanding the morphology of dried product is essential to optimize the extraction and yield of antioxidants in lemon slices.

- To investigate the effect of Coulomb force on the moisture diffusion mechanism with the impedance analyzer (a devise used to calculate cell permeabilization index).
- To investigate the effect of Coulomb force at voltage higher than 15kV on drying kinetics and also product quality of dried lemon slices.
- To integrate ultrasonic system into Coulomb force assisted heat pump dryer for the purpose of further improve the drying kinetics and also the quality of heat sensitive biomaterials.
- To study the potential of Coulomb force assisted heat pump drying method for materials with poor heat-transfer characteristics such as bricks, ceramic, and glass fibres.

REFERENCES

Abano, E.E. and Sam-Amoah, L.K., 2011. Effects of different pretreatments on drying characteristics of banana slices. *Journal of Engineering and Applied Sciences*, 6, pp. 121 - 129.

Adams, G., 2007. The Principles of Freeze-Drying. In: Day, J.G., and Stacey, G.N. (eds.). *Cryopreservation and Freeze-Drying Protocols*. Humana Press., pp. 15 - 38.

Agrawal, Y.C. and Singh, R.P., 1977. Thin-layer drying studies on short-grain rice. *ASAE Paper*, 77.

Aktaş, M., Ceylan, İ. and Yilmaz, S., 2009. Determination of drying characteristics of apples in a heat pump and solar dryer. *Desalination*, 239, pp. 266 - 275.

Alves-filho, O., Eikevik, T., Mulet, A., Garau, C. and Rossello, C., 2007. Kinetics and mass transfer during atmospheric freeze drying of red pepper. Drying Technol, 25(7-8), pp. 1155 - 1161.

Antal, T., 2015. Comparative study of three drying methods: freeze, hot airassisted freeze and infrared-assisted freeze modes. *Agronomy Research*, 13(4), pp. 863 - 878.

AOAC. Official Methods of Analysis, Arlington; Association of Official Analytical Chemists; Method 934.06, 1996.

Artnaseaw, A., Theerakulpisut, S. and Benjapiyaporn, C., 2010. Drying characteristics of shiitake mushroom and jinda chili during vacuum heat pump drying. *Food and Bioproducts Processing*, 88, pp. 105 - 114.

Asami, D.K., Hong, Y.J., Barrett, D.M. and Mitchell, A.E., 2003. Comparison of the total phenolics and ascorbic acid content of freeze-dried and air-dried marionberry, strawberry, and corn grown using conventional, organic, and sustainable agricultural practices. *Journal of Agricultural and Food Chemistry*, 51, pp. 1237 - 1241.

Ayub Hossain, M., Gottschalk, K. and Shoeb Hassan, M., 2013. Mathematical model for a heat pump dryer for aromatic plant. *Procedia Engineering* , 56, pp. 510 - 520.

Babalis, S.J. and Belessiotis, V.G., 2004. Influence of the drying conditions on the drying constants and moisture diffusivity during the thin-layer drying of figs. *Journal of Food Engineering* , 65(3), pp. 449 - 458.

Bai, Y. X. and Sun, B., 2011. Study of electrohydrodynamic (EHD) drying technique for shrimps. Journal of Food Processing and Preservation, 35, pp. 891 - 897.

Bai, Y. X. et al., 2013. Electrohydrodynamic drying of sea cucumber (Stichopus japonicus). *LWT - Food Science and Technology*, 54, pp. 570 - 576.

Bakalis, S., Knoerzer, K. and Fryer, P.J., 2005. *Modeling food processing operations*. Elsevier.

Bantle, M., Käfer, T. and Eikevik, T.M., 2013. Model and process simulation of microwave assisted convective drying of clipfish. *Applied Thermal Engineering*, 59(1-2), pp. 675 - 682.

Barba, A.A., Dalmoro, A. and d'Amore, M., 2013. Microwave assisted drying of cellulose derivative (HPMC) granular solids. *Powder Technology*, 237, pp. 581 - 585.

Bardy, E., Hamdi, M., Havet, M. and Rouaud, O., 2015. Transient exergetic efficiency and moisture loss analysis of forced convection drying with and without electrohydrodynamic enhancement. *Energy*, 89, pp. 519 - 527.

Barzegar, M., Zare, D. and Stroshine, R.L., 2015. An integrated energy and quality approach to optimization of green peas drying in a hot air infrared-assisted vibratory bed dryer. *Journal of Food Engineering*, 166, pp. 302 - 315.

Basiry, M. and Esehaghbeygi, A., 2010. Electrohydrodynamic (EHD) drying of rapeseed (Brassica napus L.). *Journal of Electrostatics*, 68, pp. 360 - 363.

Başlar, M., Kılıçlı, M., Toker, O.S., Sağdıç, O. and Arici, M., 2014. Ultrasonic vacuum drying technique as a novel process for shortening the drying period for beef and chicken meats. *Innovative Food Science & Emerging Technologies*, 26, pp. 182 - 190.

Belessiotis, V., and Delyannis, E., 2011. Solar drying. *Solar Energy*, 85(8), pp. 1665 - 1691.

Bennett, L.E. et al., 2011. Total polyphenolics and anti-oxidant properties of selected dried fruits and relationships to drying conditions. *Journal of Functional Foods*, 3(2), pp. 115 - 124.

Berk, Z., 2013. Dehydration. In: *Food Process Engineering and Technology*. 2nd ed. Academic Press, pp. 511 - 566.

Berk, Z., 2016. *Citrus fruit processing*, 1st ed. Academic Press.

Berteli, M.N., Rodier, E. and Marsaioli Jr, A., 2009. Study of the microwave vacuum drying process for a granulated product. *Brazilian Journal of Chemical Engineering*, 26(2), pp. 317 - 329.

Bonazzi, C. and Dumoulin, E., 2011. Quality changes in food materials as influenced by drying processes. In: Tsotsas, E. and Mujumdar, A.S. (eds.). *Modern Drying Technology Volume 3: Product Quality and Formulation*. Wiley-VCH.

Bradshaw, S.M., Van Wyk, E.J. and De Swardt, J.B., 1998. Microwave heating principles and the application to the regeneration of granular activated carbon. *The Journal of The South African Institute of Mining and Metallurgy*, pp. 201 - 212.

Burg, P. and Fraile, P., 1995. Vitamin C destruction during the cooking of a potato dish. *LWT - Food Science and Technology*, 28(5), pp. 506 - 514.

Cárcel, J.A., García-Pérez, J.V., Benedito, J. and Mulet, A. 2012. Food Process Innovation Through New Technologies: Use of Ultrasound. *Journal of Food Engineering , 110* (2), 200–207.

Carcel, J.A., Golas, Y., Benedito, J. and Mulet, A., 2002. Influence of power ultrasound in osmotic dehydration of apple slices. *Proc Int Drying Symposium 2002*, pp. 936 - 942.

Cao, W., Nishiyama, Y. and Koide, S., 2004. Electrohydrodynamic drying characteristics of wheat using high voltage electrostatic field. *Journal of Food Engineering*, 62, pp. 209 - 213.

Çelen, S., Kahveci, K., Akyol, U. and Moralar, A., 2013. Drying behaviour of tomato sices under vacuum conditions. *Termotehnica*, pp. 58 - 65.

Chaudhari, A.D. and Salve, S.P., 2014. A review of solar dryer technologies. *International Journal of Research in Advent Technology*, 2(2), pp. 218 - 232.
Chin, S.K. and Law, C.L., 2014. Maximizing the retention of ganoderic acids and water-soluble polysaccharides content of ganoderma lucidum using two-stage dehydration method. *Drying Technology*, 32(6), pp. 644 - 656.

Chin, S.K., Law, C.L. and Cheng, P.G., 2011. Effect of drying on crude ganoderic acids and water-soluble polysaccharides content in ganodermalucidum. *International Journal of Pharmacy and Pharmaceutical Sciences*. pp. 38 - 43.

Chin, S.K., Law, C.L., Supramaniam, C.V. and Cheng, P.G., 2009. Thin layer drying characteristics and quality evaluation of hot air dried ganodermatsugae murrill. *Drying Technology*, 27(9), pp. 975 - 984.

Chong, C.H., Law, C.L., Figie, A., Wojdyło, A. and Oziembłowski, M., 2013. Colour, phenolics content and antioxidant capacity of some fruits dehydrated by a combination of different methods. *Food Chemistry*, 141, pp. 3889 - 3896.

Chua, K.J., Chou, S.K. and Yang, W.M., 2010. Advances in heat pump systems: a review. *Applied Energy*, 87(12), pp. 3611 - 3624.

Cihan, A., Kahveci, K. and Hacihafizoglu, O., 2006. Modelling of intermittent drying of thin layer rough rice. *Journal of Food Engineering*, 79, pp. 293 - 298.

Closas, A.A. and Villanueva, E.P., 2014. An experimental investigation of the fruit drying performance of a heat pump dryer. *International Conference on Agriculture, Biology and Environmental Sciences (ICABES'14)*, pp. 25 - 29.

Coradi, P.C., Helmich, J.C., Fernandes, C.H. and Peralta, C.C., 2015. Drying kinetics, mathematical modeling and volumetric shrinkage of sunflower seeds (Helianthus Annuus L.). *Energia NA Agricultura*, 30, pp. 319 - 330.

Crank, J., 1975. *The mathematics of diffusion*. Oxford University Press.

Cui, Z.W., Xu, S.Y. and Sun, D.W., 2004. Microwave-vacuum drying kinetics of carrots slices. *Journal of Food Engineering*, 65, pp. 157.

Daghigh, R. et al., 2010. Review of solar assisted heat pump drying systems for agricultural and marine products. *Renewable and Sustainable Energy Reviews*, 14, pp. 2564 - 2579.

Dak, M. and Pareek, N., 2014. Effective moisture diffusivity of pomegranate arils under going microwave-vacuum drying. *Journal of Food Engineering*, 122, pp. 117 - 121.

Darvishi, H., Rezaei Asl, A. and Azadbakht, M., 2012. Determine of moisture diffusivity as function of moisture content and microwave power of some biomaterials. *International Journal of Agricultural and Food Science*, 2(3), pp. 90 - 95.

Djendoubi Mrad, N., Boudhrioua, N., Kechaou, N., Courtois, F. and Bonazzi, C., 2012. Influence of air drying temperature on kinetics, physicochemical properties, total phenolics content and ascorbic acid of pears. *Food and Bioproducts Processing*, 90(3), pp. 433 - 441.

Fatouh, M., Metwally, M.N., Helali, A.B. and Shedi., 2005. Herbs drying using a heat pump dryer. *Energy Conversion and Management*, 47(15-16), pp. 2629 - 2643.
Feng, H., Barbosa-Cánovas, G.V. and Weiss, J., 2010. *Ultrasound Technologies for Food and Bioprocessing*. Springer Science & Business Media.

Feng, H., Yin, Y. and Tang, J., 2012. Microwave drying of food and agricultural materials: basics and heat and mass transfer modeling. *Food Engineering Reviews*, 4(2), pp. 89 - 106.

Finck-Pastrana, A.G., 2014. Nopal (Opuntia Lasiacantha) drying using an indirect solar dryer. *Energy Procedia*, 57, pp. 2984 - 2993.

Gabel, M. M., Pan, Z. L. Amaratunga, K. S. P., Harris, L. J. and Thompson, J. F., 2006. Catalytic infrared dehydration of onions. *Journal of Food Science*, 71(9), pp. 351- 357.

Gallego-Juarez, J.A., 2010. High-power ultrasonic Processing: recent developments and prospective advances. *Physics Procedia*, 3(1), pp. 35 - 47.

Geankoplis, C.J., 2003. *Transport processes and separation process principles (Includes unit operations)*, 4th ed. Prentice Hall Professional Technical Reference.

Genwali, G. R., Acharya, P. P. and Rajbhandari, M., 2013. Isolation of gallic acid and estimation of total phenolic content in some medicinal plants and their antioxidant activity. *Nepal Journal of Science and Technology,* 14(1), pp. 95 - 102.

Ghanem, N., Mihoubi, D., Kechaou, N. and Mihoubi, N.B., 2012. Microwave dehydration of three citrus peel cultivars: effect on water and oil retention capacities, color, shrinkage and total phenols content. *Industrial Crops and Products*, 40, pp. 167 - 177.

Goh, L.J., Yusof Othman, M., Mat, S., Ruslan, H. and Sopian, K., 2011. Review of heat pump systems for drying application. *Renewable and Sustainable Energy Reviews*, 15, pp. 4788 - 4796.

Gupta, S., Cox, S. and Abu-Ghannam, N., 2011. Effect of different drying temperatures on the moisture and phytochemical constituents of edible irish brown seaweed. *LWT - Food Science and Technology*, pp. 1 - 7.

Haghi, A.K. and Ghanadzadeh, H., 2005. A study of thermal drying process. *Indian Journal of Chemical Technology*, 12, pp. 654 - 663.

Haque, M.N. and Sargent, R., 2008. Standard and superheated steam schedules for radiate pine single board drying: model prediction and actual measurements. *Drying Technol*, 26(2), pp. 186 - 191.

Hashinaga, F., Bajgai, T. R., Isobe, S. and Barthakur, N. N., 2007. Electrohydrodynamic (EHD) drying of apple slices. *Drying Technology*, 17(3), pp. 479 - 495.

Hemis, M., Choudhary, R., Gariépy, Y. and Raghavan, V.G., 2015. Experiments and modelling of the microwave assisted convective drying of canola seeds. *Biosystems Engineering*, 139, pp. 121 - 127.
Henderson, S.M., 1974. Progress in developing the thin layer drying equation. *Transactions of the ASAE*, 17(6), pp. 1167 - 1168.

Hui, Y.H., 2008. *Food Drying Science and Technology: Microbiology, Chemistry, Applications.* DEStech Publications.

Ibarz, A. and Barbosa-Cánovas, G.V., 2003. *Unit Operations in Food Engineering*. CRC Press.

Ibrahim, M., Sopian, K. and Daud, W., 2009. Study of the drying kinetics of lemon grass. *American Journal of Applied Sciences*, 6(6), pp. 1070 - 1075.

Jain, D. and Tewari, P., 2015. Performance of indirect through pass natural convective solar crop dryer with phase change thermal energy storage. *Renewable Energy*, 80, pp. 244 - 250.

Jangam, S.V. and Mujumdar, A.S., 2011. *Industrial Drying: Principles and Practice (Lecture Note)*.

Jaroenkit, P., Matan, N. and Nisoa, M., 2013. Microwave drying of cooked brown rice and the effect on the nutrient composition and trace elements. *International Food Research Journal*, 2(1), pp. 351 - 355.

Jiao, A., Xu, X. and Jin, Z., 2014. Modelling of dehydration-rehydration of instant rice in combined microwave-hot air drying. *Food and Bioproducts Processing*, 92(3), pp. 259 - 265.

Kaasová, J., Kadlec, P., Bubník, Z. and Pour, V., 2001. Microwave treatment of rice. *Czech Journal of Food Sciences*, 19, pp. 62 - 66.

Kaasová, J., Kadlec, P., Bubník, Z., Hubáčková, B. and Příhoda, J., 2002. Physical and chemical changes during microwave drying of rice. *Chemical Papers-Slovak Academy of Sciences*, 56(1), pp. 32 - 35.

Kalogirou, S.A., 2013. *Solar Energy Engineering: Processes and Systems*, 2nd ed. Academic Press.

Kammoun Bejar, A., Ghanem, N. and Mihoubi, D., 2011. Effect of infrared drying on drying kinetics, color, total phenols and water and oil holding capacities of orange (citrus sinensis) peel and leaves. *International Journal of Food Engineering*, 7(5).

Kaya, A., Aydın, O. and Kolaylı, S., 2010. Effect of different drying conditions on the vitamin C (ascorbic acid) content of Hayward kiwifruits (Actinidia deliciosa Planch). *Food and Bioproducts Processing*, 88, pp. 165 - 173.

Kivevele, T. and Huan, Z., 2014. A review on opportunities for the development of heat pump drying systems in south africa. *South African Journal of Science*, 110(5/6), pp. 11.

Koné, K.Y. et al., 2013. Power density control in microwave assisted air drying to improve quality of food. *Journal of Food Engineering*, 119(4), pp. 750 - 757.
Kouchakzadeh, A., 2013. The effect of acoustic and solar energy on drying process of pistachios. *Energy Conversion and Management*, 67, pp. 351 - 356.

Kudra, T. and Mujumdar, A.S., 2002. *Advanced Drying Technologies.* New York: Marcel Dekker Inc.

Kudra, T., 2008. Pulse-combustion drying: status and potentials. *Drying Technol*, 26(12), pp. 1409 - 1420.

Kutsakova, V.E., 2007. Effect of inert particles properties on performance of spouted bed dryers. *Drying Technol*, 25(4), pp. 617 - 620.

Lai, F. C., 2010. A prototype of EHD-enhanced drying system. *Journal of Electrostatics*, 68, pp. 101-104.

Lai, M.W., 2014. *Vitamin C Retention of Freeze Dried Lemon Fruit Slices Under Different Freeze Drying Conditions.* FYP Report, Universiti Tunku Abdul Rahman, Chemical Engineering.

Le, T.Q. and Jittanit, W., 2015. Optimization of operating process parameters for instant brown rice production with microwave-followed by convective hot air drying. *Journal of Stored Products Research*, 61, pp. 1 - 8.

Li, F. D., Li, L. T., Sun, J. F. and Tatsumi, E., 2006. Effect of electrohydrodynamic (EHD) technique on drying process and appearance of okara cake. *Journal of Food Engineering*, 77, pp. 275 - 280.

López-Vidaña, E.C., Méndez-Lagunas, L.L. and Rodríguez-Ramírez, J., 2013. Efficiency of a hybrid solar-gas dryer. *Solar Energy*, 93, pp. 23 - 31.

Madamba, P.S., Driscoll, R.H. and Buckle, K.A., 1996. The thin-layer drying characteristics of garlic slices. *Journal of Food Engineering*, 29(1), pp. 75 - 97.

Maekawa, Y., 1994. Instantaneous vacuum drying system. *Proc Int Drying Symposium 94*, pp. 359 - 366.

Manjarres-Pinzon, K., Cortes-Rodriguez, M. and Rodríguez-Sandoval, E., 2013. Effect of drying conditions on the physical properties of impregnated orange peel. *Brazilian Journal of Chemical Engineering*, 30, pp. 667 - 676.

Marnoto, T., Sulistyowati, E., Mahreni and Syahri, M., 2012. The characteristic of heat pump dehumidifier drier in the drying of red chili (Capsium Annum L). *International Journal of Science and Engineering*, 3(1), pp. 22 - 25.

Martynenko, A. and Zheng, W. W., 2016. Electrohydrodynamic drying of apple slices: Energy and quality aspects. *Journal of Food Engineering*, 168, pp. 215 - 222.

Midilli, A., Kucuk, H. and Yapar, Z., 2002. A new model for single-layer drying. *Drying Technology*, 20(7), pp. 1503 - 1513.

Miller, F.P., Vandome, A.F. and McBrewster, J., 2009. *Fick's Law of Diffusion*. VDM Publishing.

Mitra, J., Shrivastava, S.L. and Rao, P.S., 2011. Process optimisation of vacuum drying of onion slices. *Czech Journal of Food Sciences*, 29(6), pp. 586 - 594.

Mohanraj, M., 2014. Performance of a solar-ambient hybrid source heat pump drier for copra drying under hot-humid weather conditions. *Energy for Sustainable Development*, 23, pp. 165 - 169.

Moraes, I.C., Sobral, P.J., Branco, I.G., Ré, T.B. and Gomide, C.A., 2013. Dehydration of “dedo de moça” pepper: kinetics and phytochemical concentration. *Ciência e Tecnologia de Alimentos*, 33, pp. 134 - 141.

Mortezapour, H., Ghobadian, B., Minaei, S. and Khoshtaghaza, M.H. 2012. Saffron drying with a heat pump–assisted hybrid photovoltaic–thermal solar dryer. *Drying Technology*, 30, pp. 560 - 566.

Motevali, A., Minaei, S., Banakar, A., Ghobadian, B. and Darvishi, H., 2014. Energy analyses and drying kinetics of chamomile leaves in microwave-convective dryer. *Journal of the Saudi Society of Agricultural Sciences*.

Mujumdar, A.S., 2014. *Handbook of Industrial Drying*, 4th ed. CRC Press.

Mujumdar, A.S. and Devahastin, S., 2000. *Mujumdar's Practical Guide to Industrial Drying*. Montreal, Canada: Exergex Corporation.

Mujumdar, A.S. and Jangam, S.V., 2011. Some innovative drying technologies for dehydration of foods. *In Proceedings of ICEF*, pp. 555 - 556.

Mukherjee, S. et al., 2011. Evaluation of comparative free-radical quenching potential of brahmi (Bacopa monnieri) and mandookparni (Centella asiatica). *AYU*, 32(2), pp. 258 - 264.

Mustayen, A., Mekhilef, S. and Saidur, R., 2014. Performance study of different solar dryers: A review. *Renewable and Sustainable Energy Reviews*, 34, pp. 463 - 470.

Ndawula, J., Kabasa, J. and Byaruhanga, Y., 2004. Alterations in fruit and vegetable β-carotene and vitamin C vontent vaused by open-sun drying, visqueen-covered and polyethylene-covered solar-dryers. *African Health Sciences*, 4(2), pp. 125 - 130.

Ndukwu, M.C., Ogunlowo, A.S., Olukunle, O.J. and Olalusi, A.P., 2011. Analysis of moisture variation in layers of cocoa bean during drying. *NIAE Ilorin 2011*, 32, pp. 354 - 358.

Nielsen, S.S., 2010. Vitamin C determination by indophenol method. In: *Food Analysis Laboratory Manual*, 2nd ed. Springer. pp. 55 – 60.

Nikolopoulos, N. et al., 2015. Report on comparison among current industrial scale lignite drying technologies (a critical review of current technologies). *Fuel*, 155, pp. 86 - 114.

Nindo, C.I. and Tang, J., 2007. Refractance window dehydration technology: a novel contact drying method, Drying Technol, 25(1), pp. 37 - 48.

Nireesha, G. et al., 2013. Lyophilization / freeze drying - an review. *International Journal of Novel Trends in Pharmaceutical Sciences*, 3, pp. 87 - 98.

Nollet, L.M. and Toldra, F., 2008. *Handbook of Processed Meats and Poultry Analysis*. CRC Press.

O'Callaghan, J., Menzies, D. and Bailey, P., 1971. Digital simulation of agricultural drier performance. *Journal of Agricultural Engineering Research*, 16(3), pp. 223 - 244.

Paengkanya, S., Soponronnarit, S. and Nathakaranakule, A., 2015. Application of microwaves for drying of durian chips. *Food and Bioproducts Processing*, 96, pp. 1 - 11.

Pal, U.S., Khan, M.K. and Mohanty, S.N., 2008. Heat pump drying of green sweet pepper. *Drying Technology*, 26(12), pp. 1584 - 1590.

Panda, D.H., 2013. *The Complete Book on Fruits, Vegetables and Food Processing*. Niir Project Consultancy Services.

Patel, K.K. and Kar, A., 2012. Heat pump assisted drying of agricultural produce – an overview. *Journal of Food Science and Technology*, 49(2), pp. 142 - 160.

Pathare, P.B., Opara, U.L. and Al-Said, F.A.J., 2013. Colour measurement and analysis in fresh and processed foods: a review. *Food and Bioprocess Technology*, 6(1), pp. 36 - 60.

Pati, J.R., Hotta, S.K. and Mahanta, P., 2015. Effect of waste heat recovery on drying characteristics of sliced ginger in a natural convection dryer. *Procedia Engineering*, 105, pp. 145 - 152.

Paul Singh, R. and Heldman, D.R., 2009. *Introduction to Food Engineering*, 4th ed. Academic Press.

Pei, F. et al., 2014. Changes in non-volatile taste components of button mushroom (Agaricus Bisporus) during different stages of freeze drying and freeze drying combined with microwave vacuum drying. *Food Chemistry*, 165, pp. 547 - 554.

Phadke, P.C., Walke, P.V. and Kriplani, V.M., 2015. A review on indirect solar dryers. 10(8), pp. 3360 - 3371.

Piotrowski, D., Lenart, A. and Borkowska, O., 2007. Temperature changes during vacuum drying of defrosted and osmotically dehydrated strawberries. *Polish Journal of Food and Nutrition Sciences*, 57(2), pp. 141 - 146.

Pirnazari, K., Esehaghbeygi, A. and Sadeghi, M., 2014. Assessment of quality attributes of banana slices dried by different drying methods. *International of Food Engineering*, 10(2), pp. 251 - 260.

Povey, M. and Mason, T., 1998. *Ultrasound in Food Processing*. Springer Science & Business Media.

Proctor, A., 2011. *Alternatives to Conventional Food Processing*. Royal Society of Chemistry.

Pu, Y.Y. and Sun, D.W., 2015. Vis–NIR hyperspectral imaging in visualizing moisture distribution of mango slices during microwave-vacuum drying. *Food Chemistry*, 188, pp. 271 - 278.

Ramos, I.N., Brandão, T.R. and Silva, C.L., 2015. Simulation of solar drying of grapes using an integrated heat and mass transfer model. *Renewable Energy*, 81, pp. 896 - 902.

Ratti, C., 2008. *Advances in Food Dehydration*. CRC Press.

Reyes, A., Mahn, A. and Vásquez, F., 2013. Mushrooms dehydration in a hybrid-solar dryer, using a phase change material. *Energy Conversion and Management*, 83, pp. 241 - 248.

Richter Reis, F., 2014. Studies on Conventional Vacuum Drying of Foods. In: *Vacuum Drying for Extending Food Shelf-Life*. Springer. pp. 7 - 18.

Rudy, S. et al., 2015. Influence of pre-treatments and freeze-drying temperature on the process kinetics and selected physico-chemical properties of cranberries (Vaccinium Macrocarpon Ait). *LWT-Food Science and Technology*, 63(1), pp. 497 - 503.

Saha, S., Hossain, F., Anisuzzman, M. and Islam, M.K., 2013. Pharmacological evaluation of musa seminifera lour. fruit. *Journal of Integrative Medicine*, 11(4), pp. 253 – 261.

Salunkhe, D.K. and Kadam, S., 1995. *Handbook of Fruit Science and Technology: Production, Composition, Storage, and Processing*. CRC Press.

Sangamithra, A. et al., 2014. An overview of a polyhouse dryer. *Renewable and Sustainable Energy Reviews*, 40, pp. 902 - 910.

Santos, P.H. and Silva, M.A., 2008. Retention of vitamin C in drying processes of fruits and vegetables-a review. *Drying Technology: An International Journal*, 26(12), pp. 1421 - 1437.

Sarker, M., Ibrahim, M., Aziz, N. A. and Punan, M., 2015. Application of simulation in determining suitable operating parameters for industrial scale fluidized bed dryer during drying of high impurity moist paddy. *Journal of Stored Products Research*, 61, pp. 76 - 84.

Sekone, A.K., Hung, Y.Y., Yeh, C.T. and Lee, M.T., 2015. Experimental study and analysis of porous thin plate drying in a convection dryer. *International Communications in Heat and Mass Transfer*, 68, pp. 200 - 207.

Sevik, S., Aktas, M., Dogan, H. and Koçak, S., 2013. Mushroom drying with solar assisted heat pump system. *Energy Conversion and Management*, 72, pp. 171 - 178.

Shekofteh, M., Cherati, F.E., Kamyab, S. and Hosseinpor, Y., 2012. Study of shrinkage of potato sheets during drying in thin-layer dryer. *Research Journal of Applied Sciences, Engineering and Technology*, 4(16), pp. 2677 - 2681.

Shi, Q., Zheng, Y. and Zhao, Y., 2013. Mathematical modeling on thin-layer heat pump drying of yacon (Smallanthus Sonchifolius) slices. *Energy Conversion and Management*, 71, pp. 208 - 216.

Shirazi, O. U. et al., 2014. Determination of Total Phenolic, Flavonoid Content and Free Radical Scavenging Activities of Common Herbs and Spices. *Journal of Pharmacognosy and Phytochemistry*, 3(3), pp. 104 - 108.

Singh, A., Orsat, V. and Raghavan, V., 2012. A comprehensive review on electrohydrodynamic drying and high-voltage electric field in the context of food and bioprocessing. *Drying Technology*, 30, pp. 1812 - 1820.

Singh, B. and Gupta, A., 2007. Mass transfer kinetics and determination of effective diffusivity during convective dehydration of pre-osmosed carrot cubes. *Journal of Food Engineering*, 79, pp. 459 - 470.

Somogyi, L., Ramaswamy, H.S. and Hui, Y.H., 1996. *Processing Fruits: Science and Technology*, Vol. 1. CRC Press.

Song, X.Y., 2013. Banana chip drying using far infrared-assisted heat pump. *The Philippine Agricultural Scientist*, 96, pp. 275 - 281.

Sontakke, M.S. and Salve, S.P., 2015. Solar drying technologies: a review. *International Refereed Journal of Engineering and Science*, 4(4), pp. 29 - 35.

Stawczyk, J., Li, S. and Zylla, R., 2004. Freeze drying of food products in a closed system. *Drying 2004 – Proceedings of the 14th International Drying Symposium (IDS 2004)*. Taylor & Francis. pp. 949 - 953.

Sun, D.W., 2014. *Emerging Technologies for Food Processing*, 2nd ed. Elsevier.

Taghian Dinani, S. and Havet, M., 2015. Effect of voltage and air flow velocity of combined convective-electrohydrodynamic drying system on the physical properties of mushroom slices. *Industrial Crops and Products*, 70, pp. 417 - 426.

Talens, C., Castro-Giraldez, M. and Fito, P.J., 2015. A thermodynamic model for hot air microwave drying of orange peel (Article in Press). *Journal of Food Engineering*, pp. 1 - 10.

Taylor, S., 2004. *Advances in Food and Nutrition Research*. Vol. 48. Gulf Professional Publishing.

Thirumaleshwar, M., 2009. *Fundamentals of Heat and Mass Transfer*. Pearson Education India.

Thuwapanichayanan, R., Prachayawarakorn, S. and Soponronnarit, S., 2008. Drying characteristics and quality of banana foam mat. *Journal of Food Engineering*, 86(4), pp. 573 - 583.

Toshniwal, U. and Karale, S., 2013. A review paper on solar dryer. *International Journal of Engineering Research and Applications (IJERA)*, 3(2), pp. 896 - 902.

Touil, A., Chemkhi, S. and Zagrouba, F., 2014. Moisture diffusivity and shrinkage of fruit and cladode of opuntia ficus-indica during infrared drying. *Journal of Food Processing, 2014,* pp. 9.

Varzakas, T. and Tzia, C., 2015. *Handbook of food processing: Food preservation*. CRC Press.

Vega-Gálveza, A. et al., 2009. Effect of air drying temperature on physico-chemical properties, antioxidant capacity, color and total phenolics content of red pepper. *Journal of Food Chemistry*, 117(4), pp. 647 - 653.

VijayaVenkataRaman, S., Iniyan, S. and Goic, R., 2012. A review of solar drying technologies. *Renewable and Sustainable Energy Reviews,* 16(5), pp. 2652 - 2670.

Wang, C.Y. and Singh, R.P., 1978. Use of variable equilibrium moisture content in modeling rice drying. *Transactions of ASAE*, 11, pp. 558 - 572.

Wang, S.J. and Mujumdar, A.S., 2007. Three-dimensional analysis of flow and mixing characteristics of a novel in-line opposing-jet mixer. *Ind Eng Chem Res*, 46(2), pp. 632 - 642.

Wankhade, P. K., Sapkal, R. S. and Sapkal, V. S., 2012. Drying Characteristics of Okra Slices using Different Drying Methods by Comparative Evaluation. *Proceedings of the World Congress on Engineering and Computer Science 2012 Vol II*.

White, G., Ross, I. and Poneleit, C., 1981. Fully-exposed drying of popcorn. *Transactions of the American Society of Agricultural Engineers,* 24(2), pp. 466 - 468.

Wu, L., Orikasa, T., Ogawa, Y. and Tagawa, A., 2007. Vacuum drying characteristics of eggplants. *Journal of Food Engineering*, 83(3), pp. 422 - 429.

Xiao Dong, C. and Mujumdar, A.S., 2009. *Drying Technologies in Food Processing*. John Wiley & Sons.

Yang, M. S. and Ding, C. J., 2016. Electrohydrodynamic (EHD) drying of the chinese wolfberry fruits. 5:909.

Yang, Z., Zhu, E., Zhu, Z., Wang, J. and Li, S., 2013. A comparative study on intermittent heat pump drying process of chinese cabbage (Brassica Campes Tris L.Ssp) seeds. *Food and Bioproducts Processing*, 91(4), pp. 381 - 388.

Ye, J.S., Li, X.L., Hou, H.Y. and Li, Z.Y., 2007. Sorption drying of soybean seeds with silica gel in a fluidized bed dryer. *Proc 5th Asia-Pacific Drying Conference*, pp. 608 - 613.

Zakipour, E. and Hamidi, Z., 2011. Vacuum drying characteristics of some vegetables. *Iranian Journal of Chemistry and Chemical Engineering*, 30(4), pp. 97 - 105.

Zarein, M., Samadi, S.H. and Ghobadian, B., 2015. Investigation of microwave dryer effect on energy efficiency during drying of apple slices. *Journal of the Saudi Society of Agricultural Sciences*, 14(1), pp. 41 - 47.

Zhang, M., Tang, J., Mujumdar, A.S. and Wang, S.J., 2006. Trends in microwaverelated drying of fruits and vegetables. *Trends in Food Science & Technology*, 17(10), pp. 524 - 534.

Zielinska, M., Zapotoczny, P., Alves-Filho, O., Eikevik, T.M. and Blaszczak, W., 2013. A multi-stage combined heat pump and microwave vacuum drying of green peas. *Journal of Food Engineering*, 115, pp. 347 - 356.

Zogzas, N., Maroulis, Z. and Marinos-Kouris, D., 1996. Moisture diffusivity data compilation in foodstuffs. *Drying Technology*, 14(10), pp. 2225 - 2253.