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PINEAPPLE DRYING: MATHEMATICAL MODELLING AND EXPERIMENTS USING HIGH-PRECISION SYSTEM AND A GREENHOUSE-TYPE SOLAR DRYER

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PINEAPPLE DRYING: MATHEMATICAL MODELLING AND EXPERIMENTS USING HIGH-PRECISION SYSTEM AND A GREENHOUSE-TYPE SOLAR DRYER

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To my beloved daughter

Annette Liliana López García

The one and the only

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SECADO DE PIÑA: MODELACIÓN MATEMÁTICA Y EXPERIMENTOS USANDO UN SISTEMA DE ALTA PRECISIÓN Y UNO SOLAR TIPO INVERNADERO

PINEAPPLE DRYING: MATHEMATICAL MODELLING AND EXPERIMENTS USING HIGH-PRECISION SYSTEM AND A GREENHOUSE-TYPE SOLAR DRYER

Ignacio López Cerino[1]; Irineo L. López Cruz[2]

RESÚMEN

La opción más económica para la conservación de productos agrícolas ha sido el secado solar. Sin embargo, actualmente se requiere de conocimientos nuevos y nueva tecnología para secar grandes cantidades de productos, donde calidad y seguridad en los alimentos son requisitos que deben satisfacer los productos deshidratados. Especialmente se requiere la optimización del desempeño de secadores solares de acuerdo a las características del producto y del medio ambiente. El objetivo principal en esta investigación fue generar conocimiento básico que permita mejorar el manejo del secado solar de piña (*Ananas Comosus*, L.) bajo secadores tipo invernadero. Se llevaron a cabo dos experimentos de secado para generar modelos de capa delgada para frutos de piña. El primero usó un secador laboratorio de alta precisión en la Universidad de Hohenheim, Alemania. Se obtuvieron curvas de secado de piña bajo temperaturas y velocidades del aire constante. El segundo experimento se llevó a cabo en un secador solar tipo invernadero en la Universidad de Silpakorn, Nakhon Pathom, Tailandia. Se determinaron curvas de secado de piña bajo condiciones variables de temperatura, humedad relativa y velocidad del aire. Se encontró que el modelo matemático para capa delgada propuesto por Hasibuan and Daud predice en forma adecuada las mediciones de contenido de humedad del producto en ambos experimentos.

Palabras Clave: *Ananas Comosus*; Modelo Matemático: Modelos de secado.

ABSTRACT

The most economical option for preserving agricultural products has been solar drying. However, new knowledge and technology are currently required for drying large quantities of products, where quality and food safety are requirements that dehydrated products must meet. Performance optimization of solar dryers according to the characteristics of the product and the environment is especially required. The main goal in this research was to generate basic knowledge to improve the management of solar drying of pineapple (*Ananas Comosus*, L.) under greenhouse–type dryers. Two drying experiments were carried out to generate thin-layer models for pineapple fruit. The first used a high-precision laboratory dryer at the University of Hohenheim, Germany. Pineapple drying curves were obtained under constant air temperatures, relative humidity and air velocity. The second experiment was conducted in a greenhouse-type solar dryer at Silpakorn University, Nakhon Pathom, Thailand. Pineapple drying curves were determined under variable conditions of air temperature, relative humidity and air velocity. It was found that the thin-layer mathematical model proposed by Hasibuan and Daud predicts adequately the moisture content measurements of the product in both experiments.

Keywords: *Ananas Comosus*; Mathematical model; Drying models.

[1]Author of thesis, [2]Director of thesis

Chapter 1

Introduction

1.1 Presentation

Most of the agricultural product produced in the world is by temporal, means that for short time of the year is produced in a lot of quantity and the price drop, agricultural producer find a difficult time to sell the product with good price and the best option is to sell cheap or to leave it on the field because of the high cost to harvest. One of the best and cheap option for conservation of the agricultural product is the solar drying. This is an antique practice and consist on removing the water of the product with the solar energy, having the advantage to be cheap also have disadvantage like to be expose to dust, insects and animals. Contamination bring low quality and risk for the consumer. Another problem that it is found on drying is the amount required for market. Exist lot of research on how to dry food, quality is high and the time is reduced using solar dryers. Many forms and size has been developed. Cheap and small devices has been designed to common people in the way that they can dry their own agricultural product just for themselves. This is a good start but is not solving for an agricultural farmer the problem of low price selling, batch of 10 – 15 kg is not enough for thousands of kg produced on field.

New technology is required to dry lot of quantity of agricultural food, high quality and safe product is necessary to make the product able to sell on the market. Greenhouse solar drying make possible all this, giving to the product a new high value using clean solar energy. The farmer can have an increase in his income, product would be consumed all year around, social impact can reach more families with employment and it is a good chance to reduce hunger.

1.2 General objectives

- To find mathematical models that can fit experimental data for better prediction of system behavior, for use in improving control or management of solar greenhouse drying system.
- To do optimization of the pineapple drying with solar greenhouse dryer in any place that have the minimum conditions to dry it.

1.3 Particular objectives

- To make experiment at laboratory level in Hohenheim University, Stuttgart, BW, Germany, using a high precision laboratory dryer developed at the Hohenheim University. Data would be collected, analyzed and used to model thin layer drying mathematical model, also, physic- chemical analysis for quality determination would be done with fresh and dry pineapple: color, pH, %Brix, water activity and Vitamin C determination.
- Carry out second experiment at Silpakorn University, Nakhon Pathom, Thailand, with fresh (1 cm width) slice pineapples in a village-scale greenhouse-type solar dryer, data collected for experiments will be analysed and use to calculate mathematical modelling using energy and humidity balance. The types of data that should be collected are: drying time, moisture content fresh, moisture content dry, initial weight product and final weight product on pineapple.

1.4 Problem statement

The high moisture content of pineapple (85 %), makes it highly perishable, thus the fruit is less shelf stable and prone to quick spoilage. Pineapple is a seasonal fruit, and it is abundant during periods of harvest, which give rise to postharvest losses. Drying can be used to reduce these postharvest losses and thus make shelf-stable products last longer. Drying is the simplest method for preservation of fruits. However, longer drying times and uncontrolled drying conditions may lead to poor quality at the end of the process. With all these in mind, having the knowledge of the drying kinetics help subsequently to the optimization of the drying process for greater efficiency. Mathematical modeling of the dehydration process is very useful in the design and optimisation of dryers.

Chapter 2

An overview of large-scale greenhouse solar drying systems

2.1 Introduction

Drying is defined as the process of reduction of moisture up to a safe limit of moisture content. Dryness of product depends on the moisture content in the produce either on a wet basis or dry basis. Safe limits for several crops are already known (Prakash and Kumar, 2014). The goal of drying is to slow down the activity of enzymes, yeast, bacteria, and moulds.

Two basic moisture transfer mechanism are involved in drying (Belessiotis and Delyannis, 2011):

- Migration of moisture from the mass inside to the surface.
- Transfer of the moisture from the surface to the surrounding air, in the form of water vapor.

In general, conventional drying principles and phenomena are independent of the type of energy used. Ekechukwu and Norton (1999) gives a comprehensive review of fundamental principles and theories governing the drying process.

Drying is one of the main steps to determine quality and cost of products. This means between 45 to 60% of the costs (Sánchez Chavarria and Zavala Buechsel, 2013) being an important reason to evaluate technical and viable alternatives to do an efficient drying. To the quality and cost we have to add that it is required to dry large amount of product in order to make the process profitable. Greenhouse solar drying is a viable alternative to dry in a natural way (solar drying in open air). This technology can help to reduce cost, keeping quality and drying large amounts of product. A greenhouse solar dryer is a closed structure made by different materials like wood, concrete, UV plastic, polycarbonate etc. where it is possible to control the air flow, temperature, humidity and other factors (dust, insect infestation, enzymatic reactions, microorganism growth and mycotoxin development). With cultural and industrial development, artificial mechanical drying came into practice. This process is highly energy intensive and expensive, which ultimately increases product cost. Thus solar drying is the best alternative as a solution of all the drawbacks of natural drying and artificial mechanical drying (Vijayavenkataraman et al., 2012).

Some advantage of the greenhouse solar dryers are: they are very useful device that save energy, also can save lot of time, it uses less area, quality of products are improved, process are more efficient, protect the environment and can be used for entire drying process or for supplementing artificial drying systems which help to reduce fuel energy.

Because huge amounts of tropical fruits and vegetables are produced annually, medium-scale and large scale greenhouse dryer are necessary to respond to the demand of dried food (domestic and international markets). A general review of all recent developments of greenhouse solar dryer, focused on large scale, is presented in this work.

2.2 Classification of greenhouse solar drying.

Greenhouse-type solar dryer can be classified based by structure (dome shape and roof even type) or by heat transfer (greenhouse dryer under natural circulation and forced circulation).

The objective of Dome type greenhouse dryer is to get the maximum solar radiation and to avoid damage by strong wind. The advantage of the roof even type is the proper mixing of air inside the dryer (Prakash and Kumar 2014).

2.2.1 Natural circulation large scale greenhouse solar dryer

Success achieved by natural convection solar dryers has been limited due to low buoyancy induced air flow. Here are described two of the most significate large scale greenhouse-type solar dryers.

Ekechukwu and Norton, 1997 show an experimental solar-energy tropical dryer which consists of a transparent semi-cylindrical drying chamber with an attached cylindrical "chimney", rising vertically out of one end, while the other end is equipped with a door" for air inlet and access to the drying chamber (Figure 2-1). The drying chamber measures approximately 6.67 m long by 3.02 wide by 2.3 m high. The chimney has a maximum possible height of 3.0m above the chamber and a diameter of 1.64 m. The site for the dryer was at the National Centre for Energy Research and Development at the University of Nigeria, Nsukka.

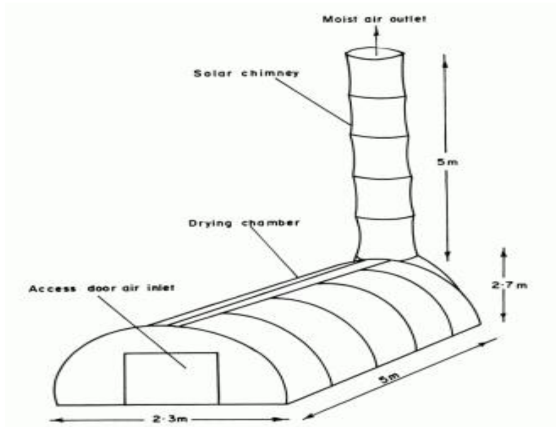

Figure 2-1. Natural convection large scale greenhouse dryer with chimney (Ekechukwu and Norton 1997).

Other natural circulation solar greenhouse dryer is the Brace Research Institute glass-roof solar dryer (Figure 2-2), which consisted of two parallel rows of drying platforms (along the long side) of galvanised iron wire mesh surface laid over wooden beams. Fixed slanted glass roof over the platform allowed solar radiation over the product. To improve absorption of solar radiation, the greenhouse had black coated internal walls. To provide an air exit vent, a ridge cap was made of folded zinc sheet over the roof and to regulate the air inlet, shutters at the outer sides of the platforms were installed (Weiss and Buchinger 2004).

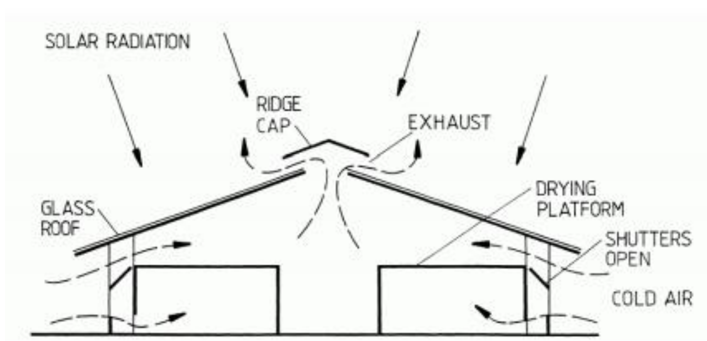

Figure 2-2. Natural convection glass roof greenhouse dryer (Weiss and Buchinger 2004).

2.2.2 Forced circulation large scale greenhouse solar dryer

A forced circulation greenhouse solar dryer is defined like the one that only depend solely on solar-energy as the heat source but employs motorized fans and/or pumps for forced circulation of the drying air. A classification can be seeing in Figure 2-3, which was taken from (Ekechukwu and Norton, 1999) that divide in two: one is Integral-type forced solar-energy drying systems and the second one is distributed-type forced solar-energy drying systems. Integral-type are solar drying designs in which the solar-energy collection unit is an integral part of the entire system, air is not separated in ducting to another chamber. In the distributed-type, solar collector and drying chamber are separate units. The four basic components are: i) Drying chamber; ii) Solar air heater; iii) Fan and/or pump and iv) Ducting.

2.2.3 Hybrid large scale greenhouse solar dryer

If the solar-heated air is warm enough, can be use directly for the drying process, otherwise a fossil-fuel fired dehydrator would be used to raise the drying air temperature to the required level (for example during night or periods of low insolation levels). Ambient air is first passed through the solar air heater where it is heated and then to the greenhouse. Drying is then achieved by direct exposure in the greenhouse and also by forced convection (Ong, 1999).

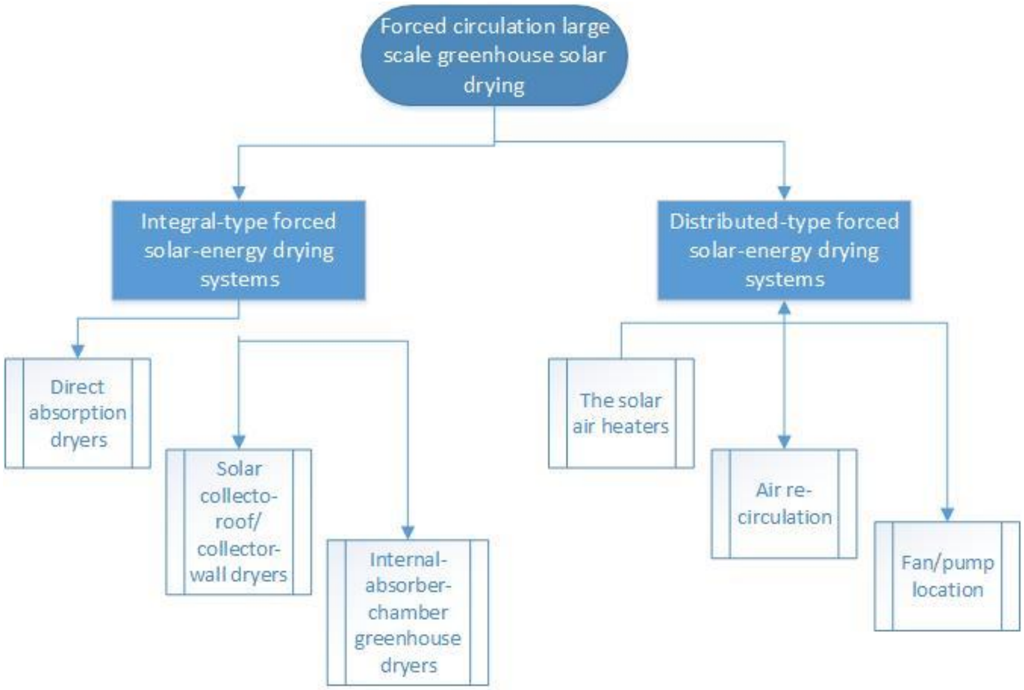

Figure 2-3. Forced solar drying systems classification.

2.3 Asian greenhouse-type dryers

2.3.1 Solar dryer in the Asia-Pacific region

Ong (1999) investigated the state-of-art on the applications of solar energy for the drying showing a number of potential solar dryer designs for use in the region, here it will be shown just two type: greenhouse-type solar dryer and hybrid system (the last one described before). Also an extensive literature review on solar drying technology and solar dryers can be found elsewhere (Janjai and Bala 2012)

2.3.1.1 Greenhouse-type solar dryer

One of the solar dryer studied here is an alternatively-ventilated greenhouse for preserved fruits built in China. The glass cover is South-oriented with a brickwork insulation North wall. Entry and exit doors are located on the side. The fruit to be dried are placed on trays which are stacked on the material stand in the drying chamber. The common and inherent problem of uneven temperature distribution in conventional greenhouse dryers is eliminated by providing air flow in both directions within the dryers. When natural ventilation is adopted, fresh air enters from outside through a vent pipe situated at the South side of the greenhouse dryer. This internal vent pipe is perforated on its wall facing the materials stand. Air flows in through the holes, passes through the material to be dried and discharges through the exhaust pipe in the upper part of the North wall. If the axial ventilator fan installed at the end of the vent pipe is started, the direction of air flow will be reversed – air enters from the top chimney and flows downward through the material to be dried and three portable axial blowers recirculate and increase air speed over the material to intensify drying during the initial stage.

2.3.2 Double-pass solar dryer in Vietnam.

The main objective of Banout et al. (2011) was to design a new model of forced convection indirect type solar dryer called Double-pass solar dryer, test it under the tropical conditions in central Vietnam and compare it to the typical solar cabinet dryer (CD) and traditional open-air sun drying technique. Red chilli (*Capsicum annum* L.) was chosen due to its high prevalence in Vietnamese cuisine. The Double-pass solar dryer (DPSD) was designed at the Institute of Tropics and Subtropics, Czech University of Life Science Prague, Czech Republic in 2007. The dryer is classified as a forced convection indirect type. The dimensions of the dryer are as follows: length 5 m, width 2 m and height 0.30 m as shown in Figure 2-4. The dryer consists of five equal modules that are connected together.

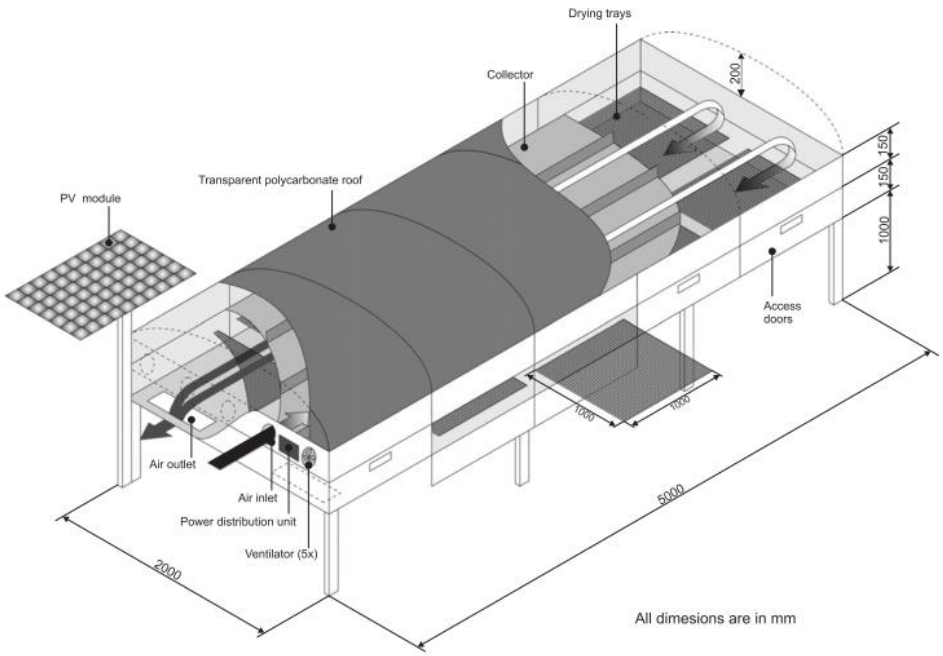

Figure 2-4. Description of Double-pass solar dryer (DPSD) (Banout et al., 2011)**.**

2.3.2.1 Drying performance

An average drying temperatures and corresponding drying air relative humidity during all experiments were 53.76±7.6°C, 23.73±9.5%; 46.44±6.4°C, 35.86±10.6% and 34±1.8°C, 56.33±5.6% for DPSD, CD and open-air sun drying respectively. The best drying efficiencies were achieved in case of DPSD. The overall drying efficiency of DPSD is in the range of 20-30% which is typical for forced convection solar dryers. The first day drying efficiency was about 5.9% higher in case of DPSD comparing to CD and two times higher comparing to the open-air sun drying. Focusing on the pick-up efficiency the results shows that DPSD has about 3% higher pick-up efficiency comparing to typical cabinet dryer. The highest drying rate occurred in case of DPSD where the final moisture content 0.05±0.003 kgkg^{-1} (db) was reached after 23 h of drying followed by CD with 0.09±0.01

kgkg^{-1} (db) after 29 h and open-air sun drying with 0.18±0.09 kgkg^{-1} (db) after 36 h of drying (excluding nights). These results correspond to the fact that DPSD use forced convection ensuring higher air-flow rate which results in higher water removal from the red chilli.

2.3.2.2 Dried product quality

There was no significant difference ($p \leq 0.05$) between ASTA colour value of chilli samples dried in the CD and open-air sun drying. Significantly higher mean colour value 43.105±0.94 was obtained from samples dried in DPSD. These results correspond to the fact that the drying in DPSD was conducted under moderate drying temperatures and in shadow. Vitamin C content between DPSD and open-air sun drying show no significant difference (($p \leq 0.05$). Significant lower mean vitamin C content was observed during cabinet drying. Lower concentration of ochratoxin A, aflatoxins B1, B2, G1, G2 and sum of aflatoxins were measured in samples obtained from DPSD followed by CD and open-air sun drying. Samples from traditional open-air sun drying have shown considerably higher aflatoxin contamination compared to samples from the solar dryers.

2.3.2.3 Economic aspect of drying

The construction cost of DPSD was significantly higher than in CD, the drying costs per one kilogram of chilli were by 39% lower in case of DPSD as compared to CD. The payback period was more or less by one year shorter in case of CD, however taking in to the consideration the life of both dryers the payback period of DPSD is preferable. Double-pass solar dryer was found to be technically and economically suitable for drying of red chillies under the specific conditions in central Vietnam.

2.3.3 PV-ventilated solar greenhouse dryer in Thailand.

The objectives of the work from Janjai et al.(2009) was to investigate experimentally the performance of a PV-ventilated greenhouse dryer and to develop a mathematical model for predicting the performance of this dryer for drying peeled longan (*Dimocarpus longan*) and banana (*Musa paradisiaca*). A village-scale greenhouse type solar dryer was constructed at Silpakorn University, Nakhon Pathom, Thailand. It consists of a parabolic roof structure made from polycarbonate plate on a concrete floor (see Figure 2-5). The structure of the dryer is made of galvanized iron bars. The products to be dried were placed in a thin layer on two arrays of trays. Three DC fans operated by a 50-W PV-module were installed in the wall opposite to the air inlet to ventilate the dryer.

Figure 2-5. Pictorial view of the village scale greenhouse dryer (S. Janjai et al., 2009)**.**

Peeled longan and banana were dried to demonstrate the potentials of the PV-ventilated solar greenhouse dryer. A total of ten full scale experimental runs were carried out during the period of December 2006-January 2008, five runs for each of peeled longan and banana. For each drying test, 100 kg of fresh fruit was used and the dryer was loaded as

15 kg m^{-2} for banana and 10 kg m^{-2} for peeled longan. The moisture content of peeled longan in the solar dryer was reduced from an initial value of 81% (wb) to a final value of 12% (wb) within 3 days. The moisture content of banana in the dryer decreased from 70% (wb) to 24% (wb) within 4 days. The colour of fresh longan and banana changes from white to red-yellow after drying with different degrees of intensity of colour. Results of the sensory evaluation show that solar dried longan and banana have the higher liking score in terms of appearance, colour, texture, flavor, taste, and overall acceptance as compared to sun dried products and there is a significant difference between the liking scores for solar and sun dried longan and banana at 0.05 level. The price of dried products obtained from this dryer is about 20% higher than that obtained from the open-air sun drying. Based on the production scale and the capital and operating costs of the drying system of peeled longan and banana, the payback periods of the greenhouse solar drying system for drying of peeled longan and banana are estimated to be 2.3 years. This relatively short payback period is likely due to the fact that dried peeled longan and banana obtained from this dryer can be sold with significantly higher price than that of the products from the open-air sun drying and the dryer is used year around.

A system of partial differential equations for heat and moisture transfer has been developed for solar drying of peeled longan and banana in the solar greenhouse dryer. The simulated air temperatures inside the dryer reasonably agreed with the observed temperature data. Reasonable agreement was found between the experimental and simulated moisture contents of peeled longan and banana during drying and the accuracy was within the acceptable range. The model developed can be used for providing design data for solar greenhouse dryers and also for optimization of this type of solar dryer.

2.3.4 Large-scale solar greenhouse dryer in Thailand.

The research of S. Janjai et al., (2011) presented the experimental performances of the greenhouse dryer for drying of chilli, banana and coffee in the tropical climatic conditions of Lao PDR and mathematical drying model to simulate the drying of these products. The greenhouse type solar dryer was constructed at Chapasak (15.13 °N, 105.79 °E) in Lao PDR under a collaborative project on renewable energy between Lao PDR and Thailand. It consists of a parabolic roof structure made of polycarbonate sheets on a concrete floor. The dimension of the dryer is 7.5 m wide, 20.0 m long and 3.5 m high. All sides of the dryer are covered with polycarbonate sheets with the thickness of 6 mm in order to create the greenhouse effect inside the dryer. The maximum loading capacity of these dryer for fresh fruit such as banana, is approximately 1000 kg. Nine DC fans operated by three 50-W solar cell modules were installed in the wall opposite to the two air inlets to suck out moist air from the inside of the dryer to the surrounding environment. A pictorial view of the dryer is shown in Figure 2-6.

Chilli, coffee and banana were dried to demonstrate the potentials of the solar greenhouse dryer for drying these products. A total of seven experimental runs were conducted during the period of September-December, 2007, five runs for coffee, one run for banana and one run for chilli. Quantity of coffee dried in each drying test was of 200 kg, whereas it was 300 kg for chilli and 1000 kg for banana. Assumptions in developing the mathematical model for the solar greenhouse dryer are: a) air flow is unidirectional and there is no stratification of the air inside the dryer, b) drying calculation is based on a thin layer drying model since the products are dried in thin layers and c) specific heat of the air, the cover and the products are constant. For the solution procedure, the system of equations were solved numerically using the finite difference method. On the basis of the drying air temperature and relative humidity inside the dryer, the drying parameters A and B and the equilibrium moisture content of the products were computed.

The moisture content of chilli in the solar dryer was reduced from an initial value of 75% (wb) to a final value of 15% (wb) within 3 days whereas the moisture content of the natural sun-dried samples was reduced to 42% (wb) in the same period. The moisture content of coffee in the solar dryer was reduced from an initial value of 52% (wb) to a final value of 13% (wb) within 2 days. The dried banana obtained from the dryer has a honey-brown colour and this colour corresponds to a colour of high quality dry banana. Also, the colour of the dried chilli was comparable to that of a good quality dried chilli. Thus, drying in the solar greenhouse dryer reduces drying time and produces a high quality dried product.

Figure 2-6. A pictorial view of a large scale greenhouse solar dryer (S. Janjai et al., 2011).

To evaluate the simulated performance of the dryer, the simulated moisture contents of the products during drying were compared with the experimental data. The coffee dried faster followed by chilli and banana because of the difference in shape, size and moisture content of the product. Predicted moisture contents and measured values are in reasonable agreement with the measured values. The root mean squared differences (RMSD) between the predicted and the measured values for banana, chilli and coffee are 11.4, 12.9 and 14.6%, respectively. The errors in the predictions of the moisture contents of chilli and coffee might be due to the differences in varieties. However, these values are within the acceptable limits. The capital cost for construction and installation of the solar greenhouse dryer is 14,980 USD and capacity of dryer is 1000 kg. The estimated payback period of the greenhouse solar dryer is about 2.5 years.

2.3.5 Greenhouse solar dryer with LPG burner in Thailand.

The objective of the work of Janjai et al. (2012) was to evaluate the performance of a greenhouse solar dryer for drying longan fruits. The characteristic of the greenhouse solar dryer are same like Janjai et al. (2011). To ensure a continuous drying during night time, cloudy or raining periods, and a 48-kW LPG burner was incorporated into the dryer to supply supplementary heat to the dryer. The dryer was installed at the experimental site of the Physics Department, Silpakorn University, Nakhon Pathom in Thailand. A total of three drying experiments were conducted in September, 2011. For each experiments, 1000 kg of longan fruits was used. The consumption of LPG was very low as compared to the LPG consumption of the static-bed dryer for drying longan fruits (Janjai et al., 2006).

In conclusion, the performance of a greenhouse solar dryer has been evaluated. It was found that the drying air temperature varied in an acceptable range and good quality dried longan fruits were obtained. Additionally, due to the utilization of solar energy, this dryer allow users to save significantly LPG consumption for drying longan.

2.3.6 Solar tunnel dryer in India.

Ayyappan and Mayilsamy (2012) describe development of a natural convection solar tunnel dryer integrated with heat storage material (sand) for copra drying. The experiments were carried out under the meteorological conditions of Pollachi in India during 20-23/03/2009. A community model solar greenhouse dryer of size 4 m wide x 10 m large x 3 m high at center was designed and constructed at Negaman village. The semicircular portion of the dryer was covered with UV (200 micron) stabilized polyethylene film. No post is used inside the greenhouse, allowing a better use of inside space. Three exhaust vents with adjustable butterfly valves operated manually have been provided at the top of the roof for removing the humid air from the dryer. Inside the dryer the cement flooring was coated with black paint to improve its performance. The dryer is shown in Figure 2-7.

About 5000 coconuts with 52.3% average initial moisture content was taken for study and loaded in the trays of solar tunnel dryer. During the experiments, the sky was clear and the maximum solar radiation observed was 685 W/m^2. The maximum temperature attained inside the solar tunnel dryer was 61 °C with heat storage material and 52 °C without heat storage material compared to a maximum ambient temperature of 32 °C.

Figure 2-7. Solar tunnel dryer in India (Ayyappan and Mayilsamy 2012).

The average moisture content of the coconut was reduced from about 52.3% (w.b) to about 7% (w.b.) in 52 and 78 hours in the solar tunnel dryer integrated with and without heat storage material respectively. The maximum efficiency of the dryer was found to be around 24% and the minimum was 12% with an average efficiency of 18%. The efficiency of the solar tunnel dryer using sand as the heat storage material was found to be 1-2% more than the efficiency without using heat storage material. The copra obtained from the solar tunnel dryer is of high quality, fetching more market price for the farmers.

2.4 American greenhouse-type dryers

2.4.1 Solar dryer Dome type in Guatemala (Cruz Palacios, n.d.-b.)

A greenhouse solar dryer dome type was designed to dry coffee in Guatemala (Figure 2-8). This consisted basically of a structure of wooden and PVC tube, the floor is bare soil and a greenhouse polyethylene (nylon) cover with UV protection is used. It measures 3.40 meters wide by 10 meters long by 2.25 meters high, the cold air intake is 15 cm. at the bottom, the ventilation windows are 0.30 m by 0.80 m and have a curtain of the same nylon to coat at night. Inside, there are 20 screens stretchers of 1.20 meters long by 0.91 meters wide, constructed of wood and stainless steel mesh, each of which has a capacity of 22.7 kilos of wet coffee for a total of 454 kg, the height of the mass of coffee should not exceed 0.04 m. The stretchers are mobile same the pallets and rules, this in order to use the facility for other purposes when no coffee are drying. On the sides, a trench coated with cement for drainage of rainwater was constructed.

2.4.1.1 General management and maintenance of the dryer (Cruz Palacios, n.d.-b)

- It must not be interrupted airflow placing sheets or other materials for protection around.
- If the place is too cold or windy, you can reduce the air inlet at the bottom, 10 cm to avoid some input but never close completely because the dryer stops running from lack of circulation of air.
- The mass of coffee have to be moved every 45 or 60 minutes for the drying be even, it should be done as quickly as possible to avoid dehydration because of high temperature that can be achieved.
- The curtains on the windows must be closed at night to prevent moisture penetration and should be open during the day or when there is a lot of heat inside the dryer to allow losing moisture of the coffee going out because of the dry air circulation.
- The door must always be closed to prevent the ingress of dust, dirt and animals.

Some conclusion that are obtained from this experience are:

- The coffee obtained from solar dryer has very good physical appearance and free of dust, dirt and other contaminants.

- The coffee placed within the solar dryer is protected from the weather, especially from the rain that may affect the physical and chemical quality of a high quality coffee.
- The service life of the entire infrastructure of solar dryer is about eight years, except for polyethylene cover, which is between two and three years of life and have to be replaced every time it is damaged.
- Dry wood for construction is preferably to be used than resin wood as coffee could absorb any odor or taste similar.

Figure 2-8. Greenhouse solar dryer Dome type (Cruz Palacios, n.d.-a)**.**

2.4.2 Performance of forced convection in a greenhouse solar dryer in Argentina.

Condori and Saravia (1998) perform an analytical study of their energy performance of the greenhouse dryers. Their analytical study gives an understanding of the influence of the operational and design parameters, such as ambient temperature, ambient humidity, solar radiation, air flow, product moisture content and product initial weight. This study is restricted to forced air flow dryers. Two greenhouse dryer types are studied, the single chamber and the double chamber systems.

The single chamber is a whole greenhouse structure while a fan circulates outside air through the chamber removing the water vapor. The double chamber greenhouse dryer incorporates a simple change in the inner disposition of the dryer. A scheme including successive working stages is shown in Figure 2-9. The greenhouse is divided in two chambers, A and B, and the fan is placed between both of them, in a transparent separation wall. In the initial stage, Figure 2-9a, the product is loaded in chamber A and the air flows from B to A. Chamber B works as a solar collector preheating the ambient air. When the drying process reaches half the cycle the second stage begins. Fresh product is loaded in chamber B and the air flow is reversed from A to B, Figure 2-9b. The product in A is n an advanced drying stage and a small amount of water is incorporated in the air. Chamber A practically works as a preheating collector for chamber B where a higher evaporation rate is being produced. At the end of the second stage the product in A is dried, then it is unloaded and replaced by new fresh product, the air flow is reversed again and the third stage begins as shown in Figure 2-9c. This proposed operation strategy for the second system increases the use of the available energy.

It is performed an analysis of both dryers and a performance parameter is defined to compare both systems. The definition considers the two potential notion sources of drying: the solar energy and the humidity content of the incoming air. Finally, the performance of both dryers types are compared in a simulated test. The comparison is done using the conditions of an experimental set-up for a red pepper drying in a 50 m^2 dryer.

At the end of the process, the single chamber dryer dried 200 kg of initial load in 110 h, obtaining 18.8 kg of dried product. The double chamber dryer needed 53 h to treat 56 kg of half dried product placed in the chamber A, originated in 180 kg of initial load, and it will be necessary an equal time to finish the drying of the chamber B load, obtaining 33.8 kg of dried product in a cycle, that is, a production improvement of 87% since the used time has been reduced significantly for a larger initial load. Temperatures in chamber B are always below those corresponding to chamber A, because of the evaporative cooling produced by the fresh product. During the day, the gap relative to the ambient temperature increases at the end of process, when the product in chamber B is half dried.

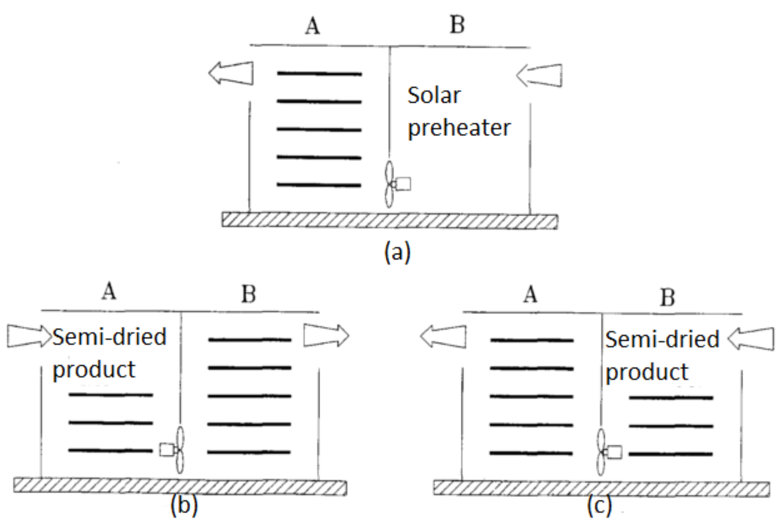

Figure 2-9. Scheme of a forced air flow in a double chamber dryer (Condori and Saravia 1998).

In conclusion: A general and simple model for the air forced dryer, were both the drying kinetic and the dryer design parameters are taken into account, has been developed. Two drying potentials were considered as available energy sources: the air saturation deficit and the incident solar radiation. The simulation results show that a higher production rate can be obtained improving the use of the drying potentials. Particularly, the productivity of the double chamber greenhouse dryer compared to the single chamber type is increased by 87% for the same dryer area. The necessary changes needed to implement the double chamber dryer are simple and inexpensive reducing significantly the drying cost.

2.4.3 Solar drying using a tunnel greenhouse dryer (Argentina).

A new low cost solar greenhouse design is proposed by Condorí, et al. (2001): the tunnel greenhouse dryer. In Figure 2-10 is shown. The tunnel, built with transparent polyethylene plastic and wood, is placed under the greenhouse cover dividing it in two working zones: the drying tunnel and the rest of the greenhouse. The last one works as solar collector heating the ambient air that is introduced in the tunnel. The product is placed in several trays stacked on carts. Their movement is manually performed, using two tracks on the soil along the tunnel as a guide. Two axial fans are placed in the tunnel ceiling, one near to the input door and other at the opposite end.

This new design has several important improvements when it is compared with the other greenhouse dryers.

- The counter current circulation between the air flow and the product in the carts improves the drying efficiency.
- The carts allow a partial mechanization of the product handling, lowering the labor cost.
- A conventional heater using wood or other fuel can be easily installed to keep an almost constant production, improving the results to be obtained from an economical point of view.

The prototype was part of an integral system where the dryer and the cultivation greenhouse was combined. The greenhouse had a total soil area of 350 m^2, 91 m^2 corresponding to the dryer while the rest was dedicated to the cultivation. The structure was 7 m wide and 13 m long with its main axis in the North-East direction, since this is the predominant direction of the local wind. The maximum height of the structure was 3.70 m. The dryer was separated from the cultivation greenhouse by means of a plastic wall. The polyethylene plastic used to cover the structure was 150 µm thick and incorporates UV and far infrared protection. The drying tunnel was built under the greenhouse cover along its central axis, using wood frames buried in the soil, with 1.9 m of separation between them. The tunnel dimensions were 1.2 m wide by 13 m long and 1.9 m high. The tunnel structure was completed with wire ties between the frames supporting the polyethylene plastic.

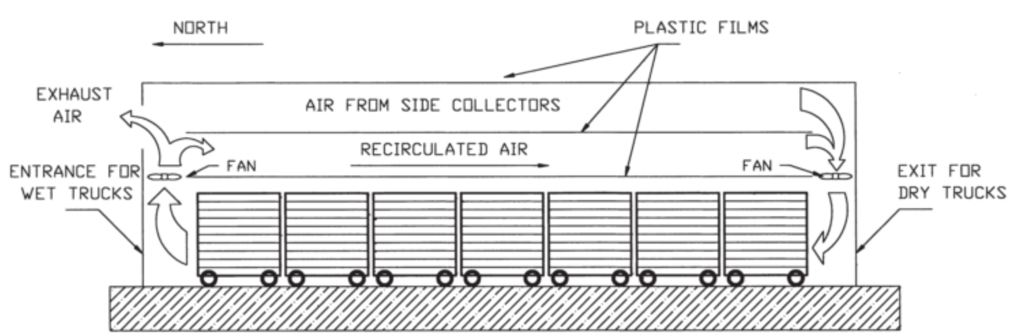

Figure 2-10. Scheme of the tunnel greenhouse dryer (Condorí et al., 2001)**.**

The carts were 1 m wide and 1.5 m long and they were built with rectangular black tubes. The tunnel has a total capacity of seven carts and 10 trays, 15 cm high, may be stacked on each cart. The trays were built with a 4.2 mm diameter iron mesh and a plastic mesh with smaller weave was placed over the metal to avoid the direct contact of the product with the oxidized iron.

In conclusion the proposed tunnel greenhouse dryer has been tested under real working condition, obtaining a good thermal performance during sunny days. An auxiliary heating system is needed to improve the production during the whole drying season and to avoid product losses. The prototype dryer was tested using sweet pepper and garlic as load products, obtaining a good drying rate, final moisture content and dried product aspect. The forced air flow allows a better hot air distribution through the trays, improving the importance of the convective transfer compared to the radiative process and improving the drying uniformity.

Another important improvement was the carts system, with its continuous product charge and discharge facility improving its handling and reducing the worker labor. The tunnel greenhouse dryer showed an acceptable load capacity, i.e. fresh product mass by unit area, around 50 kg/m^2, if only the tunnel area where the product is placed is computed.

A change in the initial design, incorporating an auxiliary energy source, is necessary to work during high humidity days. Also, a complementary energy source will allow an increase of the working time interval, improving the drying rate and the drying production. The non-renewable energy consumption is increased, but still the conventional energy saving would be considerable.

2.5 Conclusions

This review chapter is focused on the available solar dryer greenhouse-type. The general review presented various design and operational principles of some variety of practically realized design of solar dryer greenhouse-type. The greenhouse dryer presented can be suitably employed at small-scale factories or at rural farming villages. The main advantages of these systems are for example: no need for grid-connected-electricity, can be installed close to the field production, employment can be created on rural area, large quantity of crop production can be handle, inside temperature can be control by the fans and high quality of products are obtained.

A large-scale greenhouse solar dryer with LPG burner has been well tested and its performance has been long investigated. Simulation models proposed by the researcher provide the design data and also optimization of this type of solar dryer.

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Chapter 3

Thin layer drying of Pineapple (*Ananas comosus, L.*)

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Pineapple drying kinetics and mathematical model describing best fit were studied. A High precision dryer laboratory, developed at Hohenheim University, was used to dry 1 cm width slices of Pineapple at temperature of 50, 60 and 70 °C with air velocity of 0.5, 1.0 and 1.5 ms^{-1} and specific humidity of 25 $g_{water}kg_{air}^{-1}$. Conditions of temperature, air velocity and specific humidity were controlled. From a total of six studied thin layer models, the one proposed by Hasibuan and Daud got the best fitting. Predicted and experimental data observed very good agreement. Simulation and optimization for efficient drying operation can use the Hasibuan and Daud model to assess the drying behaviour of pineapple. Pineapple colour after drying present a yellow colour lightly going dark and it remains unchanged at 50, 60 or 70 °C. Therefore, the quality of dried Pineapple was acceptable. Constant rate period of drying was not observed.

Keywords: Pineapple; Mathematical Model; Drying models; High precision laboratory dryer.

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3.1 Introduction

Pineapple (*Ananas*, *comosus*, L.) fruit is appreciated by its exotic tropical flavor and nutritional value also, it is used as a fruit as well as for producing juice. It has served also like symbol throughout the human history. Pineapple is originally from the Western Hemisphere and it is second only to bananas as America's favorite tropical fruit.

Fruit drying process is fruit from which thermally volatile components are removed, like solvents and specially water in a natural way, using sun drying, or through the use of specialized dryers or dehydrators. Although drying characteristics of *Ananas comosus*, L. have already been investigated by some researchers (Agarry et al., 2013; Herman et al., 1999; Hossain et al., 2001; Kingsly et al., 2009; Nicoleti et al., 2001; Olanipekun et al., 2014; Ramallo and Mascheroni, 2012; Simal et al., 2007; Talla et al., 2005) mainly by using air drying techniques, high precision drying laboratory has not been used so far to study thin layer of pineapple. A recent study on thin layer for pineapple (Agarry et al., 2013) was focused on the effects of a physical blanching pre-treatment on the product. Drying kinetics study refers to fitting of measured drying properties into empirical equations to predict the drying parameters and behaviours of material at other conditions. The data obtained from drying kinetics experiments typically contain inaccuracies, spurious points and noise. Thus, it is important to remove these and obtain a smoothed curve that can be used for design purposes (Kemp et al., 2001). Experiments carried out in the high precision laboratory dryer at Hohenheim University at Stuttgart, Germany. Ensuring reliable data because of the high technology used to measure and to control of process parameters. Thin layer drying experiments of pineapple are first time carried out with a laboratory dryer. Also, to our best knowledge, no researcher neither has studied nor used pineapple variety MD2. The objectives of this study are: (a) to study the effect of temperature (50, 60 and 70 °C) and air velocity (0.5, 1.0 and 1.5 m s^{-1}) on

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drying characteristics of Pineapple and (b) to find a suitable thin-layer drying model to provide design data and also for simulation and optimal design of dryers for drying Pineapple.

3.2 Materials and methods

3.2.1 Materials

Mature pineapple (*Ananas comosus,* L.) fresh fruit of the MD2 variety (large size, 1.5 – 2.2 kg, oval shape and mostly yellow with light green colour), were obtained at the local market (Stuttgart, BW, Germany) and stored at 8 °C. The fruits were hand peeled, transversely cut with 10 mm thickness using an electrical slicer (Bosch, Germany) and cored. Initial moisture content was about 456-683 % (db) (Reeb & Milota, 1999). The trays with pineapple slices (see Figure 3-1) was placed inside the drying chamber of a high precision laboratory dryer with over flow direction.

Figure 3-1. Pineapple on trays for thin layer drying experiment.

3.2.2 Experimental dryer

The laboratory dryer used is described by schematic diagram shown in Figure 3-2 Pineapple drying experiments were carried out using the high precision laboratory dryer designed at the Institute of Agricultural Engineering, University of Hohenheim (Stuttgart, Germany). In this system a wide range of operating parameters can be controlled. Four units are the main structure: (1) an air flow control unit, (2) an air conditioning unit with a thermostat-controlled water bath and sprayed Raschig-ring bed, (3) a heating control unit with primary and secondary heating elements, and (4) two drying compartments to provide either through-flow or over-flow of the drying products (Argyropoulos et al., 2011).

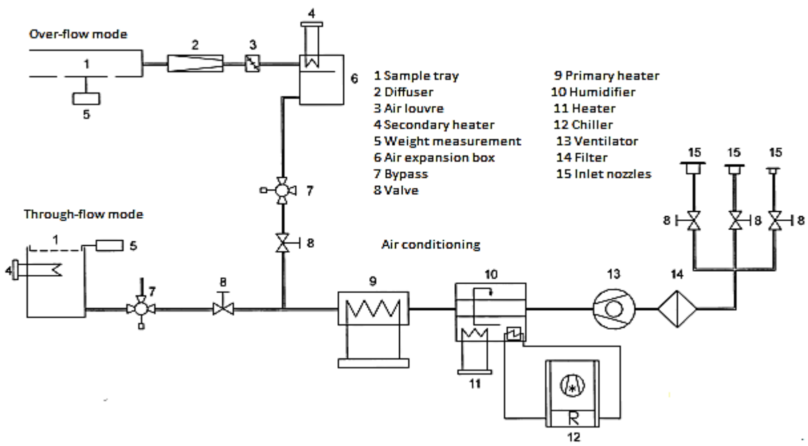

Figure 3-2. Schematic diagram of the laboratory dryer.

Each unit is electronically controlled by a PID control. A detailed description of the working process with schematic figures can be found elsewhere (Janjai et al, 2011).

3.2.3 Drying conditions

Before starting a drying experiment, the laboratory dryer was allowed to run for at least two hours in order to obtain steady-state parameters. Thin layer drying of pineapple was set up at a temperature of 50, 60 and 70°C; air velocity of 0.5, 1.0 and 1.5 ms^{-1} and specific humidity of 25 $g_{water}kg_{air}^{-1}$. Each 30 minutes the weight of pineapple samples was measured automatically. A total of nine experiments with three replicates each were carried out.

3.2.4 Moisture content

It was determined the moisture content (M_{mass}, %) by mass which is defined as:

$$M_{mass} = \frac{m_{wet} - m_d}{m_d} * 100 = \frac{m_{water}}{m_d} . 100 \quad (1)$$

where m_w(kg) is the mass of water and $m_{material}$(kg) the mass of the dry material.

The moisture in the material originates, in general, from three sources: external water, internal liquid water and water vapor present in the surrounding air. Gravimetric determination is a direct method and the best and most absolute method for determining the average moisture content, i.e. to measure sample weight before and after drying (Erich and Pel, 2011).

3.3 Moisture content representation can be defined like:

- Wet basis moisture content (M_{wb}). Ratio of the mass of water (m_w) to the mass of dry matter plus mass of water (m_w + m_{dm}).

$$\boldsymbol{M_{wb} = \frac{m_w}{m_w + m_d}} \qquad (2)$$

- Dry basis moisture content (M_{db}). Ratio of the mass of water (m_w) to the mass of dry matter (m_{dm}).

$$\boldsymbol{M_m = \frac{m_w}{m_{dm}}} \qquad (3)$$

If we multiply by 100, then we have our results in percent. This method is called oven-dry test, (Reeb & Milota, 1999), drying it to a constant weight, reweighing, and doing the calculation. Samples need to be representative of the lot of product from which they are taken. The sample should either be weighed immediately after cutting or each sample should be stored in a separate plastic bag. Once the weight is taken and the sample begins to dry, there is no going back so it is important to keep a good record. The time to dry is typically about 24 hours. The correct method is to dry a constant weight. Do not add wet samples to the oven when other samples are almost dry. Water will evaporate from the wet samples and be picked up by the drier ones causing an error when they are weighed due to a temporary increase in moisture content. After calculating a value, make sure it sense compared to what you measured.

3.3.1 Basic quality specifications for pineapple (MD2).

3.3.1.1 Determination of total soluble solids or sugar (TSS) by refractometry.

During the development of pineapple flesh, nutrients are stored as starch, which during the ripening process is transformed into sugars (OECD). Refractometer ATAGO model PR-201, Pallet Type was used for determination of TSS. Checking and recalibration to zero was done for each test. Juice sample was extracted uniformly.

3.3.1.2 Determination of pineapple acids by Titration.

Sugar/acid ratio contributes to the characteristic flavour of pineapple so it is an indicator of commercial and organoleptic ripeness. During the ripening process the fruit acids are degraded, the sugar content increases and the sugar/acid ratio achieves a higher value (OECD). The method used for the determination of the titratable acidity of pineapple (%) was the Potentiometric, using a pH meter.

3.3.2 Colour measurement

The colour of fresh and dried samples was evaluated using a Konica Minolta Colorimeter (CR-300; Minolta Co., Ltd., Osaka, Japan). Calibration of the device was done with a standard white tile at D_{65} illumination before measuring samples ($Y = 85.8,\ X = 0.314,\ y = 0.331$). Three readings were performed per pineapple slice surface by placing the colorimeter head directly above the slice. For both fresh and dried pineapple samples the mean value of twenty seven measurements was considered in each experiment.

The CIE L^*, a^*, b^* colour space is commonly used in the food industry (Pathare et al., 2013). Colour parameters are described by L^* describing lightness ($L^* = 0$ for black, $L^* = 100$ for white), a^* describing intensity in green-red ($a^* < 0$ for green, $a^* > 0$ for red), b^* describing intensity in blue-yellow ($b^* < 0$ for blue, $b^* > 0$ for yellow). Colour differences are defined as $\Delta L^* = L_d^* - L_f^*$ for lightness, $\Delta a^* = a_d^* - a_f^*$ for redness and $\Delta b^* = b_d^* - b_f^*$ for yellowness, where subscript "f" refers to fresh samples and "d" to the values of dried materials. Total colour difference is expressed as $\Delta E^* = ((\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2)^{1/2}$ and a larger ΔE^* denotes greater colour change from the fresh material. Chroma (C^*) is defined as:

$$C^* = (a^{*2} + b^{*2})^{1/2} \tag{4}$$

and indicates colour saturation, which is proportional to its intensity. The hue angle (h) is defined as

$$h = \begin{cases} tan^{-1}\left(b^*/a^*\right) & (when\ a^* > 0) \\ 180 + tan^{-1}\left(b^*/a^*\right) & (when\ a^* < 0) \end{cases} \tag{5}$$

For the h value, an angle of 0° or 360° indicates a red hue, while angles of 270°, 180° and 90° indicate blue, green and yellow hue, respectively (Argyropoulos et al., 2011), (Pathare et al., 2013). Because of Chroma (C^*), considered the quantitative attribute of colourfulness, it is used to determine the degree of difference of a hue in comparison to a grey colour with the same lightness. The higher the Chroma values, the higher is the colour intensity of samples perceived by humans (Pathare et al., 2013).

3.3.3 Moisture ratio calculations

Data obtained at different drying temperatures were transformed to the moisture content ratio (MR, dimensionless) and is expressed as:

$$MR = \frac{M - M_e}{M_0 - M_e} \tag{6}$$

where: M,db decimal, $M_0, db\ decimal$ and $M_e, db\ decimal$ are the moisture content at any given time of a product measured or calculated during drying, the initial moisture content and equilibrium moisture content, respectively. The value of M_e is moisture content of a product in equilibrium with mean dry bulb temperature and relative humidity of the drying air, expresses as dry basis. In this work, the final moisture content which has achieved equilibrium (it has become constant for considerable period of time under constant conditions of temperature and relative humidity), was assumed as the equilibrium moisture content of the products.

3.3.4 Drying models

Drying is a process putting together heat and mass transfer with, between and surrounding the surface of the material. Many models have been used to describe the drying process for different agricultural products. The described models are used to estimate drying time of pineapple under different drying conditions, and how to have an efficiency in the drying process and also the design and operation of dryers. Several investigators have proposed numerous mathematical models for thin layer drying of many agricultural products.

The term "thin layer" is been applied to (Ertekin & Firat, 2015):

- A single kernel freely suspended in the drying air or one layer of grain kernels,
- A polylayer of many grain thicknesses if the temperature and the relative humidity of the drying air can be considered for the purpose of the drying process calculations, as being in the same thermodynamic state at any time of drying.

Empirical drying models often give the best results in predicting drying behaviour. The equations can be employed with confidence within the temperature, relative humidity, air flow velocity and moisture content range for which they were derived. These models can be used in automatic controls of drying processes for economy and short calculation time (Koua, Fassinou, Gbaha, & Toure, 2009). The empirical models constitute a direct relationship between the average moisture content and drying time. They neglect the fundamentals of the drying process and therefore their parameters have no physical meaning.

Drying curve generated by data obtained in the High Precision Dryer at Hohenheim, were fitted to six empirical and semi theoretical thin-layer drying expressions (Table 3-1) suggested by (Ertekin & Firat, 2015). These models were chosen since they have shown better fit for this kind of drying experiments (Janjai et al., 2011; Koua et al., 2009; Togrul and Pehlivan, 2002).

Table 3-1. Thin-layer drying models

Equation	Name
1. $MR = a\exp(-kt) + (1-a)\exp(-kbt)$	Diffusion Approximation (Erbay & Icier, 2009)
2. $MR = aexp\left[\frac{-(t-b)^2}{2c^2}\right]$	Haghi and Angiz – IV (Haghi & Angiz, 2007)
3. $MR = 1 - at^n\exp(-kt^m)$	Hasibuan and Daud (Hasibuan & Daud, 2004)
4. $MR = a_0/[1 + aexp(kt)]$	Logistic (Soysal, Oztekin, & Eren, 2006)
5. $MR = \exp(-kt^n) + bt$	Modified Midilli – I (A. Midilli, Kucuk, & Yapar, 2002)
6. $MR = \exp(-kt^n) + bt + c$	Sripinyowanich and Noomhorm (Sripinyowanich & Noomhorm, 2011)

The way to choose the equations was evaluating a total of six models and discarding the ones with high Root Mean Square Error (RMSE). Estimation of the constants and RMSE with nonlinear regression was performed using the Optimization Toolbox for use with MatLab® (Version R2013b). Although it was found in literature that Logarithmic model produced good fitting in predicting drying pineapple (Kingsly et al., 2009), results with data from the high precision laboratory showed that the fitting is not good enough and was decided not to be included.

3.3.5 Statistical evaluation

The selection of models that describe the drying pineapple process are presented in Table 3-1. Six different thin layer drying models were selected to fit the thin layer experimental data of Pineapple. Root Mean-Square Error (RMSE) was one of the main criteria for selecting the best equation. RMSE should be lower and it is defined as:

$$RMSE = \left[\frac{\sum_{i=1}^{N}\{M_{pre,i} - M_{obs,i}\}^2}{N}\right]^{0.5} \quad (7)$$

where $M_{pre,i}$ and $M_{obs,i}$ are the predicted and observed dimensionless moisture ratios, respectively and N is the number of measurements.

RMSE is a kind of generalized standard deviation. A measure of the difference between locations that are known and locations that have been interpolated or digitized.

Another criteria for selection was mean absolute error (MAE), which is a statistical measure of how far estimates or forecasts are from actual values. MAE avoids compensation between under- and over-prediction. The MAE is given by:

$$MAE = \frac{1}{N}\sum_{i=1}^{N}|f_i - y_i| = \frac{1}{N}\sum_{i=1}^{N}|e_i| \quad (8)$$

Where f_i is the prediction and y_i the true value; $|e_i|$ is an average of the absolute errors, units of MAE are the same as y_i, furthermore, there is no over-weighting of large differences here.

Modeling efficiency (EF) consider distances measures which have an upper and/or lower bound to compare completely different cases (different data, different models) and it is defined as

$$EF = 1 - \frac{\sum_{i=1}^{N}(y_i - f_i)^2}{\sum_{i=1}^{N}(y_i - \bar{Y})^2} \quad (9)$$

Where $\bar{Y}$ is the average of the y_i.

3.4 Results and discussion

3.4.1 Drying behaviour of pineapple.

Figure 3-3 shows changes in moisture contents with different drying air temperature and constant air velocity. Final moisture content under different conditions ranges from 8.54% to 15.53% (db.). By comparing Figure 3-3a, 3-3b and 3-3c is apparent that the time to reach the final moisture content is smaller due to a higher drying rate for higher air temperature.

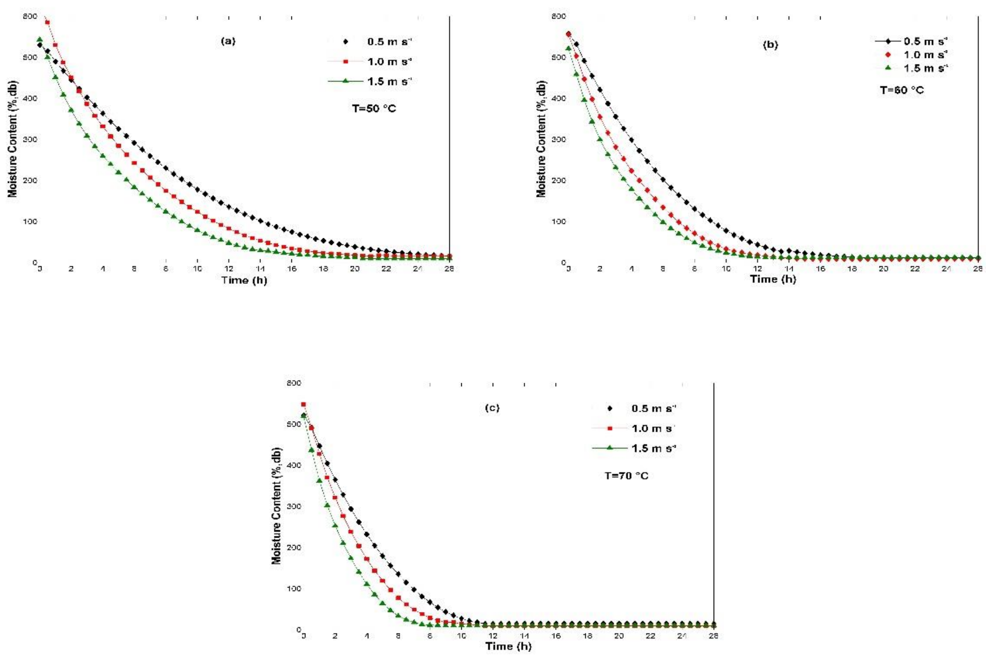

Figure 3-3. Thin layer drying of pineapple at different temperatures (50, 60 and 70°C)

Also for all the temperatures, the initial drying rates are larger for higher air velocities. This effect is better showed on Figure 3-4a, 3-4b and 3-4c, which show the variation of moisture content time affected by air velocity in the range of 0.5 ms^{-1} to 1.5 ms^{-1}. By comparing Figure 3-4a, 3-4b and 3-4c is observed that higher air velocities increase the drying rate of pineapple.

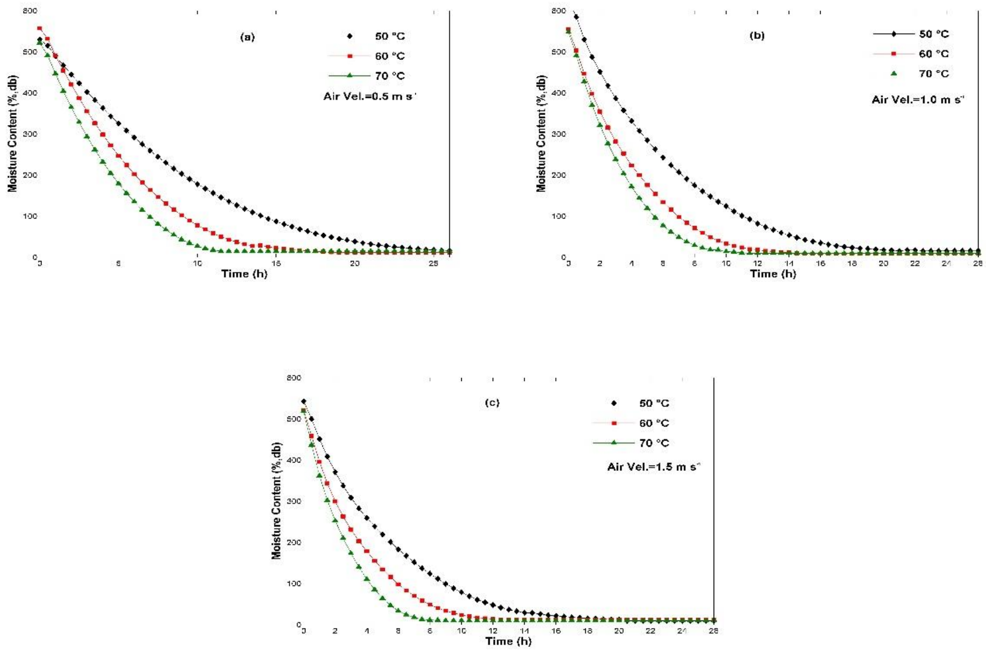

Figure 3-4. Thin layer drying of pineapple at different air velocity (0.5, 1.0 and 1.5 ms^{-1})

3.4.2 Modelling of thin-layer drying

Moisture ratios of Pineapples dried at different temperature and air velocity were fitted with six thin layer models. Parameter values, RMSE, MAE and EF are shown in Table 3-2. Hasibuan and Daud model was the best followed by Haghi and Angiz IV and Sripinyowanich and Noomhorm. For these three cases the value of RMSE was less than 5.5 %, indicating a good fit. The average value of RMSE for the Hasibuan and Daud model was 1.9576%, the MAE was 1.47959 and EF= 0.99677. Empirical expressions were developed for the drying parameters of Hasibuan and Daud model.

3.4.3 Comparison of drying models and experimental data.

Figure 3-5 shows predicted and experimental data of thin layer drying of pineapple for Hasibuan and Daud. Prediction and measured values showed good agreement. Successful models express moisture ratio of pineapple as functions of empirical parameters and time. Pineapple has homogenous texture, then, can be applicable to most pineapple in market. Plots of the residuals of moisture content against measured moisture content show an acceptable random behaviour. Figure 3-6 shows the residual between observed moisture content (M_{obs}) and predicted moisture content (M_{pre}) of pineapple. Figure 3-7 shows the comparisons of the predicted and experimental data for three different temperatures 50, 60 and 70 °C for Hasibuan and Daud model, all values are around and close to the 1:1 line. The meaning is that this model is capable to predict drying behaviour of pineapple. In fact, anyone of the three best models may be considered to describe the thin-layer drying behaviour of pineapple. Models obtained here are fairly generic because the moisture ratio of pineapple is expressed as functions of empirical parameters and time. At the same time, parameters are written as functions of drying conditions (temperature (T) and air velocity (Av)) as seen in Table 3-3. Another point to consider, pineapple is composed only of flesh, therefore, can be expected that these models could be applicable to most pineapple available in markets.

3.5 Physicochemical properties of dried products

3.5.1 Basic quality specifications for pineapple (MD2).

Table 3-4 shows the basic quality specification for fresh and dry samples of pineapples. TSS dry values indicate around 35 % of sugar concentration increment from fresh to dried pineapple, giving to the dried pineapple a sweeter taste. Titratable acidity (TA) and juice pH are measured to give an overview of pineapple maturity at harvest. A minimum soluble solids content of 12 % and a maximum acidity of 1 % will assure minimum flavor acceptability by most consumers (Kader 1996).

Table 3-2. Parameter values, root mean square error (RMSE), mean absolute error (MAE) and modeling efficiency (EF).

Models	T(°C)	Air Vel. (m/s)	a0 (h-1)	a (-)	b (-)	c (-)	d (-)	g (h-1)	k (-)	k0 (h-1)	k1 (h-1)	m (-)	n (-)	RMSE (%)	MAE	EF
Diffusion Aproximation	50	0.5		-15.82	0.9632				0.1906					2.544	2.1708	0.9892
	60	0.5		-14.09	0.9558				0.3112					3.8314	4.1105	0.9738
	70	0.5		-23.3	0.9697				0.4098					6.3484	3.4733	0.9772
	50	1		-20.19	0.9855				0.2178					4.7382	3.1087	0.9864
	60	1		13.04	0.9666				0.1574					5.068	4.0841	0.9793
	70	1		-24.67	0.9769				0.4973					4.3499	3.2667	0.9887
	50	1.5		8.944	0.9686				0.145					4.1152	5.1725	0.9760
	60	1.5		-11.2	0.9752				0.3704					4.0535	3.3115	0.9905
	70	1.5		15.17	0.9684				0.2419					5.2309	3.8381	0.9887
Haghi and Angiz-IV	50	0.5		2.522	-20.66	15.27								1.44	0.8692	0.9983
	60	0.5		2.14	-11.13	9.086								3.5118	3.4110	0.9820
	70	0.5		1.525	-5.567	6.095								2.8585	3.3928	0.9782
	50	1		34.5	-47.76	17.92								3.9044	2.6278	0.9903
	60	1		4.525	-15.04	8.642								3.4831	2.9097	0.9895
	70	1		2.515	-7.844	5.781								2.7752	2.7824	0.9918
	50	1.5		106.5	-53.44	17.48								4.0385	2.3402	0.9951
	60	1.5		53.11	-31.05	11.01								3.4322	2.3297	0.9953
	70	1.5		3.454	-7.941	5.027								4.1608	3.3956	0.9912
Hasibuan and Daud	50	0.5		0.08283					0.08695			0.8377	1.164	0.7076	0.4775	0.9995
	60	0.5		0.1371					0.1621			0.7926	1.233	2.1696	1.4865	0.9966
	70	0.5		0.162					0.1137			0.9309	1.187	1.5932	2.2900	0.9901
	50	1		0.1707					0.1071			0.7865	0.9584	2.1264	1.7061	0.9959
	60	1		0.223					0.1329			0.8333	1.016	2.2778	1.8041	0.9960
	70	1		0.2625					0.1796			0.8417	1.113	1.7763	1.5535	0.9974
	50	1.5		0.205					0.1644			0.7172	0.9915	2.8204	1.1915	0.9987
	60	1.5		0.3128					0.2613			0.6772	1.024	2.1316	1.3836	0.9983
	70	1.5		0.3186					0.06939			1.141	0.8984	2.0157	1.4235	0.9984
Logistic	50	0.5	1.987	0.9846					0.1621					1.889	1.5518	0.9945
	60	0.5	1.841	0.8362					0.2663					3.1635	4.1404	0.9734
	70	0.5	1.59	0.5928					0.3691					4.7308	3.6869	0.9743
	50	1	4.282	3.335					0.1866					4.7508	2.5255	0.9910
	60	1	2.49	1.514					0.3117					4.7241	3.8773	0.9813
	70	1	1.996	1.005					0.4281					3.7563	3.5178	0.9868
	50	1.5	4.354	5.304					0.2095					4.5084	3.9064	0.9863
	60	1.5	4.9	3.938					0.3134					4.2046	3.0315	0.9920
	70	1.5	2.313	1.34					0.5128					5.6933	4.5860	0.9839
Modified Midilli	50	0.5			-0.0005208				0.07345				1.17	2.3149	1.9660	0.9912
	60	0.5			-0.0001017				0.1155				1.223	3.9769	4.0304	0.9748
	70	0.5			-0.003794				0.1474				1.206	2.6174	3.7980	0.9727
	50	1			-0.0007251				0.1546				1.016	4.539	3.1869	0.9857
	60	1			-0.000974				0.2031				1.09	4.877	4.0104	0.9800
	70	1			-0.0009882				0.2357				1.161	4.3016	2.7997	0.9917
	50	1.5			-0.0005134				0.1801				1.017	4.5278	2.0563	0.9962
	60	1.5			-0.001654				0.2677				1.006	3.3761	3.5733	0.9889
	70	1.5			-0.00258				0.3384				1.084	5.5547	4.4715	0.9847
Sripinyowanich and Noomhorm	50	0.5			-0.0001959	-0.007063			0.07014				1.185	2.1956	1.8102	0.9925
	60	0.5			0.0005825	-0.01099			0.1088				1.244	3.7717	3.9171	0.9762
	70	0.5			-0.003624	-0.001515			0.1462				1.21	2.6736	3.7471	0.9734
	50	1			-0.0002277	-0.009908			0.1472				1.031	4.4259	3.9466	0.9868
	60	1			-8.78E-05	-0.01203			0.1926				1.109	4.7247	3.9466	0.9806
	70	1			-2.84E-05	-0.009597			0.2264				1.178	4.1918	2.8361	0.9915
	50	1.5			-4.92E-06	-0.009298			0.1726				1.03	4.4714	2.0844	0.9961
	60	1.5			-0.001367	-0.003279			0.2642				1.011	3.428	3.4192	0.9898
	70	1.5			-0.001282	-0.01044			0.3257				1.101	5.5373	4.4276	0.9850

Table 3-3. Equation of drying parameters.

Model	Equation of drying parameter
Hasibuan and Daud	a=-1.077+0.03358*T+0.1515*Av-0.0002403*T^2 k= -2.567+0.08445*T+0.3845*Av-0.00065*T^2+0.01243*Av^2-0.00609*T*Av m= 5.185-0.1368*T-1.232*Av+0.001081*T^2+0.1157*Av^2+0.01653*T*Av n= 1.383+0.001408*T-0.6542*Av+0.2154*Av^2

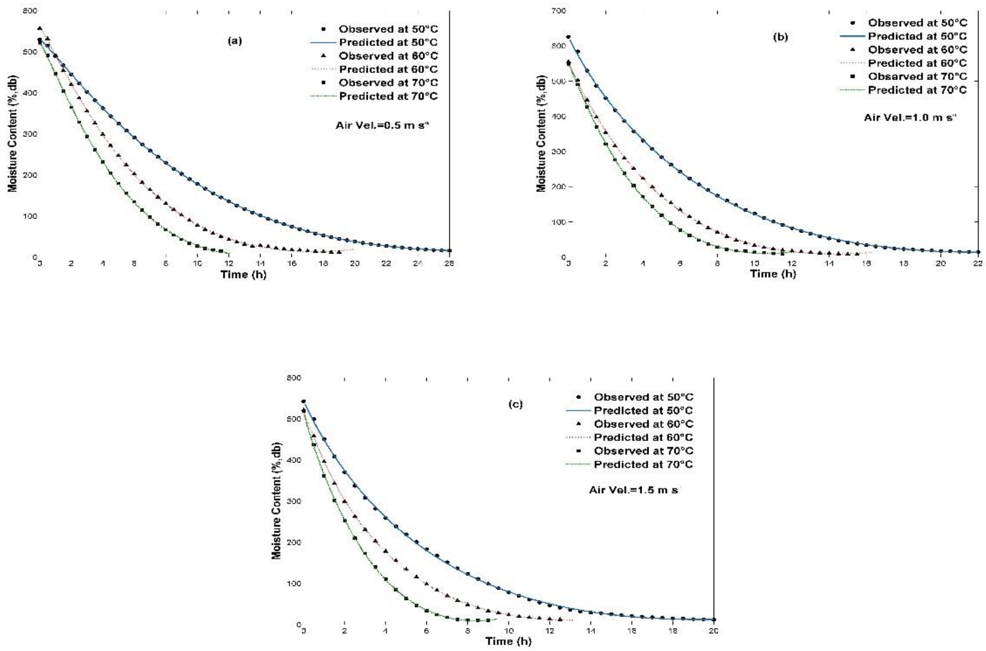

Figure 3-5. Predicted and observed moisture content of pineapple using Hasibuan and Daud model for a) T= 50, 60 and 70 °C and air velocity 0.5 ms^{-1}, b) T= 50, 60 and 70 °C and air velocity 1.0 ms^{-1} and c) T= 50, 60 and 70 °C and air velocity 1.5 ms^{-1}.

3.5.2 Colour change

Pineapple colour was measured before and after drying and three set of experiments were conducted. Drying temperatures and the colour indexes for Pineapple are shown in Figure 3-8. It is observed that the lightness is a little bit higher in dried than in fresh pineapple.

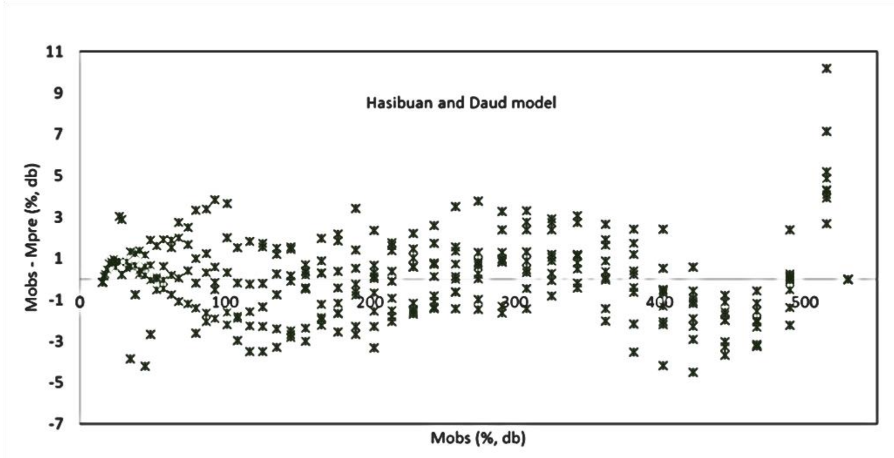

Figure 3-6. Plot of residual between observed moisture content (M_{obs}) and predicted moisture content (M_{pred}) of pineapple from Hasibuan and Daud model for different temperatures and air velocity.

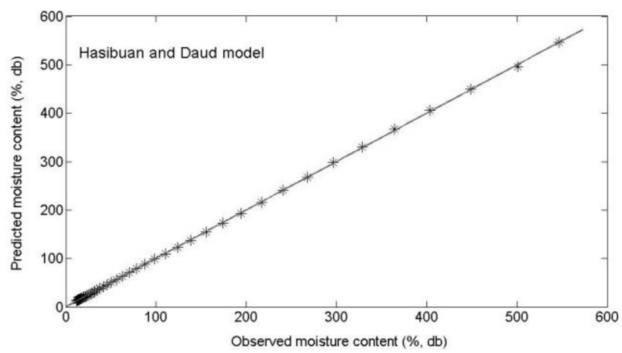

Figure 3-7. Comparison of predicted moisture content from Hasibuan and Daud model and observed moisture content of pineapple at different temperatures and air velocity (0,999).

Table 3-4. Basic quality specifications for fresh and dry samples of pineapple.

TEMP(°C)	AIR VEL(ms-1)	TSSFresh(%Brix)	TSSDry(%Brix)	TA(%)	pH Fresh	MC(%)Fresh	MC(%)Dry	aw Fresh(-)	awDry(-)
50	0.5	13.46	51.78	0.98	3.48	85.40	11.25	0.98	0.56
60	0.5	12.98	43.15	1.17	3.49	85.79	11.00	0.98	0.56
70	0.5	13.42	52.76	0.93	3.44	85.02	11.57	0.97	0.61
50	1	13.15	55.10	1.00	3.51	87.97	12.83	0.98	0.58
60	1	12.79	31.68	0.86	2.35	57.71	9.81	0.97	0.53
70	1	13.07	34.29	1.04	3.49	85.65	8.93	0.98	0.51
50	1.5	13.73	48.80	0.80	3.49	86.89	13.31	0.97	0.55
60	1.5	13.19	62.47	0.95	3.61	85.86	11.17	0.99	0.55
70	1.5	13.43	57.62	1.02	3.50	57.38	8.45	0.98	0.46

Redness and yellowness are not significantly increased, which means that yellow colour in Pineapple is changing lightly. The Chroma (C*) is behaving same than redness and yellowness (no significant change) indicating that no colour saturation is present. Hue angles (h) of the dried pineapple decrease no more than 8 units, meaning that pineapple move slightly towards red and yellow, giving to the dry pineapple a very little brown colour (Not significant). Thus, there is not significant change colour indexes for drying at 50°C, 60°C and 70°C, remaining almost the same. These temperatures are suitable for drying Pineapple.

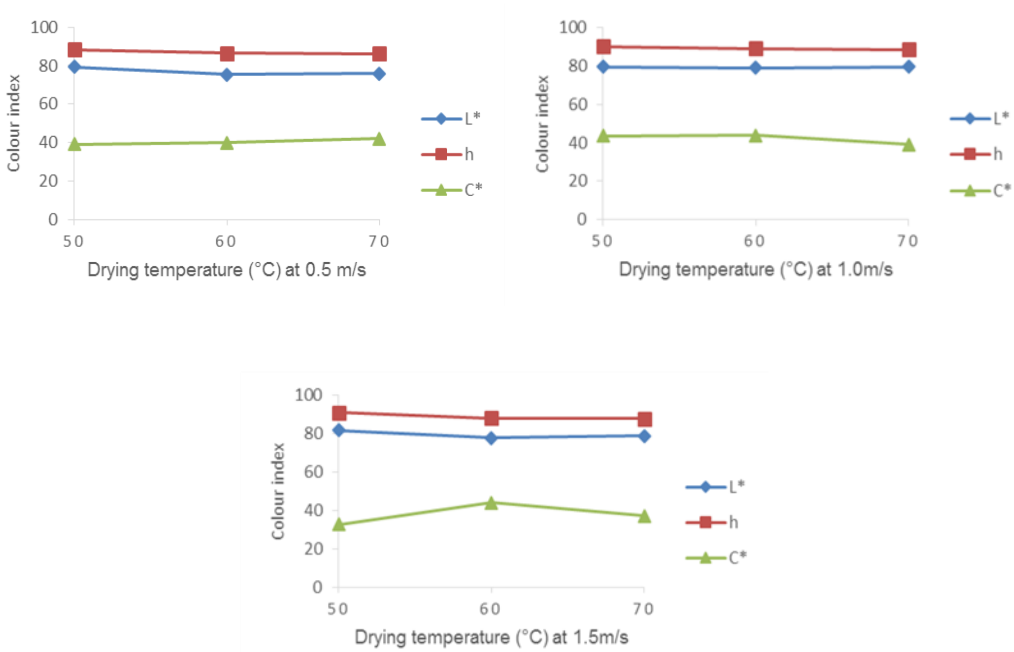

Figure 3-8. Influence of drying temperature on lightness L*, hue angle (h) and Chroma (C*) of Pineapple at different air velocity (0.5, 1.0 and 1.5 ms^{-1}).

3.6 Conclusions

Thin-layer drying of pineapple was investigated experimentally and it was found that when the temperature and air velocity are increased, drying time decreased. From 50 to 70 °C at 0.5 ms^{-1}, drying time decreased from 26 to 12 hours; from 50 to 70 °C at 1.0 ms^{-1}, drying time decreased from 20 to 10 hours and from 50 to 70 °C at 1.5 ms^{-1}, drying time decreased from 16 to 8 hours. Constant rate period of drying was not observed.

Six thin-layer drying models were fitted to measured data. The Hasibuan and Daud model had the best performance followed by Haghi and Angiz-IV and Sripinyowanich and Noomhorm. Empirical expressions were found for the drying parameters being them a function of temperature and air velocities. Predicted and experimental data observed showed good agreement. Simulation and optimisation of the dryer for efficient operation can use the Hasibuan and Daud model to assess the drying behaviour of pineapple.

Pineapple colour after drying present a yellow colour lightly going dark and it remains unchanged at 50, 60 or 70 °C. Quality of colour is acceptable. Sugar concentration content was raised giving to the pineapple a sweeter flavour.

3.7 Acknowledgements

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Chapter 4

MATHEMATICAL MODELLING OF THE THIN LAYER OF PINEAPPLE: EXPERIMENT AT VILLAGE-SCALE GREENHOUSE-TYPE SOLAR DRYER

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The objectives of this research were twofold: firstly to investigate the behaviour of the thin layer drying of pineapple (*Ananas Comosus*, L.) experimentally in a greenhouse-type solar dryer and secondly the description of best fit with drying kinetic and mathematical model taken from literature. A large scale greenhouse designed and installed at Silpakorn University, Nakhon Pathom, Thailand was used to dry 1 cm width slices at temperature between 25-60 °C and relative humidity between 50-90 %. Six statistical models, which are empirical or semi-empirical, were tested to validate the experimental data. A non-linear regression analysis using a statistical computer program was used to evaluate the constants of all the models. Results of comparisons of the predicted moisture content by the Hasibuan and Daud model and observed moisture content of pineapple for two experiment are presented. The Hasibuan and Daud drying model turned out to be the best description of the solar drying curves of pineapple. Condition of temperature, air velocity and specific humidity were those prevailing in village-scale greenhouse-type solar dryer.

Keywords: Ananas Comosus; Thin-layer drying; Drying models; Greenhouse dryer

Sent to: Agrociencia; November 2015

4.1 Introduction

Pineapple (*Ananas Comosus* L.) is the leading edible member of the family Bromeliaceae which embraces about 2,000 species, mostly epiphytic and many strikingly ornamental. Is a terrestrial herb 0.75 to1.5 m high with a spread of 0.9 to 1.2 m; a very short stout stem and a rosette of waxy, strap_like leaves, long-pointed, 50 to 180 cm long; usually needle tipped and generally bearing sharp, up curved spines on the margin. As individual fruits develop from the flowers they join together forming a cone shaped, compound, juicy, fleshy fruit to 30 cm or more in height, with the stem serving as the fibrous but fairly succulent core. Pineapple is usually, by sugar syrup pre-treatment, treated in the way to conserve the fruit. Thailand is located in the tropical regions of the Southeast Asia and receives annual average daily solar radiation of 18.2 MJ m^{-2} day^{-1} (Janjai et al., 2006). Thus, the use of solar energy to produce high quality dried pineapple is viable. Several studies on pineapple drying have been reported (Hossain et al., 2001; Talla et al., 2005; Simal et al., 2007; Kingsly et al., 2009; Ramallo and Mascheroni 2012; S. E. Agarry et al., 2013 and Olanipekun et al., 2014) but none has been reported for solar dryer greenhouse type.

The design of a solar drying system demands to set up particular drying requirements to the specific product in order to reach an optimal performance. Basic parameters like temperature, relative humidity, dimensions and airflow rate should be investigated. Predicting performance of solar dryer, can be done using simulation model. Some have been investigated by John and Sangamithra (2014).

In the current study, the thin layer drying behaviour of pineapple in a village scale greenhouse-type solar dryer is investigated. Furthermore, the mathematical models describing the thin layer drying curves is determined by non-linear regression analysis. A large scale greenhouse developed at Silpakorn University, Nakhon Pathom, Thailand was used to dry 1 cm width slices at temperature between 25-60 °C and relative humidity between 50-90 %. The purpose of this paper is to provide answer to the conservation of the pineapple product, this application and the model can be used for all countries in the world which have tropical climate.

4.2 Materials and methods

4.2.1 Drying experiments

4.2.1.1 Experimental set up

Solar dryer greenhouse village-scale type designed and built at Silpakorn University, Nakhon Pathom, Thailand with a parabolic roof structure made from polycarbonate plate on a concrete floor, was used to carry out the experiments of pineapple drying. This is located at 14°01' 42.5'' N latitude and 99° 58' 12.1''E longitude. The product was placed in a thin layer on three arrays of trays. Trays were placed on single level raised platforms with passage in between for loading and unloading the product inside the greenhouse dryer. A similar village-scale type solar dryer is fully described by Janjai et al., (2009). With three DC fans, operated by a 50-W PV-module, the air is moved out from inside the greenhouse removing humidity. Greenhouse solar dryer structure characteristics and dimension, as well as sensors position to get temperature, relative humidity and samples weights, are showed in Figure 4-1.

4.2.1.2 Experimental procedure

Two experiments of pineapple drying were carried out during the month of November 2014. Conditions were same for both experiments only the days were different. Pineapple was dried in order to get drying data that will be used to fit mathematical models, helping to understand and improve the drying process of pineapple at solar greenhouse dryer.

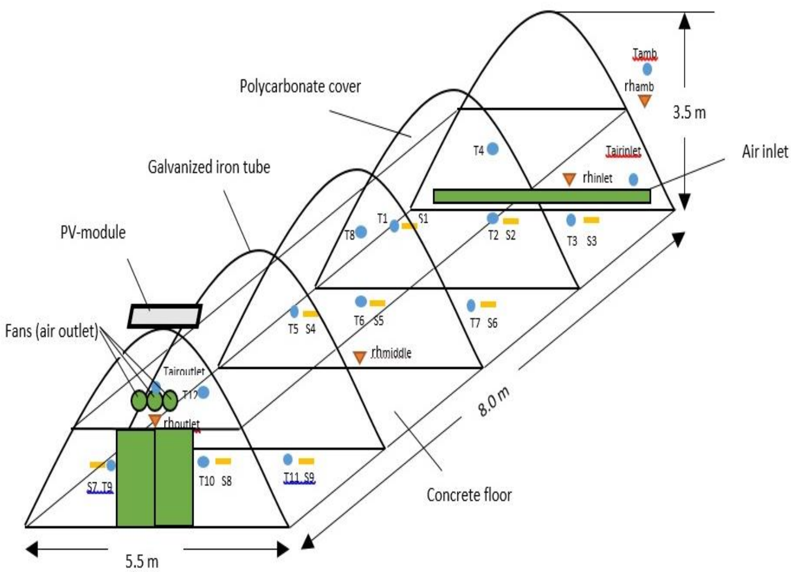

Figure 4-1. Positions of the thermocouples (T), hygrometer (rh) and product samples for weights (S) inside the structure of the dryer.

Thermocouples (K type, accuracy ± 2%) were used to measure air temperature in the dryer at different positions. Thermocouple position for temperature and relative humidity are shown in Figure 4-1. The relative humidity of ambient air and drying air were measured by hygrometers (Electronik, model EE23, accuracy ± 2%). Solar radiation was measured by a pyranometer (Kipp and Zonen CM 11, accuracy ± 0.5%). A multi-channel data logger (Yokogawa, model DC100) was used to record every 10 minutes a signal voltage from the pyranometer, hygrometers and thermocouples. Calibration were done for the pyranometer and hygrometers.

Pineapples used in this study were purchased from a local fruit market of Nakhon Pathom Province (Thailand). For each experiment a sample of 100 kg of pineapple was used, placed in a single level platforms with thin layer on arrays of trays, leaving passage between the platforms for loading and unloading the product inside the greenhouse dryer. For drying operations, good quality fruits were selected. For each fruit, the flesh was separated from the stone and sliced into samples of 10 mm thick using an electrical slicer. The obtained slices were uniformly laid out on trays for greenhouse solar drying operations as seen in Figure 4-2. Experiment lasted from 8:00 am to 6:00 pm. To reach the desire moisture content the drying was on subsequent days. At one-hour intervals, the samples placed at various position were weighed using a digital balance (Kern, model 474-42, accuracy ± 0.1 g). Oven method was used to measure the exact dry solid weight of the products sample (105°C for 24 hours, accuracy ± 0.5 %).

Figure 4-2. Pineapple slices uniformly laid out on trays for greenhouse solar drying operations.

4.2.2 Moisture content

It was determined the moisture content ($M_{mass}, db, \%$) by mass which is defined as:

$$M_{mass} = \frac{m_w}{m_{material}} . 100\% \tag{10}$$

where m_w (kg) is the mass of water and $m_{material}$(kg) the mass of the dry material.

The moisture in the material originates, in general, from three sources: external water, internal liquid water and water vapor present in the surrounding air. Gravimetric determination is a direct method and the best and most absolute method for determining the average moisture content, i.e. to measure the sample weight before and after drying (Erich and Pel 2011).

Weight difference between wet and dry sample is used for determination of the absolute moisture content (M_m) in kg kg^{-1}.

$$M_m = \frac{m_{wet} - m_{dry}}{m_{dry}} \tag{11}$$

where m_{wet}(kg) is the mass of the wet material and m_{dry}(kg) the mass of the dry material.

4.3 Mathematical modelling

4.3.1 Calculation of moisture ratio

Data obtained at different drying temperatures were transformed to the moisture ratio (MR) and is expressed as:

$$\boldsymbol{MR = (M - M_e)/(M_0 - M_e)} \tag{12}$$

where: MR is the dimensionless moisture content ratio; and M, M_0 and M_e are the moisture content at any given time, the initial moisture content and equilibrium moisture content, respectively.

4.3.2 Drying models

Drying curve generated by data obtained in the greenhouse-type solar dryer, were fitted with nine empirical and semi theoretical thin-layer drying expressions (Table 4-1) taken from Ertekin and Firat (2015) because they have shown better fitting for this kind of drying experiments (Togrul and Pehlivan 2002; Koua et al., 2009 and Janjai et al., 2012).

The way to choose the equations was evaluating nine and discarding the one with high Root Mean Squared Error (RMSE). Estimation of the constants and RMSE with nonlinear regression was performed using the Optimization Toolbox for use with MatLab® (Version R2013b). Although Kingsly et al., (2009) argue that Logarithmic model produced good fitting in predicting drying pineapple, results with data from greenhouse-type solar dryer showed that the fitting is not good enough and was decided not to be included.

Table 4-1. Thin-layer drying models

Equation	Name
1. $MR = a\exp(-kt) + (1 - a)\exp(-kbt)$	Diffusion Approximation
2. $MR = \left[\frac{a+b*t}{1+c*t+dt^2}\right]$	Haghi and Angiz - III
3. $MR = aexp\left[\frac{-(t-b)^2}{2c^2}\right]$	Haghi and Angiz - IV
4. $MR = 1 - at^n\exp(-kt^m)$	Hasibuan and Daud
5. $MR = a\exp(-kt^n) + \mathrm{c}\exp(-gt^n)$	Hii
6. $MR = a_0/[1 + aexp(kt)]$	Logistic
7. $MR = \exp(-kt^n) + bt$	Modified Midilli - I
8. $MR = \exp(-kt^n)$	Page
9. $MR = \exp(-kt^n) + bt + c$	Sripinyowanich and Noomhorm

4.3.3 Statistical evaluation

The coefficient RMSE was one of the main criteria for selecting the best equation. RMSE should be lower and it is defined as:

$$RMSE = \left[\frac{\sum_{i=1}^{N}\{M_{pre,i} - M_{obs,i}\}^2}{N}\right]^{0.5} \quad (13)$$

where $M_{pre,i}$ and $M_{obs,i}$ are the predicted and observed dimensionless moisture ratios, respectively and N is the number of measurements. The Root Mean-Square Error (RMSE) is a kind of generalized standard deviation.

Another criteria for selection was mean absolute error (MAE), a measure of the difference between locations that are known and locations that have been interpolated or digitized, which is a statistical measure of how far estimates or forecasts are from actual values. MAE avoids compensation between under- and over-prediction. The MAE is given by:

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|f_i - y_i| = \frac{1}{n}\sum_{i=1}^{n}|e_i| \tag{14}$$

Where f_i is the prediction and y_i the true value; $|e_i|$ is an average of the absolute errors, units of MAE are the same as y_i, furthermore, there is no over-weighting of large differences here. Modeling efficiency (EF) consider distances measures which have an upper and/or lower bound to compare completely different cases (different data, different models) and it is defined as

$$EF = 1 - \frac{\sum_{i=1}^{n}(y_i - f_i)^2}{\sum_{i=1}^{n}(y_i - \bar{Y})^2} \tag{15}$$

Where $\bar{Y}$ is the average of the y_i.

4.4 Results and discussion

Greenhouse solar drying pineapple experiments were carried out. First experiment from November 19 to 21 and the second from November 24 to 26 in 2014. During the three days of pineapple drying, solar radiation was high from 8 am to 18 pm. Data of the variation of solar radiation during the experimental run can be observed in Figure 4-3.

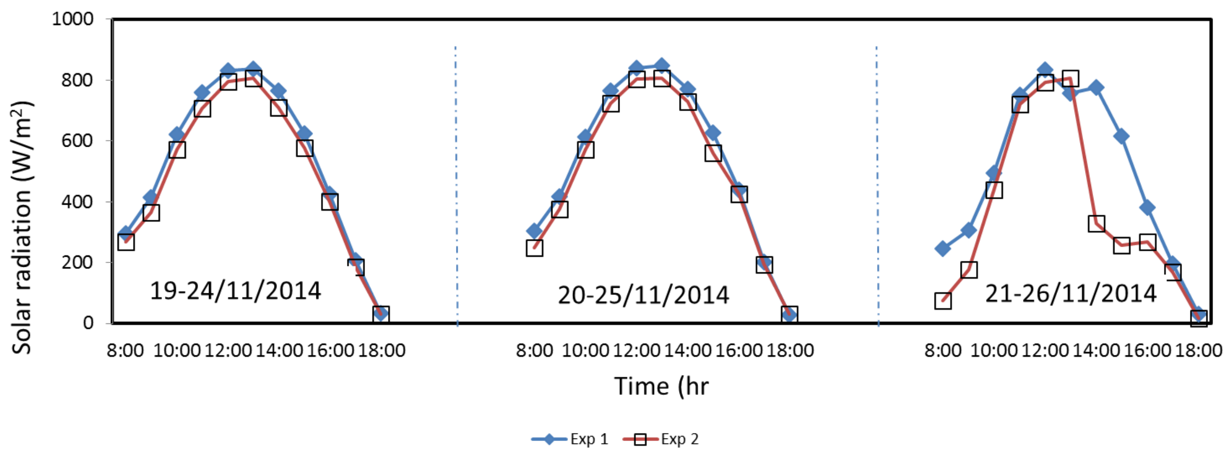

Figure 4-3. Behaviour of solar radiation with time of the day during drying of pineapple in experiment one and two.

The behavior of temperature inside of the central greenhouse dryer and the outside temperature is showed in Figure 4-4. It can be seen that the temperature vary in a narrow band and with the outside temperature the difference is more significant. In the case of Figure 4-5 is showed the behavior of the relative humidity inlet, outlet and ambient which can be seen how close the curves are from experiment one (November 19, 20 and 21) and experiment two (November 24, 25 and 26), where the conditions of the two experiments were similar.

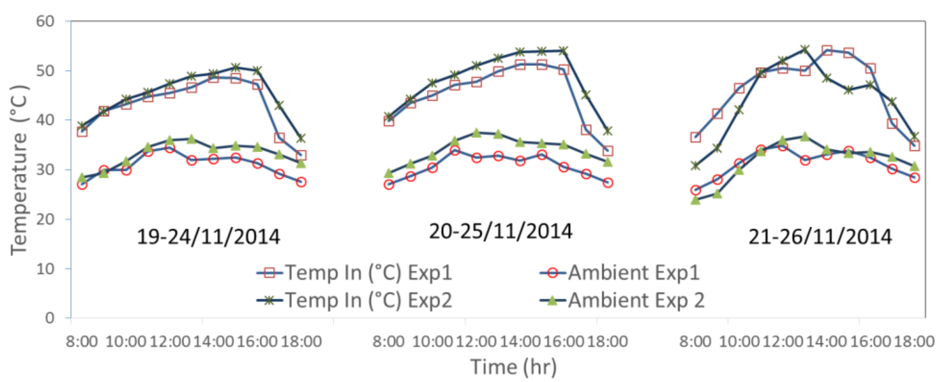

Figure 4-4. Behaviour of temperature inside the greenhouse solar dryer (Temp In) and ambient temperature of pineapple in experiment one and two.

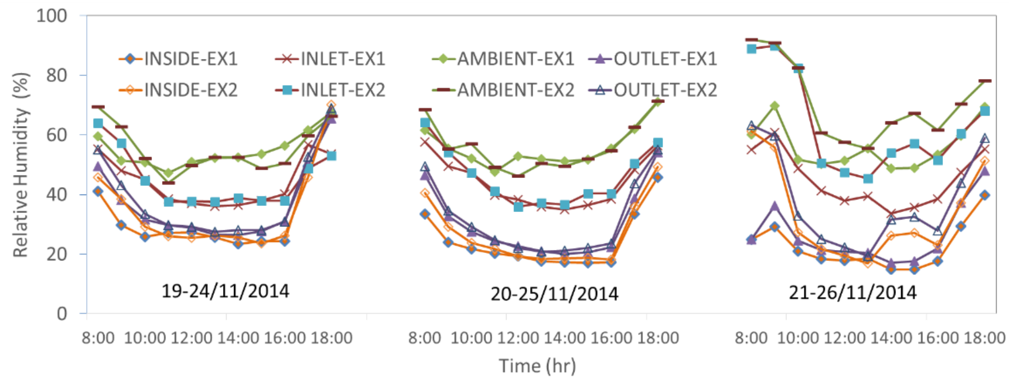

Figure 4-5. Behaviour of relative humidity inlet, inside, outlet and ambient from the greenhouse solar dryer in experiment one and two.

4.4.1 Drying kinetics

Final moisture content of pineapple reached 22 db% (reached when three consecutive weight reading were constant during drying) in the greenhouse solar dryer after three days of drying. The changes of moisture content for the two experiments are showed in Figure 4-6, and Figure 4-7. As can be observed a total of nine samples (MC1, MC2… MC9) were used to measure the mass of the product at each hour inside the greenhouse-type solar dryer.

4.4.2 Drying behaviour of pineapple

It can be observed that higher solar radiation makes faster the moisture desorption in comparison with lower radiation. Higher initial moisture removal rate can be observed at the first day than the removal rate during the next days. This is a typical moisture desorption behavior of food material which has been reported by Olanipekun et al., (2014), a short constant rate drying period and a large falling rate period.

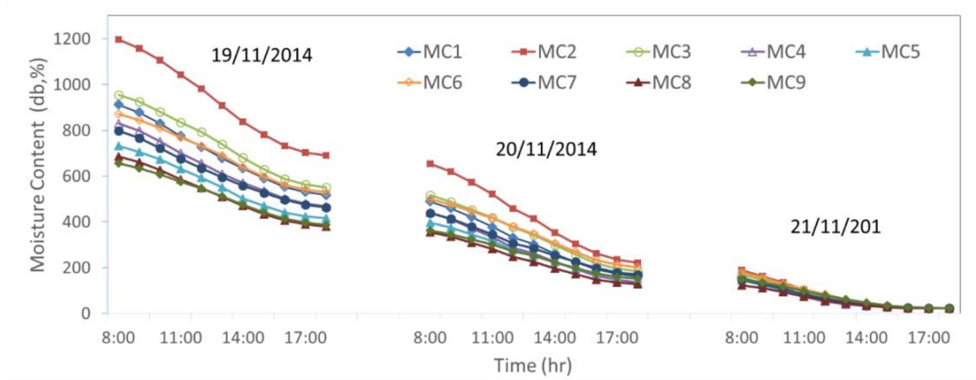

Figure 4-6. Behaviour of the drying process of pineapple in the greenhouse solar dryer with sunny days in experiment one.

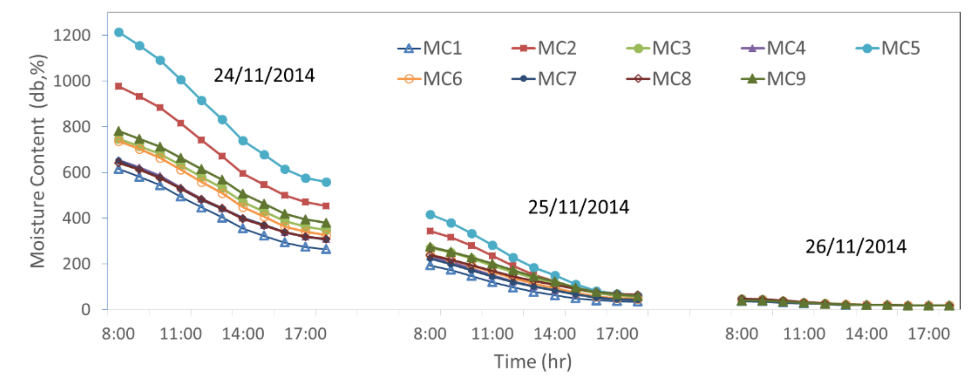

Figure 4-7. Behaviour of the drying process of pineapple in the greenhouse solar dryer with sunny days in experiment two.

4.4.3 Modelling of thin-layer drying

Moisture ratios of Pineapples dried at different temperature and air velocity were fitted with nine thin layer models. Statistics values, RMSE, MAE and EF are shown in Table 4-3 for all nine models. Hasibuan and Daud model was the best followed by Sripinyowanich and Noomhorm and Modified Midilli. For these three cases the value of RMSE was less than 13.17 %, indicating a good fitting. The average value of RMSE for the Hasibuan and Daud model was 11.89%, the MAE was 8.53 and EF= 0.96.

4.4.4 Evaluation of drying models

Nine thin-layer drying models were fitted to the experimental data of moisture ratio of pineapple dried in two different experiments, where temperature, relative humidity and air velocity were changing with time. Models are shown in Table 4-1. The parameter values, RMSE, MAE and EFF of the three best fitted models, are shown in $Table$ 4-2. The Hasibuan and Daud model was found to be the best, followed by the Sripinyowanich and Modified Midilli.

Comparisons between the predicted and experimental data of thin-layer drying of pineapple can be seen at Figure 4-8, for Hasibuan and Daud, Sripinyowanich and Modified Midilli. The agreement between the prediction and measured values of these models is good. In contrast with a high-precision dryer where the temperature, air velocity and humidity ratio can be study under constant conditions, and therefore the parameters of the thin-layer models can be related to those environmental variables (Janjai et al., 2011; López-Cerino et al. 2015 in preparation), in case of the experiments carried on under large-scale dryer conditions, we cannot determine a relationship between the parameters of the models and environmental variables because them were not constant.

Validation of the best fitting model for Hasibuan and Daud is made by comparing the predicted moisture content with the experimental moisture content in any particular experiment of greenhouse solar dryer. The performance of the model is illustrated in Figure 4-9 and 4-10. For experiment one RMSE equal to 12.13 and for experiment two RMSE equal to 10.72. The predicted data generally band around 1:1 straight line representing experimental data, which indicate the suitability of the Hasibuan and Daud mathematical model in describing drying behaviour of pineapple.

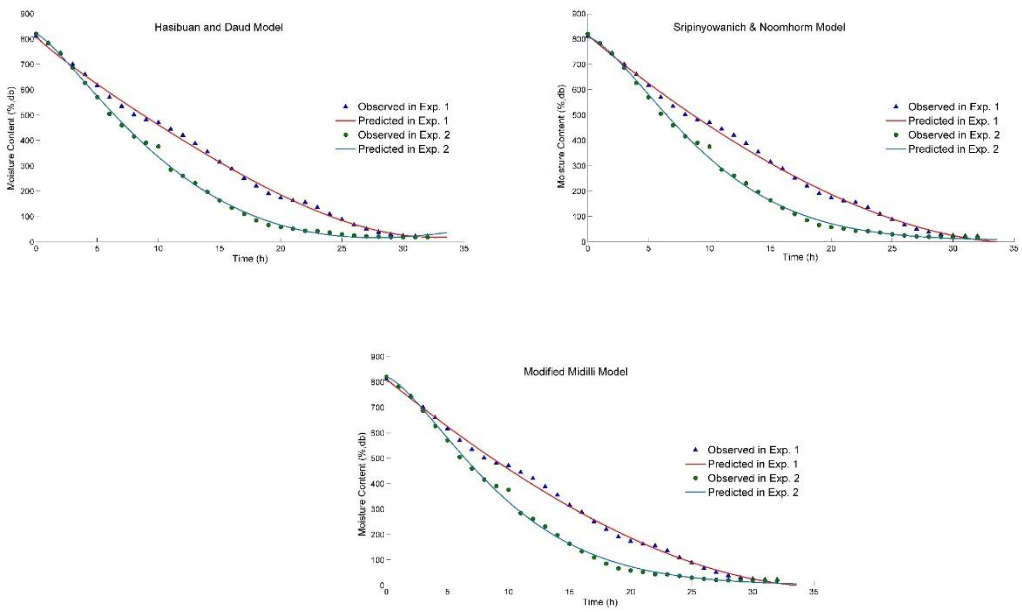

Figure 4-8. Thin layer drying of pineapple experiment one and two.

Table 4-2. Values of statistical parameters for the three best fitted mathematical models

Models	Exp.	RMSE (%)	MAE	EF
Hasibuan and Daud	1	12.6605	9.6947	0.9485
	2	11.1192	7.3709	0.9728
Sripinyowanich and Noomhorm	1	13.1707	10.3487	0.9419
	2	12.8613	8.4586	0.9642
Modified Midilli	1	12.9862	10.4532	0.9401
	2	13.0928	8.6416	0.9631

Table 4-3 Modelling of moisture content according to drying time for pineapple.

Models	Exp.	a_0 (h-1)	a (-)	b (-)	c (-)	d (-)	g (h-1)	k (-)	m (-)	n (-)	RMSE (%)	MAE	EF
Diffusion	1		-58.68	0.9865				0.1335			27.0412	21.6163	0.7361
Aproximation	2		-31.12	0.9729				0.1931			14.6581	9.7710	0.9521
Haghi and	1		0.9979	-0.0313	0.0138	0.0008					14.6015	11.5781	0.9270
Angiz-III	2		0.9936	-0.0318	0.0027	0.0067					15.6761	10.9570	0.9403
Haghi and	1		1.133	-8.5160	15.7300						18.5344	15.4706	0.8663
Angiz-IV	2		1.264	-8.0530	12.0300						12.1733	9.2901	0.9576
Hasibuan and	1		0.05605					4.386E-07	3.784	0.8874	12.6605	9.6947	0.9485
Daud	2		0.04493					0.05073	0.9873	1.333	11.1192	7.3709	0.9728
Hii	1		0.2445		0.7382		0.0015	0.04454		2.229	10.2689	8.2829	0.9626
	2		-56.03		57.1200		0.1669	0.1685		0.9885	26.6336	19.3248	0.8103
Logistic	1	1.27	0.3081					0.1381			20.757	17.2578	0.8326
	2	1.396	0.3921					0.1826			12.1887	8.5377	0.9637
Modified	1			-0.0747				-0.02639		1.011	12.9862	10.4532	0.9401
Midilli	2			0.0000				0.0366		1.399	13.0928	8.6416	0.9631
Page	1							0.02455		1.378	24.799	20.8915	0.7626
	2							0.03674		1.396	12.8829	8.7284	0.9624
Sripinyowanich	1			-0.0702	0.0058			-0.01907		1.082	13.1707	10.3487	0.9419
and Noomhorm	2			0.0006	-0.0159			0.03258		1.435	12.8613	8.4586	0.9642

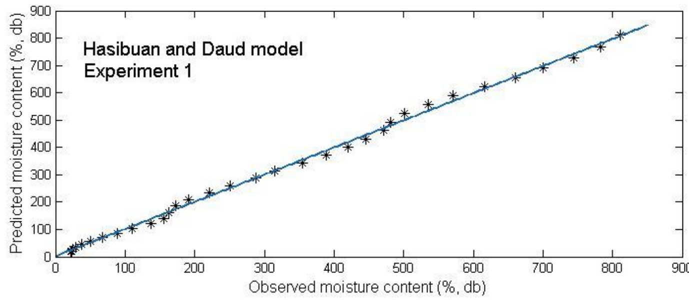

Figure 4-9. Comparison of predicted moisture content and observed moisture content of pineapple in experiment one from Hasibuan and Daud model.

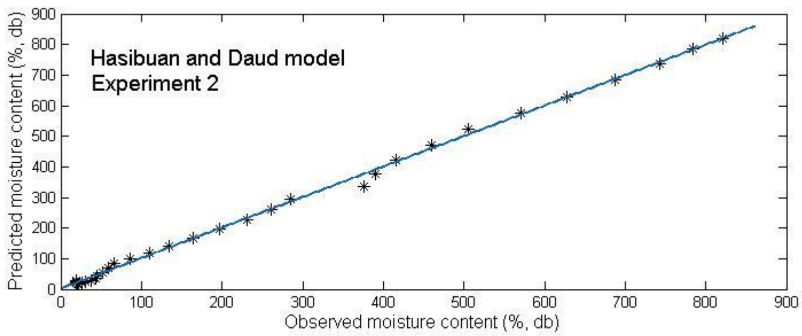

Figure 4-10. Comparison of predicted moisture content and observed moisture content of pineapple in experiment two from Hasibuan and Daud model.

4.5 Conclusions

Two pineapple drying experiments were carried out at Silpakorn University during sunny days. Similar data for solar radiation, temperature and relative humidity were obtained for both experiments. For the third day in the second experiment some cloudy hours were present. The following results are drawn from the drying kinetics of pineapple in a greenhouse-type solar dryer. Drying curves obtained from experiments showed that the constant drying and the falling drying rate periods exist.

Nine thin-layer drying models were fitted to two experimental data, to describe the drying characteristics of pineapple. The parameter values, root mean square error (RMSE), mean absolute error (MAE) and modeling efficiency (EFF) of the nine models, were calculated. The Hasibuan and Daud model was found to be the best, followed by the Sripinyowanich and Modified Midilli. The agreement between the prediction and measured values of these models was very good.

4.6 Acknowledgements

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Results and discussion

The purpose of this research was to help to solve the problem of quick spoilage of pineapple, being a seasonal fruit and abundant in short period of the year. An economical and high quality way to preserve it is the solar drying in a greenhouse type solar dryer. Advantages are that can be dried large quantity of agricultural products and to have high quality characteristics of them. In order to achieve this goal, the use of semi-empirical model is required to fit the experimental data and to be able to put the parameters in function of the temperature and air velocity.

Mathematical models that can fit experimental data for better prediction of the behavior of pineapple drying were found. These models turned to be different than those reported in literature for similar product or even for same pineapple. In this work, the pineapple samples were slices of one centimeter width and the core was taken out. In previous works different cutting manner of the pineapple samples were done, but this is not a factor for selecting a mathematical model. Using a high precision laboratory dryer, ensure that temperature, relative humidity and air velocity parameters are constant during all the drying process, and because the weighing of the samples are done automatically without taking the samples out of the laboratory dryer, no ambient factors affected the samples. The pineapple samples drying weight decreases in a smooth manner and data fitting was better. The success of the models are because models express moisture ratio of pineapple as functions of empirical parameters and time. All these three models studied adjust fairly well. Difference between the three models in both experiments (high precision dryer and greenhouse solar dryer) are very small, thus, for optimization and design can be good to use anyone of the three models fitted in each experiment.

Results of the basic quality specification for fresh and dry samples of pineapples indicate around 35 % of sugar concentration increment which mean that when water is evaporated, the pineapple acquire a sweeter taste and also the acidity is less (1 %). Color of the dry pineapple change slightly, being no significant. These results assure maximum flavor and visual acceptability by most consumers.

Conclusions

Thin layer drying experiments of pineapple were by first time carried out with a laboratory dryer. The effect of three different temperatures (50, 60 and 70 °C) with different air velocity (0.5, 1.0 and 1.5 ms^{-1}) and specific humidity of 25 $g_{water}kg_{air}^{-1}$, showed that at higher temperature and higher air velocity, the drying happened faster. From 50 to 70 °C at 0.5 ms^{-1}, drying time decreased from 26 to 12 hours; from 50 to 70 °C at 1.0 ms^{-1}, drying time decreased from 20 to 10 hours and from 50 to 70 °C at 1.5 ms^{-1}, drying time decreased from 16 to 8 hours. A constant rate period of drying was not observed.

A second experiment was done at Silpakorn University, Nakhon Pathom, Thailand where pineapple cut in slices and without core were used, with one centimeter width to match the experiment done at Hohenheim University. Around 120 kg of pineapple product was used and weather conditions was very good with high solar radiation. The drying time lasted three days, obtaining at the end high quality pineapples dried.

After a total of six thin-layer drying models were fitted it was found that the one proposed by Hasibuan and Daud achieved the best fitted model for both experiments: high precision laboratory dryer and greenhouse-type solar dryer. Simulation and optimization of the dryer for efficient operation can use the Hasibuan and Daud model to assess the drying behavior of pineapple. Dried pineapple showed homogenous texture, then, can be applicable to most pineapple in market.

Pineapple color after drying presented a yellow color lightly going dark and it remains unchanged at 50, 60 or 70 °C. Quality of color is acceptable. Sugar concentration content was raised giving to the pineapple a sweeter flavor.

Appendix

A third greenhouse solar drying pineapple experiments were carried out from December 02 to 05 in 2014. During the four days of pineapple drying, solar radiation was irregular from 8 am to 18 pm. Data of the variation of solar radiation during the experimental run can be observed in Figure 1. Cloudy days were presented in all the days that last the experiment, solar radiation was low in comparison with the experiment 1 and 2.

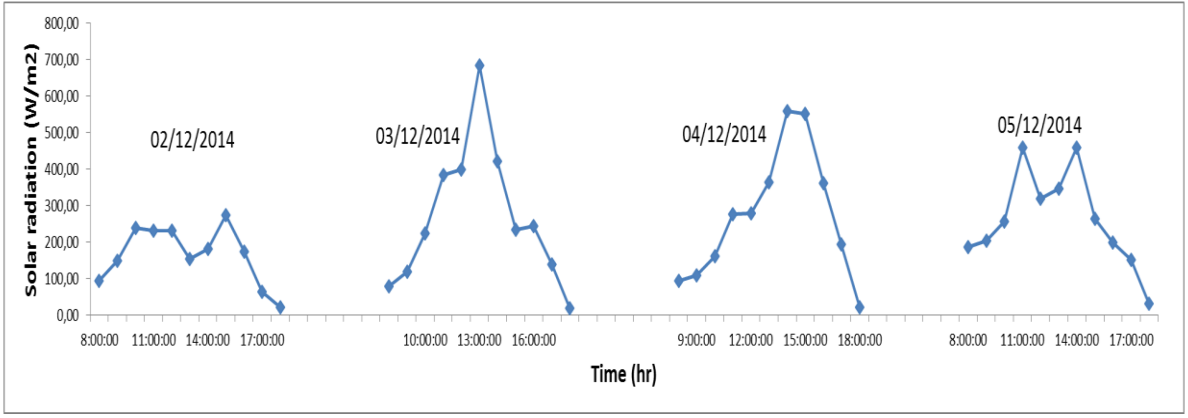

Figure 1. Behaviour of solar radiation with time of the day during drying of pineapple in experiment third.

The behavior of temperature inside and outside of the greenhouse solar dryer is showed in Figure 2. It can be seen that inside and outside temperature have a small difference because of the cloudy days. In the case of Figure 3 is showed the behavior of the relative humidity inlet, outlet and ambient. In this case, we can observe, that relative humidity are very similar in values inside and outside the greenhouse. This similitude in relative humidity can explain why the experiment last one day more than the experiment one and two.

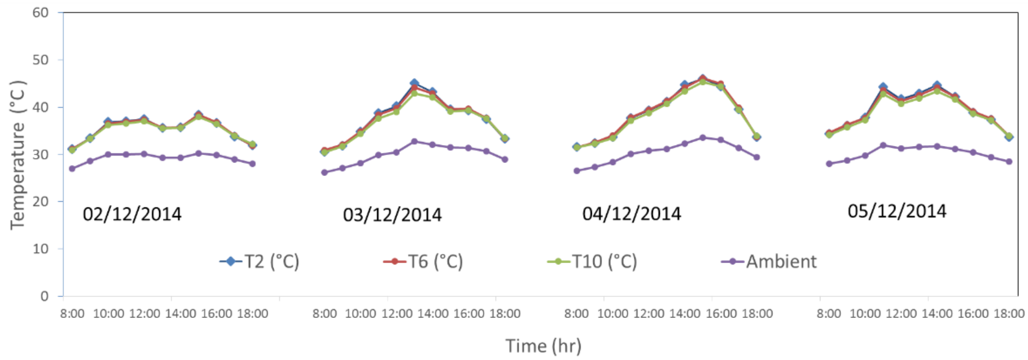

Figure 2. Behaviour of temperature inside the greenhouse solar dryer and ambient temperature of pineapple in experiment three.

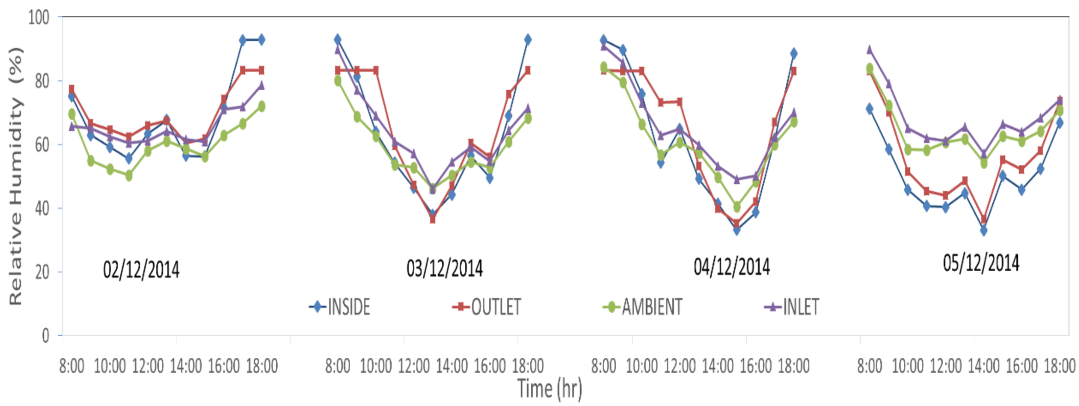

Figure 3. Behaviour of relative humidity inlet, inside, outlet and ambient from the greenhouse solar dryer in experiment three.

Drying kinetics

Final moisture content of pineapple reached 24 db% (reached when three consecutive weight reading were constant during drying) in the greenhouse solar dryer after four days of drying. The changes of moisture content for the third experiment are showed in Figure 4-6. As can be observed a total of nine samples (MC1, MC2… MC9) were used to measure the mass of the product at each hour inside the greenhouse-type solar dryer.

Drying behaviour of pineapple

Higher solar radiation makes faster the moisture desorption in comparison with lower radiation, to show this, it is presented the third experiment were cloudy days were presents in all experiment. Slower initial moisture removal rate can be observed at the first day and it is observed the same in next days. A slow drying behaviour is present through all the time that last the experiment.

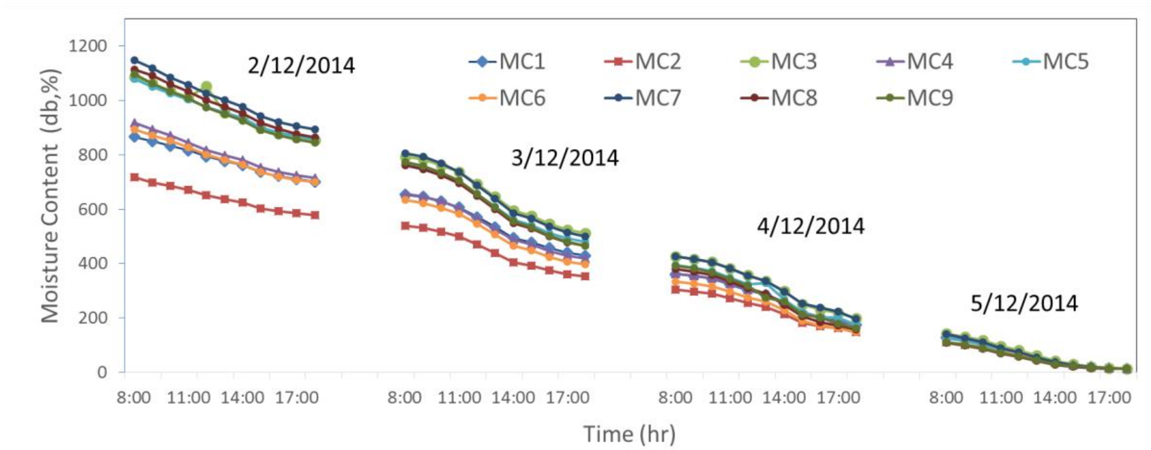

Figure 4. Behaviour of the drying process of pineapple in the greenhouse solar dryer with cloudy days in experiment three.