NTNU – Trondheim
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Thin-layer modeling in heat pump drying of green peas

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Sustainable Energy	
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MASTER THESIS

for

Alexandre Zaragosa Ferrer

Autumn 2014

Thin-layer modeling in heat pump drying of green peas

Modellering av sjikt i varmepumpe tørkede grønne erter

Background and objectives

The current drying of heat sensitive materials is mostly done by conventional vacuum freeze drying. The major challenges are a long residence time, a low drying capacity and high energy use.

An innovative drying process has been developed at NTNU. This process is based on non-freeze and freeze drying at atmospheric pressure by application of heat pump technology. The advantages are energy efficiency, process sustainability and high product quality.
However, there are still possibilities to improve the process by modeling kinetics and there is a need to study potential procedures to further reduce drying time and increase energy efficiency.

This thesis work objectives includes a literature review and experimental tests in a laboratory heat pump dryer. The literature on the current and past research in this field will provide the status of the engineering in heat pump drying and will indicate further needs in the present research.

Experiments will be performed at different heat pump drying conditions and using multi thin-layer of green peas. The experimental results of the drying tests will be acquired and analyzed concerning to kinetics, drying rates, moisture content as function of time, energy use, density and color of the dried green peas.

The results will indicate how the heat pump drying temperatures, air psychrometric properties and position of the green pea layers will reflect upon the residence drying time, efficiency and quality of the product.

Additionally, suggestions will be made for further experiments and studies on heat pump drying of green peas and other sensitive vegetables.

A large batch of green peas will be mixing and homogenizing. Then it will sub-divided into fifteen uniform batches to proceed to the drying tests that will be done in three series according the following experimental design.

EXPERIMENTAL SERIES A:

Run	**A1**	**A2**	**A3**	**A4**	**A5**
Height, cm	0	5	10	15	20
t, °C	45	tA2	tA3	tA4	tA5
φ, %	20	φA2	φA3	φA4	φA5

EXPERIMENTAL SERIES B:

Run	**B1**	**B2**	**B3**	**B4**	**B5**
Height, cm	0	5	10	15	20
t, °C	35	tB2	tB3	tB4	tB5
φ, %	20	φB2	φB3	φB4	φB5

EXPERIMENTAL SERIES C:

Run	**C1**	**C2**	**C3**	**C4**	**C5**
Height, cm	0	5	10	15	20
t, °C	15	tC2	tC3	tC4	tC5
φ, %	20	φC2	φC3	φC4	φC5

The following tasks are to be considered:

1. to review the literature on drying of green peas and vegetables
2. to prepare the fifteen batches of green peas for the drying tests
3. to perform tests according to the experimental design
4. to collect and to analyze data on kinetics, energy and quality
5. to write and to submit the thesis.

Within 14 days of receiving the written text on the master thesis, the candidate shall submit a research plan for his project to the department.

When the thesis is evaluated, emphasis is put on processing of the results, and that they are presented in tabular and/or graphic form in a clear manner, and that they are analyzed carefully.

The thesis should be formulated as a research report with summary both in English and Norwegian, conclusion, literature references, table of contents etc. During the preparation of the text, the candidate should make an effort to produce a well-structured and easily readable report. In order to ease the evaluation of the thesis, it is important that the cross-references are correct. In the making of the report, strong emphasis should be placed on both a thorough discussion of the results and an orderly presentation.

The candidate is requested to initiate and keep close contact with his/her academic supervisor(s) throughout the working period. The candidate must follow the rules and regulations of NTNU as well as passive directions given by the Department of Energy and Process Engineering.

Risk assessment of the candidate's work shall be carried out according to the department's procedures. The risk assessment must be documented and included as part of the final report. Events related to the candidate's work adversely affecting the health, safety or security, must be documented and included as part of the final report. If the documentation on risk assessment represents a large number of pages, the full version is to be submitted electronically to the supervisor and an excerpt is included in the report.

Pursuant to “Regulations concerning the supplementary provisions to the technology study program/Master of Science” at NTNU §20, the Department reserves the permission to utilize all the results and data for teaching and research purposes as well as in future publications.

The final report is to be submitted digitally in DAIM. An executive summary of the thesis including title, student’s name, supervisor's name, year, department name, and NTNU's logo and name, shall be submitted to the department as a separate pdf file. Based on an agreement with the supervisor, the final report and other material and documents may be given to the supervisor in digital format.

☒ Work to be done in lab (Water power lab, Fluids engineering lab, Thermal engineering lab)
☐ Field work

Department of Energy and Process Engineering, 14 December 2014

Olav Boll

Olav Bolland
Department Head

Odilio Alves-Filho
Academic Supervisor

Abstract

Drying is one of the most essential and common processes nowadays applied to industry and, among other things, in food treatment and preservation. The main purpose is to process the food for consumption by increasing its shelf life. Hence, the drying process allow to achieve this by removing the moisture content from the raw material, reducing and eliminating biological activity and spoilage of the fresh products.

Common drying is known for its elevated energy consumption and therefore it is costly. The conventional drying has also a negative effect on the environment and climate. That explains the importance on developing sustainable technologies like heat pump drying to look after our most valuable asset that is nature and its resources.

Heat pump drying is a relatively new technology developed at NTNU. It merges the drying and heat pump cycles in which the heat pump is used to recycle energy, for reheat the air during drying the raw material. Due to this recycling of heat from the drying exhaust air, energy is saved and the total energy input to the system is significantly reduced.

Other important challenge for the drying process is to maintain as much as possible the fresh qualities in the final product after processing or drying. Lots of research work and experiments done in HPD technology have indicated a high potential in achieving high qualities and energy saving with this technology.

Experiments in a laboratory scale heat pump dryer were conducted using green peas. Three set of tests with twelve trays were performed with varying the temperature and relative humidity of the drying air. All results and conclusions are discussed and description clearly made by the author to facilitate the understanding of the reader.

Acknowledgements

Primarily, I would like to thank my supervisor Professor Dr. Odilio Alves-Filho to give me the opportunity to write this master thesis with him in this interesting and innovative topic as Heat Pump Drying is. He gave me support during all the working period and even in the difficult moments that as a student doing, for the first time, a work of these characteristics that I could have had. It was difficult to not being motivated with his constant positivity and his guidance when I have needed.

I am also thankful to the Department of Energy and Process Engineering at NTNU for also giving me the possibility to work with these admirable installations and for the hospitality that I have found in every person working there.

Neither, I cannot forget my home university “Universitat Politécnica de Valencia” and, especially , “Escuela Técnica Superior de Ingenieros Industriales (ETSII)”. Thanks to their cooperation with NTNU, making possible to perform this thesis work.

Last, my special gratitude goes for my family, my brother Carles and my mother Mª Teresa and even more special goes to my father, Eduardo Zaragozà Camarena, who passed away last august 2014 and who encourage me as my mother always do to pursue my dreams. This and what will come in the future goes for you.

Contents

Nomenclature

GHG	greenhouse gases	
CFC	chlorofluorocarbon	
HFC	hydrofluorocarbon	
HCFC	hydrochlorofluorocarbon	
HPD	heat Pump Drying	
ODP	ozone depletion potencial	
SMER	specific moisture extraction ratio	
R&D	research and development	
GWP	global warming potential	
COP	coefficient of performance	
COP_{Carnot}	maximum theoretical coefficient of performance	
$\dot{Q}_0$	evaporator heat	KW
$\dot{W}_C$	compressor work	KW
$\dot{W}_f$	fan work	KW
w_{db}	moisture content in dry basis	
w_{wb}	moisture content in wet basis	
m_w	mass of water in the product	
m_t	Total mass of the product	
m_d	dry mass fraction of the product	
ρ_b	bulk density	
m	mass	
V	total volume	

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1. Introduction

The last decades have had a progressive concern with the environmental issues ranging from air or water pollution to depletion of natural resources and impact to climate change. Fossil fuel consumption and emissions of harmful gases have had high contribution to these damages and impacts. [1] As a result there have been several resolutions like the Kyoto, Montreal and Copenhagen's Protocols and Accord recommending the developed countries to reduce their emissions of greenhouse gases and to improve energy efficiency.

From this viewpoint, it is desired that the industrialized countries invest on developing sustainable and renewable energy processes, new sources and design new or enhance systems using thermal energy. [1] Therefore in the recent years a large part of R&D efforts have been directed to developing these new and alternative technologies.

Drying, also known as dewatering, demands lots of energy and is one of the industrial R&D activities that is evolving and adapting to the current environmental and energy requirements. As one of the most energy intensive unit operations, drying accounts for up to 15% (or more) of all industrial energy utilizations [3,5] implying a real justification for enhancements and better design focusing on energy efficient and environmentally sustainable.

The drying food is a particular sector that has been an important industrial application. Drying is a commonly utilized industrial method to increase the shelf life of the perishable fresh products. Because most products of biological origin are heat sensitive, it is important to reduce their water activity and moisture content and so to increase their shelf life without degrading their quality attributes. [5] This enables the food preserve for longer time and gives possibility of easy and cheaper transportation the dried food to anywhere as well as to non-producing regions as to provide additional choice for consumption by local people.

The important factors for the drying process are the drying kinetics and product quality. It is necessity to maintain the original features of the fresh product as well as essential to reduce the drying time and use low energy in the drying process. Heat pump drying is the new technology accomplishing by far these requirements and specifications as demanded by the society and industries in these days.

Lots of experiments using this technology have shown the technology high potential for energy saving and attainment of the required product qualities. This is due to, among others, the wide possibilities of controlling the drying medium conditions, such as the air temperature and relative humidity. For these reasons this new drying technology is already being used in several industries for specific materials and products. The research and development conducted now and in the near future, will apply this technology to new materials and other products as to promote this technology with advantages to consumers, society and industry.

2. Objectives

The main goals of this master thesis is to carry out the experiments on drying green peas applying a pilot scale heat pump dryer and to study the effects of air temperature, psychrometrics or relative humidity on the moisture extraction kinetics and on the final product characteristics or quality. These effects were measured and observed during and after the experiments.

In order to investigate effects of the operating conditions on the moisture transport and products features the independent variables were kept fixed during the tests. These included air velocity, temperature of drying air, initial moisture content and initial batch mass. Under these conditions the drying temperatures were set in three levels with a slightly variable range of relative humidity. Each individual drying test provided measured data to study the effect of the dependent variable kinetics behavior and product features. The mass transfer and product quality or characteristics were measured and analyzed prior, during and after each drying test.

Focus is given on the transient changes of moisture content, moisture ratio, drying rate and quality or characteristics as indicated by measurements of color, bulk and particle densities during and after the tests.

The work specific objectives and tasks were:

- To review the literature related to heat pump drying (HPD) technology and, in particular, the drying of green peas and similar vegetables.
- To prepare and carry out the experiments with the HPD technology.
- To perform all measurements related to moisture extraction and product features.
- To collect and analyze the data and measurements and to draw the conclusions consistent with the experimental data.

3. Literature review

Current drying is highly energy demanding and thermal ineffective processes. Drying process is applied to most industrial sectors such as pharmaceutical, chemical, and food industries. Particular problems are the process efficiency associated environmental pollution and the fluids contributing to green house gas emissions are now of great concern. Alves-Filho (2013) reported that “It is obvious that conventional dryers consume large amounts of energy and have an equivalent contribution to the emission of greenhouse gas (*GHG*) to the atmosphere. Another significant contributor to *GHG* emission is the artificially produced chemical refrigerants and foam-blowing agents.

The living space of our planet is made of three envelopes which are atmosphere, hydrosphere and the Earth’s crust. The temperature and related conditions in this living space depends on two delicate net balances.

The first net balance is based on the energy received by the sun’s radiation as well as the energy rejected as infrared radiation with longer wavelengths. A disturbance of this balance causes an increasing warming of the biosphere as a result of the gases blocking the emission of infrared radiation from Earth to outer space. These gases, known as greenhouse gases, include carbon dioxide, chlorofluorocarbons (*CFCs*), hydrofluorocarbons (*HFCs*), hydrochlorofluorocarbons (*HCFCs*), hydrocarbons, methane, nitrous oxide and others.

The second is the net mass balance of oxygen and carbon dioxide as greenhouse gas. This balance is under the influence of the sun’s radiation, all the green vegetation still untouched by a man, and the *GHGs* emitted by natural and artificial processes. A brief summary of this principle is, the sun’s photons successfully cross the atmosphere, strike the green plants and triggers a process called photosynthesis that uses the energy of the sun to combine carbon dioxide with water producing carbohydrates and oxygen (a byproduct) molecules. This principle must be protected for it removes *GHG* and manufactures substances essential for life as we know it. Photosynthesis produces building blocks of plants comprising the base of the food chain that supplies nourishment to herbivores, later eaten by carnivores and humans.

Besides that, the most important aspect of this photon-leaf release of oxygen and capture of carbon dioxide is keeping a balance and tolerable concentration of atmospheric gases for life supporting biosphere.

This photosynthesis process is in equilibrium with the carbon dioxide released by natural means including cellulose decomposition, volcanism, etc. Thus, any disturbance of the net oxygen-*GHG* mass balance results in over-heating of the biosphere and many appalling effects in the hydrological and carbon dioxide-air cycle. Unfortunately, *GHGs* are still being produced and released in the increased concentration mostly by the energy dependent industries, direct combustion users, transport, agriculture, wastes, chemicals and solvents processing plants. The photon-leaf mass balance is still a colossal phenomenon but it may eventually be unable to cope with increasing carbon dioxide concentration in Earth's atmosphere. The most extensive initiatives to reduce the *GHG* production and emission occur in Europe through proposals and incentives. But, due to varying resources and priorities of the countries involved it is difficult to reach the set targets. The *GHG* reduction progress is promising in Scandinavian countries.
The estimated artificial emission of *GHGs* in 2011 is about 33.4 Gt. It is also estimated that the produce of *GHGs* in year 2050 will increase to about 50 Gt. This value does not show an optimistic future for planet's life cycle if the current trend continues as so far.

Another consideration is the chemical substance degradation effect on the living space stratosphere. The indicator is the ozone depletion potential (*ODP*).

In the early 20th century, conception of the *CFCs* and *HCFCs* contributed to the widespread use of commercial refrigeration and aerosol agents, with no concern for the long-term effect of these chlorinated substances on the environment, and overall health and safety. At the end of the last century, scientists found that chlorine molecules in *CFCs* and *HCFCs* cause severe damage to the stratospheric ozone layer. A consequence of the Montreal Protocol was that these refrigerants were phased out and replaced by *HFCs* that have zero *ODP* and *GWP*. The next environment protecting rules appeared in the Kyoto Protocol dealing with the *GHGs* emission and their outcome in the climate change. It demands reduction of the

GHGs and the global warming potential (*GWP*) which becomes an essential trait in the refrigerant selection. Therefore, *HFCs* are to be reduced gradually by replacement, low charge, containment, recycling and destruction of the fluid after the end of life of refrigeration equipment. This also shows that *HFCs* will eventually be phased out."[1]

There are opposite aspects in drying, one is that it is an energy intensive process the other is that the process should be designed at competitive cost. Therefore, the main objectives of drying processes are to produce a dried product of desired quality while designing the process for minimum cost and maximum throughput. Some of the current challenges for the industries are enhanced properties of the dried product, reduced energy consumption, and high throughput to entail lower product costs. Industries willing to be competitive in the international market must comply with these requirements.[6],[8]

Researchers have been studying the applicability of new drying methods to obtain a balance between the required high quality of dried products and the low operating costs. One emerging alternative to tackle this balance is a new technology that has been recently developed at NTNU based on the heat pump drying. [3]

The energy lost in conventional dryers through the air exhaust is in the form of latent and sensible enthalpies that can be recycled between a heat pump fluid and drying air in well designed heat exchangers of heat pump dryer (Alves-Filho, 2013). This is in agreement with Chua, Chou, Ho and Hawlader, 2002 stating that: “The principal advantages of heat pump dryers emerge from the ability of heat pumps to recover energy from the exhaust air as well as their ability to control independently the drying air temperature and humidity. In most of the research studies conducted, the common conclusion was that heat pump drying (HPD) offers products of better quality with reduced energy consumption.

Many researchers have acknowledged the importance of heat pump dryers in producing a range of precise conditions to dry a diversity of products and to improve their quality. Heat sensitive food products, requiring low-temperature drying, can be processed with improvement by the heat pump drying technology (Pal & Khan, 2007). Recently, there has been a significant growth in the potential market for heat pump dryers, aided by the impact of new designs under development or recently introduced into the market."[6]

Strommen et al. after several experiments found out that heat pump dryers consume 60 to 80% less energy than conventional dryers operating at the same temperature. Taking in account this information implies such dryers are feasible options for users who are not satisfied with the comparatively high energy consumption of directly heated dryers. [3]

Dust emission and air pollution can also be tackled by the dryer's design and choice of the heat pump fluid. It has been reported by several scientists that: "The closed drying loop in the heat pump dryer (HPD) also eliminates the common problem concerned to dust release to the atmosphere. A HPD using natural refrigerants such as carbon-dioxide (CO2) or ammonia (NH3) as working fluid implies no depletion of the ozone layer and no damage to the global environment. Also, HPD can use inert gas (CO2 or N2) as a drying medium as a replacement air when it is detrimental to the product quality (Strømmen, 2001; Alves-Filho and Mujumdar, 2002; Mujumdar and Alves-Filho, 2003).

An advantage of this process compared with vacuum mode is a simplified design and absence of vacuum chamber or ancillary devices and reduction in energy utilization or operation costs. An especial feature of the HPD is that it can operate at atmospheric pressure while performing modes of freeze and positive temperature. This is combining temperature cycles and drying times can be adjusted accordingly as to control the final product physical properties, including floatability, rehydration ability and bulk density. A possible drawback in atmospheric pressure freeze drying is increased drying times when the drying rates are low. However, the drying rate can be greatly enhanced by agitation of the material being dried or by fluidization, which improve the mass and heat transfer coefficients (Alves-Filho and Mujumdar, 2003; Di Matteo et al., 2003)."[4]

The rate of heat recovery in a heat pump dryer depends on the area available for heat transfer and properties of heat pump fluid and the drying moist air.
This rate of heat recovered as well as the heat pump coefficient of performance (COP) and drying specific moisture extraction ratio (SMER) depend on those properties and, additionally on the refrigerant evaporating and condensing temperature. The last condition defines the heat pump dryer COP or SMER and is highly influenced by the number of stages of the heat pump dryer, type of cycle and fluid (Alves-Filho, 2011; Alves-Filho, 2013).

The heat pump cycles, components layout, drying mode and chamber design have been recently investigated. A related report is: "Research and development work is, currently, receiving considerable attention for designing better heat pump drying system. Most of this work is directed mainly at the heat pump cycle. However, some studies, such as Chou et al., 1999, have also been devoted to investigate systematic ways to design the drying chamber economically. There are also other complimentary works being done in the area of dryer control strategy and product quality. In the subsequent sections, the some of the latest development and new trend in heat pump drying will be described.

The most important considerations concerning heat pumps are summarized as follows (Strumillo et al., 1995):

- Compressors of heat pump dryers should be able to operate continuously for extended periods without undergoing periodic maintenance considering the fact that most dryers are expected to operate twenty-four a day to produce consistent product throughput.
- Heat capacity and working temperature of the heat pump refrigerant should suit the drying process.
- For optimum system performance, the heat pump should operate at the same thermal load (i.e., the amount of latent energy released at the evaporator) to minimize the amount of energy consumed at the compressor to provide for additional sensible heating at the condenser.

- The temperature difference between the evaporator and condenser for a single-stage vapor-compression heat pump should not exceed 40 °C to maintain the COP in the range of 3 to 4.

As previously described, the recent developments in heat pump drying have been focused on control process and on heat pump component, particularly the compressor. Latest development in scroll compressor in terms of energy efficiency and size of the compressor has made it technically attractive to be integrated into heat pump drying system. Also, heat exchangers with enhanced features, such as internal tube ribbed surface (Matsuo et al., 1984) and external wavy fins are used to promote better heat transfer and reduce the size of heat exchangers. These features make heat pump dryers more compact, increasing energy efficient (through better heat recovery) and allow the implementation of better air control strategies.

As many processes require both hot and cold drying, frost build up on evaporator surface is a common occurrence. Once frosting occurs, the heat transfer between evaporator and drying air deteriorates. Research studies, such as Sanders, 1985, have been undertaken to investigate ice buildup and its influence on dehumidification with the eventual objective to come up with better mechanisms to reduce the rate of build-up.”[7]

A important issues are now concerned to dryer's enhanced capacity or drying rate and the dried improved product's quality. This has been the focus of recent investigations on heat pump and drying made by Alves-Filho (2013), who states that: "Hybrid techniques composed of complementary drying methods can be applied to improve product quality, reduce drying time, and enhance the drying rate. It was reported that heat pump atmospheric freeze drying as a first step in drying preserves the product quality with minimal changes. In the next step, the material can be transferred to a different type of dryer to increase the drying rate. A combination of heat pump and microwave drying may provide the desired drying conditions to achieve a fast drying rate, lower shrinkage, better product appearance, and low operational cost. Although numerous drying technologies have demonstrated the potential for cost-effective application in postharvest processing, much R&D remains to be done. There is a lack of information concerning the drying kinetics of combined multistage methods and structural changes that occur during dehydration of agri-food products."

4. Theory

4.1 Drying processes and governing mechanisms

Drying is a very old process used to preserve foods and other material. The wet material to be dried is exposed to an air or gas stream that causes moisture extraction from the product and transport out of the drying loop. Hence, this phenomenon involves:

- Heat transfer from the external surroundings to the surface and core of the food material being dried by combined with heat convection and conduction within the material.
- Mass transfer from inside of the material to its surface followed by external transport of moisture from surface to the surroundings.

The two main mechanisms of heat transfer in air or gas and porous solids drying processes are:

- Convection: when the hot air or gas flows through the material and supply heat for both evaporation and carrying away the evaporated moisture from the product. Most of the heat transfer in commonly used in industrial drying is governed by this mechanism.

- Conduction: when the material is in contact with a hot solid surface that is part of the drying chamber, as existing in tray, drum or rotary dryers and in shelf-vacuum freeze-dryers. Heat is supplied by conduction to heat the material but moisture can be either evaporated or sublimated and carried away by air or through vacuum for condensation.

4.2 Psychrometry of moist air related to water removal

A convective drying involves both exchange of moisture and heat between the material being dried and the moist air stream. The intensity of this exchange depends on the magnitude of the driving forces provided by the temperature and vapor pressure gradients between interior of the material and at the air boundary layer over the surface. The moist air is the considered the best choice as drying media because it has convenient properties and is nearly cost free and is easily available everywhere. Thus, the comprehension of the moist air properties at each state point of drying is crucial in the calculations of water removal, energy utilization and drying capacity. Psychrometric charts, equations and software libraries are used to determine the moist air properties that are essential in design, analysis and evaluation of energy, moisture removal and capacity in conventional and in heat pump dryers. The continuous phase in the majority of convective drying processes is a mixture of air and water vapor. The state points and properties of the mixture change as it circulates through the components of the heat pump drying processes. The changes must be calculated at the inlet and outlet of the heat exchangers and the drying chamber to define the state points in each process and for calculations of energy use and water removal during drying.

The main properties of the moist air and therefore that must be known for the better work and design of the heat pump dryer are the temperature (t), specific enthalpy (h), vapor pressure (p_v), specific volume (v), absolute humidity (x) and relative humidity (φ). These essential properties are determined by equations and graphically by the psychrometric charts or diagrams. Figure 4.1 illustrates how to identify the moist air properties through the constant lines and curves that are always shown in the Mollier diagram (Dossat, 1981; Mujumdar, 2008, O. Alves-Filho, 2013).

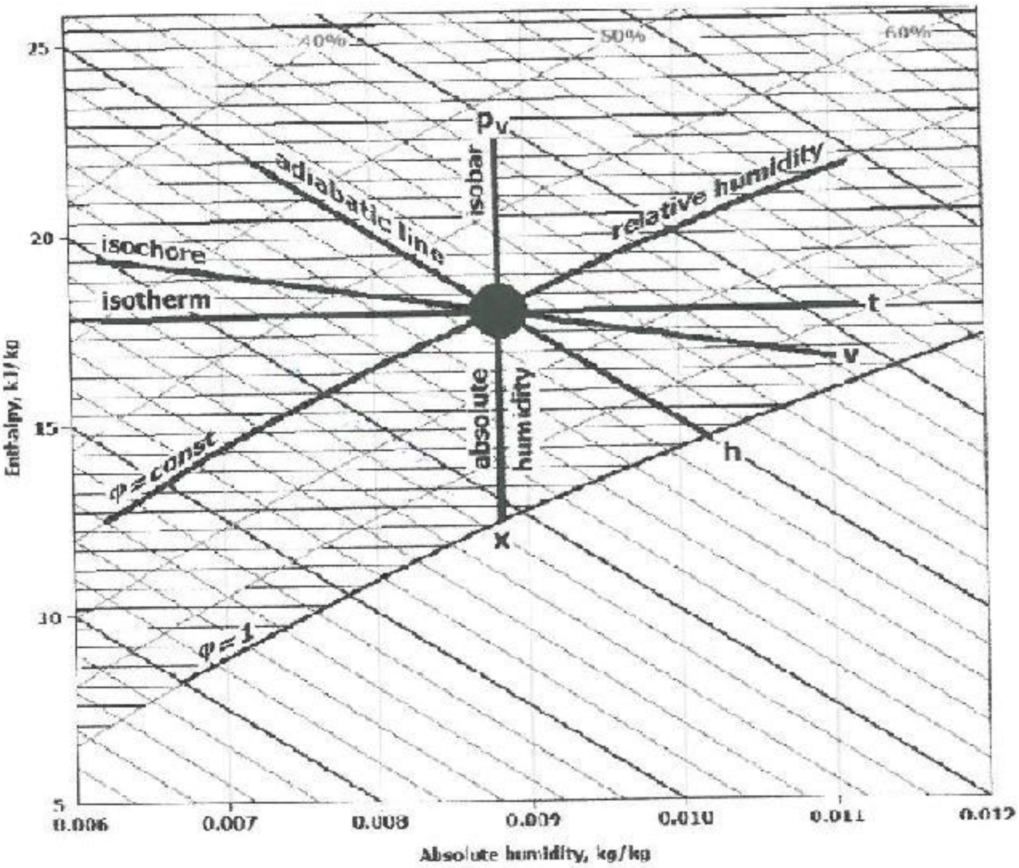

Figure 4.1 Illustration of the psychrometric chart for identification main properties of the moist air (O. Alves-Filho, 2013)

4.3 The basics of the heat pump technology

The main components of a single stage heat pump system are the expansion valve, evaporator, internal and external condensers and compressor as illustrated in Figure 1. After flowing through the evaporator and condenser of the heat pump dryer, the warm air is ready to go into the drying chamber in which the wet material has been placed. This simplified heat pump dryer has two separated loops with common heat exchangers. The drying air loop (*abcd*) contains the air cooler (*EVA*), heater (*CON*), blower and drying chamber. The refrigerant loop (*12341*) main components are the expansion valve (*THR*), evaporator (*EVA*), condenser (*CON*) and a compressor (*COM*). The fluid of the heat pump and drying air loops are coupled through the common evaporator and condenser to recover the exhaust energy. [1]

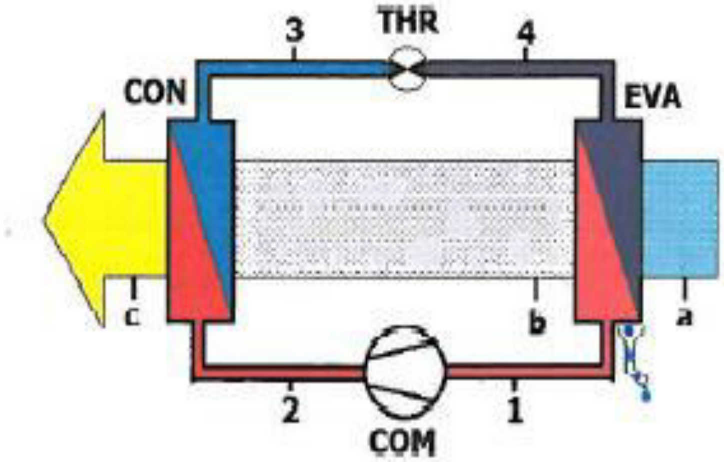

Figure 4.2 Principle of operation in a simplified heat pump dryer (O. Alves-Filho, 2013)

Considering the refrigerant, the heat pump dryer's closed cycle is composed of four processes as shown in Figure 2.

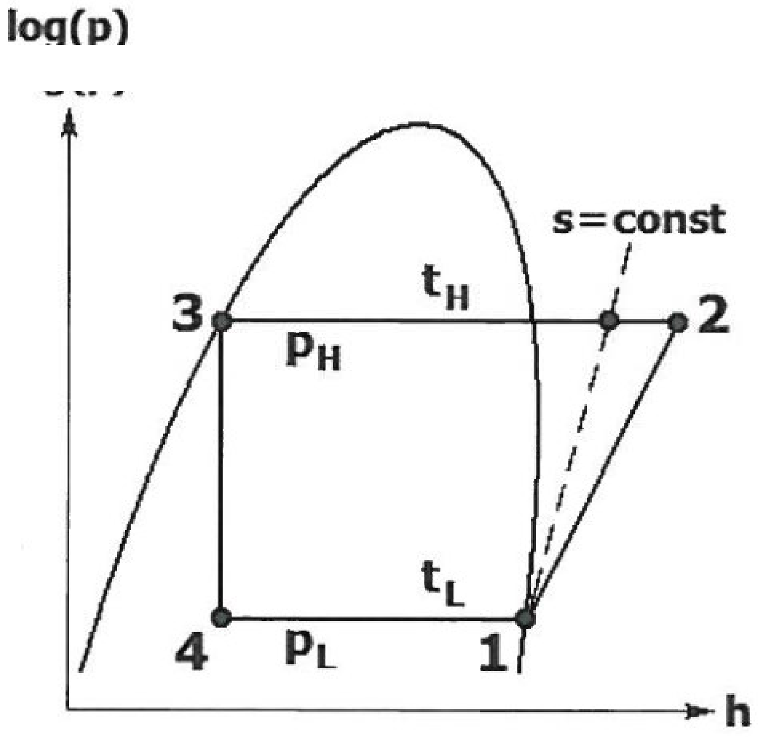

Figure 4.3 Simplified heat pump cycle on the log(p)-h diagram (O. Alves-Filho, 2013)

“These for processes are explained as follows:

1 – 2: **non-isentropic compression**. Here the saturated or slightly superheated vapor is compressed from the evaporating pressure to condensing pressure and temperature and becomes superheated vapor.
2 – 3: **isobaric condensation**. The superheated vapor rejects superheat in the first section of the condenser and becomes saturated vapor. Then, the vapor releases further heat as it flows through the last section of the condenser, changes phase to saturated liquid and is collected in the receiver.
3 – 4: **adiabatic expansion**. Here the saturated or subcooled liquid at high pressure enters the expansion valve and is throttled adiabatically to the lower pressure. At the exit of the valve it becomes a vapor-liquid mixture and flows into the evaporator.
4 – 1: **isobaric evaporation**. The refrigerant mixture flows through the evaporator, takes up the heat from the moist air and changes phase to saturated vapor at the exit of the evaporator. This saturated vapor flows into the compressor to re-start the cycle.” [1]

“The closed heat pump drying air cycle is composed of three processes shown in the Mollier diagram in Figure 4.3:

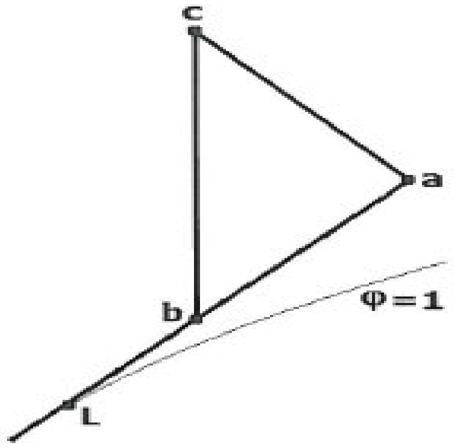

Figure 4.4 Drying air cycle on the Mollier diagram (O. Alves-Filho, 2013)

c – *a*: adiabatic drying process where the drying air at the set temperature flows through the drying chamber and removes moisture from the bed of wet material.

a – *b*: cooling the moist air and water vapor condensation with liquid drainage. As the moist air flows through the evaporator the vapor condenses to liquid and is drained out of the drying loop. To perform this, the evaporator surface is kept at state point *L* with a temperature below the dew-point temperature at the air at the inlet drying chamber (point *c*).

b – *c*: heating of the moist air by the condenser using the energy recovered by the evaporator. The low temperature energy absorbed in the evaporator promotes boiling of the refrigerant, than it is compressed to high temperature energy and re-used by the condenser to heat the drying air. This completes the cycle of energy recovery in the heat pump dryer." [1]

4.4 Principle of heat pump drying

Figure 4.5 represents a schematic configuration of the heat pump drying circuit. The inlet drying air passes through the drying chamber at point 1 and picks up moisture from the product. The moisture-laden air at point 2 is then directed to the evaporator. The dehumidification process occurs from point 2 to 3, where the air is first cooled sensibly to its dew point. Further cooling results in water being condensed from the air. Latent heat of vaporization is then absorbed by the evaporator for boiling of the refrigerant. The recovered heat is recovered in the condenser. The cooled and dehumidified air then absorbed the heat at the condenser moving from point 4 to 1 for sensible heating to the desired temperature.

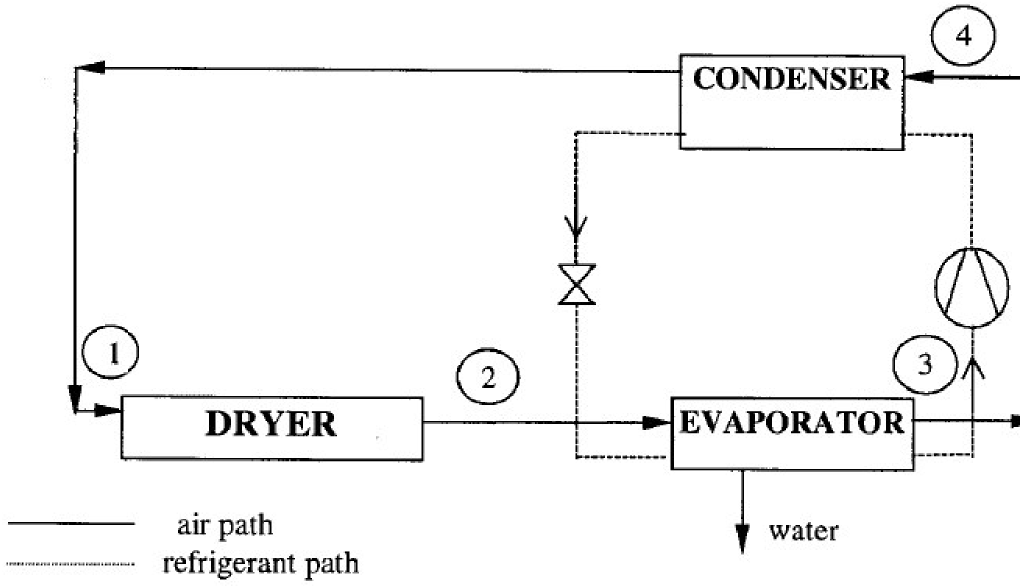

Figure 4.5 Schematic representation of a heat pump drying system [7]

The coefficient of performance (COP) and the specific moisture extraction ratio (SMER) are used as indicators for the dryer performance.

The energy efficiency of the heat pump is related to the coefficient of performance defined as the ratio of the heat absorbed in the evaporator or released by the condenser divided by the energy input to the compressor and blower. Then, the COP is given by:

$$COP = \frac{Evaporator\ heat}{Work\ input} = \frac{\dot{Q}_0}{\dot{W}_c + \dot{W}_f}$$

The maximum theoretical heat pump efficiency is given by the Carnot efficiency as:

$$COP_{Carnot} = \frac{T_{cond}}{T_{cond} - T_{evap}}$$

The COP_{Carnot} is ideal and cannot be physically accomplished but is used to compare a heat pump system with an ideal value. In practice, the actual efficiency of a heat pump is about 40 to 50% of the theoretical Carnot efficiency.

The capacity of water removal of the dryer based on energy input is defined by the SMER as follows:

$$SMER = \frac{amount\ of\ water\ evaporated}{energy\ input\ to\ the\ dryer}$$

Therefore, the SMER (kg/kWh) depends on the heat pump dryer thermal efficiency, temperature and relative humidity of the air in the inlet and outlet of the evaporator and condenser.

4.5 Benefits and limitations

The benefits of heat pump drying are [7]:

- Energy efficiency is improved compared to a conventional dryer. The moisture-laden air leaving the drying chamber has a large amount of latent energy. This energy is recovered when the air passes through the evaporator and recycled back to the heat pump drying cycle. Low energy consumed is achieved per unit of water removed.
- Accurate and independent control of temperature, humidity and airflow rates are possible. This benefits heat-sensitive materials and produce better product quality.
- The dryer is versatile to dry different types of materials requiring operation in a wide range of drying conditions (typically from -20 to 100ºC) and air relative humidities can be generated.
- HPD can be designed accommodating the present trend of using environmentally friendly fluids or natural refrigerants like ammonia, carbon-dioxide and water.

The limitation of this process is:

- Regular and simple maintenance of the compressors, refrigerant filters, heat exchangers etc. are necessary to keep the dryer in optimum operating condition.

5. Materials and Methods

5.1 Experimental design

The experiments were done in the laboratory heat pump drying system shown in Figures 5.1 and 5.2.

Figure 5.1 Side view of the lab heat pump dryer

Figure 5.2 View of the control panel of the heat pump dryer

Three sets of tests were performed under different drying chamber inlet temperatures and psychrometric conditions. Each test had four trays each containing a thin layer of green peas in each one. Hence, a layer of green peas was placed in each tray that was positioned at different heights in the drying chamber, i.e., one tray above the other. Table 5.1 shows the tray numbers for each of the tests and their heights from the perforated plate at the base of the drying chamber, where the height is taken as 0 mm.

Tray	Test A	Test B	Test C	Height (mm)
1	A1	B1	C1	37
2	A2	B2	C2	74
3	A3	B3	C3	111
4	A4	B4	C4	148

Table 5.1 Trays and tests designations and height of each tray from the base of the drying chamber

Initially the frozen green peas were mixed and homogenized to form a large batch. Afterwards, the large batch was portioned into four small batches to be placed in each of the four trays.

The initial mass of each batch of raw material placed in each of the four trays had a 300 ± 0.2 grams, which means that the total initial mass in the drying chamber for each test was 1200 ± 0.8 grams. The frozen green peas were dried at three constant values of drying air temperature and three ranges of relative humidity. The drying chamber inlet temperatures were 25, 35 and 45 °C and the respective ranges of relative humidity are listed in Table 5.2. All the tests were done in stationary bed mode adjusting the air velocity to approximately 1 m/s.

Test	Drying air temperature (°C)	Relative humidity (%)
A	25	25-30
B	35	15-20
C	45	12-20

Table 5.2 Experimental conditions for the three heat pump drying tests

The drying period of the three tests was 4 hours and 20 minutes and the drying chamber was taken out every 20 minutes for sampling and for measuring the change in mass of green peas in the tray. Therefore there are 14 measurements including the initial mass at time 0.

5.2 Heat Pump

The heat pump dryer consists in two separate loops. One loop is used for the working fluid and the other for flowing the drying medium or air. The heat pump's main components are the compressor, condenser, evaporator and throttling valve.

The air entering the drying chamber is set according to experimental psychrometric conditions (temperature and relative humidity). Then, it flows through the batch of green peas removing the moisture. After that the air leaves the bed with higher relative humidity and lower temperature. A consequence of this is that the air capacity to carry water decreases as it moves upward in the next tray in the chamber.

The moist air exhausted from the top tray it is recycled to condense the vapor and drain out of the drying loop the moisture previously removed from the green peas bathes. This is involves moist air cooling in the evaporator, where the moist air is cooled down below the dew point of the mixture causing the water vapor to condense to liquid that is drained out of the system.

After the liquid water is taken out, the dry air flows through the condenser and blower and it is heated to the experimental set point temperature, restarting the drying cycle process.

During the moist air cooling in the evaporator, the heat pump working fluid flows into the inlet of the evaporator, receives energy and at reaching the exit of the evaporator it changes phase to saturated vapor. At this state point it enters the suction line to be compressed to high pressure and temperature.

After this, the heat pump working fluid flows through the condenser and chnges phase from superheated vapor, to saturated vapor and later to saturated liquid. Then, it enters the expansion valve or throttling device where its pressure is reduced as it re-enters the evaporator inlet in a state of vapor-liquid mixture, repeating the process.

5.3 The drying trays and supporting cabinet

The drying trays are placed inside the isolated wooden cabinet made of plywood with styrofoam insulation. The cabinet dimensions are 0.8×0.8 meters in cross section and height of 1.5 meters. The trays are inserted in the drying loop inside the cabinet that has a sampling access door. During sampling this door is opened and closed using two external locks. The cabinet is connected with the drying loop by the inlet and the outlet tubes. The inlet tube is connected with the central base of the cabinet and to the cylindrical trays where the green peas are placed. As previously mentioned the four trays are numbered as 1, 2, 3 and 4. The tray number 1 is the first that receives the inlet air followed by number 2, 3 and the last the tray number 4. The air carrying the water removed from the green peas leaves the cabinet by the outlet tube that is positioned at the upper part of the cabinet. Figure 5.3 shows the wooden cabinet and where the drying air inlet (1) and outlet (2) tubes are positioned.

Figure 5.3 Wooden cabinet and drying air inlet and outlet tubes numbered as (1) and (2) respectively

5.4 Measuring devices

A Mettler Toledo scale (XP 600 2M Delta Range with an accuracy of 0.1 g) was used for measuring the mass of each batch of green peas loaded in each tray. This was done according to the time intervals set for taking out of the four trays from the supporting cabinet.

A color meter, model CFEZ 0531 was used for measuring the color components such as brightness, red-green and yellow-blue.

The density was determined based on standard measurements of mass and volume, using a precision scale (Mettler PM1200, accuracy ± 0.001 g) and a graduated cylinder with an accuracy of ± 1 ml.

5.5 Analysis of data and measurements

5.5.1 Data logger and computer storage

The required experimental and processing conditions were acquired using data logger and stored in computer files. The data of the drying conditions were given by three sensors distributed in different locations and components of the heat pump dryer and drying loops. To obtain the conditions such as temperature and relative humidity of the inlet air a sensor was placed before the entrance of the cabinet. Another sensor was placed at the chamber outlet or in the tube connected to the exhaust of the cabinet. The last sensor was located between the evaporator and the condenser. Finally, another sensor provided the data of the air velocity.

5.5.2 Water content

The water content of the green peas sample is defined either on wet basis or on dry basis. The moisture content on wet basis (w_{wb}) is calculated by dividing the initial mass of water (m_w) in the sample with the total mass (m_t) of the sample. This total mass is the sum of the mass of water in the sample and mass of dry matter (m_d). Then, the moisture content on wet basis is obtained according to equation 1:

$$w_{wb} = \frac{m_w}{m_t} = \frac{m_w}{m_w + m_d} \qquad (1)$$

And the moisture content on dry basis (w_{db}) is calculated by dividing the mass of water (m_w) in the sample with the mass of dry matter (m_d) as shown in the equation 2:

$$w_{db} = \frac{m_w}{m_d} \qquad (2)$$

The procedure to measure the moisture content was as follows: three samples of green peas were placed in three pirex-glass containers whose mass was already measured. Then, containers with the sample were put inside an oven set on 105 °C and left for 24 hours. After this period the containers were taken out from the oven and the mass measure again. The difference in these masses represented the evaporated water from the raw material. With this information and using the equations (1) and (2) the moisture contents, in wet and dry basis, were calculated. Finally, the average moisture contents from triplicates samples were more accuracy obtained. Details of this data measurements are listed in the chapter “Results and Discussion”.

5.5.3 Color measurements

To measure the color parameters, small samples were taken from each of the dried batches. These samples were crushed using a porcelain mortar and pestle. This provided a uniform mass that was placed into a standard container that was held below the optical sensor of the color meter. The measured color components correspond to three values that are defined as follows:

- L: Brightness and darkness of the sample
- a: red and green content of the sample
- b: yellow and blue content of the sample

5.5.4 The bulk density

The bulk density (ρ_b) is defined as the mass of green peas particles divided by the total volume they occupy. The total volume includes particle volume, inter-particle void volume and internal pore volume [Wikipedia]. This is expressed on the equation (3):

$$\rho_b = \frac{m}{V} \qquad (3)$$

The fresh and dried samples were placed in the graduated cylinder and the volumes were measured. Then, the cylinder whose mass was already known, was placed in a scale to measure the mass and the each net sample mass was obtained by difference. The bulk densities were calculated using these values and equation (3).

6. Results and discussion

6.1 Drying kinetics

Table 6.1 shows the moisture content on dry basis of the test A that was done with a temperature of 25 °C and relative humidity in the range of 25 to 30%. It shows the evolution of drying every 20 minutes in the four trays. These trays were placed one above the other in different heights as it has been explained in the chapter 5.

Moisture content in dry basis (%) for test A				
Time (min)	A1	A2	A3	A4
0	314.78	314.78	314.78	314.78
20	246.28	284.93	311.45	324.16
40	197.29	239.77	280.38	303.44
60	162.20	196.54	241.29	274.16
80	136.79	162.84	201.65	240.05
100	116.77	137.70	167.81	204.83
120	100.89	118.36	141.84	172.92
140	87.92	102.62	121.82	146.54
160	77.97	90.60	106.62	126.51
180	69.41	79.97	93.09	109.52
200	61.96	70.85	81.76	95.30
220	56.44	64.08	73.20	84.80
240	50.50	57.32	64.91	75.00
260	47.46	53.45	60.22	69.33

Table 6.1 Experimental data of w_{db} versus time for test A

It is observed from the test that the tray in the bottom (A1) is the one with the lowest moisture content during and at the end of the drying. Similar tendency is presented by each of the lower positioned trays, that has lower moisture content or more moisture is extracted from that batch. Although, as it is shown in Table 6.1, this difference decreases as time goes by and at the final time the trend is, for the four trays, to have similar moisture contents. These data are plotted in Figure 6.1 that very clearly confirms the mentioned tendency.

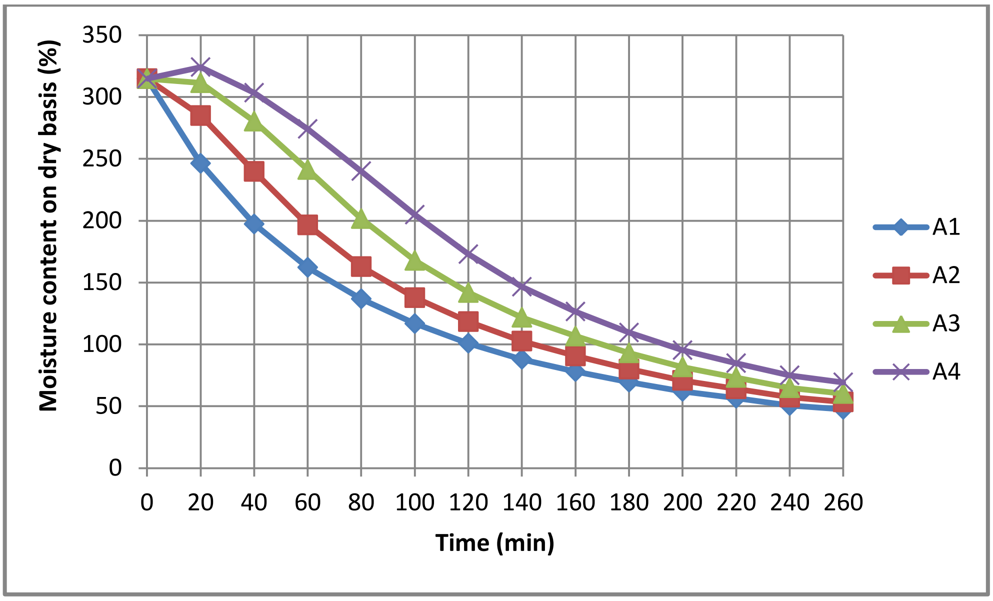

Figure 6.1 Moisture content in dry basis versus time for test A

Table 6.2 shows the development of moisture content on dry basis for the test B done with a temperature of 35 °C and relative humidity in the range of 15 to 20%. The interval of the sampling and the positions of the four trays are the same as the previous test.

Moisture content in dry basis (%) for test B				
Time (min)	B1	B2	B3	B4
0	314.78	314.78	314.78	314.78
20	211.70	253.30	286.02	312.69
40	157.12	187.15	223.69	268.76
60	121.48	143.23	167.99	212.80
80	96.88	114.50	131.92	165.14
100	79.61	94.06	107.59	132.25
120	65.66	71.96	87.83	106.42
140	55.43	65.33	73.59	88.18
160	48.25	56.21	62.53	74.36
180	40.37	46.96	52.45	61.93
200	37.61	43.50	48.16	56.40
220	32.78	37.70	41.25	47.42
240	30.01	34.25	37.24	42.58
260	27.53	31.07	33.65	37.89

Table 6.2 Experimental data of w_{db} versus time for test B

What is observed from this data is that the trend is the same as previously described and that means that the tray in the bottom (B1) is the one with the lowest moisture content and the one in the top (B4) is the one with highest moisture. Although the tests (A, B and C) will be compared later, the data shows that the water removal obtained from this test is higher than the one measured in test A.

It is also interesting to compare both tests and is observed that the difference of the final moisture contents between tray 1 (A1 and B1) and tray 4 (A4 and B4) is reduced from 21.87 to 10.36 %. Therefore there is a closer gap of water removal between the trays. The experimental data from test B is presented in Figure 6.2.

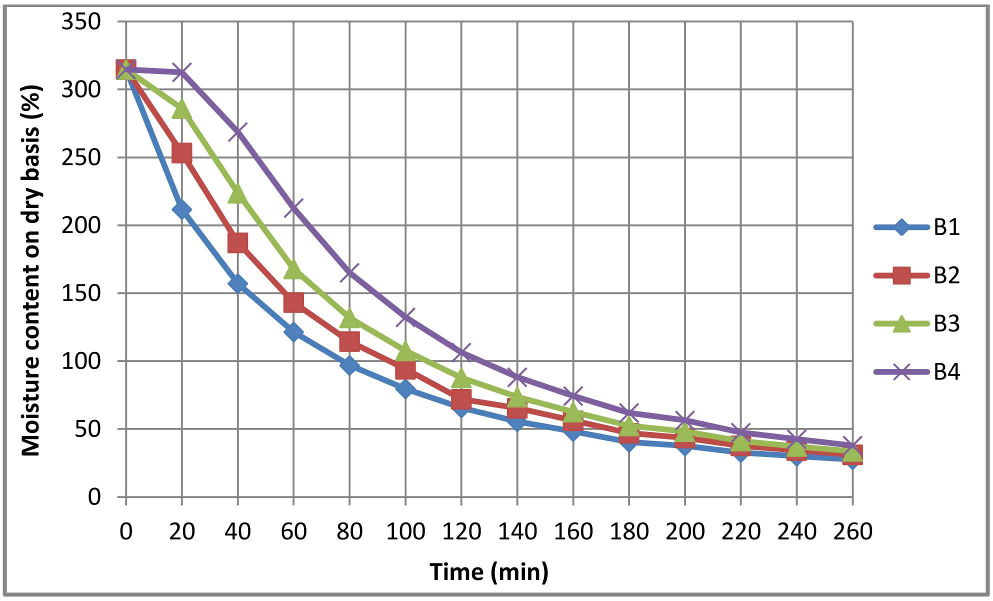

Figure 6.2 Moisture content in dry basis versus time for test B

Table 6.3 gives the experimental data for test C. This test was executed with 45 °C, the highest temperature of the three tests, and with relative humidity in the range from 12 to 20%. As the other tests, the measurements were obtained every 20 minutes and the four trays were positioned in the same way as described before.

Moisture content in dry basis (%) of the test C				
Time (min)	C1	C2	C3	C4
0	314.78	314.78	314.78	314.78
20	208.42	255.24	296.81	315.60
40	140.32	169.47	214.05	251.79
60	102.48	121.82	151.32	185.90
80	77.48	92.81	117.47	152.62
100	62.84	74.30	93.15	118.50
120	47.51	55.24	68.15	85.08
140	40.33	46.13	56.26	69.33
160	33.42	37.70	45.21	54.69
180	29.00	32.18	38.03	41.02
200	25.41	27.76	32.36	37.98
220	22.51	24.03	27.80	31.90
240	20.58	21.68	24.76	27.90
260	18.92	19.75	22.27	24.72

Table 6.3 Experimental data of w_{db} versus time for test C

The data results indicate that the tendency of the tray in the bottom to attain the lowest moisture while the tray on the top the highest moisture. As already mentioned for the two tests A and B, with the increasing in the temperature of the inlet air, the water removal difference between the four trays becomes lower. For this case, the difference is 5.80 % between tray 1 and 4, which is small value because the initial moisture content of both trays was 314.78 %. The data from Table 3 for test C is plotted in Figure 6.3.

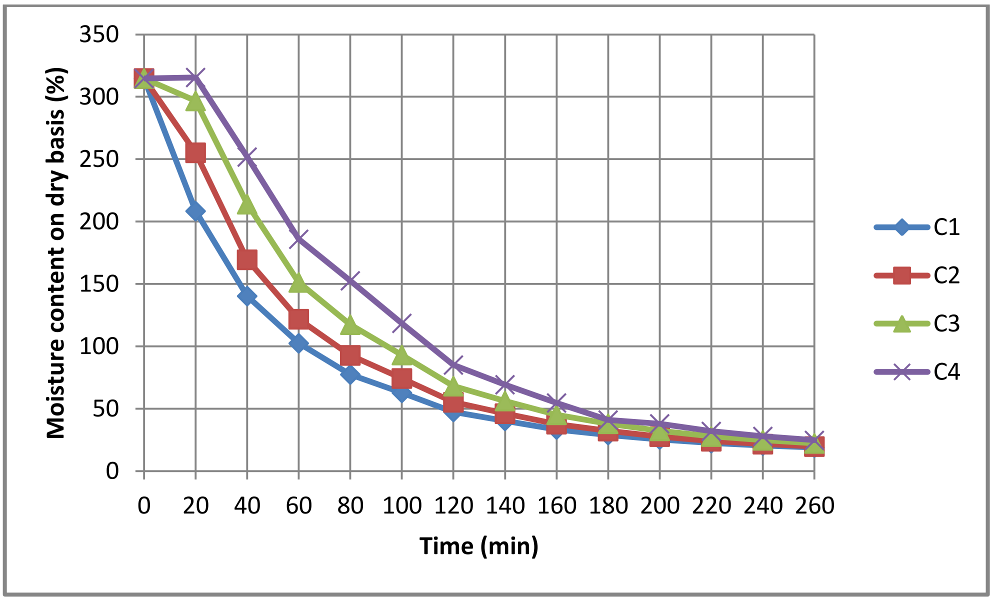

Figure 6.3 Moisture content in dry basis versus time for test C

The tests results presented so far were on development of moisture content considering the dry basis. Now the results will be presented taking into account calculations in wet basis.

Table 6.4 shows the development of moisture content on wet basis of the test A and the results are plotted in Figure 6.4.

Moisture content in wet basis (%) of the test A				
Time (min)	A1	A2	A3	A4
0	75.87	75.87	75.87	75.87
20	71.12	74.02	75.70	76.42
40	66.36	70.57	73.71	75.21
60	61.86	66.28	70.70	73.27
80	57.77	61.95	66.85	70.59
100	53.87	57.93	62.66	67.19
120	50.22	54.20	58.65	63.36
140	46.78	50.65	54.92	59.44
160	43.81	47.53	51.60	55.85
180	40.97	44.43	48.21	52.27
200	38.26	41.47	44.98	48.80
220	36.08	39.06	42.26	45.89
240	33.55	36.43	39.36	42.86
260	32.19	34.83	37.58	40.94

Table 6.4 Experimental data of w_{wb} versus time for test A

Comparison of moisture contents will now be made between four trays considering intervals in the whole drying time.

It can be observed for test A that, in the first interval of 20 minutes, tray 1 showed the highest water removal, which is about 4.75%. Also is seems that tray 4 has even gained some moisture and comparing to the initial value it changes from 75.87 to 76.42%. This is explained by air and product mass balance and relative position of trays. Since tray 4 is placed on the top of others it gains moisture because the drying air becomes saturated as it flows through and removes moisture from the trays below.
Observing at half of the drying period or between 120 and 140 minutes drying, the water removal in the four trays has been stabilized to around the 4%. In the last time interval of 240 to 260 minutes the water removal drops asymptotically in all trays.

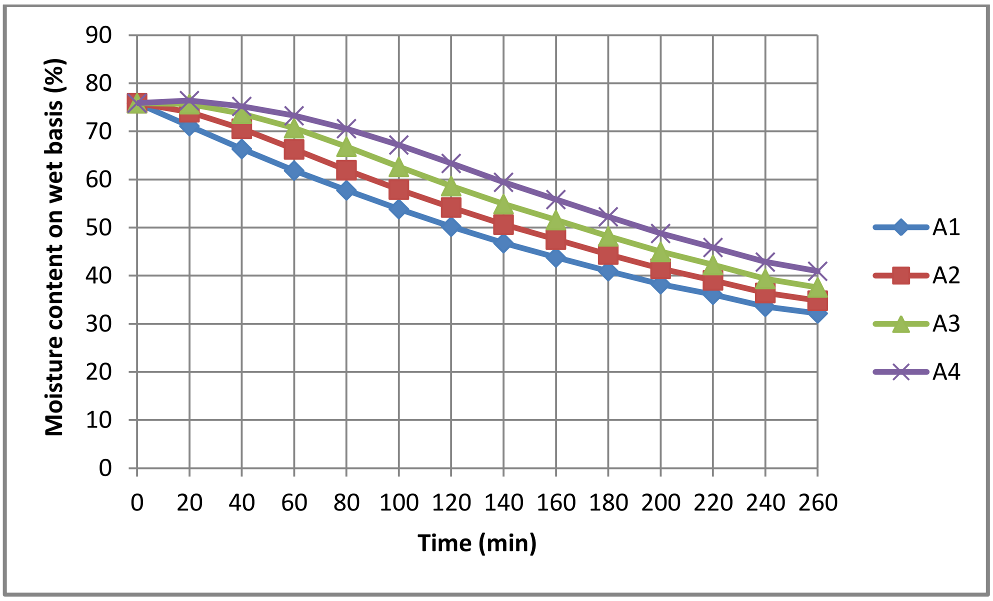

Figure 6.4 Moisture content in wet basis versus time for test A

Table 6.5 presents the development of moisture content for test B and the results are plotted in Figure 6.5.

Moisture content in wet basis (%) for test B				
Time (min)	B1	B2	B3	B4
0	75.87	75.87	75.87	75.87
20	67.92	71.70	74.09	75.77
40	61.11	65.17	69.11	72.88
60	54.85	58.89	62.69	68.03
80	49.21	53.38	56.88	62.28
100	44.32	48.47	51.83	56.94
120	39.63	41.85	46.76	51.55
140	35.66	39.51	42.39	46.86
160	32.55	35.98	38.47	42.65
180	28.76	31.95	34.40	38.24
200	27.33	30.32	32.51	36.06
220	24.68	27.38	29.20	32.17
240	23.08	25.51	27.14	29.87
260	21.58	23.71	25.18	27.48

Table 6.5 Experimental data of w_{wb} versus time for test B

Considering the first interval from 0 to 20 minutes, the highest water removal is achieved in tray 1 with a percentage value of 7.95%. The lowest removal is for tray 4 with a moisture removal of 0.10%. During the period from 120 to 140 minutes the removal was about 4 %, except for the tray 2 whose value was 2.34%. In the final period of this test, the values are between 1.5 and 2.39%, with the lowest value for tray 1 and the highest for tray 4.

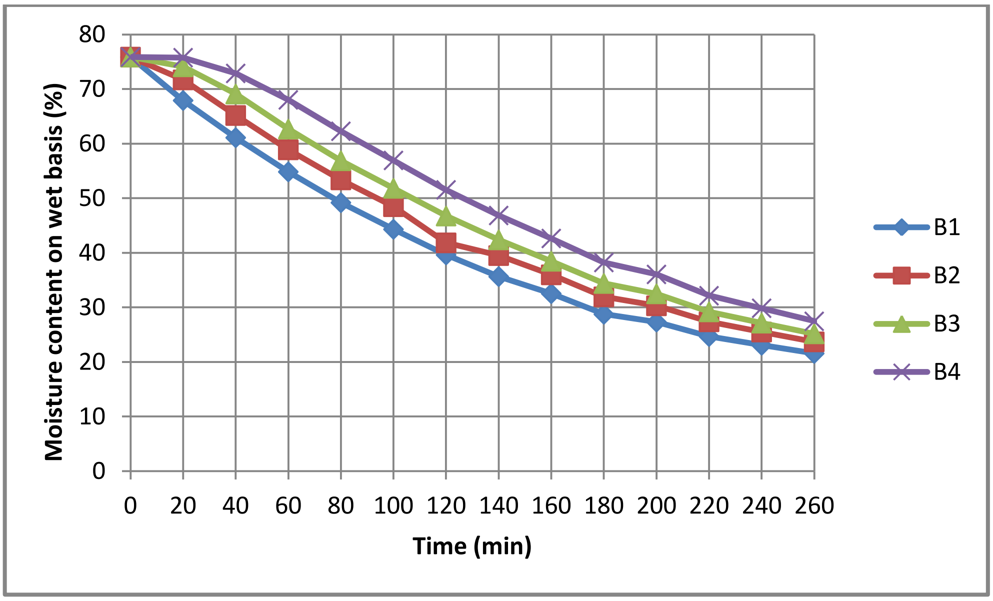

Figure 6.5 Moisture content in wet basis versus time for test B

Table 6.6 presents the experimental moisture content in wet basis of the test C.

Moisture content in wet basis (%) for test C				
Time (min)	C1	C2	C3	C4
0	75.87	75.87	75.87	75.87
20	67.58	71.85	74.80	75.94
40	58.39	62.89	68.16	71.57
60	50.61	54.92	60.21	65.02
80	43.66	48.14	54.02	60.41
100	38.59	42.63	48.23	54.23
120	32.21	35.59	40.53	45.97
140	28.74	31.57	36.01	40.94
160	25.05	27.38	31.13	35.36
180	22.48	24.34	27.55	29.09
200	20.26	21.73	24.45	27.53
220	18.37	19.37	21.75	24.19
240	17.07	17.82	19.85	21.81
260	15.91	16.49	18.22	19.82

Table 6.6 Experimental data of w_{wb} versus time for test C

As indicated in Figure 6.6 the previous tendency occurs in the first interval of time where tray 1 has the highest water removal with a value of 8.29% and tray 4 even gains 0.07% of moisture content. Between 120 and 140 minutes the trend changes and the moisture content for tray 4 drops 5.03% and for tray 1 the moisture drops to 3.47%. In the final time interval the values are between 1.16 and 1.99%, which is in a lower range of drying since most moisture has already been removed.

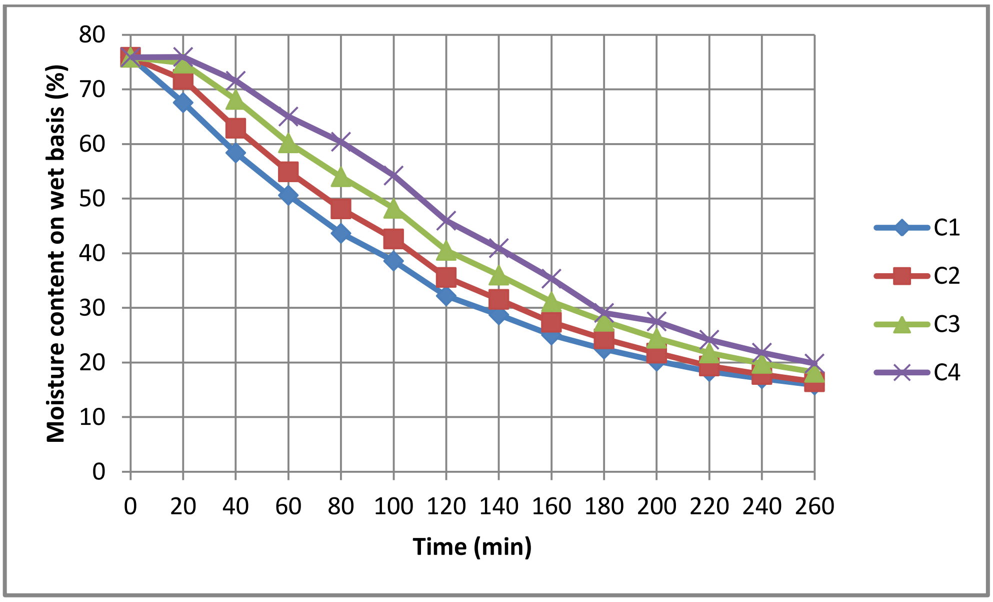

Figure 6.6 Moisture content in wet basis versus time for test C

The drying and moisture content will now be compared considering trays placed in the same levels but for different tests. Then, we first select trays in the extreme position such as tray 1 and 4. Table 6.7 shows the moisture contents for each tray 1 in the three tests and comparison is based on moisture content in wet basis.

Moisture content in wet basis (%) for tray 1 in each of the three tests			
Time (min)	A1	B1	C1
0	75.87	75.87	75.87
20	71.12	67.92	67.58
40	66.36	61.11	58.39
60	61.86	54.85	50.61
80	57.77	49.21	43.66
100	53.87	44.32	38.59
120	50.22	39.63	32.21
140	46.78	35.66	28.74
160	43.81	32.55	25.05
180	40.97	28.76	22.48
200	38.26	27.33	20.26
220	36.08	24.68	18.37
240	33.55	23.08	17.07
260	32.19	21.58	15.91

Table 6.7 Experimental data of w_{wb} versus time for tray 1 in each of the three tests

The highest moisture removal for the given drying period was for test C that reached 15.91% moisture content. Test B follows with a moisture content of 21.58% while test A reaches a 32.19% for the same drying period. Another aspect shown by these data is that the difference between tests is higher between tests A and B than between tests B and C. This is clearly seen in Figure 6.7.

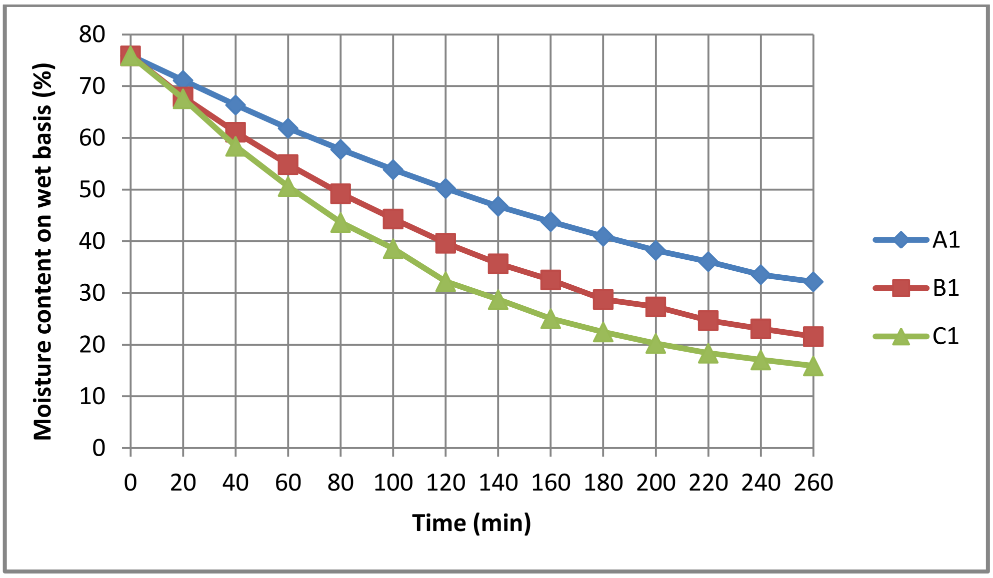

Figure 6.7 Moisture content in wet basis versus time for tray 1 for three tests

Table 6.8 shows the experimental data for tray 4 in each tests.

Moisture content in wet basis (%) for tray 4 in each of the three tests			
Time (min)	A4	B4	C4
0	75.87	75.87	75.87
20	76.42	75.77	75.94
40	75.21	72.88	71.57
60	73.27	68.03	65.02
80	70.59	62.28	60.41
100	67.19	56.94	54.23
120	63.36	51.55	45.97
140	59.44	46.86	40.94
160	55.85	42.65	35.36
180	52.27	38.24	29.09
200	48.80	36.06	27.53
220	45.89	32.17	24.19
240	42.86	29.87	21.81
260	40.94	27.48	19.82

Table 6.8 Experimental data of w_{wb} versus time for tray 4 in each of the three tests

Observing the data for tray 4 confirms similar trend as for tray 1. The difference between test C and B is smaller than between test A and B. It is also observed that in the initial period of drying that the moisture content rises but at the period between 120 to 140 minutes the difference stabilizes and remains as such until the end of drying. These results and mentioned discussions are observed in the graph in Figure 6.8.

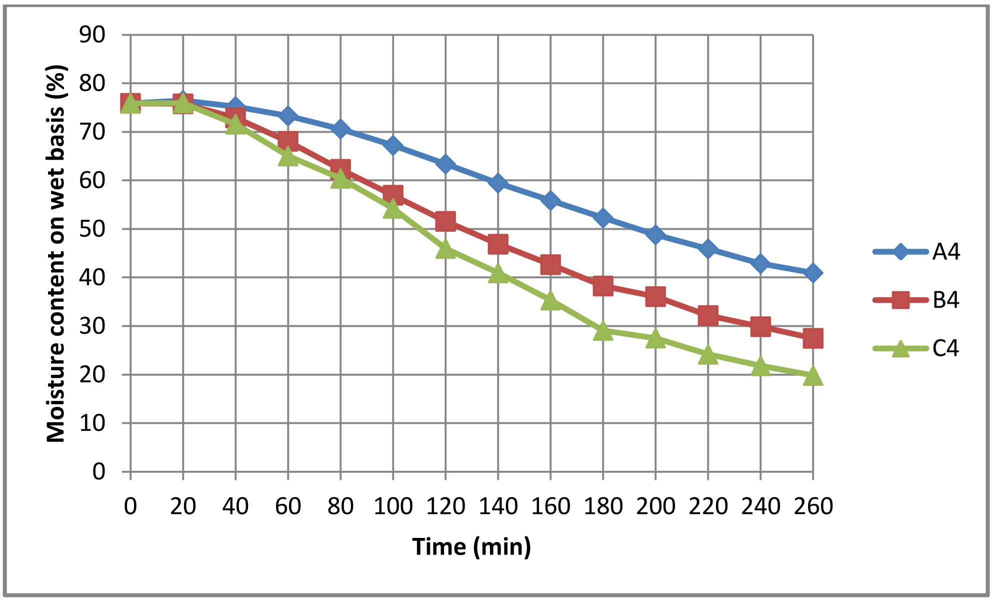

Figure 6.8 Moisture content in wet basis versus time for tray 4 for three tests

6.2 Color

The color measurements for the tests are shown in Table 6.9, 6.10 and 6.11 and results are plotted in Figures 6.9, 6.10, 6.11, 6.12, 6.13 and 6.14. Table 6.9 gives the measured color data for trays in test A as well as the reference color of the frozen green peas (Jovanović, Alves-Filho 2003).

Color measurements in test A				
Test	Tray	L	a	b
Frozen	Reference*	53.51	-8.81	71.33
A	A1	50.65	-9.95	35.04
	A2	48.25	-10.57	31.07
	A3	48.61	-8.98	27.88
	A4	45.71	-8.58	27.05

Table 6.9 Color measurements for trays in test A (* reference from Jovanović, Alves-Filho 2003)

The data in Table 6.9 shows that the green peas in tray 1 have the highest values for brightness and yellow color content, while the peas in tray 2 present the highest green color value. Contrarily, peas in tray 4 present the lowest values of these colors. These results are more evident when plotted as done in Figure 6.9.

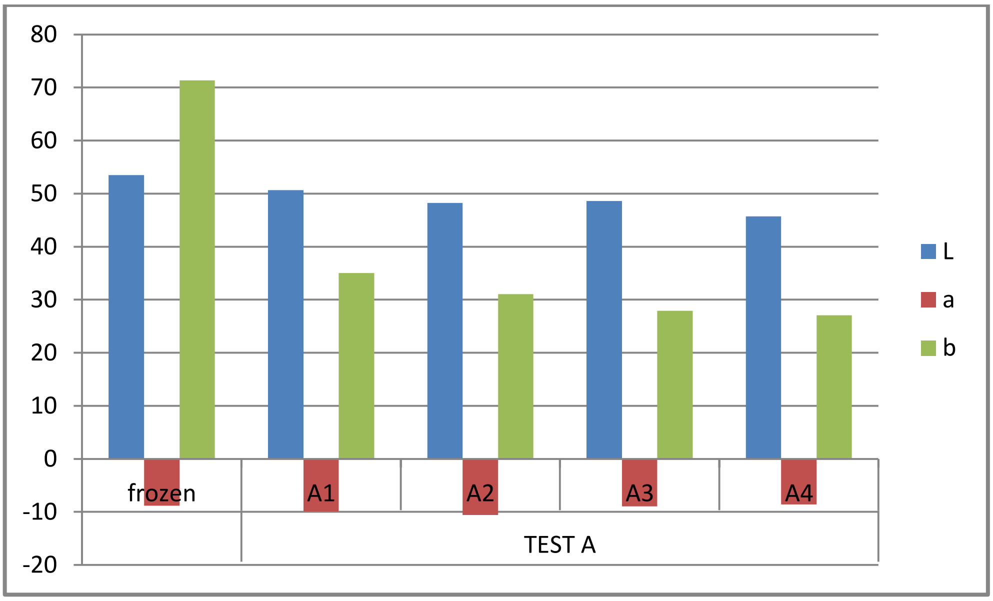

Figure 6.9 Color measurements of green peas in frozen state and dried in test A

The color measurements for test B are shown in Table 6.10.

Color measurements in test B				
Test	Tray	L	a	b
Frozen	Reference	53.51	-8.81	71.33
B	B1	50.24	-10.34	29.54
	B2	49.09	-9.32	28.80
	B3	49.43	-9.54	28.22
	B4	48.47	-10.33	30.16

Table 6.10 Color measurements for trays in test B

Comparing the four trays in test B it can be seen that, similarly to test A, the highest value of brightness is in the tray 1 and the lowest in the tray 4. As related to the green content, the data shows that trays 1 and 4 have the highest values. Trays 4 and 2 have the highest and the lowest yellow content among the batches. The results are graphically shown in Figure 6.10.

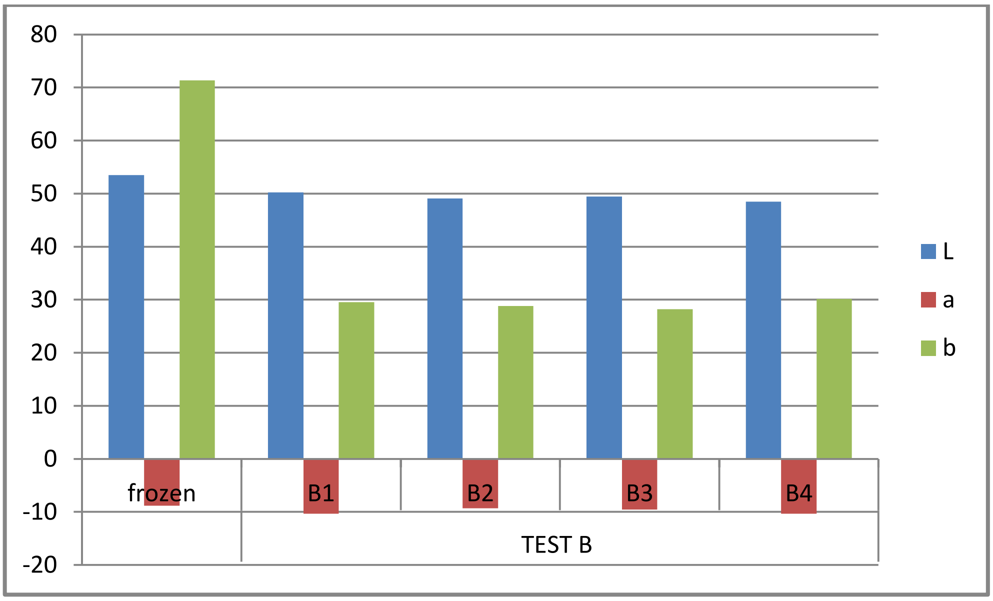

Figure 6.10 Color measurements for green peas in frozen state and dried in test B

Table 6.11 gives the results of color measurements for frozen green peas and product dried in trays of test C.

Color measurements in test C				
Test	Tray	L	a	b
Frozen	Reference	53.51	-8.81	71.33
C	C1	52.96	-10.06	31.42
	C2	48.81	-9.85	29.41
	C3	50.91	-9.83	30.68
	C4	50.26	-9.42	29.32

Table 6.11 Color measurements for green peas in frozen state and dried in test C

The data and results are also plotted in Figure 6.11. It shows that the brightness for test C follows similar trends as the other two tests. The highest brightness value is achieved in tray 1. Also the highest green and yellow contents are achieved in tray 1. The lowest brightness is for the tray 2 and the lowest green and yellow components are for the tray 4.

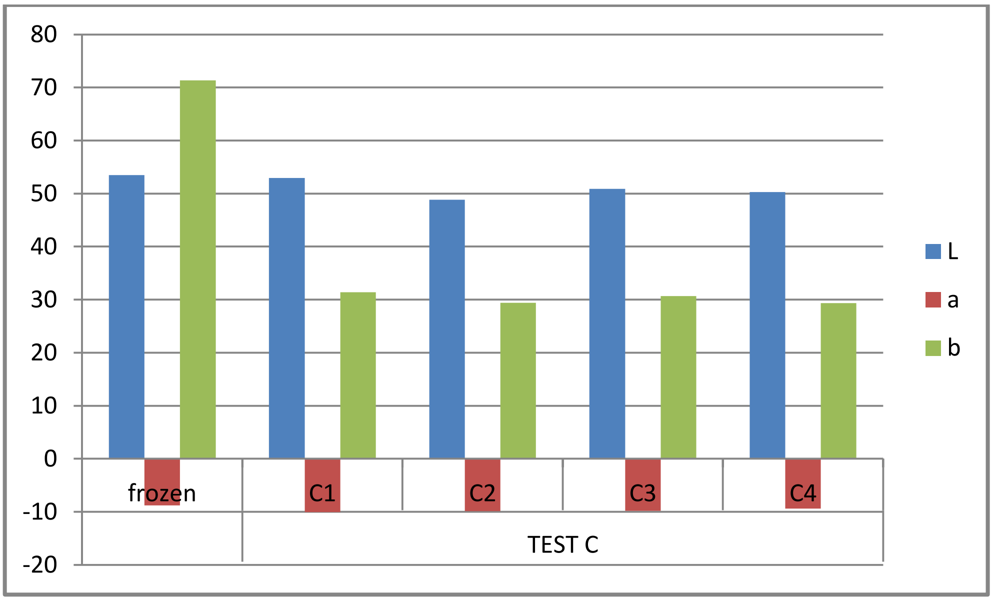

Figure 6.11 Color measurements for green peas in frozen state and dried in test C

So far we have compared samples dried at different trays or heights while drying was done at the same air inlet temperature. Let's now compare differences in all tests dried at different temperatures and different trays. The results on brightness for the three tests and each of the four trays are plotted in Figure 6.12.

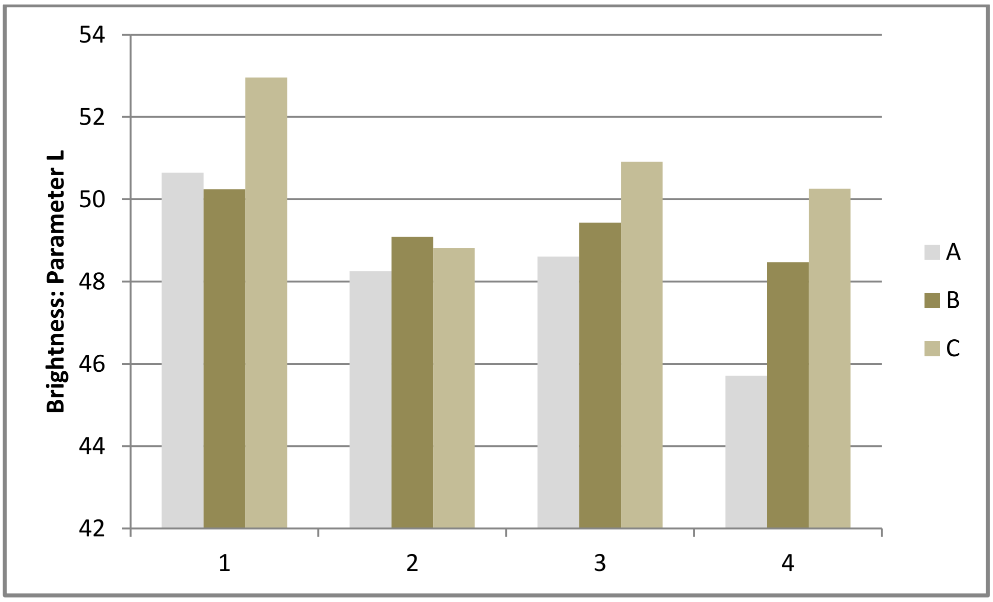

Figure 6.12 Comparison of brightness for the three tests and each of the four trays. Heat pump dried at A: 25°C, B: 35°C and C: 45°C

It is observed that test C samples, dried at 45°C, presents higher brightness in all trays except tray number 2 with brightness very close to the value achieved in test B. The lowest brightness values are samples dried at 25 °C in test A, except samples in tray 1 that with brightness slightly higher than test B. The intermediate brightness values are for samples dried at 35°C in test B, as indicated for trays 1, 3 and 4 while it presents the highest brightness in tray 2.

The results on green color content for all tests and trays are shown in Figure 6.13.

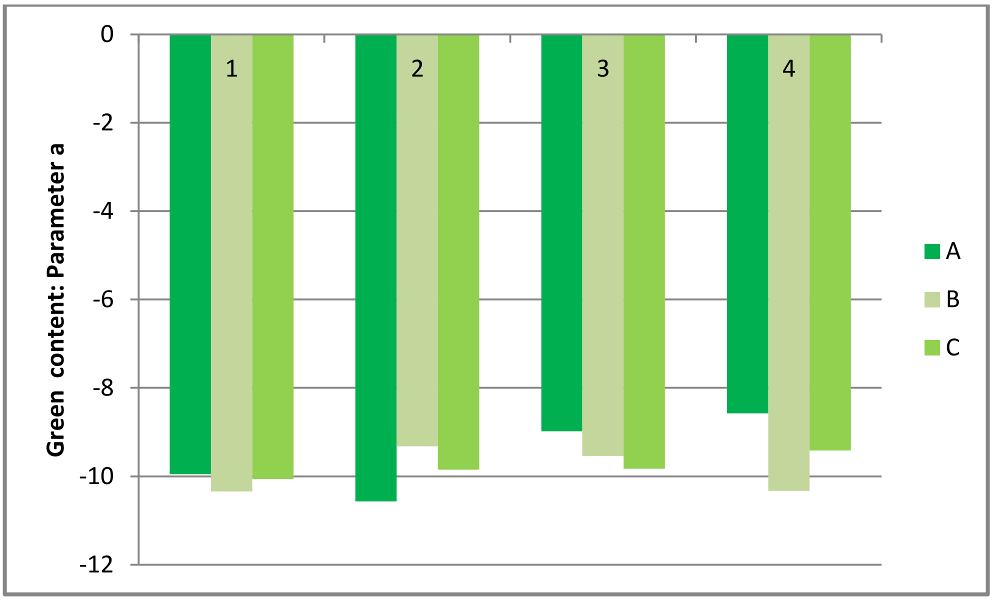

Figure 6.13 Comparison of green color content for the three tests and each of the four trays

The results show that the samples with highest green content in first and last trays are for test B that was dried at 35°C. The highest green content in the second and third trays are for test A dried at 25°C and for test C dried at 45°C, respectively.

The results on yellow color content for the three tests and four trays are plotted in Figure 6.14.

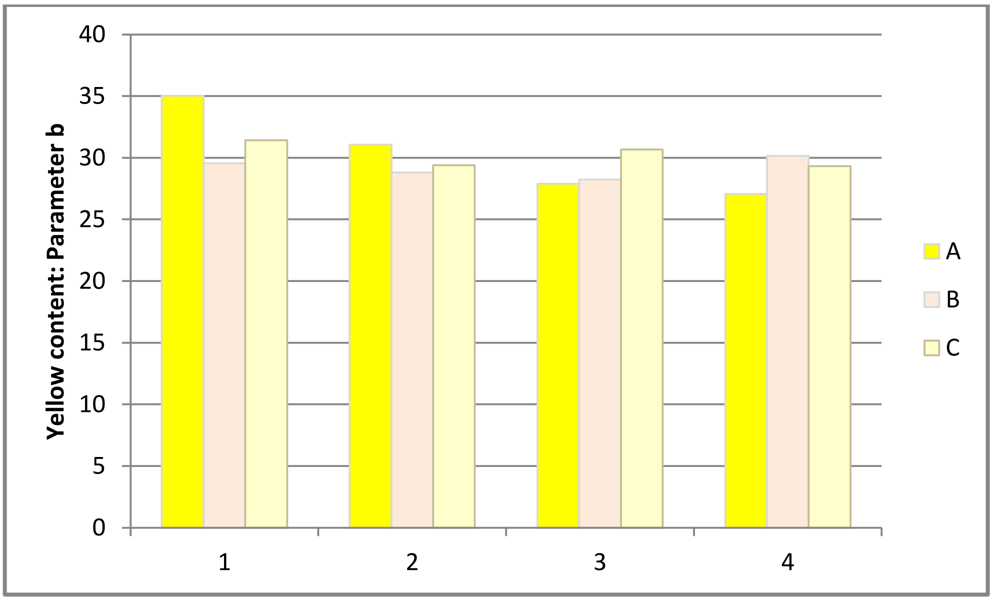

Figure 6.14 Comparison of yellow color content for the three tests and each of the four trays

The results show that test A has the highest yellow color contents in the first and second trays. Test A has the lowest amounts of yellow in the third and fourth trays, where the highest values are for test C and B, respectively. However, the lowest yellow values are very similar in the two intermediate trays.

6.3 Bulk density

The bulk density of the green peas dried in the three tests and four tray levels are presented in Table 6.12. For better comparison the results are plotted in Figures 6.15 and 6.16.

Bulk density measurements for the tests A, B and C		
Test	Tray	Bulk density
A	1	312.39
	2	305.20
	3	354.31
	4	360.48
B	1	322.70
	2	327.01
	3	332.65
	4	334.92
C	1	344.36
	2	350.78
	3	362.20
	4	361.22

Table 6.12 Bulk density measurements of the three tests and four trays

The density data in Table 6.12 can be better compared by plotting the results in two different ways. The first procedure is shown in Figure 6.15 where it is possible to compare the bulk density for all tests and for the four trays.

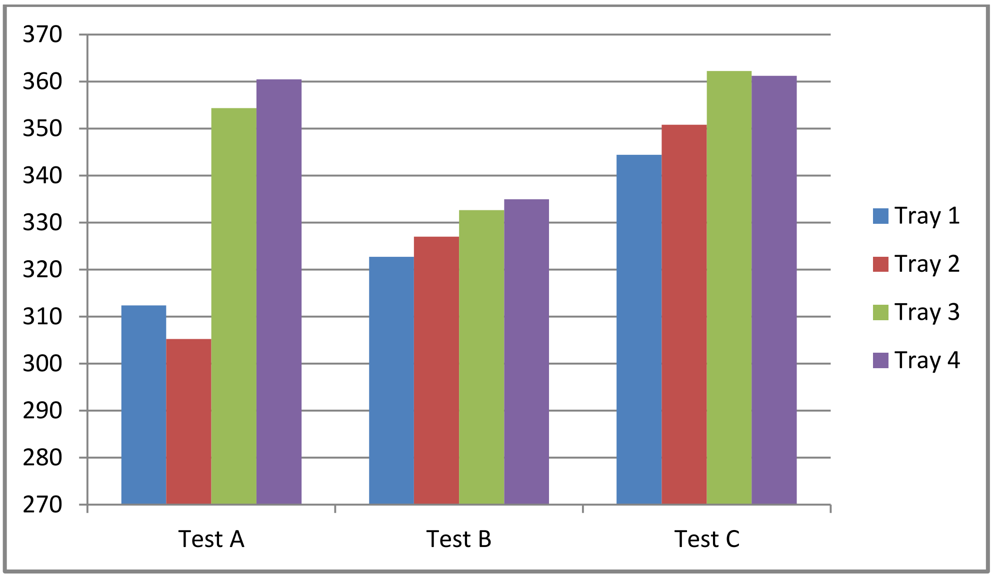

Figure 6.15 Comparison of bulk density data for the three tests and four trays (1)

It is generally observed that the bulk density increases directly with the tray height for all tests. This is a regular pattern in the three tests except for test A and small difference in test C. Then, in test A the bulk density is higher for tray 1 than for tray 2 and in test C the bulk density is slightly higher in tray 3 than in tray 4 but this difference is very small.

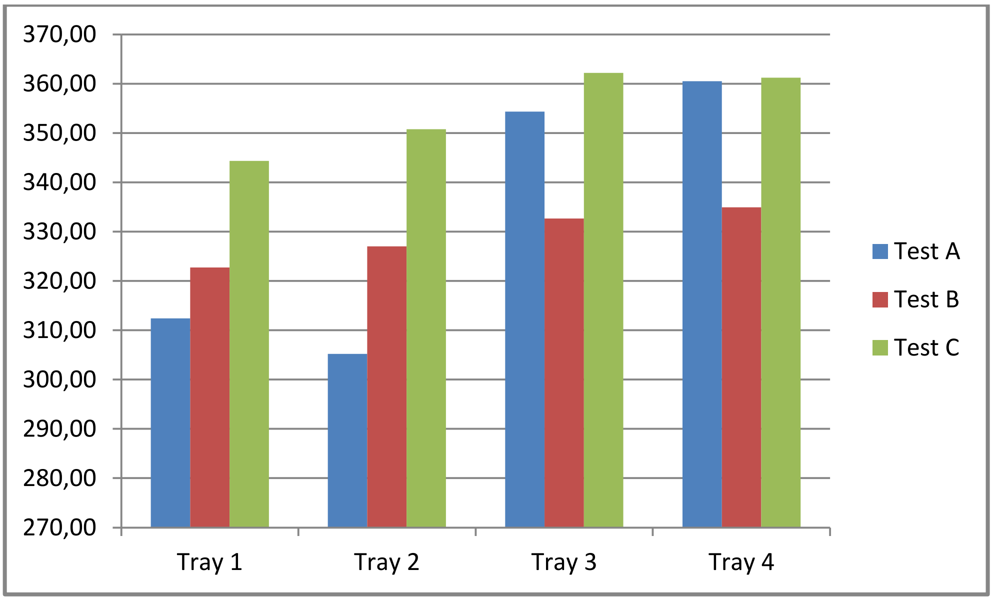

Figure 6.16 Comparison of bulk density for the three tests and four trays (2)

The other way to compare the density data is presented in Figure 6.16, which allows easy comparison between the three tests and trays.

It is observed that test C, dried at 45^{o}C, has the highest bulk density considering the four trays. The lowest bulk density is test A dried at 25^{o}C while the intermediate bulk density is for test B dried at 35^{o}C.

7. Conclusions

This master thesis work focused on the evaluation of the capacity of water removal from green peas applying a new laboratory heat pump dryer. Measurements made both during and after the drying period provided data and analysis was done on the attributes related to quality and characterization the product. The experiments were divided into three tests (A, B and C) and 12 drying trays. The green peas drying conditions for were set differently for each test. Test A was set at 25°C and relative humidity between 25 and 30%, Test B at 35°C and relative humidity between 15-20% and the test C was set at 45 °C and relative humidity in the range of 12-20%.

The conclusion drawn from experimental drying kinetics is that, during and after drying, the top and bottom trays present lowest and highest moisture contents, respectively. This is commonsense but the results indicated two factors affecting such moisture difference between trays. The first is that as drying time increases the moisture difference between trays drops. For instance, for the drying period of 260 minutes the difference between trays was smallest than any period smaller than time. Another factor is that as the drying temperature increases the moisture difference drops. The smallest moisture difference between trays was for Test C done with the highest drying temperature.

Based on the results and range, tests with higher inlet air temperature produced the highest water removal. It is well accepted that air inlet relative humidity inversely affects kinetics. Test B and C were done at the same range of relative humidity and both had higher water removal than test A done at lowest temperature. However, test C, done at higher temperature, had much higher water removal than test B. This indicates that temperature strongly governs water removal when compared to the relative humidity used in the tests.

The qualities examined in fresh and dried green peas were color and bulk density.
As related to color the first conclusion is that the brightest color attributes is for green peas in tray 1, which is the first to receive the drying air. The same tray in Test A and C has also the highest yellow color content and in Test B and C it achieves the highest green color content. Comparing brightness of the dried green peas it is observed that Test C has highest values while Test A has the lowest.

The conclusion drawn for bulk density is that, generally, the higher the drying air temperature the higher the final bulk density achieved. Usually, the density increases as the position of the tray is higher. Therefore, tray 4 has the highest values and the tray 1 the lowest. However, the density difference with height for Test A and Test C was small.

8. Recomendations for future reaserch

We find that there can be several further research works for the thin-layer modeling in heat pump drying. The first one could be to have a wide range and variety of independent variables such as the temperatures and the relative humidities of the inlet air. We propose to move to colder and warmer temperatures and especially varying the relative humidity for each temperature at least in two values. After that way we can evaluate which is the role of both independent variables and which one favors more directly the thin-layer drying of green peas. Also it would be interesting to study the effect of several heights in the efficiency of the heat pump drying process. Therefore it would be important to calculate the amount of energy spent in each of the processes with varying settings of the operating conditions.

Another consideration is that our experiments have been executed as a batch process, which is important in small production. However, for large industrial manufacturing the tests should be in continuous operation as required in large scale. Hence, it would be constructive to consider the continuous mode to portray similar conditions of the industries applications.

It would be profitable to add in drying kinetics the calculations and propose a model taking in account the temperature, the relative humidity of the drying air and also the different heights were the green peas are placed in the drying chamber.

Finally, further works must be focused on improving the efficiency of the drying process, since we know that an effective drying processes as well as product quality are always important for the industry and the costumer.

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