NTNU – Trondheim
Norwegian University of
Science and Technology

Quality Characterization and Modeling Experimental Kinetics in Pilot Scale Heat Pump Drying of Green Peas

Stefan Jovanovic

Master's Thesis
Submission date: June 2013
Supervisor: Odilio Alves-Filho, EPT

Norwegian University of Science and Technology
Department of Energy and Process Engineering

NTNU
Norwegian University
of Science and Technology

Department of Energy
and Process Engineering

EPT-M-2013-61

MASTER THESIS

for

STEFAN JOVANOVIC

Spring 2013

Quality Characterization and Modeling Experimental Kinetics in Pilot Scale Heat Pump Drying of Green Peas

Kvatlitet karakterisering og modellering kinetiks i Pilotskala varmepumpe for tørking av grønne erter

Background and objective

Heat pump drying is an innovative drying technology developed at NTNU to operate at atmospheric pressure and controlled temperatures for high coefficient of performance. The tests made have indicated that his new dryer has high energy efficiency, produce superior quality product and that it is an environmentally friendly process. Another advantage related to acquiring experimental data is that the pilot is available at the laboratory.

This master work covers the experiments and modeling green peas drying on a pilot scale heat pump dryer. Focus will be given on the effect of heat pump operating conditions, drying temperature and relative humidity on kinetics and on the dried product characteristics. Other measurements and analysis will include moisture content, moisture ratio, drying rate, color, sorption isotherms and bulk-particle density.

The procedure will involve mixing and homogenizing a large batch of green peas that will sub-divided into eight uniform batches and stored in frozen state. After that the drying tests will be done according the following experimental design.

Run	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
t, °C	**45**	45	35	35	35	15	15	15
φ, %	40	20	60	40	20	60	40	20

The following tasks are considered in this work:

1. to review the literature on drying of green peas and vegetables
2. to prepare the eight batches of green peas for the heat pump drying tests
3. to perform tests according to the experimental design
4. to collect and to analyze data on kinetics and quality parameters
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, 16. January 2013

Prof. Olav Bolland, PhD
Department Head

Prof. Odilio Alves-Filho, PhD
Academic Supervisor

Acknowledgements

In this section I would like to thank all the people who gave me support to put my thoughts into action and realization. Without you this master thesis would not have been possible.

Firstly, I would like to thank Professor Dr. Odilio Alves–Filho for giving me his trust and allowing me to work under his supervision, who gave me guidance, advice and practical help on the thesis work, and for his patience and understanding.

I would like to thank Professor Trygve Magne Eikevik for his advice and the time he has given to help me.

I would like to thank the NTNU Office of International Relations and in particular Miss Julia Zazhigina for giving me the opportunity to study at NTNU.

I would like to thank professors Dr. Vlastimir Nikolić, Dr. Dragica Milenković and others from the Faculty of Mechanical Engineering at University of Niš who have given me support and encouraged me to pursue my dreams.

My special thanks and gratitude goes to my family, my father Dragan, my mother Suzana and sisters Miljana and Jovana. Without you I could not have come as far as I have. If I am a navigator you are my guiding star.

“Fortune favors the brave.”

Thesis title: Quality Characterization and Modeling Experimental Kinetics in Pilot Scale Heat Pump Drying of Green Peas

Name: Stefan D. Jovanović

Date: 31/05/2013

Supervisor: Odilio Alves-Filho

Abstract:

Drying is one of the most necessary process and technology in today's world and it is used, among other things, for food processing. The basic goal is to process the food for consumption by increasing its shelf life, and in order to achieve this moisture must be removed from raw material as moisture, which is the main promoter of biological activity and spoilage of the fresh products. Conventional drying is known for its high energy consumption and therefore it is costly. The conventional drying has also a negative impact on the environment and climate, providing the basis for heat pump drying development to ensure sustainable practice within the food industry.

Heat pump drying is a relatively new technology developed at NTNU. It unifies 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. By recycling the heat from the dryer exhaust, energy is saved and the total energy input to the system is drastically reduced.

In this master thesis a laboratory heat pump dryer is applied for drying green peas. The drying air was set on temperature regimes of 45°C, 35°C and 15°C with three levels of relative humidity: 60%, 40% and 20%, from which temperature regime of 45°C was set on 40% and 20%. Therefore, eight drying tests were performed and each test was done in period of three hours. The drying of green peas was conducted in fluidized bed mode.

The results have shown that higher temperatures increase the rate of moisture removal from the green peas. Difference in relative humidity of the drying air also plays an important role in the process although the effect is much less compared to the temperature.

The tests performed on heat pump drying of green peas provided the experimental data used for modeling and analysis of mass effective diffusivity, moisture content and ratio.

The kinetics for all experiments on heat pump drying of green peas were successfully modeled based on the solution of the transient and three-dimensional general equation. Analysis and discussion were also done on the influence that these factors have on color, water activity, bulk and particle density, as well as particle size.

Overall the project has shown that heat pump drying has many advantages in producing a satisfactory quality dried green peas, economy and sustainability. Therefore is justifiable to continue further studies and development of heat pump drying technology.

Content list

List of Figures

List of Tables

Abbreviations

R&D	Research and development
HPD	Heat pump drying
HPAFD	Heat pump atmospheric freeze drying
HFB-AFD	Hybrid fluidized bed heat pump atmospheric freeze drying
FB-AFD	Fluidized bed heat pump atmospheric freeze drying
US	Ultrasound
MW	Microwave
PF	Pulse-fluidization
IR	Infrared emission
HP	Heat pump

SMER	Specific moisture extraction ratio
CFC	Chlorofluorocarbons
FBD	Fluidized bed dryers
RVP	Relative vapor pressure

Notations

u_{mf}:	Minimum fluidization velocity
a_w :	Water activity
P:	Vapor pressure of the food
P_0:	Vapor pressure of pure water at the same temperature as p
w_{wb}:	Moisture content on wet basis
m_w:	Mass of water
m_t:	Total mass of the sample
w_{db}:	Moisture content on dry basis
m_d:	Mass of dry-matter
L:	Brightness and darkness of the sample
a:	Red-green content of the sample
b:	Yellow-blue content of the sample
ρ_b:	Bulk density
ρ_p:	Particle density
Rh:	Relative humidity
x, y, z:	space coordinates
D_e:	effective mass diffusivity
ρ:	mass concentration

1. Introduction

Today's world is facing an increase in human population and consequently need to produce more fresh and dried products for this expanding population. The consequence is a worldwide market rapid expansion, demanding more products and goods to be placed on trade as well as for the larger diverse range of products. Major factors in fulfilling these requirements are process development, economical profitability and sustainability of the environment and society.

At the same time these new technologies should fulfill the objective of economical profitability, which is mostly dependable on energy efficiency due to the trend of increasing energy cost and cost of resources used to produce that energy, mostly carbon based fuels. Currently, as a process drying consumes up to 50% of the total amount of energy used in industrial purposes. One of the relatively new technologies that fulfill all these requirements is heat pump drying (HPD).

The 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.

Alves-Filho (2013) states that "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."[6]

Drying, also known as dewatering is one of the oldest ways to preserve food and prevent decay caused by microbial activity. Although conventional driers are the most widely applied the appearance of new regulations and trends have stimulated the R&D of new technical solutions in the field of energy and process technology. One of the most prospective approaches to drying is heat pump drying which is an approach ready to be used in industrial applications.

The extensive experiments conducted at NTNU have shown high potential of HPD in improving product quality and multiple possibilities in controllability of drying medium parameters and high energy efficiency. This technology resulted in significant contribution to both profitability and environmental friendliness. The HPD is one of the most logical solution and a viable alternative to energy use and environmental problems.

The most comprehensive studies and research in HPD have been done by the heat pump drying group at Department of Energy and Process engineering at NTNU currently under the supervision of professors Odilio Alves-Filho and Trygve Magne Eikevik.

2. Objectives

This master thesis covers the experiments and modeling green peas drying on a pilot scale heat pump dryer. Focus will be given on the effect of heat pump operating conditions, drying temperature and relative humidity on kinetics and on the dried product's characteristics. Other measurements and analysis will include moisture content, moisture ratio, drying rate, modeling kinetics, color, sorption isotherms and bulk-particle density. In order to form a large batch of raw material the frozen green peas were mixed and homogenized. The large batch was then sub-divided into eight uniform batches and stored in frozen state. All eight batches are to be subjected to the drying tests.

In order to investigate the effects of the operating conditions on the moisture transport and products characteristics the input parameters such as air velocity, temperature of drying air, initial moisture content and initial batch mass or volume were fixed as independent variables. The temperatures were set in three levels and each of the level had relative humidity variation set in three levels with the exception of 45^{o}C regime which was tested for 40% and 20% of relative humidity, and was kept constant only in an individual test, to study their effect on the dependent variable behavior. The mass transfer and quality or product characteristics were measured and analyzed prior, during and after each drying test.

The focus is put on transient changes of moisture content, moisture ratio, drying rate, modeling kinetics color of the product, sorption isotherms and bulk-particle density.

Therefore, the tests have been performed on the heat pump drying of green peas in order to study the effects that relative humidity and temperature of drying medium has on green peas. Particular emphasis is given on the green peas quality attributes such as color, sorption isotherms, bulk and particle density.

The specific objectives and tasks were:

- to review the literature on drying of green peas and vegetables,
- to prepare the eight batches of green peas for the heat pump drying tests,
- to perform tests according to the experimental design,
- to collect and analyze data on kinetics, properties and quality parameters,

3. Literature review

“Drying technology has vast applications in many branches of industrial production. It is irreplaceable in chemical and petrochemical industry, in medicine, food production, fruit and vegetable drying technology as well as in processing of grain, lumber and many other organic and nonorganic materials. In today’s world of rapidly advancing technology, drying is an important component of industrial process engineering.

Drying is one of the major aspects of agricultural production and manufacturing. Almost all materials need drying before they can be marketed and processed.

It is an energy efficient operation, (Chou, 1996) reported that the energy used in drying operations is estimated at about 20% of the total energy used for industrial production. Conventionally, materials are dried either in the field (sun drying) or with the use of high temperature dryers. Different dryers are used depending upon the products dried. For food drying, the hygiene aspect must be considered. This compares with wood drying that requires a low level of sanitation. For agricultural processes, solar dying is very common.

Successful outdoor drying depends upon good weather and indeterminate weather can render a product worthless”. [6] [8]

There are advances in industrial and R&D and it’s now possible to shorten the production time of the dried product by increasing the moisture removal rate. The main components of the heat pump drying system are the expansion valve, evaporator, internal and external condenser and compressor. After flowing through the heat pump evaporator and condenser the dry and warm air is ready to flow into the drying chamber. The simplified heat pump dryer has two separated loops with common heat exchangers. The drying air loop contains the air cooler, heater, blower and drying chamber. The main components of the refrigeration loop are the expansion valve, evaporator, condenser and a compressor. The heat pump fluid and drying air loops are coupled through the common evaporator and condenser to recover the exhaust energy. [6]
“Chou (1996) reported that application of the system would offer the following:

- Ensuring hygienic process of drying,
- Enable consistent product capacities of the food product,
- Improve the overall energy efficiency of the drying process,
- Longer period in the retention of product flavors,
- Reduction in the color degradation of the food product when dried under the most favorable drying conditions,
- Reduction in the loss of thermal sensitive vitamins embedded in the food product”. [7]

At the Norwegian University of Science and Technology experts have developed adiabatic heat pump fluidized bed dryers during the last 15 years. [16]

“Experiments on atmospheric two-stage fluidized bed drying of protein with a heat pump were carried out at the Norwegian University of Science and Technology in Trondheim, Norway. The investigation covers innovative fluidized bed heat pump drying of protein. The two-stage drying consists of atmospheric moisture sublimation immediately followed by evaporation. Studies were done on the effects of conditions and drying time on the product quality and properties focusing on kinetics, residual moisture content and color. The drying kinetics modeling was carried out to establish the optimal conditions for enhanced water removal rates. A linear mass-transfer equation and the Fick's second law of molecular diffusion were used to describe the first and the second stage of the atmospheric freeze and non-freeze drying. The equations allowed the determination of mass-transfer coefficients and mass diffusivities for all runs. The deviation between the model and measurements was less than 4%."[8]

"The heat pump atmospheric freeze drying (HPAFD) technology has also been developed at NTNU. The world's largest HPAFD plant was built in Europe and is currently producing dried vegetables and herbs. This technology complies with the requirements for high quality products with the benefits of continuous operation and low energy utilization. However, the technology adoption in global markets required improvements of processing-product for competitiveness. Therefore, the R&D drying at NTNU now focuses on a new process called "Hybrid Fluidized Bed Heat Pump Atmospheric Freeze Drying". It combines the benefit of HPAFD with accelerated processes for heating, vibrating and suspending particles. Promising processes are the ultrasound, pulse-fluidization, microwave and infrared radiation. The hybrid drying technology has potential to produce cost competitive products and to develop wide range of novel products. The hybrid drying technology is expected to be compact, cheaper and more efficient than the plants available today.

Heat pump atmospheric freeze-drying has been recently applied to the industry. The major benefits of this technology are continuous operation, low energy use and high product quality. However there are refinements and enhancements to be made concerning dryer capacity and rates of heat-mass transport. This is critical in the first drying stage and in the final drying period where vapor diffusion is internally controlled. Yet, high product quality requires gentle operations and low air temperature, where deterioration takes place if the temperature is too high. As a result, the overall moisture removal is relatively low due to long product retention time. Therefore, it is important to find alternatives to improve throughput, drying rates, energy reduction while keeping product quality.

A promising technology being currently developed at NTNU is the "Hybrid Fluidized Bed Heat Pump Atmospheric Freeze Drying", HFB-AFD. It combines the benefits FB-AFD with processes for pulsing, vibration, suspending, and assisted heating of the bed of particles. The potential technologies for HFB-AFD are ultrasound (US), microwave (MW), pulse-fluidization (PF) and infrared emission (IR). Each technology has its own features influencing moisture removal and product properties." [11]

There is also a development of heat pump drying technology with the usage of different drying mediums such as CO_2, N_2, ammonia (R717), propane (R290), R134a and R22 [6]. [12] [26]. "The heat pump dryers operation is based on energy recovery and efficiency, it is an environmentally clean technology and provides a high quality product. The dryers operate at several temperatures and relative humidity levels. The dryer has integrated air and refrigerant circuits featuring energy recovery from latent heat of water vapor in the outlet moist air. This latent heat is rejected in conventional dryers." [13]

"Atmospheric freeze drying with heat pumps has been used for drying of materials to be stored in biobanks. Drying tests has been executed to study the possibilities of atmospheric freeze drying as an alternative technology to storage in liquid nitrogen which is a very expensive technology used today for this purpose. Drying tests have been executed on rat liver to study the degradation of DNA and RNA. DNA was not degraded during drying. RNA, a more sensible component, also showed very little degradation during drying." [17]

There are also cases of other types of heat pump drying systems being developed such as heat pump combined with superheated steam, where water (R718) is the working fluid and special chemical heat pump dryers. [6] [27]

It seems that heat pump drying is one of the most cutting edge technologies in the drying industry today, and is in ever increasing demand for developing environmentally friendly technologies that will ensure both economic benefit and a sustainable future.

4. Theory and challenges examined

4.1 Definition of drying process

“Drying also known as dehydration has been used for centuries worldwide in order to preserve different types of food and agricultural products. At present time, the drying process is one of the mayor procedures of food preservation and an important unit operation in a wide variety of food industries” (Kenneth J. Valentas, Enrique Rotstein and R. Paul Singh, 1997).

Another author (Arun S. Mujumdar, 2007) states that “Drying commonly describes the process of thermally removing volatile substances (moisture) to yield a solid product. Moisture held in loose chemical combination, present as a liquid solution within the solid or even trapped in the microstructure of the solid, which exerts a vapor pressure less than that of pure liquid, is called bound moisture. When a wet solid is subjected to thermal drying, two processes occur simultaneously:

- Transfer of energy (mostly as heat) from the surrounding environment to evaporate the surface moisture;
- Transfer of internal moisture to the surface of the solid and its subsequent evaporation due to process of previously mentioned transfer of energy.”

4. 2 Heat pump drying

“Heat pump dryers have been known to be energy efficient when used in conjunction with drying operations. The principal advantage of heat pump dryers emerge from the ability of the heat pumps to recover energy from the exhaust gas as well as their ability to control the drying gas temperature and humidity. Many researchers have demonstrated the importance of producing a range of precise drying conditions to dry a wide range of products and improve their quality.

Any dryer that uses convection as the primary mode of heat input to the dryer (with or without supplementary heat input by other modes of heat transfer) can be fitted with a suitably designed heat pump (HP). Although batch shelf, tray dryers, or kilns (for wood) are the most commonly reported dryers used in conjunction with heat pumps, other types may also be used, e.g., fluid beds (Alves-Filho and Strømmen, 1996; Strømmen and Jonassen, 1996) and rotary dryers. However dryers that require large amounts of drying air, e.g., flash or spray dryers, are not suited for HP operations" (Arun S. Mujumdar, 2007).

4.3 The basics of a heat pump

The main components of the single stage heat pump system are the expansion valve, evaporator, internal and external condenser and compressor as illustrated in figure 1. After flowing through the evaporator and condenser of the heat pump the dry and warm air is ready to flow into the drying chamber in which the material, which is to be processed, is being placed. The 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. [6]

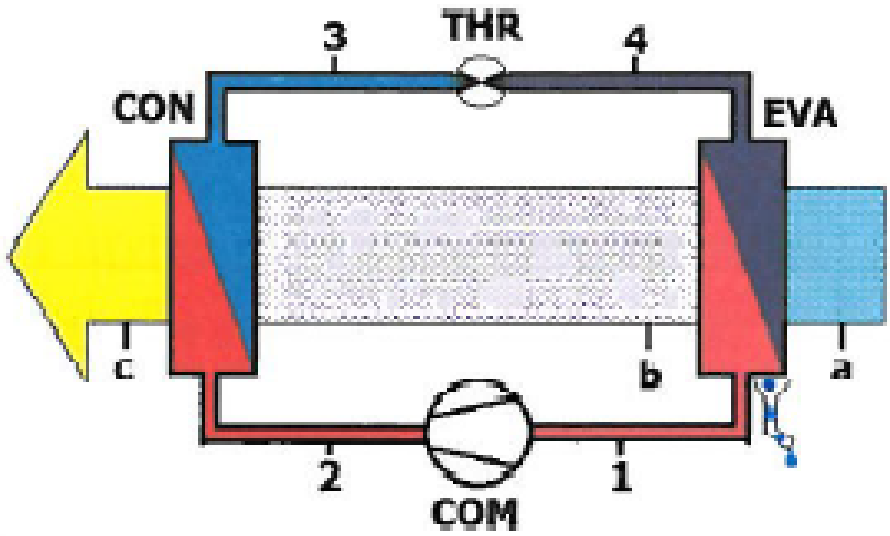

Figure 1 Principle of operation in a simplified heat pump dryer (O. Alves-Filho, 2013)

"The closed cycle of refrigerant is composed of four processes as shown in Figure 2.

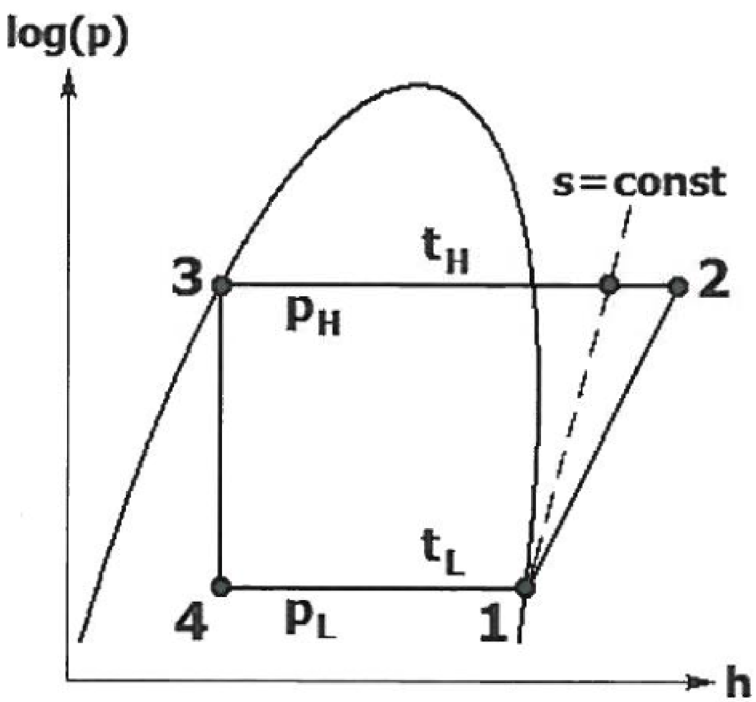

Figure 2 Simplified heat pump cycle on the *log(p)-h* diagram (Odilio Alves-Filho, 2013)

1 – 2: non-isentropic compression. Here the saturated 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 rejects 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. The closed heat pump drying air cycle is composed of three processes shown in the Mollier diagram in Figure 3:

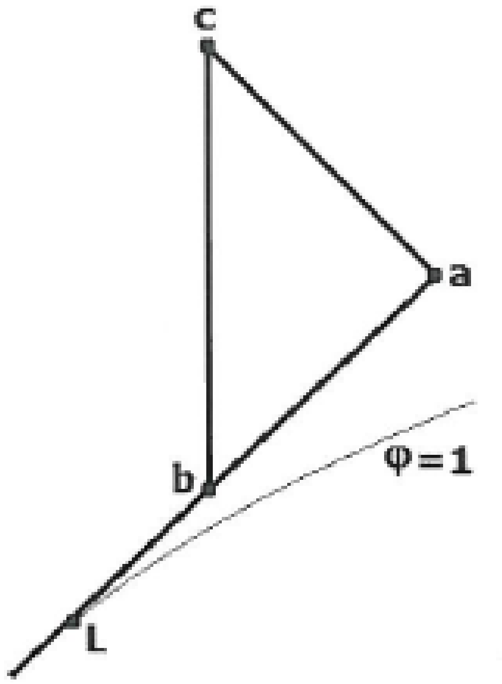

Figure 3 Drying air cycle on the Mollier diagram (Odilio Alves-Filho, 2013)

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." [6]

4.4 Principle of heat pump drying

Alves-Filho (2013) explains, "Figure 4 illustrates the isentropic and non-isentropic saturated vapor compression heat pumps with dry expansion evaporator and drying channels.

Figure 4a shows the main components: *A* – compressor, *B* – three way valve, *C* – external condenser, *D* – drying channel with air heater, *E* – liquid receiver, *F* – expansion valve, *G* – drying channel with air cooler. Also, Figures 4a and 4b show the layout and the state points in the cycles in a log pressure versus enthalpy diagram, respectively. From state point 1 the saturated vapor is isentropic and non-isentropic compressed to super-heated vapor to points 2_i and 2, respectively. Then, the vapor flows through the condensers changes phase to saturated liquid and is collected in the receiver. The saturated liquid leaves the receiver at point 3 and it is throttled to a liquid and vapor mixture at point 4. Then, the mixture flows through the evaporator and becomes saturated vapor at point 1 to be compressed again.

" [6]

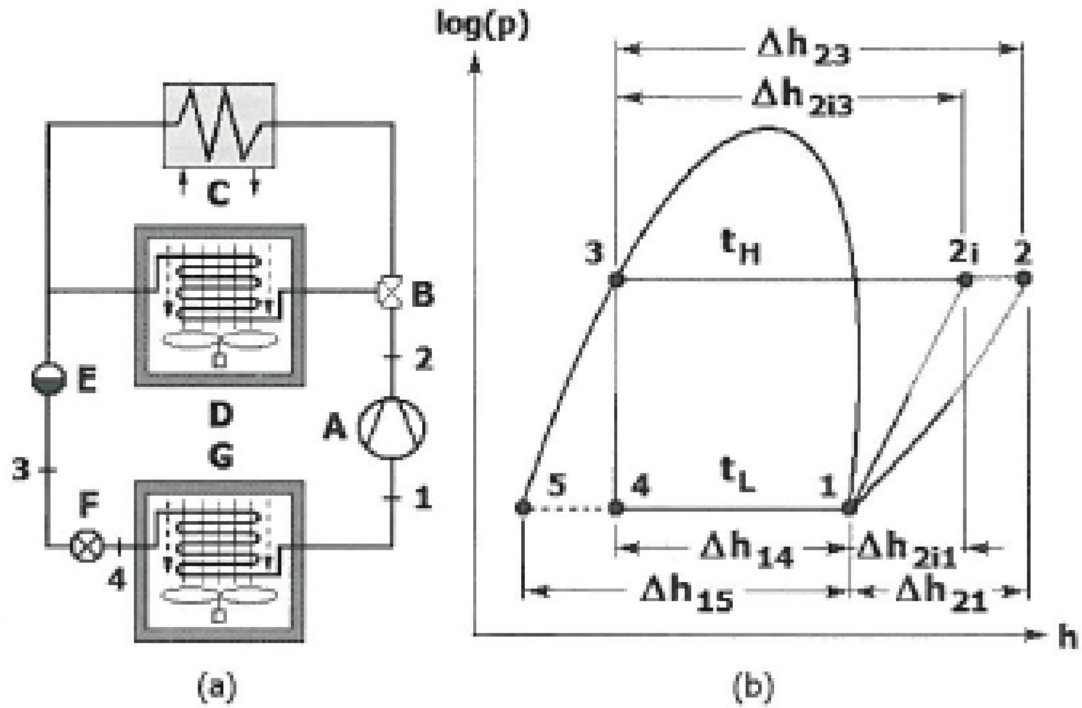

Figure 4 The isentropic and non-isentropic saturated vapour compression heat pumps indicating the corresponding specific enthalpy differences in each process (Odilio Alves-Filho, 2013)

4.5 Advantages and limitations

"The key advantages and limitations of heat pump dryers are (Arun S. Mujumdar, 2007):

Advantages:

- Heat pump drying (HPD) offers one of the highest specific moisture extraction ratio (SMER), often in range of 1.0 to 4.0, since heat can be recovered from moisture-laden air.
- Heat pump dryers can significantly improve product quality by drying on low temperatures. At low temperatures, the drying potential of the air can be maintained by further reduction of the air humidity.
- A wide range of drying conditions typically -20°C to 100°C (with auxiliary heating) and relative humidity 15 to 80% (with humidification system) can be generated.

- Excellent control of the environment for high value products and reduced electrical energy consumption for low-value products.

However, heat pump dryers must be correctly designed to operate in the desired set points.

4.6 Fluidized bed and product quality

"Fluidized bed dryers (FBD) are used extensively for the drying of wet particulate and granular materials that can be fluidized, and even slurries, pastes, and suspensions that can be fluidized in beds of inert solids. They are commonly used in processing many products such as chemicals, carbohydrates, foodstuff, biomaterials, beverage products, ceramics, pharmaceuticals in powder or agglomerated form, healthcare products, pesticides and agrochemicals, dyestuffs and pigments, detergents and surface-active agents, fertilizers, polymer and resins, tannins, products for calcination, combustion, incineration, waste management processes, and environmental protection processes. Fluidized bed operation gives important advantages such as good solid mixing, high rates of heat and mass transfer, and easy material transport.

Conventional fluidized bed is formed by passing a gas stream from the bottom of a bed of particulate solids. At low gas velocities the bed is static (packed). The bed of particles rests on a gas distributor plate. The fluidizing gas passes through the distributor and it is uniformly distributed across the bed. Pressure drop across the bed increases as the fluidizing gas velocity is increased. At a certain gas velocity, the bed is fluidized when the gas stream totally supports the weight of the whole bed. This state is known as minimum fluidization and the corresponding gas velocity is called minimum fluidization velocity, u_{mf}. Pressure drop across the bad remains nearly the same as pressure drop at minimum fluidization even if the gas velocity is increased further.

Some advantages of fluidized bed drying are the high rate of moisture removal, high thermal efficiency, ease of control and low maintenance cost. The high rate of moisture removal is due to the large interfacial surface area which is in order of 3000 to 45000 m^2/m^3 in the fluidized bed. This is also the reason for very high rates of heat transfer achieved in fluidized beds.

Some of the limitations in drying application of the fluidization are high pressure drop and high electrical power consumption for the blower. Also the drying product may be damaged in intensive fluidization or particle to particle and particle to wall collisions.

The bed can be pseudo-fluidized by vibration but there is still need for sufficient air flow to enable moisture removal. Vibration combined with upward air flow allows the particles to pseudo fluidize smoothly and thus attrition due to vigorous interactions between particles or a particle and the chamber wall can be minimized."

In order to determine the effectiveness of the drying process it is necessary to observe characteristics of the product. The main quality characteristics of the dried green peas samples in this project work are water activity, color, bulk and particle density" (Arun S. Mujumdar, 2007).

4.7 Water content

"Deterioration of foods by micro-organisms can take place rapidly, whereas enzymatic and chemical reactions take place more slowly during storage. In either case the water content is a very important factor controlling the rate of deterioration. The moisture content of foods can be expressed either on a wet basis or on a dry basis

The dry basis is more commonly used for processing calculations, whereas the wet basis is frequently quoted in food composition tables" (P. J. Fellows, 2000).

4.8 Water activity

“Knowledge of moisture content alone is not sufficient to predict the stability of foods. Some foods are unstable at a low moisture content (for example peanut oil deteriorates if the moisture content exceeds 0.6%), whereas other foods are stable at relatively high moisture content (for example potato starch is stable at 20% moisture content)(van den Berg, 1986). It is availability of water for microbial, enzymatic or chemical activity that determines the shelf life of a food, and this is measured by the water activity (a_w) of a food, also known as the Relative Vapor Pressure (RVP).

Water in food exerts a vapor pressure. The size of the vapor pressure depends on:

- the amount of water present,
- the temperature,
- the concentration of dissolved solutes (particularly salts and sugars) in the water.

Water activity is defined as the ratio of the vapor pressure of water in a food to the saturated vapor pressure of water at the same temperature, as it is shown in the next equation:

$$a_w = \frac{P}{P_0}$$

where P is the vapor pressure at the green peas surface and P_0 is the vapor pressure of pure water at the same temperature.

The effect of a_w on microbiological and selected biochemical reaction is shown in Figure 5.

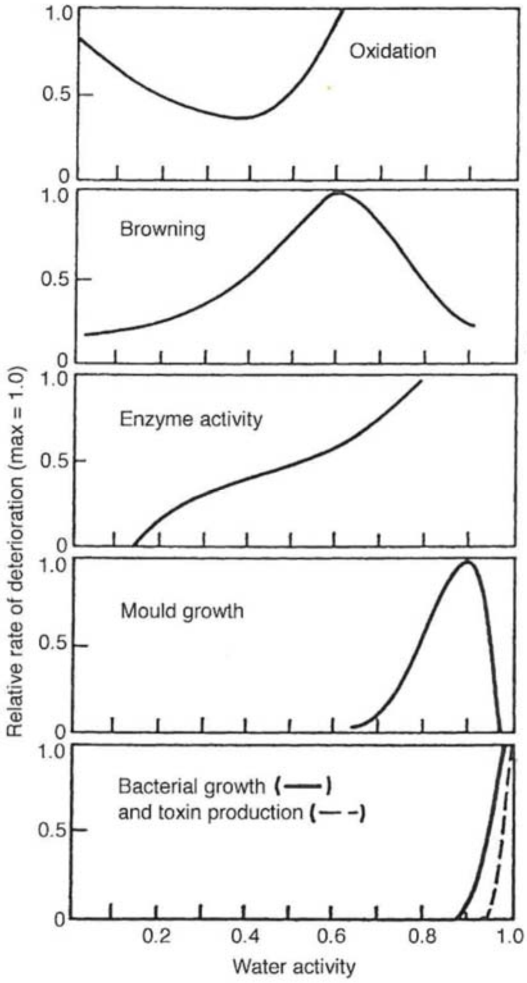

Figure 5 Effect of water activity on microbial, enzymatic and chemical changes to foods (After Karel, 1975)

Almost all microbial activity is inhibited below a_w = 0.6, most fungi are inhibited below a_w = 0.7, most yeasts are inhibited below a_w =0.8, and most bacteria below a_w = 0.9. The interaction of a_w with temperature, pH, oxygen and carbon dioxide, or chemical preservatives has an important effect on the inhibition of microbial growth" (P. J. Fellows, 2000).

4.9 Color

“Many naturally occurring pigments are destroyed by heat processing, chemically altered by change in pH or oxidized during storage. As a result the processed food may lose its characteristic color and hence its value. Synthetic pigments are more stable to heat, light and change in pH, and they are therefore added to retain the color of some processed foods” (P. J. Fellows, 2000).

4.10 Density

“Knowledge of density of foods is important in separation processes, and differences in density can have important effects on the operation of size reduction and mixing equipment. The density of material is equal to its mass divided by its volume and has units of kg m^{-3}. For particulate solids and powders there are two forms of density: the density of individual pieces and the density of the bulk of material, which also includes the air spaces between the pieces. The latter measure is termed the *bulk density* and is the mass of solids divided by the bulk volume.

The bulk density of a material depends on the solids density and the geometry, size and surface properties of the individual particles” (P. J. Fellows, 2000).

Pigment	Typical source	Oil or water soluble	Stability to the following			
			Heat	Light	Oxygen	pH change
Anthocyanins	Fruits	Water soluble	High	High	High	Low
Betalaines	Beetroot	Water soluble	Moderate	High	High	High
Bixin	Seed coat of Bixa *orellana*	Oil soluble	Moderate to low	Low	High	-
Canxanthin		Oil soluble	Moderate	Moderate	Moderate	Moderate
Caramel	Heated sugar	Water soluble	High	High	High	High
Carotenes	Leaves	Oil soluble	Moderate to low	Low	Low	High
Chlorophylls	Leaves	Water soluble	High	High	High	Low
Cochineal	Insect (*Dactylopius coccus)*	Water soluble	High	High	-	Moderate to high
Curcumin	Turmeric	Water soluble	Low	Low	Low	-
Norbixin	See Bixin	Water soluble	Moderate to low	Low	High	-
Oxymyoglobin	Animals	Water soluble	Low	-	High	Low
Polyphenols	Tea leaf	Water soluble	High	High	High	High
Quinones	Roots, bark	Water soluble	High	Moderate	-	Moderate
Xanthophylls	Fruits	Water soluble	Moderate	High	High	Low

Table 4.1 Naturally occurring pigments in foods (from P. J. Fellows, 2000).

5. Materials and methods

5.1 Experimental tests

5.1.1 Experimental design

The experiments were conducted in a heat pump drying system with a fluidized bed. Each batch of raw material placed inside the drying chamber had a mass of 1000 grams. The green peas samples were dried at three values of drying air temperature and three values for the relative humidity. The temperatures were 45°C, 35°C and 15°C and each temperature was fixed tested at relative humidity of 60%, 40% and 20% with exception of 45°C as previously mentioned. This resulted in a design of eight drying tests. The details of experimental conditions and setup for all eight tests are presented in Table 5.1.

The frozen green peas were mixed and homogenized to form a large batch that was partitioned into eight uniform batches of green peas to be dried according to the mentioned design. One drying test took 3 hours to complete. During the drying of all tests the drying chamber was taken out every 20 minutes period to measure the change in mass. Relatively small masses of dried product samples were also extracted at every 60 minute interval, which makes 3 extractions every test. The extracted material was put in small vessels whose mass was determined previously, and then the total mass of vessel with extracted sample was measured, after which they were put into preheated oven for 24 hour drying period. The drying oven was set at a temperature of 105°C and for 24 hours. The already known mass of the empty vessel and total mass of vessel with the product allows us to calculate the mass of extracted product. The product was dried in the fluidized bed with the air velocity kept at approximately 1 m/s.

Test Number	Temperature [°C]	Relative humidity [%]
1.	45	40
2.	45	20
3.	35	60
4.	35	40
5.	35	20
6.	15	60
7.	15	40
8.	15	20

Table 5.1 Experimental conditions and setup for all six heat pump drying tests

5.1.2 Heat Pump

The heat pump dryer consists of two separate loops. One loop is used for the working fluid and the other for flowing of the drying medium or air. The heat pump's main components are the compressor, condenser, evaporator, throttling valve for the refrigerant flow control. The air enters the drying chamber with the test set psychrometric conditions given by the fixed temperature and relative humidity. Air flows through the cylindrical chamber with the batch of green peas being dried. The drying medium flows over the surface of the product fluidize the bed and removes moisture in the process. The air leaves the drying chamber with lower temperature and higher relative humidity compared to the chamber inlet. Because of this the air capacity to carry water decreases as it moves upward in the chamber. The air is recirculation in the heat pump drying loop requires water vapor condensation and removal and this is done by the evaporator. The evaporator is a heat exchanger where the air carrying moisture is cooled down below its dew point and the water vapor condenses and drains out of the system. The associated heat is transferred to the refrigerant inside the evaporator and the refrigerant changes phase from liquid to vapor.

After being cooled and dehumidified by the evaporator the air flows through the condenser and fan where it reaches the desired set points for the tests. Heat gained by the air is received from the condenser where the refrigerant becomes saturated liquid and flows through the expansion valve or throttling device where its pressure is reduced so it can re-enter the evaporator in state of vapor-liquid mixture.

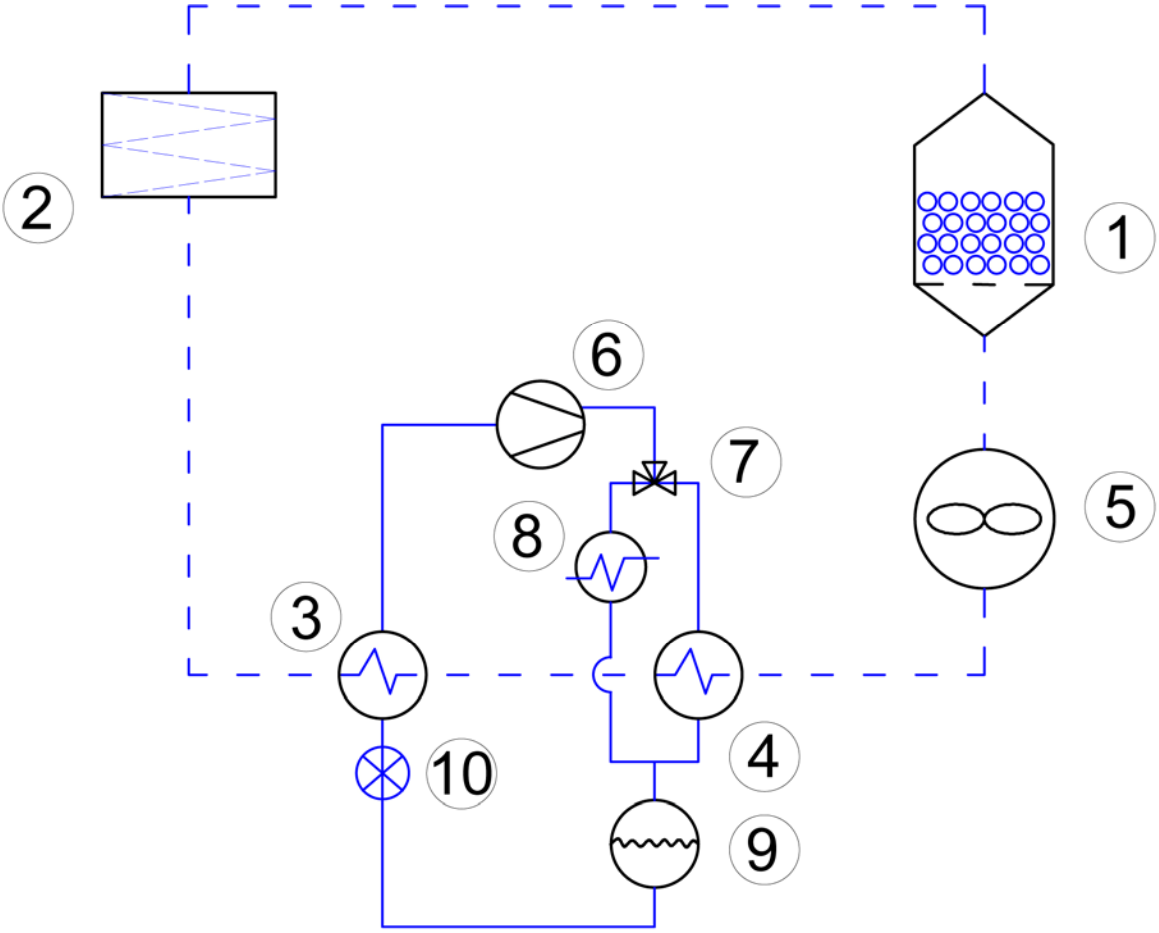

Figure 6 Sketch of the heat pump dryer.

1: drying chamber, 2: filter, 3: air cooler or evaporator, 4: internal condenser, 5: blower, 6: compressor, 7: three – way valve, 8: external condenser, 9: liquid receiver, 10: throttling valve.

5.1.3 The drying chamber and supporting cabinet

The drying chamber is placed inside the isolated wooden cabinet made of plywood with styrofoam insulation. The cabinet's dimensions are 0.8x0.8m in cross section with height of 1.5m. The drying chamber is made of plexiglas and it is easily locked and unlocked in central base positioned within the cabinet using a three pin lock-rotation mechanisms. The chamber is inserted in the drying loop but separated from outdoors by a sampling access door located in the front of the cabinet. The door is opened and closed using two external locks. There are two inlet and outlet tubes connecting the cabinet and chamber to the drying loop. The inlet tube is connected to the central base of the cabinet and to the cylindrical chamber containing the green peas. The chamber exhaust flows through the outlet tube that is positioned at the upper part of the cabinet. During the process of moisture removal the green peas contained in the cylindrical chamber is in a fluidized by controlled air flow.

5.2 Measuring devices

A Mettler Toledo scale (XP 600 2M DeltaRange with an accuracy of 0.1 g) was used for measuring the mass of each batch of green peas the whole drying chamber containing the raw material. This was done according to the set time intervals by taking out of the drying chamber from supporting cabinet.

The density was measured based on standard determination of both mass and volume. Volume was measured suing a graduated cylinder and mass by the mentioned scale.

Moisture content was measured with the use of a Mettler Toledo HB43-S moisture analyzer and the water activity was determined using the Aqua Lab CX-2 device.

A color meter, model X-RITE 948 Spectrodensitometer was used for measuring the color components such as brightness, red-green and yellow-blue.

5.3 Analysis of data and measurements

5.3.1 Data logger and computer storage

The acquired data was recorded in the PC using a data logger. The feedback is received and controlled based on the set points and signals coming from at least three sensors installed in the heat pump drying system. The first sensor was placed at the inlet of the drying chamber. A second sensor was placed at the chamber outlet or in the tube connected to the exhaust of the drying chamber and cabinet. The third sensor was located in the air-side of the tube between the evaporator and air heater of the heat pump. These sensors have been used to obtain data that related to the drying medium parameters, while another sensor placed in an orifice-meter provided input for measuring the air velocity.

5.3.2 Water content

The water content of the green peas sample is defined either on a wet or on dry basis.

The moisture content on wet basis w_{wb} is calculated by dividing the mass of water m_w in the sample with the total mass m_t of the sample. Total mass is the sum of the mass of water in the sample and mass of dry-matter in the sample. The moisture content in wet basis is calculated using the equation (1):

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

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

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

A standard method has been used to determine the moisture content. Two samples of green peas, each weighting 50 g or 100 g in total, were placed in two pirex-glass containers whose mass was already measured. The containers with the samples of raw material are then placed inside the oven set on 105°C and left for a 24 hour period. After that period the containers are removed from the oven, cooled and the mass measured again. The loss in weight represents the water evaporated from the raw material during the specific drying time. With this information, with equations (1) and (2) we were able to calculate the moisture content both on dry and wet basis.

5.3.3 Water activity

Considering the theory of water activity explained in section 4.9, the water activity measurements of the green peas were made using an “Aqua Lab CX-2” meter made by Decagon Devices, Inc., Washington.

5.3.4 Color measurement

The color measurements of green peas were made the “X-Rite 948 Spectrocolorimeter”. The measurements were made during every stage of testing and it was conducted on whole green peas. The measured color components correspond to three values which are defined as follows:

L – brightness and darkness of the sample
a – red-green content of the sample
b – yellow-blue content of the sample

5.3.5 The bulk density

We have used both the density of individual particles and the density of the bulk material, which also includes the air spaces between the particles. The latter measure is termed the *bulk density* and it is the mass of solids divided by the bulk volume as expressed through the equation (3):

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

The information required for calculating the bulk density was acquired using a graduated measuring cylinder in which a sample of green peas was placed before and after the drying process. The cylinder was weighted when empty and with the fresh, frozen or dried product inside and the mass is obtained by the mass difference. Each measurement was done by a light vibrated movement resulting in uniform distribution of the material inside the cylinder. After that the volume was measured and the bulk density calculated.

5.3.6 The particle density

To obtain the particle density from each test samples of ten individual green peas were taken and the diameters were measured using a caliper with accuracy to 1/20mm. Then, the average diameters were calculated and the ten samples where weighted on a precision scale. From the average diameter from ten measured particles the mean volume is obtained by equation (4):

$$\bar{V} = \frac{\pi}{6}\bar{d}^3 \qquad (4)$$

Similarly the particle density is obtained using ratio of the average mass of ten particles and average volume of same particles and it is expressed by equation (5):

$$\rho_p = \frac{\bar{m}}{\bar{V}} \qquad (5)$$

5.3.7 Modeling kinetics

The tests performed on heat pump drying of green peas provided the experimental data used for modeling and analysis of mass effective diffusivity, moisture content and ratio.

The modeling is based on the transient and three-dimensional general equation for mass transport is, [36] [37]

$$-\frac{1}{D_e}\cdot\frac{\partial\rho}{\partial t}=\frac{\partial^2\rho}{\partial x^2}+\frac{\partial^2\rho}{\partial y^2}+\frac{\partial^2\rho}{\partial z^2}$$

Where x, y and z are space coordinates, D_e is effective mass diffusivity, mass concentration is ρ in kg/m^3.

In the case that mass concentration is a linear function of moisture, then $\rho = K_2 \cdot x$, thus

$$-\frac{\partial x}{\partial t}=D_e\cdot\left(\frac{\partial^2 x}{\partial x^2}+\frac{\partial^2 x}{\partial y^2}+\frac{\partial^2 x}{\partial z^2}\right)$$

$$-\frac{\partial x}{\partial t}=D_e\cdot\left(\frac{\partial^2 x}{\partial r^2}+\frac{2}{r}\frac{\partial x}{\partial r}\right)$$

The initial conditions and boundary conditions are:

$$x(r,0)=x_0$$

$$x(r,\infty)=x_e$$

$$x(0,t)=0$$

By appropriately considering spherical shape for the green peas, the solution of the previous equation after integration is

$$x_r=\frac{x-x_e}{x_o-x_e}=K\sum_0^\infty\frac{1}{(2n+1)^2}\cdot\exp\left[-(2n+1)^2\frac{\pi\cdot D_e\cdot t}{r^2}\right]$$

Where, $K = \frac{6}{\pi^2}$, x_e and x_0 are equilibrium and initial contents, respectively.

The modeling of mass diffusivity, moisture content and ratio was based on this solution and minimum deviation was attained with at least three terms.

The experimental (x_{re}) and predicted (x_{rp}) values for moisture ratio and mass-effective diffusivity (De) are presented in Tables 6.9 to 6.17. The observed and modeled results for moisture content are plotted in Figures 6.11 to 6.18. The results in tables and figures shows good fitting. The model and procedure were satisfactory for predictions because and there were minimum deviations between modeled and experimental data.

6. Results and discussion

The analysis and results are based on the calculations, test facilities, instrumentation, specifications of tests and methods described in Chapter 5.

6.1 Drying Kinetics

The water content was measured using the methods as described in 5.3.2. Table 6.1 shows the values of moisture content on dry basis calculated for tests 1 and 2 done with temperature of 45°C and relative humidity of 40% and 20%. The development of moisture content on dry basis follows the kinetic measurements at time intervals of 20 minutes over a period of three hours. It is obvious that test 2 with the lowest relative humidity is the one with the lowest moisture content after this drying time. The experimental data for these tests are plotted in Figure 6.1.

Moisture content on dry basis [%]		
Elapsed time [min]	Test 1	Test 2
0	323.19	323.19
20	180.58	170.84
40	119.64	114.6
60	84.34	81.76
80	63.06	61.57
100	49.77	48.88
120	40.88	40.12
140	34.66	33.6
160	30.17	29.5
180	26.66	24.8

Table 6.1 Development of the moisture content on dry basis for tests 1 and 2

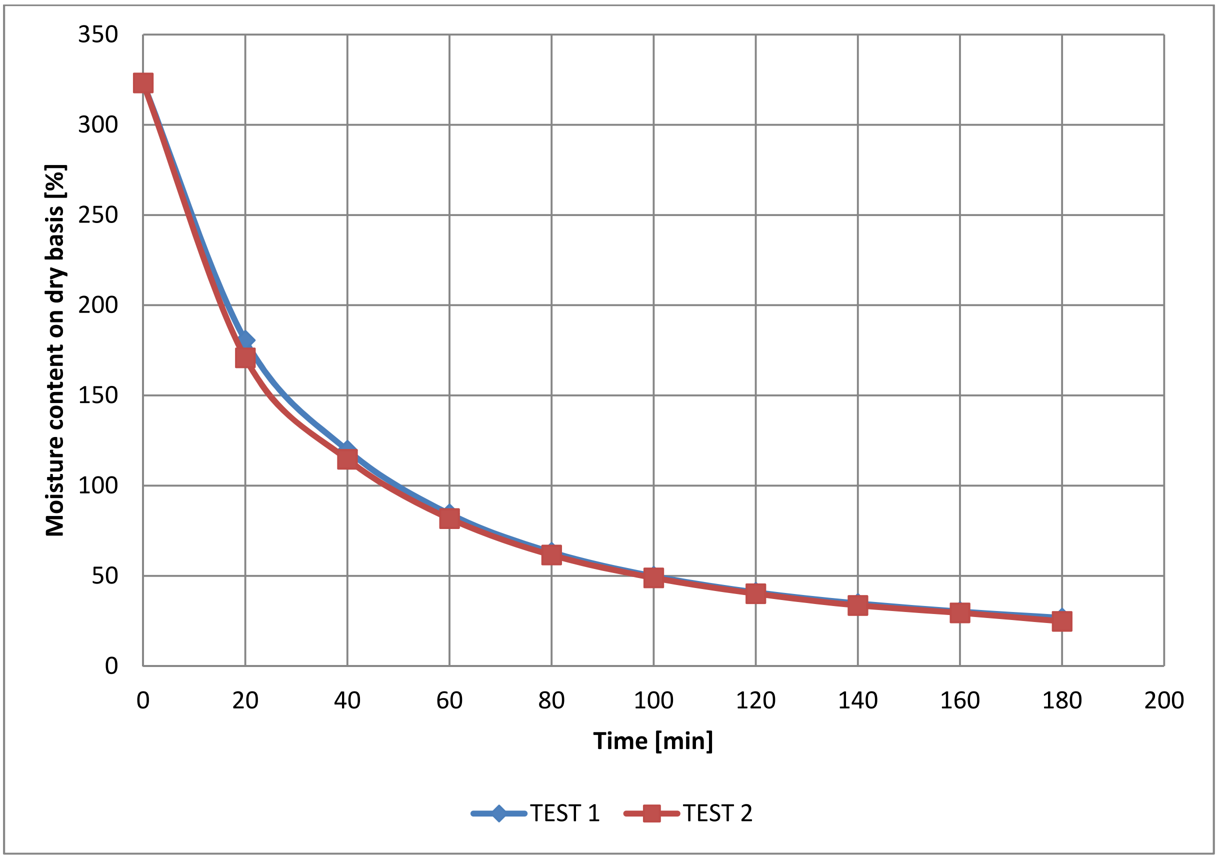

Figure 6.1 Development of water content on a dry basis for test 1 and 2

Table 6.2 shows the development of moisture content on dry basis for tests 3, 4 and 5 done with temperature of 35°C and relative humidity of 60%, 40% and 20%. The time intervals are the same as for the previous two tests. Test number 5 is the one with lowest moisture content and it is the same test in which the drying air had the lowest relative humidity. The experimental data for these tests are plotted and presented in Figure 6.2.

Moisture content on dry basis [%]			
Elapsed time [min]	Test 3	Test 4	Test 5
0	323.19	323.19	323.19
20	253.91	213.97	193.14
40	187.94	142.83	133.98
60	143.12	107.03	97.59
80	109.35	77.44	69.15
100	87.90	60.90	55.99
120	72.20	49.60	45.96
140	57.26	37.49	34.87
160	48.46	31.65	29.67
180	41.35	27.08	25.77

Table 6.2 Development of the moisture content on dry basis for tests 3, 4 and 5

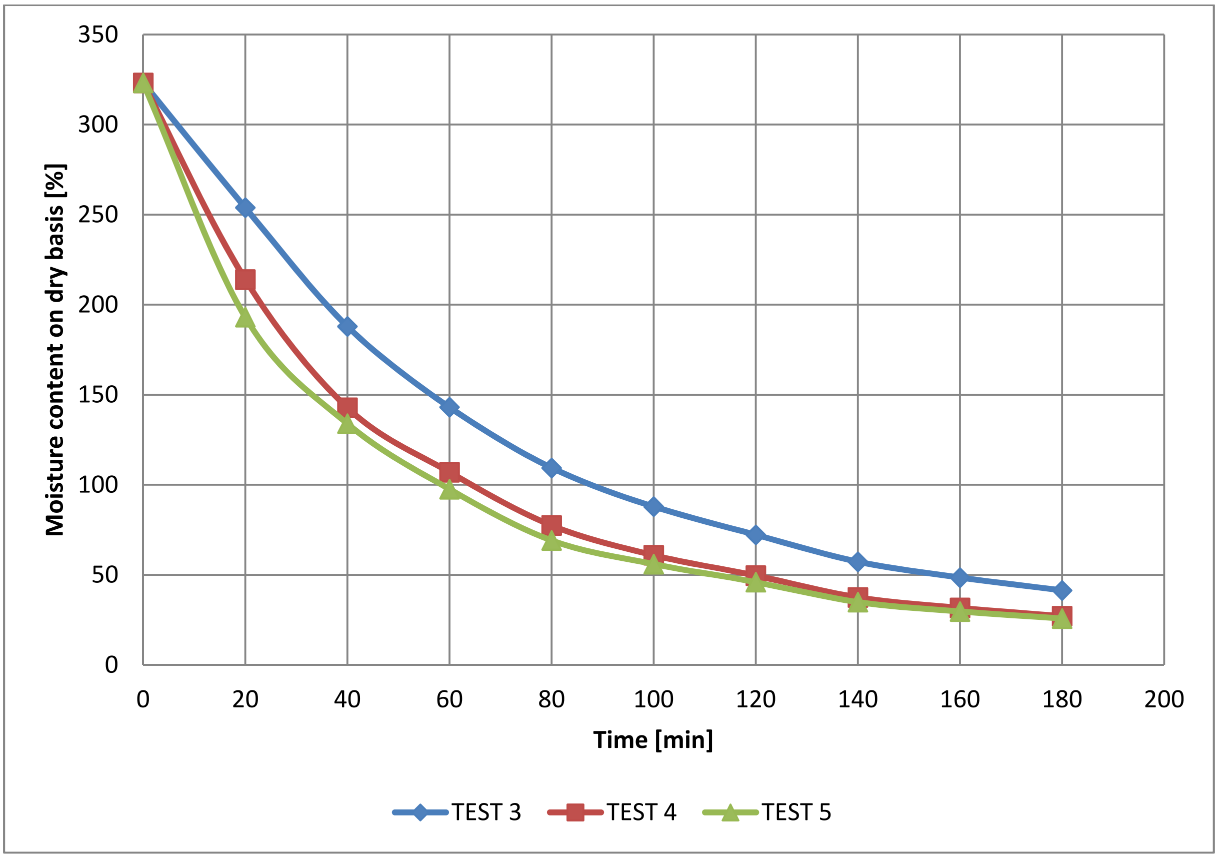

Figure 6.2 Development of water content on a dry basis for test 3, 4 and 5

Table 6.3 shows the development of moisture content on dry basis for tests 6, 7 and 8 done with temperature of 15°C and relative humidity of 60%, 40% and 20%. Test number 8 is the one with lowest moisture content and it is the same test in which the drying air had the lowest relative humidity. The experimental data for these tests are plotted and presented in Figure 6.3.

Moisture content on dry basis [%]			
Elapsed time [min]	Test 6	Test 7	Test 8
0	323.19	323.19	323.19
20	295.13	252.98	229.07
40	252.43	195.68	183.16
60	210.71	160.85	153.15
80	180.45	131.19	126.62
100	154.08	111.38	106.01
120	132.84	95.68	92.64
140	110.92	79.73	78.42
160	97.93	70.46	69.83
180	86.67	62.21	61.96

Table 6.3 Development of moisture content on dry basis for tests 6, 7 and 8

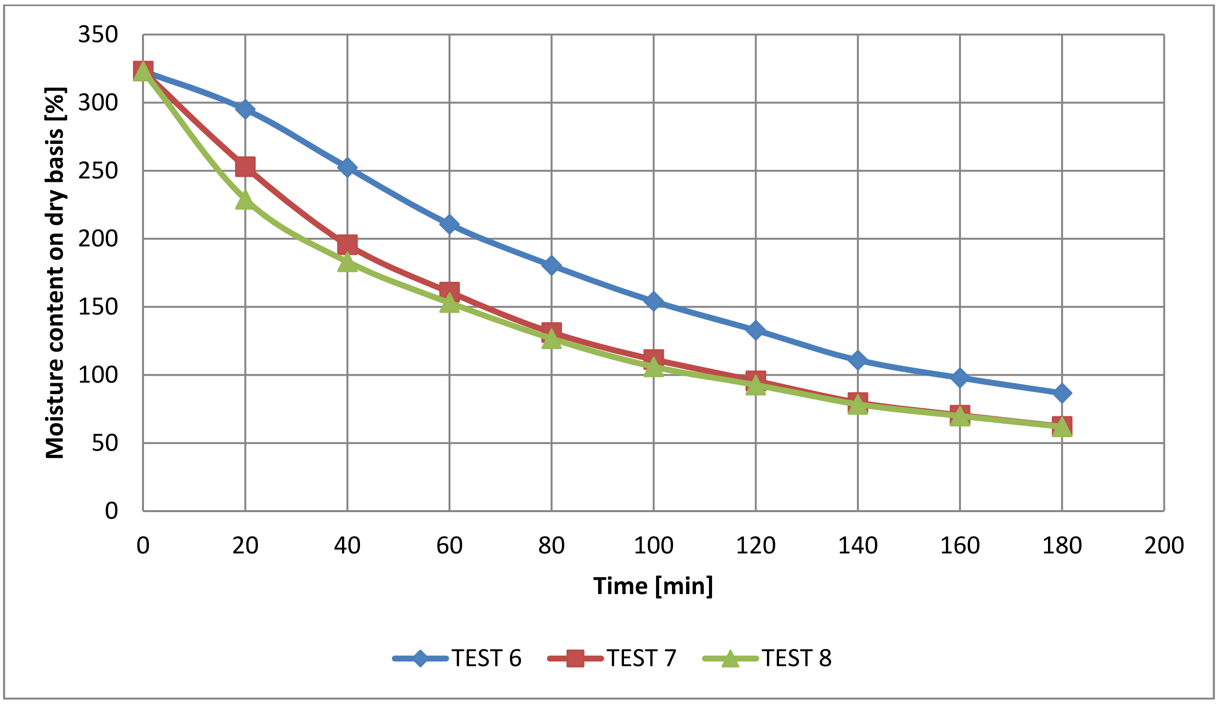

Figure 6.3 Development of moisture content on dry basis for tests 6, 7 and 8

Table 6.4 presents the development of moisture content on a wet basis for the first two tests. Test number 2 shows the lower moisture content then test number 1. It is interesting to notice that the values do not different much. The Figure 6.4 shows the plot of the data indicating the development of moisture content with the time.

Moisture content on wet basis [%]		
Elapsed time [min]	Test 1	Test 2
0	76.37	76.37
20	64.36	63.08
40	54.47	53.4
60	45.75	44.98
80	38.67	38.11
100	33.23	32.83
120	29.02	28.63
140	25.74	25.15
160	23.18	22.78
180	21.05	19.87

Table 6.4 Development of moisture content on wet basis for tests 1 and 2

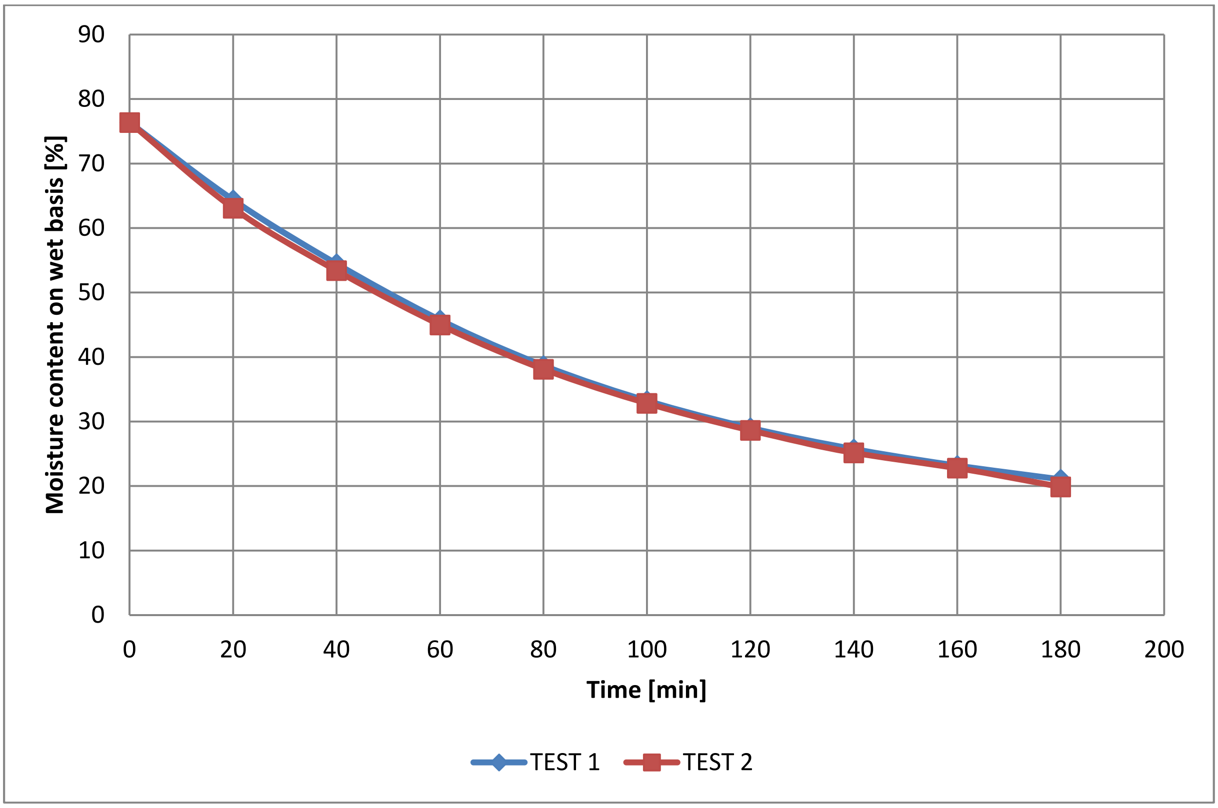

Figure 6.4 Development of moisture content on wet basis for tests 1 and 2

Table 6.5 presents the development of moisture content on a wet basis for the tests one, two and three. Test number 5 has the lowest moisture content followed by test 4 and test 3, respectively. The values between 5th and 4th test do not different much. The Figure 6.5 shows the plot of the data indicating the development of moisture content with the time.

Moisture content on wet basis [%]			
Elapsed time [min]	Test 3	Test 4	Test 5
0	76.37	76.37	76.37
20	71.74	68.15	65.89
40	65.27	58.82	57.26
60	58.87	51.70	49.39
80	52.23	43.64	40.88
100	46.78	37.85	35.89
120	41.93	33.15	31.49
140	36.41	27.27	25.86
160	32.64	24.04	22.88
180	29.25	21.31	20.49

Table 6.5 Development of moisture content on wet basis for tests 3, 4 and 5

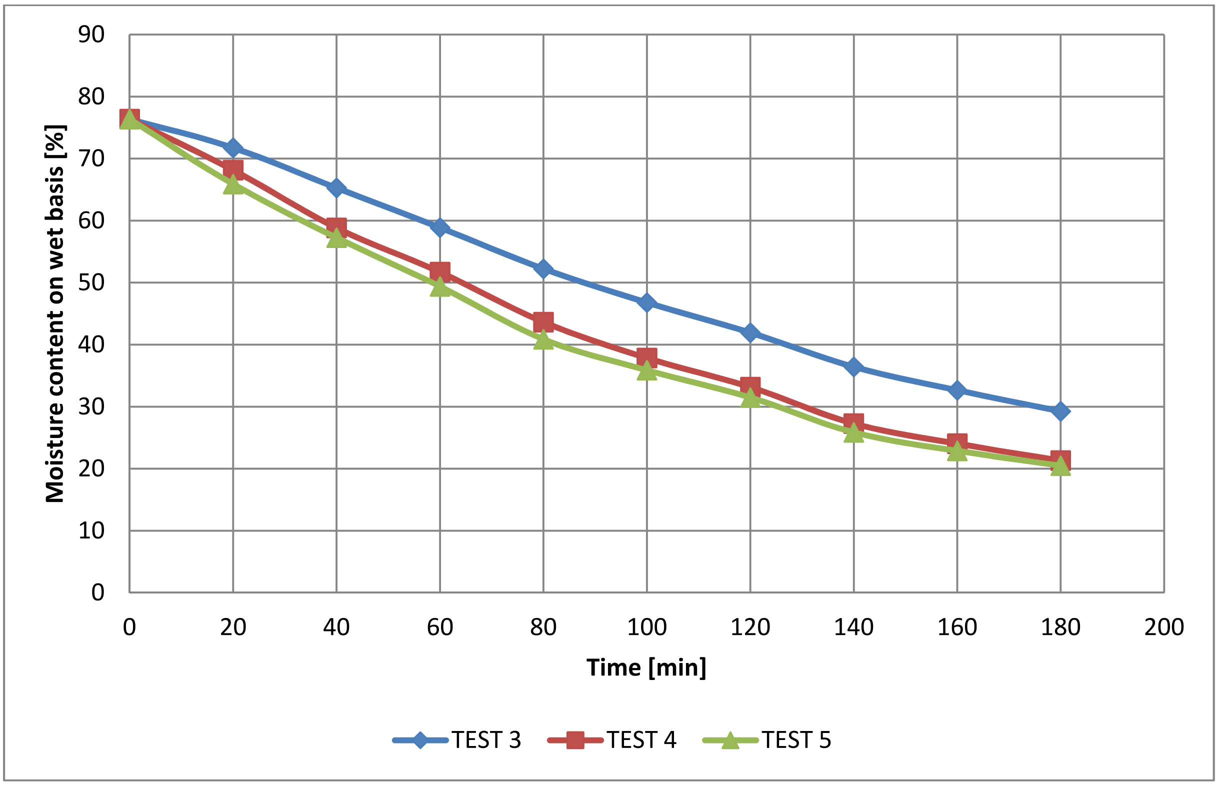

Figure 6.5 Development of moisture content on wet basis for tests 3, 5 and 6

Table 6.6 presents the development of moisture content on a wet basis for test 4, test 5 and test 6 from which the test number 8 has the lowest moisture content, which is just slightly lower than the moisture content of the test 7. Figure 6.6 shows the graph of the measured moisture content versus time.

Moisture content on wet basis [%]			
Elapsed time [min]	Test 6	Test 7	Test 8
0	76.37	76.37	76.37
20	74.69	71.67	69.61
40	71.63	66.18	64.68
60	67.82	61.66	60.50
80	64.34	56.75	55.87
100	60.64	52.69	51.46
120	57.05	48.90	48.09
140	52.59	44.36	43.95
160	49.48	41.34	41.12
180	46.43	38.35	38.25

Table 6.6 Development of moisture content on wet basis for tests 6, 7 and 8

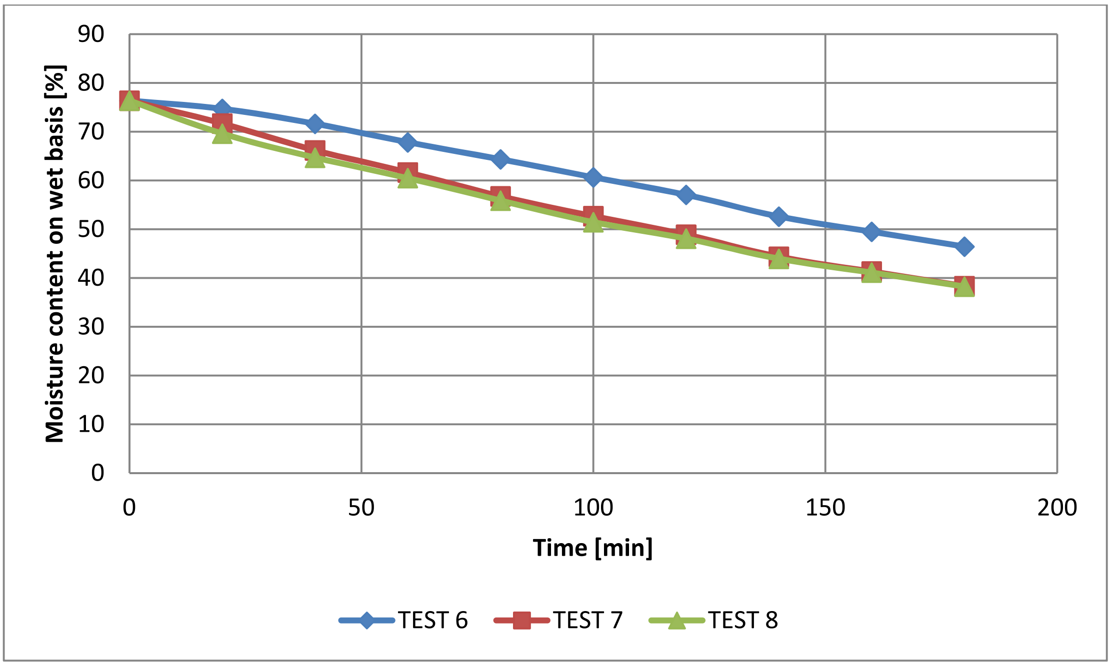

Figure 6.6 Development of moisture content on wet basis for tests 6, 7 and 8

There is an apparent difference between each group of tests when we compare the moisture content on dry basis for all six tests presented in Table 6.7 and Figure 6.7. The first difference is with higher drying temperature that has a higher moisture extraction rate. The difference can clearly be seen on Figure 6.8 that shows the water content versus time for three most efficient tests, which are test 2, test 5 and test 8.

Moisture content on dry basis [%]								
Elapsed time [min]	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8
0	323.19	323.19	323.19	323.19	323.19	323.19	323.19	323.19
20	180.58	170.84	253.91	213.97	193.14	295.13	252.98	229.07
40	119.64	114.6	187.94	142.83	133.98	252.43	195.68	183.16
60	84.34	81.76	143.12	107.03	97.59	210.71	160.85	153.15
80	63.06	61.57	109.35	77.44	69.15	180.45	131.19	126.62
100	49.77	48.88	87.9	60.9	55.99	154.08	111.38	106.01
120	40.88	40.12	72.2	49.6	45.96	132.84	95.68	92.64
140	34.66	33.6	57.26	37.49	34.87	110.92	79.73	78.42
160	30.17	29.5	48.46	31.65	29.67	97.93	70.46	69.83
180	26.66	24.8	41.35	27.08	25.77	86.67	62.21	61.96

Table 6.7 Development of moisture content on dry basis for all tests

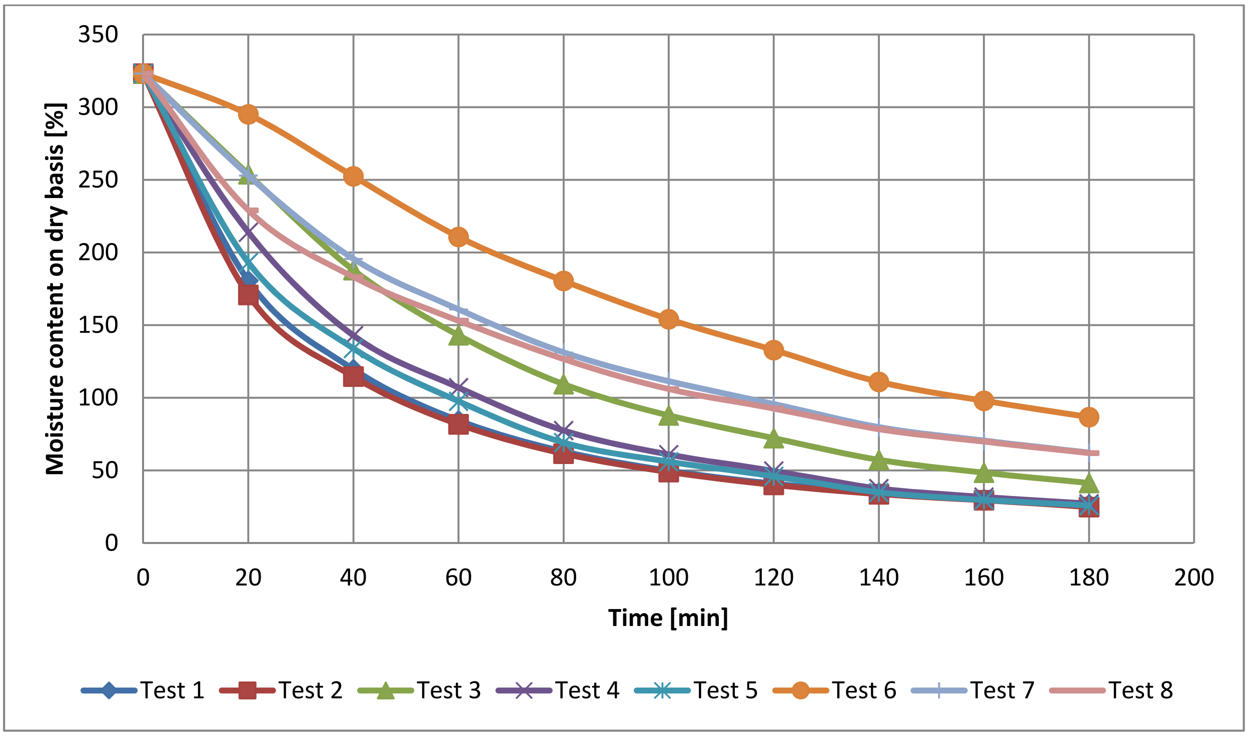

Figure 6.7 Development of moisture content on dry basis for all tests

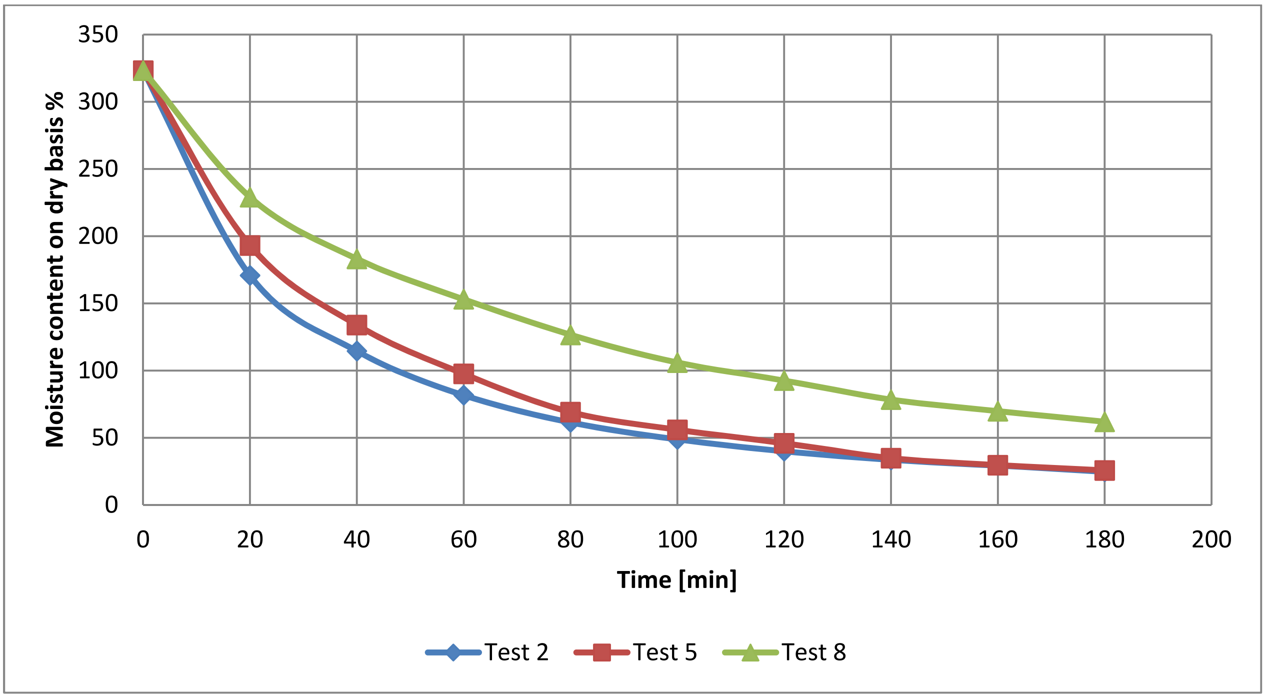

Figure 6.8 Development of moisture content on dry basis for tests 2, 5 and 8

The case of moisture content on dry basis shows the same pattern as for the wet basis where test 2 has the lowest moisture content after 3 hours of drying. These values are also shown in Figure 6.9 and the values of tests 2, test 5 and test 8 are presented in Figure 6.10.

Moisture content on wet basis [%]								
Elapsed time [min]	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8
0	76.37	76.37	76.37	76.37	76.37	76.37	76.37	76.37
20	64.36	63.08	71.74	68.15	65.89	74.69	71.67	69.61
40	54.47	53.4	65.27	58.82	57.26	71.63	66.18	64.68
60	45.75	44.98	58.87	51.7	49.39	67.82	61.66	60.5
80	38.67	38.11	52.23	43.64	40.88	64.34	56.75	55.87
100	33.23	32.83	46.78	37.85	35.89	60.64	52.69	51.46
120	29.02	28.63	41.93	33.15	31.49	57.05	48.9	48.09
140	25.74	25.15	36.41	27.27	25.86	52.59	44.36	43.95
160	23.18	22.78	32.64	24.04	22.88	49.48	41.34	41.12
180	21.05	19.87	29.25	21.31	20.49	46.43	38.35	38.25

Table 6.8 Development of moisture content on wet basis for all tests

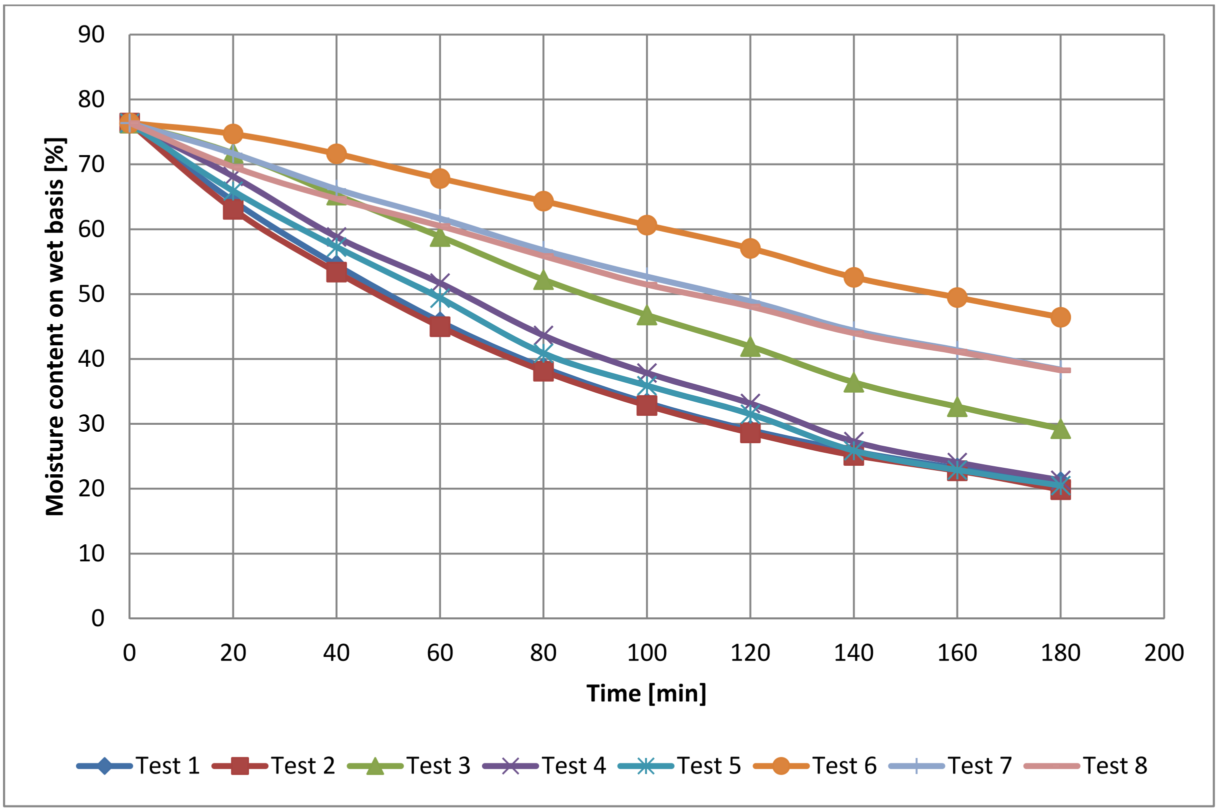

Figure 6.9 Development of moisture content on wet basis for all tests

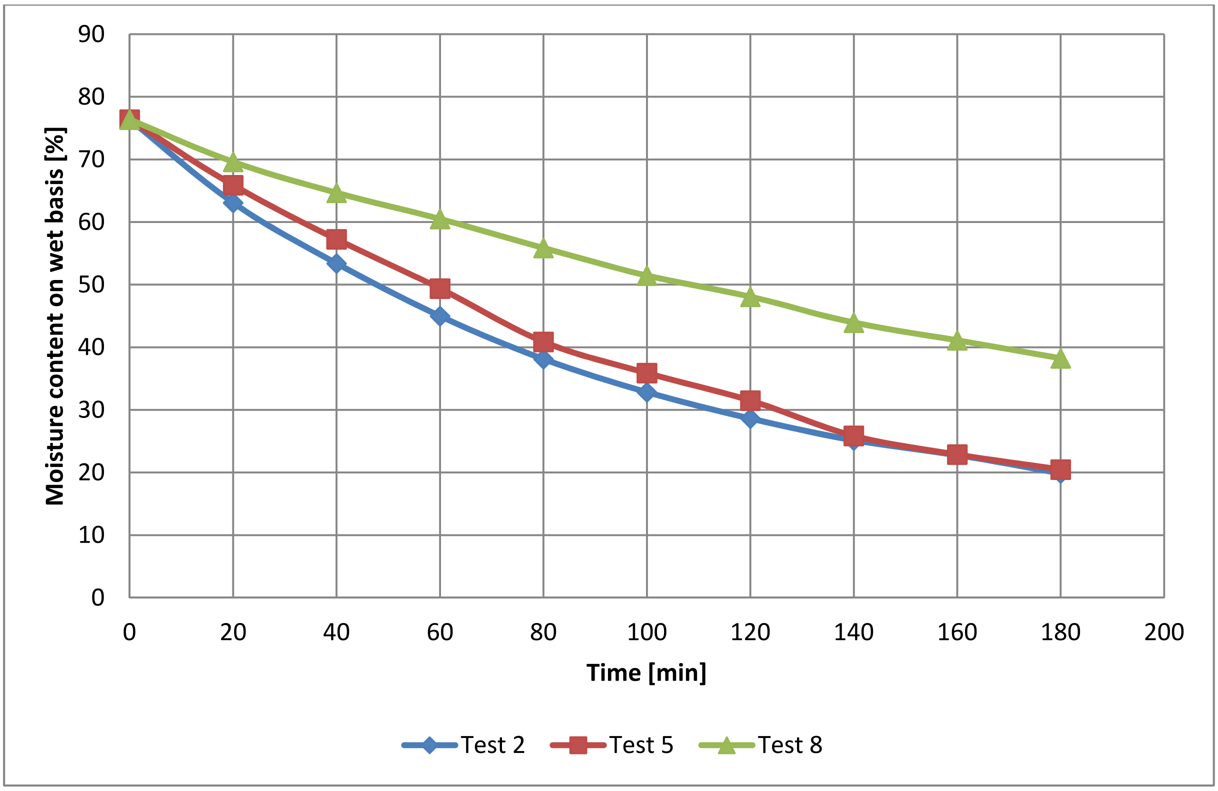

Figure 6.10 Development of moisture content on wet basis for tests 2, 5 and 8

6.2 Modeling Kinetics

.

6.2.1 Results on Modeling of Mass Diffusion and Moisture Contents

The results in Tables 6.9 through 6.18 and Figures 6.11 thorough 6.18 show that the proposed modeling provides a nearly exact fit between observed and predicted results for moisture content for all tests.

Table 6.9 and Figure 6.11 shows the experimental and predicted values for moisture ratio and mass-effective diffusivity for green peas heat pump drying at 45^{o}C and 40% relative humidity (Test 1).

Test 1			
Elapsed time [min]	x_{re}	x_{rp}	D_e [m^2/s]
0	1.0000	1.0000	-
20	0.5587	0.5587	2.08809×10^{-11}
40	0.3702	0.3702	2.95348×10^{-11}
60	0.2609	0.2609	3.05010×10^{-11}
80	0.1951	0.1951	2.96193×10^{-11}
100	0.1540	0.1540	2.80867×10^{-11}
120	0.1265	0.1265	2.64482×10^{-11}
140	0.1072	0.1072	2.48576×10^{-11}
160	0.0933	0.0933	2.33595×10^{-11}
180	0.0825	0.0825	2.20391×10^{-11}

Table 6.9 experimental and predicted moisture ratio and mass effective diffusivity for Test 1 (45^{0}C, 40%)

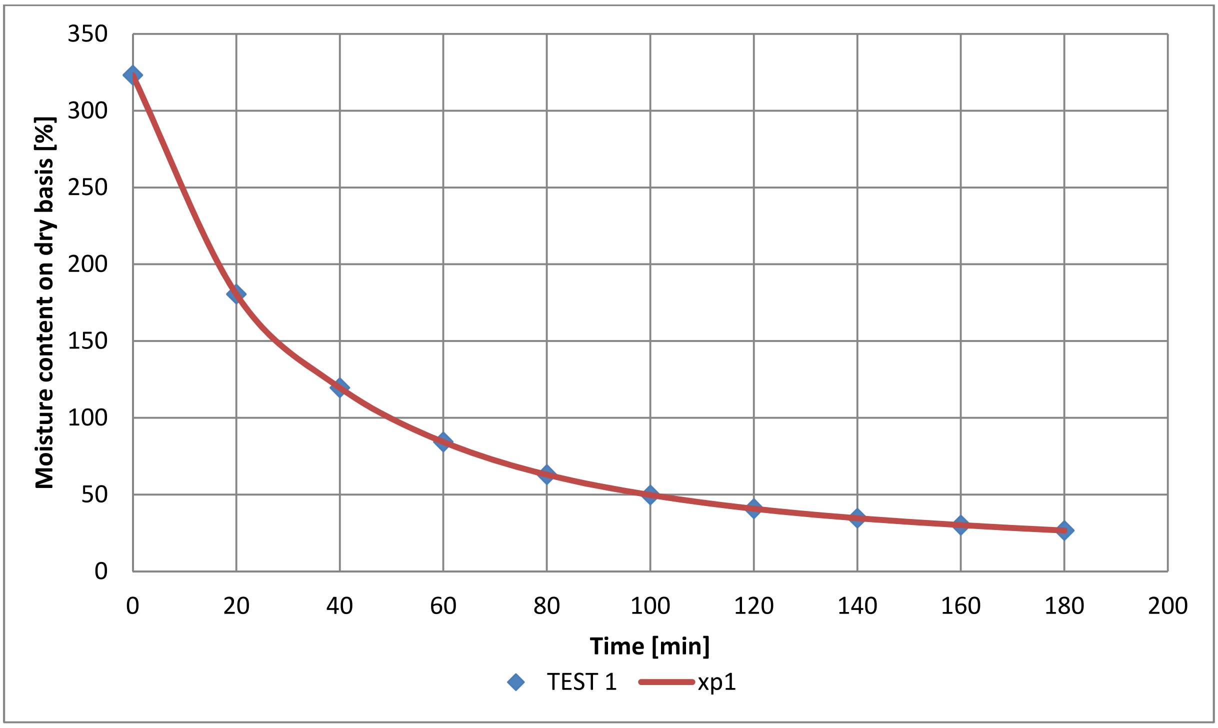

Figure 6.11 The observed and modeled results for moisture content for Test 1.

Table 6.10 and Figure 6.12 shows the experimental and predicted values for moisture ratio and mass effective diffusivity for green peas heat pump drying at 45°C and 20% relative humidity.

Test 2			
Elapsed time [min]	x_{re}	x_{rp}	D_e [m^2/s]
0	1.0000	1.0000	-
20	0.5286	0.5286	2.67930×10^{-11}
40	0.3546	0.3546	3.24626×10^{-11}
60	0.2530	0.2530	3.23912×10^{-11}
80	0.1905	0.1905	3.10653×10^{-11}
100	0.1512	0.1512	2.92613×10^{-11}
120	0.1241	0.1241	2.75284×10^{-11}
140	0.1039	0.1039	2.60159×10^{-11}
160	0.0912	0.0912	2.43178×10^{-11}
180	0.0767	0.0767	2.34579×10^{-11}

Table 6.10 experimental and predicted moisture ratio and mass effective diffusivity for Test 2 (45°C, 20%)

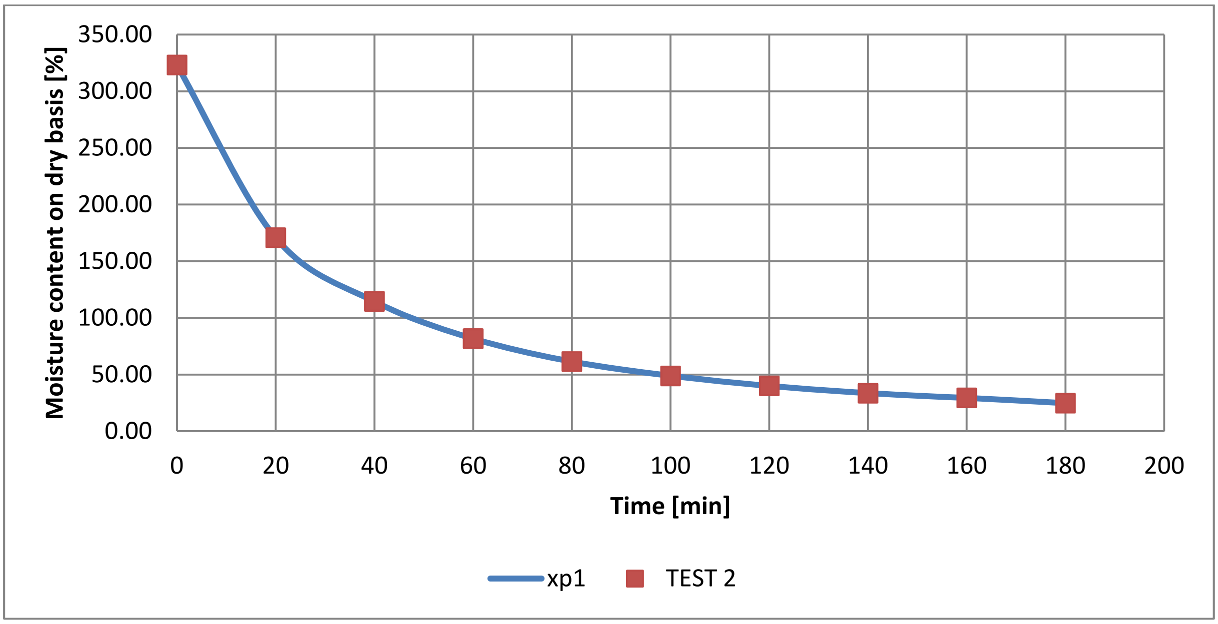

Figure 6.12 The observed and modeled results for moisture content for Test 2

Table 6.11 shows the experimental and predicted values for moisture ratio and mass effective diffusivity for green peas heat pump drying at 35°C and 60% relative humidity. Figure 6.13 provides good match between observed and modeled results for moisture content.

Test 3			
Elapsed time [min]	x_{re}	x_{rp}	D_e [m^2/s]
0	1.0000	1.0000	-
20	0.7856	0.7856	-
40	0.5815	0.5815	9.58659×10^{-12}
60	0.4428	0.4428	1.57949×10^{-11}
80	0.3383	0.3383	1.88135×10^{-11}
100	0.2720	0.2720	1.95732×10^{-11}
120	0.2234	0.2234	1.97070×10^{-11}
140	0.1771	0.1771	2.03216×10^{-11}
160	0.1499	0.1499	1.99416×10^{-11}
180	0.1279	0.1279	1.95517×10^{-11}

Table 6.11 experimental and predicted moisture ratio and mass effective diffusivity for Test 3 (35°C, 60%)

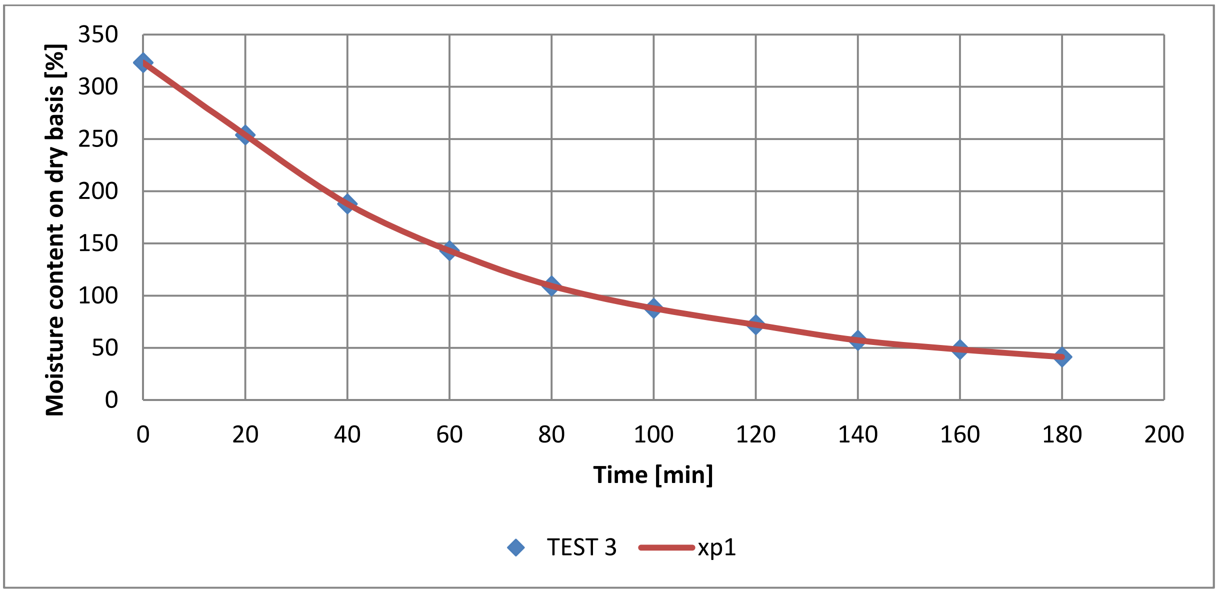

Figure 6.13 The observed and modeled results for moisture content for Test 3

Table 6.12 and Figure 6.14 shows the experimental and predicted values for moisture ratio and mass effective diffusivity in Test 4 for green peas heat pump drying at 35^oC and 40% relative humidity.

Test 4			
Elapsed time [min]	x_{re}	x_{rp}	D_e [m^2/s]
0	1.0000	1.0000	-
20	0.6620	0.6620	4.42982×10^{-12}
40	0.4419	0.4419	1.83612×10^{-11}
60	0.3311	0.3311	1.99256×10^{-11}
80	0.2396	0.2396	2.14083×10^{-11}
100	0.1884	0.1884	2.09663×10^{-11}
120	0.1534	0.1534	2.02053×10^{-11}
140	0.1160	0.1160	2.05143×10^{-11}
160	0.0979	0.0979	1.96415×10^{-11}
180	0.0838	0.0838	1.88439×10^{-11}

Table 6.12 experimental and predicted moisture ratio and mass effective diffusivity for Test 4 (35^oC, 40%)

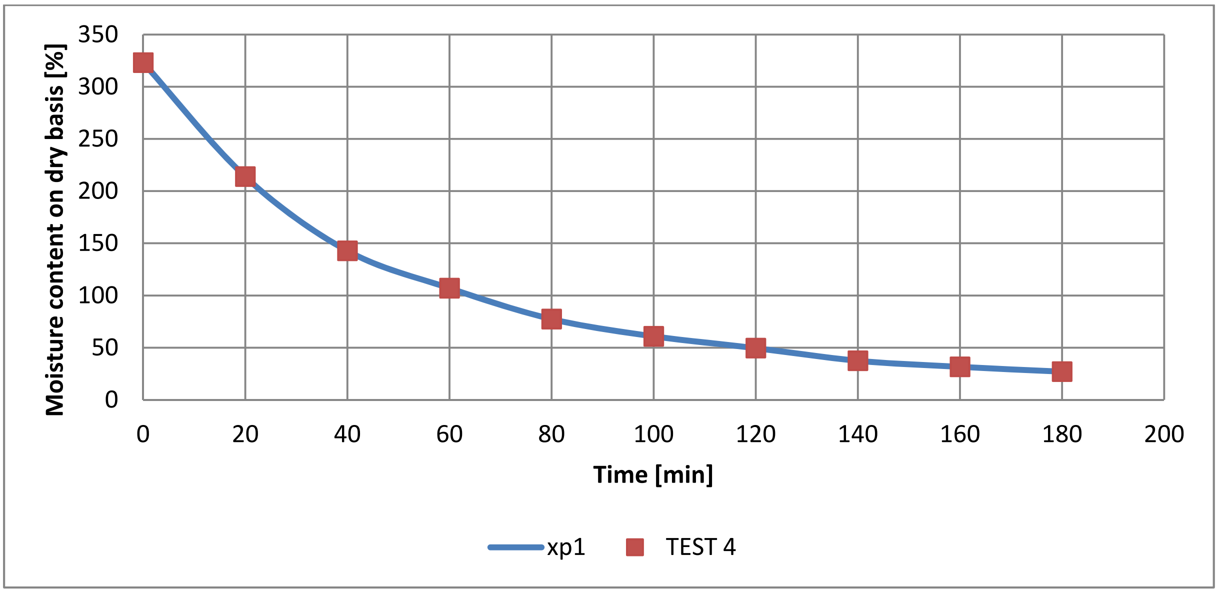

Figure 6.14 The observed and modeled results for moisture content for Test 4

Table 6.13 shows the experimental and predicted values for moisture ratio and mass effective diffusivity for green peas heat pump drying at 35^{o}C and 20% relative humidity. Modeling in Figure 6.15 provides good match between observed and modeled results.

Test 5			
Elapsed time [min]	x_{re}	x_{rp}	D_e [m^2/s]
0	1.0000	1.0000	-
20	0.5976	0.5960	1.48076 x 10^{-11}
40	0.4145	0.4109	2.45564 x 10^{-11}
60	0.3019	0.2977	2.62801 x 10^{-11}
80	0.2139	0.2098	2.77890 x 10^{-11}
100	0.1732	0.1692	2.61920 x 10^{-11}
120	0.1422	0.1385	2.49131 x 10^{-11}
140	0.1079	0.1046	2.50551 x 10^{-11}
160	0.0918	0.0887	2.38172 x 10^{-11}
180	0.0797	0.0769	2.26400 x 10^{-11}

Table 6.13 experimental and predicted moisture ratio and mass effective diffusivity for Test 5 (35^{o}C, 20%)

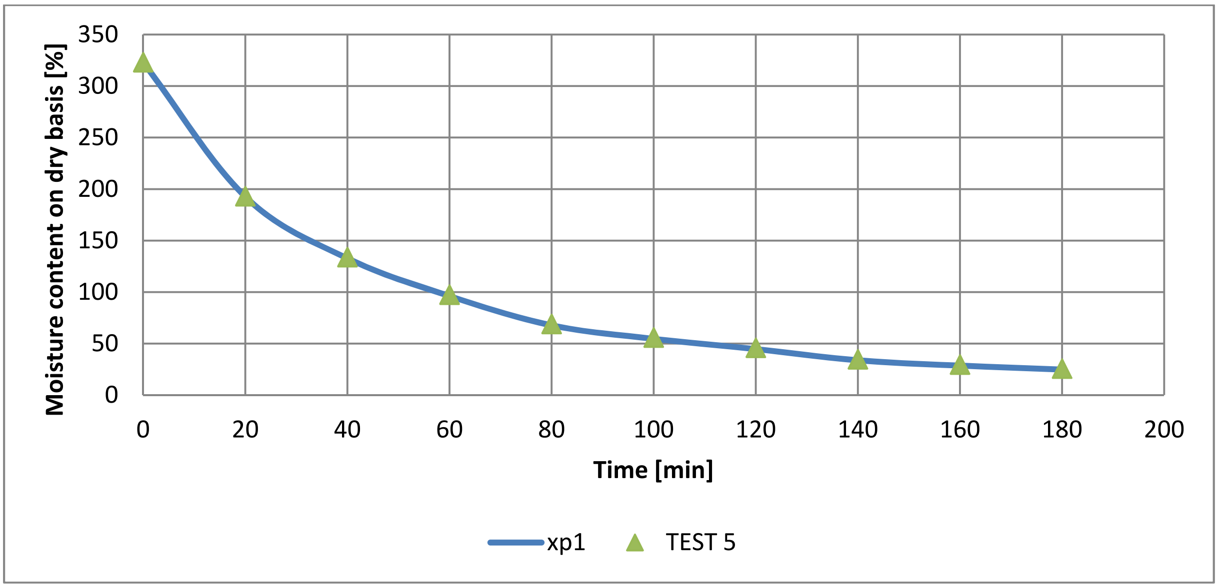

Figure 6.15 The observed and modeled results for moisture content for Test 5

Table 6.14 and Figure 6.16 show the experimental and predicted values for moisture ratio and mass effective diffusivity in test 6 for green peas heat pump drying at 15°C and 60% relative humidity.

Test 6			
Elapsed time [min]	x_{re}	x_{rp}	D_e [m^2/s]
0	1.0000	1.0000	-
20	0.9132	0.9132	-
40	0.7811	0.7811	-
60	0.6520	0.6520	2,4957 x 10^{-12}
80	0.5583	0.5583	5,9704 x 10^{-12}
100	0.4767	0.4767	8,1178 x 10^{-12}
120	0.4110	0.4110	9,3792 x 10^{-12}
140	0.3432	0.3432	1,0764 x 10^{-11}
160	0.3030	0.3030	1,1065 x 10^{-11}
180	0.2681	0.2681	1,1271 x 10^{-11}

Table 6.14 experimental and predicted moisture ratio and mass effective diffusivity for Test 6 (15°C, 60%)

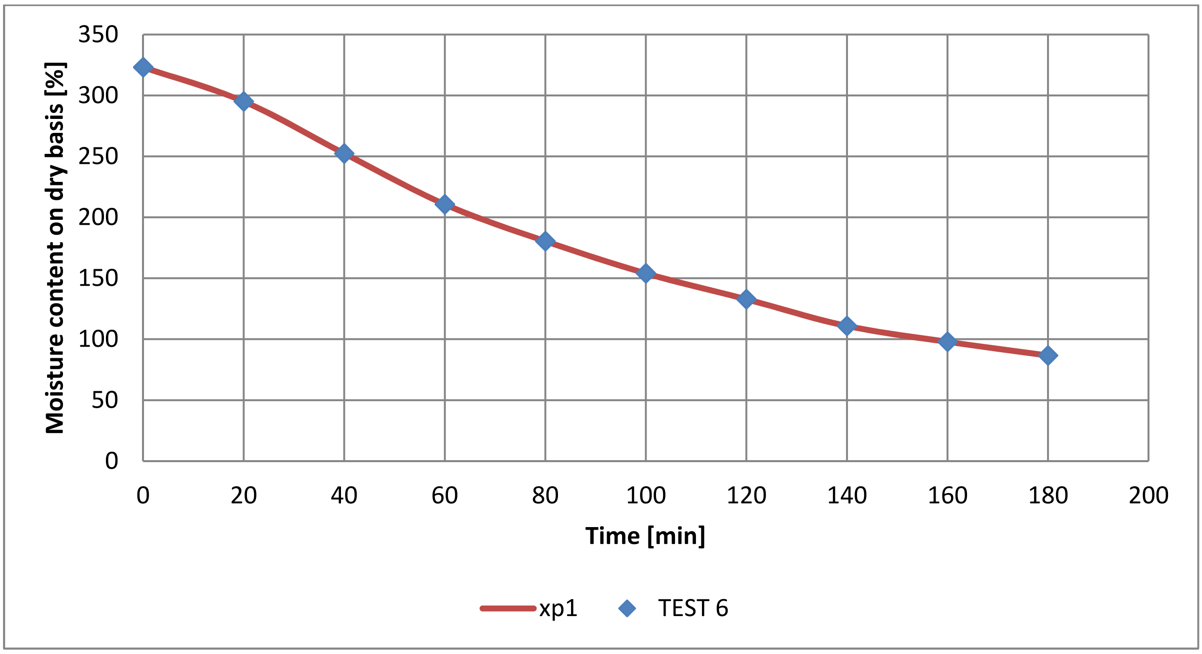

Figure 6.16 The observed and modeled results for moisture content for Test 6

Table 6.15 shows the experimental and predicted values for moisture ratio and mass effective diffusivity for green peas heat pump drying at 15°C and 40% relative humidity. The modeled and measured results for moisture content in Test 7 are presented in Figure 6.17.

Test 7			
Elapsed time [min]	x_{re}	x_{rp}	D_e [m^2/s]
0	1.0000	1.0000	-
20	0.7828	0.7828	-
40	0.6055	0.6055	8.1447×10^{-12}
60	0.4977	0.4977	1.2780×10^{-11}
80	0.4059	0.4059	1.5317×10^{-11}
100	0.3446	0.3446	1.5937×10^{-11}
120	0.2960	0.2960	1.6130×10^{-11}
140	0.2467	0.2467	1.6757×10^{-11}
160	0.2180	0.2180	1.6400×10^{-11}
180	0.1925	0.1925	1.6135×10^{-11}

Table 6.15 experimental and predicted moisture ratio and mass effective diffusivity for Test 7 (15°C, 40%)

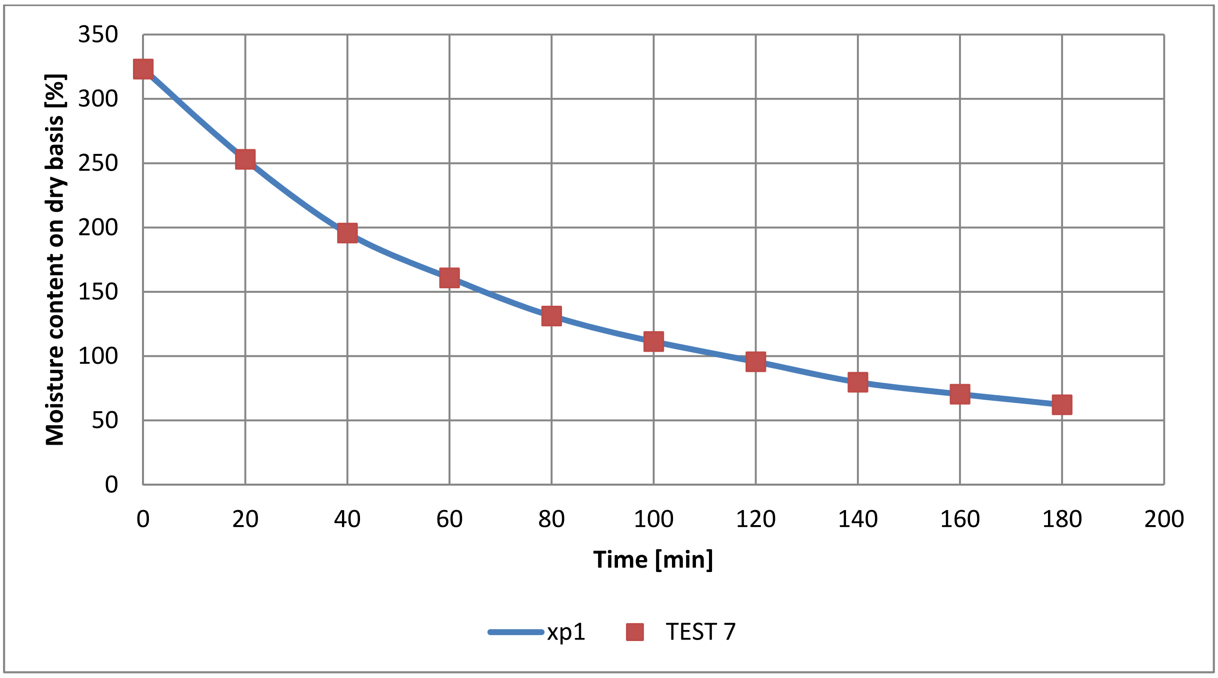

Figure 6.17 The observed and modeled results for moisture content for Test 7

Table 6.16 shows the experimental and predicted values for moisture ratio and mass effective diffusivity for green peas heat pump drying at 15^{o}C and 20% relative humidity.

Test 8			
Elapsed time [min]	x_{re}	x_{rp}	D_e [m^2/s]
0	1.0000	1.0000	-
20	0.7088	0.7089	-
40	0.5667	0.5647	9,8235 x 10^{-12}
60	0.4739	0.4708	1,2105 x 10^{-11}
80	0.3918	0.3880	1,3509 x 10^{-11}
100	0.3280	0.3239	1,4117 x 10^{-11}
120	0.2866	0.2824	1,3857 x 10^{-11}
140	0.2426	0.2384	1,4095 x 10^{-11}
160	0.2160	0.2118	1,3684 x 10^{-11}
180	0.1917	0.1876	1,3401 x 10^{-11}

Table 6.16 experimental and predicted moisture ratio and mass effective diffusivity for Test 8 (15^{0}C, 20%)

Figure 6.18 presents the modeling and test data for drying green peas at 15°C and 20% relative humidity.

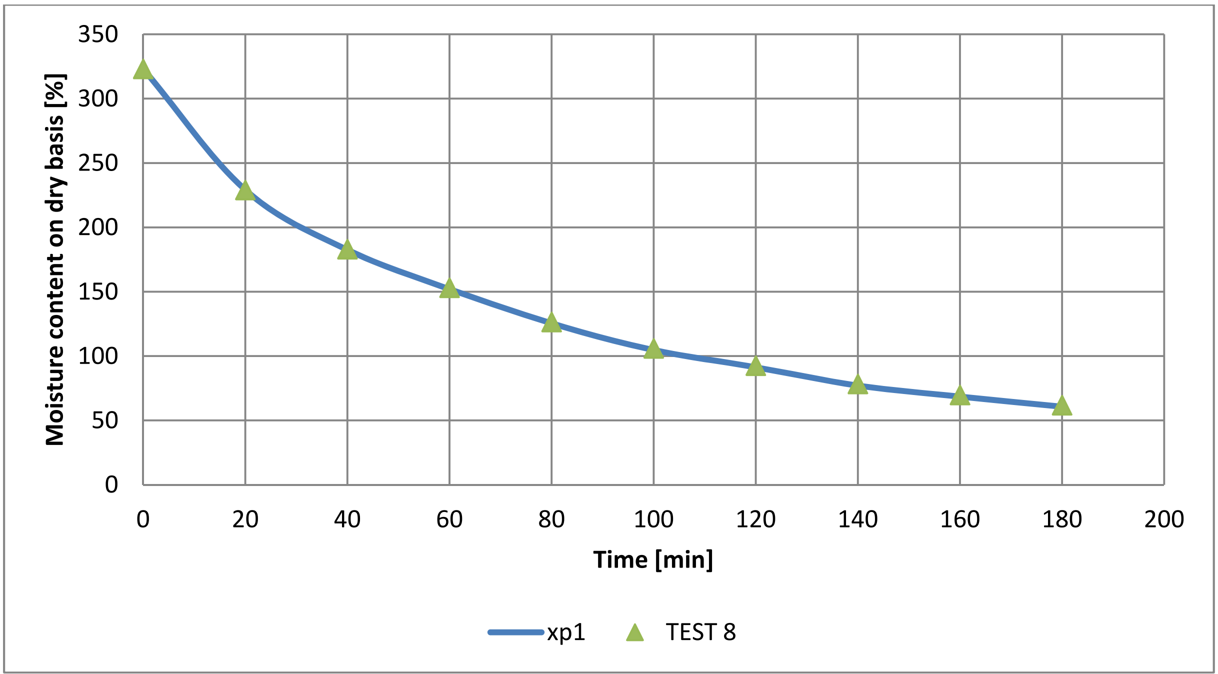

Figure 6.18 The observed and modeled results for moisture content for Test 8

6.3 Color

The results of measurements of color for all tests are shown in Table 6.17 and Figures 6.19, 6.20, 6.21, 6.22. The color of the frozen green peas was also measured and it is shown as a standard value in the table and figures. The first noticeable fact is that first four tests have highest values in all fields of color value. Test 2 has the highest value for brightness of the dried material, followed by Test 1 and Test 3, while other tests have considerably lower values of *L*. When it comes to red-green content of dried green peas, Test 3 has the highest value, followed by Test 4 and somewhat smaller valued Test 2. Other tests have considerably lower value for *a*. The results for yellow-blue content of dried green peas are with Test 3 as highest valued *b*, followed by Test 2 and tests 4 and 1. Other tests have considerably smaller values for *b* and are almost the same compared to each other. All color results are shown and compared in Table 6.18 and Figures 6.19 to 6.22.

Test	Temperature of test ^0C	rH [%]	L	a	b
Frozen	-	-	53.51	-8.81	23.78
1	45	40	43.32	-8.25	24.90
2	45	20	46.33	-9.05	26.12
3	35	60	41.43	-10.06	28.41
4	35	40	39.78	-9.48	25.73
5	35	20	35.69	-7.67	14.63
6	15	60	34.47	-7.87	14.60
7	15	40	36.03	-7.34	14.43
8	15	20	38.23	-7.31	14.84

Table 6.17 Color value for all tests depending from drying air parameters

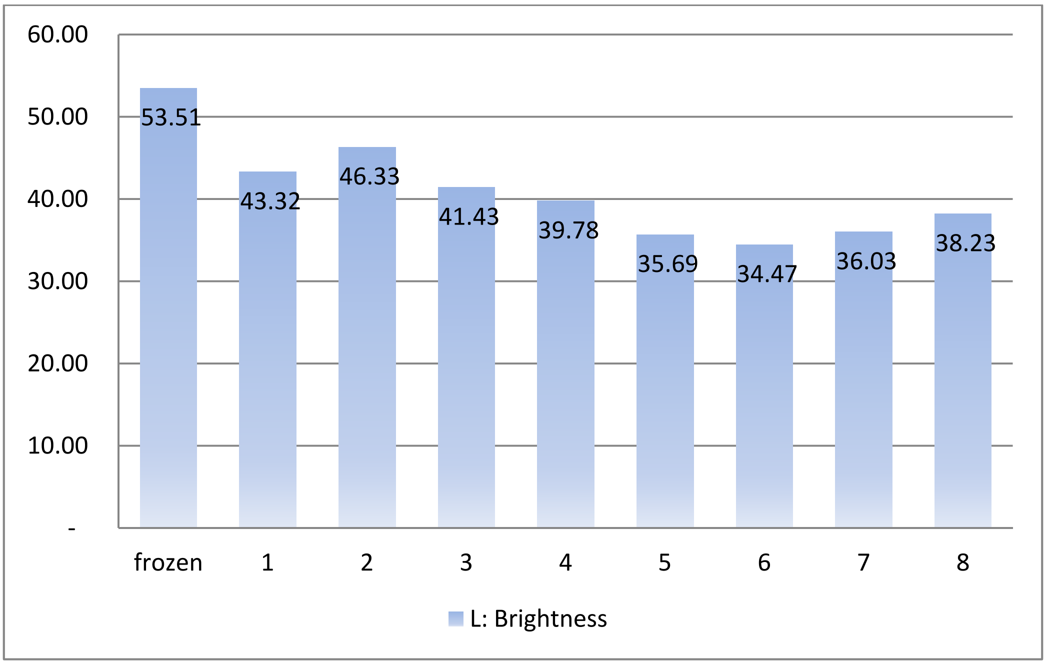

Figure 6.19 Brightness of green peas products

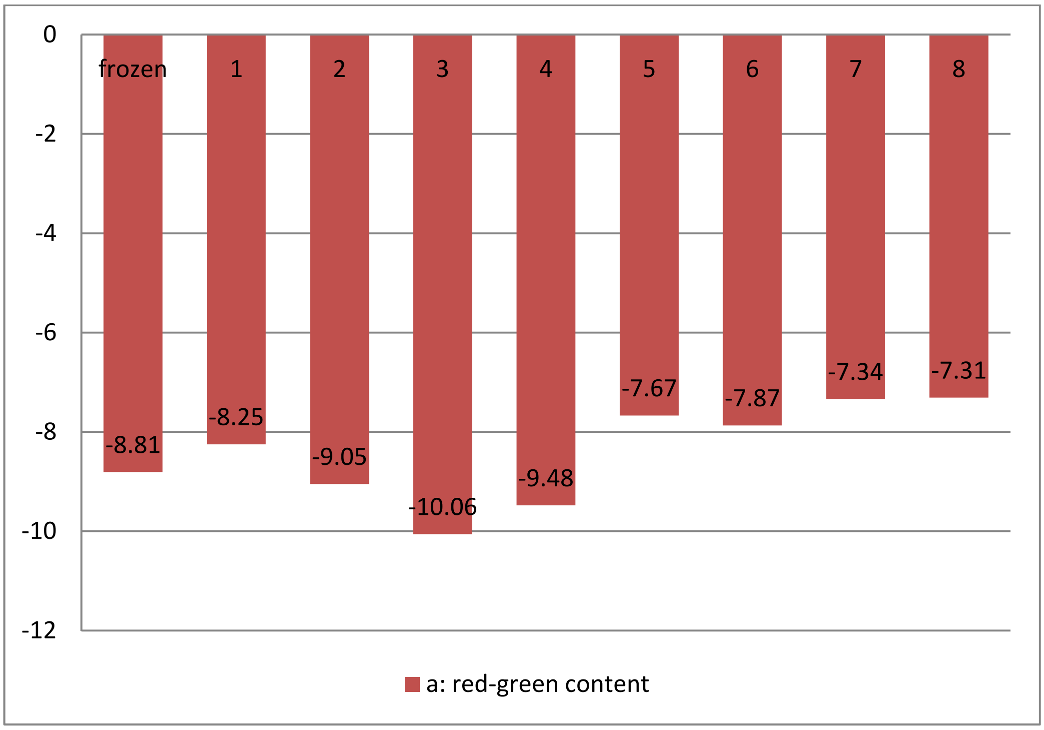

Figure 6.20 Red – green content of dried green peas

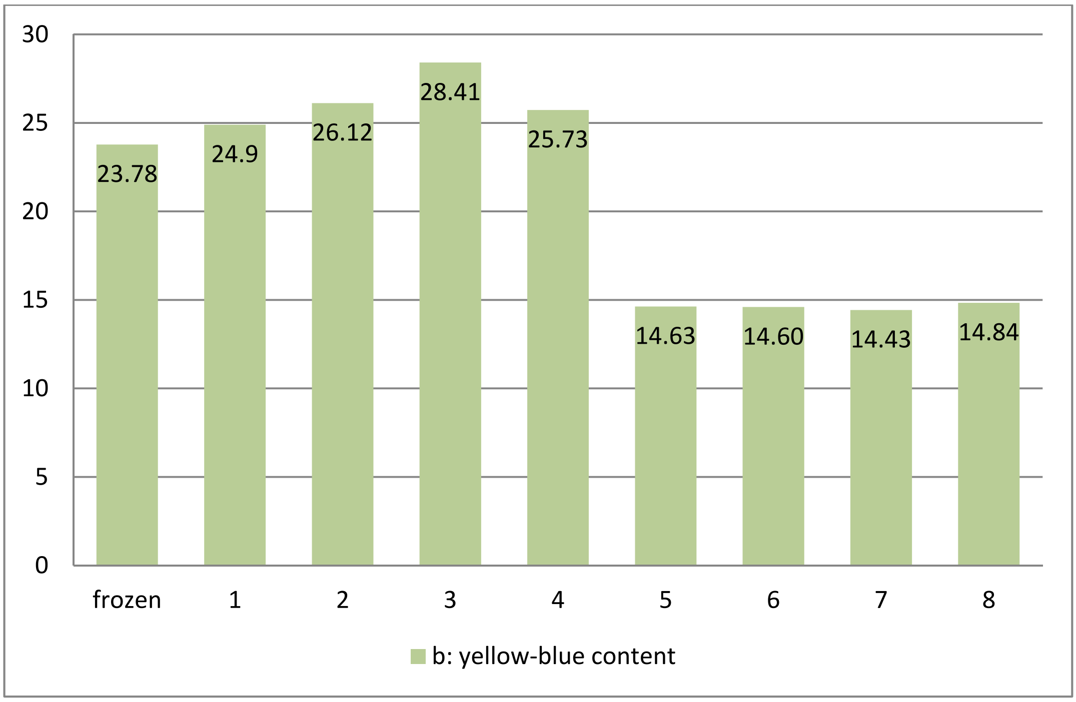

Figure 6.21 Yellow – blue content of dried green peas

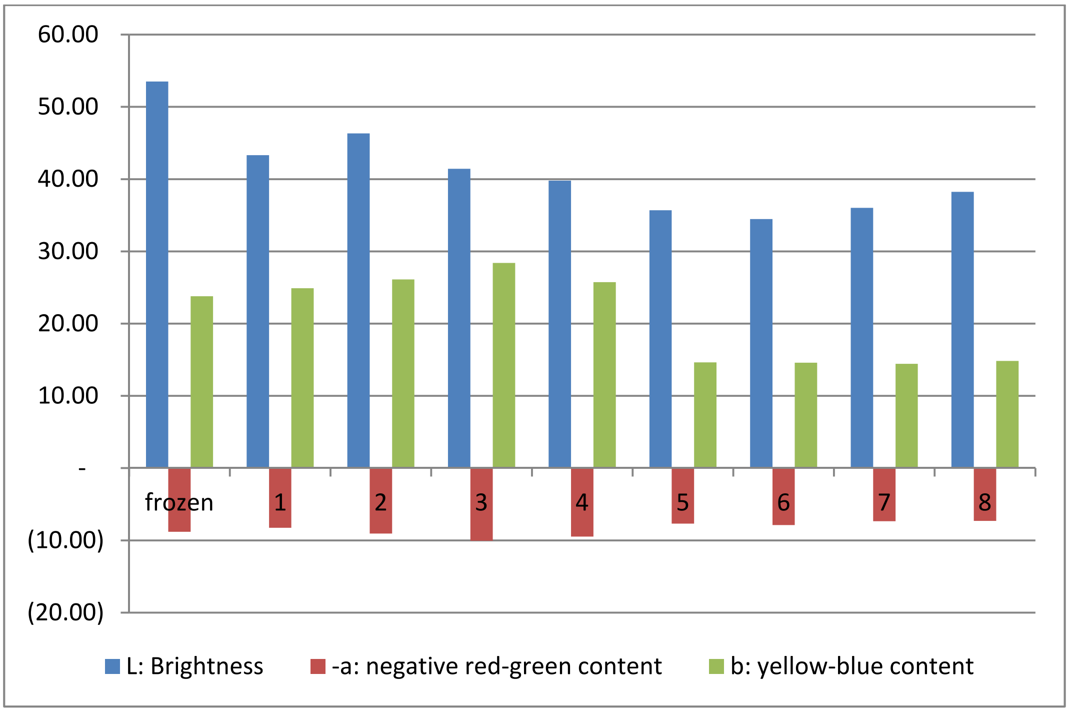

Figure 6.22 Color data for series of drying green peas tests

6.4 Water Activity

The measurements of water activity were done as mentioned in 5.3.3 and the results are shown in Table 6.18 and Figure 6.23. Test marked as test 0 refers to the frozen green peas. The lowest water activity is in green peas from Test 2 and it is considerably the lowest compared to other test's values.

Test	Temperature	Water Activity
0	24.95	0.9878
1	25.08	0.7407
2	25.02	0.6334
3	25.00	0.9128
4	25.20	0.8074
5	25.06	0.8151
6	24.95	0.9377
7	24.97	0.9146
8	25.07	0.9068

Table 6.18 Water activity with the corresponding environmental temperature

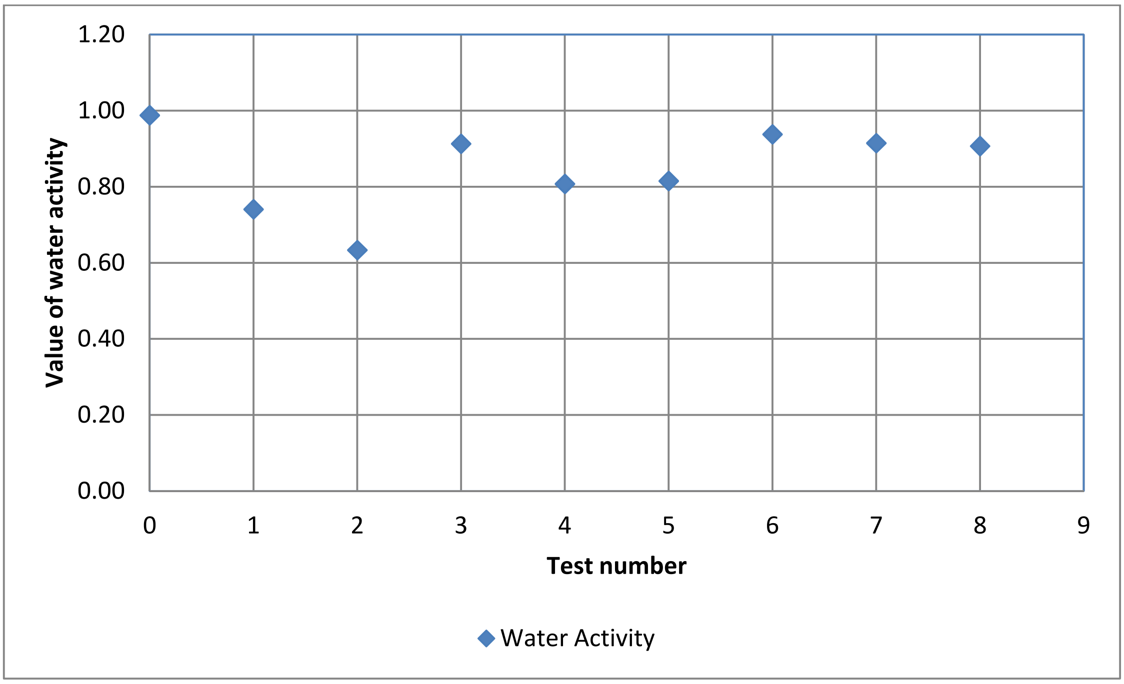

Figure 6.23 Water activity

6.5 Density

The bulk density of the green peas products are listed in Table 6.19 and presented in Figure 6.24. The frozen green peas have the highest bulk density while the smallest bulk density is the green peas from Test 2, and also has the lowest moisture content as shown in Table 6.7.

Test	Temperature	rH [%]	Bulk Density
Frozen	-	-	782.96
1	45	40	473.53
2	45	20	403.97
3	35	60	497.79
4	35	40	466.07
5	35	20	452.03
6	15	60	573.08
7	15	40	497.76
8	15	20	514.55

Table 6.19 Bulk density in function of temperature and Rh of drying medium

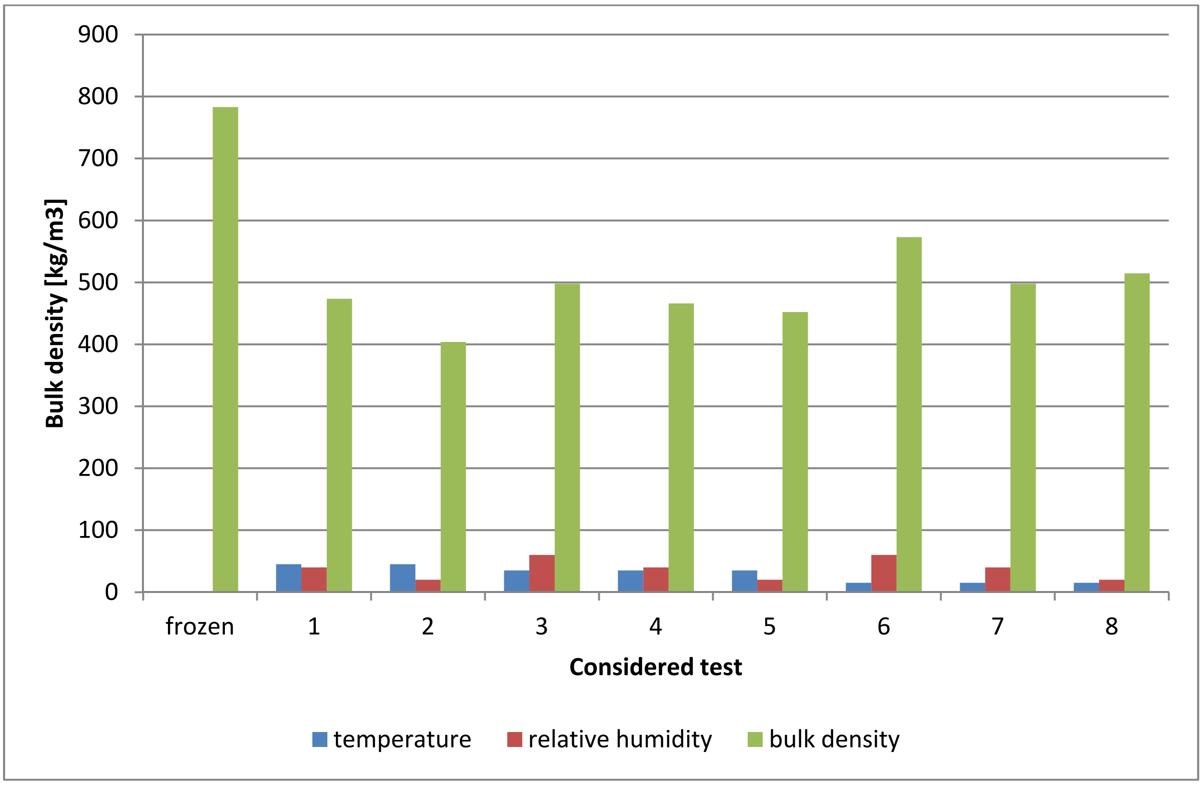

Figure 6.24 Bulk density

Table 6.20 and figure 6.25 represent the particle density of the product. From the results the lowest particle densities are measured for green peas from tests 2, 7 and 3, respectively.

Test	Temperature	rH [%]	Particle Density
Frozen	-	-	866.61
1	45	40	710.22
2	45	20	540.91
3	35	60	599.95
4	35	40	703.63
5	35	20	639.61
6	15	60	760.4
7	15	40	552.81
8	15	20	748.18

Table 6.20 Particle density

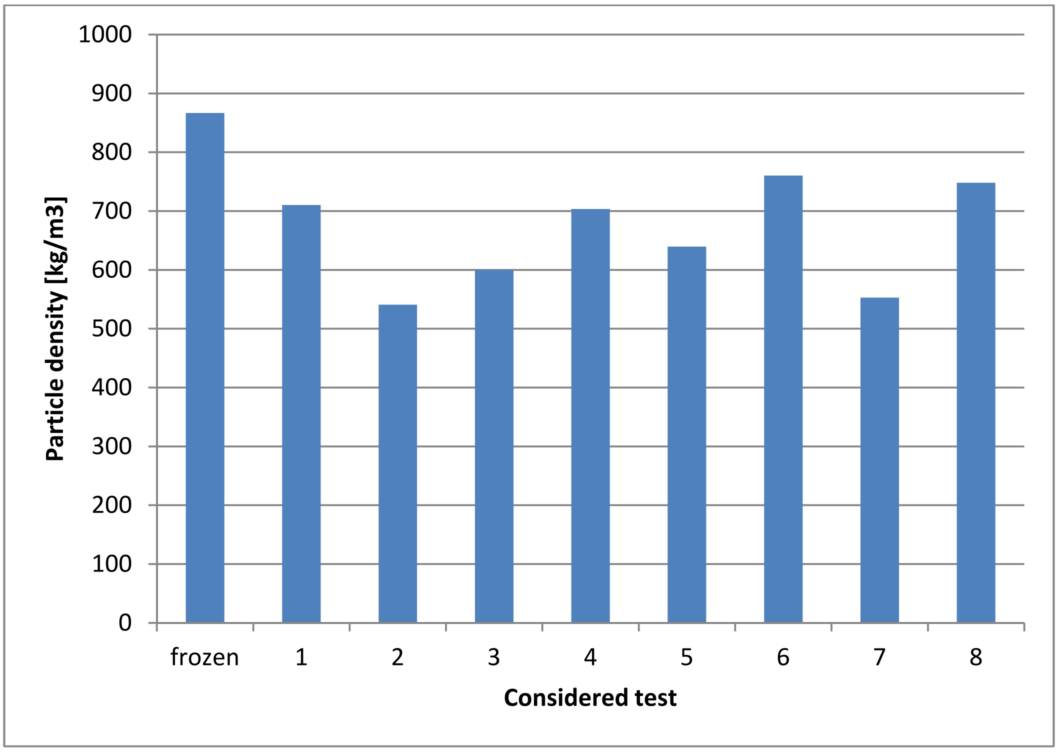

Figure 6.25 Particle density

6.6 Size of Particles

Table 6.21 and Figure 6.26 represent the particle size measured after every test. The values shown in table and on the graph are the average values of ten particles randomly selected from products that were obtained after each test. We can see that the biggest relative particle size is obtained from test 7 aside from value for frozen green peas, although the difference in size varies in interval from 7.89 to 6.65, which is only a maximum difference of 1.24 mm.

Test	Temperature	Relative Humidity [%]	Particle Size [mm]
Frozen	-	-	8.662
1	45	40	7.160
2	45	20	7.265
3	35	60	7.565
4	35	40	6.645
5	35	20	7.200
6	15	60	7.645
7	15	40	7.885
8	15	20	7.175

Table 6.21 Size of particles

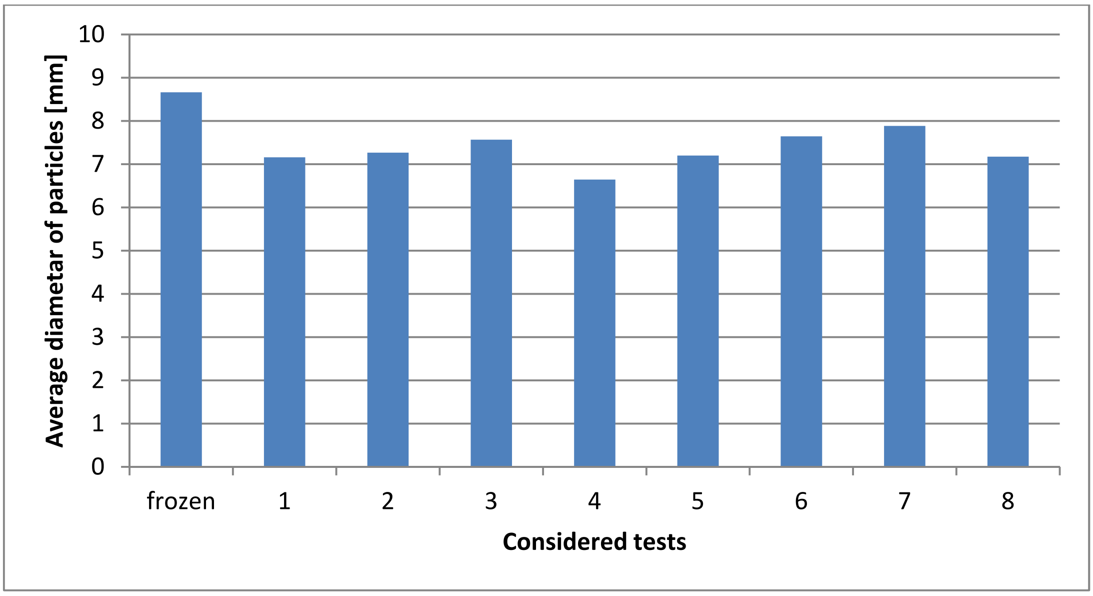

Figure 6.26 Size of particles

7. Conclusions

This project work focus on heat pump drying of green peas at varying conditions. The tests and measurements were done using three sets of temperatures combined with two and three relative humidity modes, respectively.
The results have shown that the temperature of the drying air has the highest influence on products moisture content.

There is also a significant influence of the relative humidity of the drying air on the final product’s moisture content. We can see that the tests with 45°C inlet air have faster moisture removal but also that Test 4 and Test 5 with 35°C inlet air 40% and 20% of relative humidity is approaching the value of the test 1. On the other hand the set of tests with 15°C have high values of moisture content and it is obvious that for that low temperature not even changes in relative humidity can increase moisture removal rate.

Overall, test 2 produced the dried green peas with lowest moisture content.
In terms of color a higher temperature regime influenced the most drastic change in the color properties of the final product but still the values remained relatively close between tests. The biggest difference that can be noticed is the similarity of values for Test 1 to Test 4, and also the similarity in results of color for Test 5 to Test 8.

Test 1 and test 2 which operated on a high temperature regime and lower relative humidity provided the products with the lowest water activity. But it is obvious that Test 2 has the far lowest water activity, and it can’t be described otherwise except as the influence of relative humidity which is in this case 20%.

Both bulk and particle density are quite uniform throughout the tests with slight variations. The biggest difference in this case is density values for Test 2, which is lower in both cases of bulk and particle density.

The values for particle size for all tests are relatively close to each other. We can see that different drying regimes had only a small influence on change in particle size especially if we take into consideration that the comparison was made with frozen green peas, which is expanded to some extent due to the frozen water that it contained.

When it comes to modeling mass diffusion and moisture contents, the generated plots are almost perfect fitting between predicted and experimental data, particularly for Tests 1 and 2.

The fan provided drying air flow either to achieve fluidized bed operation or operate in onset fluidization. Fluidization has an important advantage in the process of drying of green peas since it leads to good solid mixing and high rates of heat and mass transfer. Also, the process of fluidization should be done cautiously and controlled since intensity may cause damage of the product as a result of impacts and friction between particles, and between particles and walls of the drying chamber.

8. Proposal of further work

Further experiments in the field of heat pump drying should extend the range of temperature and of the dependent variables. There is also a need to include measurement of the total energy consumption and relation to different drying regimes and conditions. It this case the comparison of dried product output and energy consumption should be made. One of the goals should be procedures to get better product quality and longer shelf life and effect of fluidization on process kinetics and product quality.

The laboratory tests were done as a batch process, but for an industrial application continuous operations are required. Therefore, in later stages of process-product development, it would be beneficial to consider the continuous mode of drying or air transport in combination with both drying and continuous mode.

Furthermore, research of other methods and processes in the goal of increasing product quality and lowering the energy consumption is recommended. Additional tests should be done to extend the drying temperature range at similar relative humidity levels to compare quality, kinetics and energy use.

9. Reference list

[1] **Kenneth J. Valentas, Enrique Rotstein and R. Paul Singh.** Handbook of Food Engineering Practice. CRC Press, 1997.

[2] **Arun S. Mujumdar.** Handbook of Industrial Drying. Third Edition, Taylor & Francis, 2007.

[3] **P. J. Fellows.** Food Processing Technology – Principles and Practice. Second Edition, Woodhead Publishing Limited, Cambridge, 2000.

[4] **Jangam S. V. and Thorat B. N.** 16th International Drying Symposium (IDS2008) – Mathematical Analysis of Heat Pump Drying System. Hyderabad, India, 9 – 12 November, 2008.

[5] **Shi Y., Li S., Chai B., Wang H., Zhang Z. and Yang X.** 16th International Drying Symposium (IDS2008) – Current Status and Development Strategy of China Drying Technology Research and Industry. Hyderabad, India, 9 – 12 November, 2008.

[6] **Odilio Alves-Filho.** Heat Pump Drying: Theory, Design and Industrial Application. Department of Energy and Process Engineering, NTNU. Trondheim, Norway, 2013.

[7] **Taclan L. B. and Franco S. S.** 16th International Drying Symposium (IDS2008) – Heat Pump Drying of Onion (allium cepa). Hyderabad, India, 9 – 12 November, 2008.

[8] **Alves – Filho O., Guzev O. and Goncharova – Alves S.** 16th International Drying Symposium (IDS2008) – Kinetics and Energy Aspects of Heat Pump Drying of Protein. Hyderabad, India, 9 – 12 November, 2008.

[9] **Phaphuangwittayukul W., Changrue V., Siriplabpla P. and Raghavan G. S.** V. 16th International Drying Symposium (IDS2008) – Simultaneous Heating and Cooling for Thai Herb by Heat Pump Technique. Hyderabad, India, 9 – 12 November, 2008.

[10] **Theplib P., Srzednicki G. and Driscoll R.** 16th International Drying Symposium (IDS2008) – Effects of Tunnel vs. Heat Pump Drying on the Quality of Strawberries. Hyderabad, India, 9 – 12 November, 2008.

[11**] Alves – Filho O. and Eikevik T. M.** 16th International Drying Symposium (IDS2008) – Hybrid Heat Pump Drying Technologies for Porous Materials. Hyderabad, India, 9 – 12 November, 2008.

[12] **Poomsa – ad N., Atthajariyakul S., Wiset L. and Tipsanprom W.** 16th International Drying Symposium (IDS2008) – Performance of Heat Pump Dryer for Nam – dok – mai Mango under Different Medias. Hyderabad, India, 9 – 12 November, 2008.

[13] **Odilio Alves – Filho and Ingvald Strømmen.** 10th International Drying Symposium (IDS'96) – Performance and Improvements in Heat Pump Dryers. Krakow, Poland, 30 July – 2 August 1996.

[14] **M. N. A. Hawlader, S. K. Chou, K. J. Chua.** 10th International Drying Symposium (IDS'96) – A Heat Pump Assisted Closed – Loop Tunnel Dryer. Krakow, Poland, 30 July – 2 August 1996.

[15] **S. Prasertsan, P. Saen – Saby, G. Prateepchaikul, P. Ngamsritrakul.** 10th International Drying Symposium (IDS'96) – Effects of Product Drying Rate and Ambient Condition on the Operation Modes of Heat Pump Dryer. Krakow, Poland, 30 July – 2 August 1996.

[16] **I. Strømmen and O. Jonassen.** 10th International Drying Symposium (IDS'96) – Performance Rests of a new 2 – Stage Counter – Current Heat Pump Fluidized Bed Dryer. Krakow, Poland, 30 July – 2 August 1996.

[17] **Ingvald Strømmen, Trygve M. Eikevik and Ingrid C. Claussen.** 5th Asia – Pacific Drying Conference – Atmospheric Freeze Drying with Heat Pumps – New Possibilities in Drying of Biological Materials. Hong Kong, 13 – 15 August 2007.

[18] **Yuvanaree Namsanguan, Warunee Tia, Sakamon Devahastin and Somchart Soponronnarit.** 5th Asia – Pacific Drying Conference – Experimental Investigation of Two – Stage Superheated Steam and Heat Pump Drying of Shrimp. Hong Kong, 13 – 15 August 2007.

[19] **Zhang Bi – Guang, Li Liang, Zhou Yong – Dong and Fang Yue – Fei.** 5th Asia – Pacific Drying Conference – Experimental Study on Sludge Drying with Heat Pump Dehumidifier. Hong Kong, 13 – 15 August 2007.

[20] **Zhang Jinjiang and Wu Yaosen.** 5th Asia – Pacific Drying Conference – Experimental Study on Drying High Moisture Content Paddy by Super – Conducting Heat Pump Dryer. Hong Kong, 13 – 15 August 2007.

[21] **Li Minxia, Ma Yitai, Gong Wenjin and Su Weicheng.** 5th Asia – Pacific Drying Conference – Two – Stage Drying of CO_2 Transcritical Cycle Heat Pump. Hong Kong, 13 – 15 August 2007.

[22] **Vasile Minea.** 5th Asia – Pacific Drying Conference – Energetic and Ecological Aspects of Wood Drying with Heat Pumps. Hong Kong, 13 – 15 August 2007.

[23] **Kong Hoon Lee and Ook Joong Kim.** 5th Asia – Pacific Drying Conference – Experimental Study on the Energy Efficiency and Drying Performance of the Batch – Type Heat Pump Dryer. Hong Kong, 13 – 15 August 2007.

[24] **H. Ogura, M. Mizusima, Y. Otsubo and A. S. Mujumdar.** 5th Asia – Pacific Drying Conference – Simulation of Convective Dryer with Chemical Heat Pump. Hong Kong, 13 – 15 August 2007.

[25] **O. Alves – Filho and T. M. Eikevik.** 5th Asia – Pacific Drying Conference – Cheese Drying and Ripening Kinetics in Applications of Heat Pump Technologies. Hong Kong, 13 – 15 August 2007.

[26] **Ingvald Strømmen, Trygve M. Eikevik and Odilio Alves-Filho.** The 1st Asian-Australian Drying conference – Optimum Design and Enhanced Performance of Heat Pump Dryers. Bali, October 24-27, 1999.

[27] **Hironao Ogura, Tstsuya Yamamoto, Yasufumi Otsubo, Hiroki Ishida, Hiroyuki Kage and Arun S. Mujumdar.** The 14th International Drying Symposium – Controllability of a Chemical Heat Pump Dryer. São Paulo, Brazil, 22-25 August 2004. pp. 998-1004

[28] **Vasile Minea.** The 14th International Drying Symposium – Heat Pump for Wood Drying – New Developments and Preliminary Results. São Paulo, Brazil, 22-25 August 2004. pp. 892-899

[29] **M. N. A Hawlader, Conrad O. Perera, Min Tian, B. K. Ong and Kuan Jin Chng.** The 14th International Drying Symposium–Heat Pump Drying under Inert Atmosphere. São Paulo, Brazil, 22-25 August 2004. pp. 309-316

[30] **Odilio Alves-Filho.** Springerlink.com – Sweep Numerical Method and Mass Transport Analysis in Atmospheric Freeze Drying of Protein Particles. Journal of Heat Mass Transfer, 46: 923-928, 2010.

[31] **Odilio Alves-Filho and Trygve M. Eikevik.** International Journal of Food Engineering *Volume 4, Issue 6* – Heat Pump Drying Kinetics of Spanish Cheese. Article 6, 2008.

[32] **O. Alves-Filho, T. Eikevik, A. Mulet, C. Garau, and C. Rossello.** Journal of Drying Technology – Kinetics and Mass Transfer during Atmospheric Freeze Drying or Red Pepper. 25: 1155-1161, 2007.

[33] **W. Senadeera, O. Alves-Filho, and T. Eikevik.** Journal of Drying Technology – Influence of Atmospheric Sublimation and Evaporation on the Heat Pump Fluid Bed Drying of Bovine Intestines. 30: 1583-1591, 2012.

[34] **O. Alves-Filho, T. M. Eikevik, and S. V. Goncharova-Alves.** Journal of Drying Technology – Single and Multistage Heat Pump Drying of Protein. 26: 470-475, 2008.

[35] **O. Alves-Filho, S. Goncharova-Alves.** 17th International Drying Symposium – Infrared Radiation and Atmospheric Freeze Drying of Ocimum Basilicum Linnaeus. Magdeburg, Germany, 3-6 October 2010.

[36] Personal communication and consultation with **Professor Odilio Alves-Filho**, from august. 2012 until jun. 2013.

[37] **Odilio Alves-Filho**. EP8208 course at NTNU-Heat and Mass Transfer in Porous Media. Autumn 2012.