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Kirill Mukhatov

Green technology applying heat pump drying, modeling and simulation

Doctoral Thesis

Kirill Mukhatov

NTNU
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Science and Technology
Faculty of Engineering
Science and Technology
Department of Energy and
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Thesis for the degree of Philosophiae Doctor

Trondheim, May 2014

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PREFACE

This thesis is submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy (PhD) at the Norwegian University of Science and Technology (NTNU). The work was carried out in the Food Technology Group in the Department of Energy and Process Engineering, supervised by Professor Odilio Alves-Filho and co-supervised by Professor Trygve Magne Eikevik.

The PhD was created and funded by NTNU and the Research Council of Norway through the project "Green technology applying heat pump drying, modeling and simulation" (#81716200). My contribution and this thesis are focused on the Atmospheric Heat Pump Drying (AHPD) of green peas.

The process was examined and the experiments were done in order to collect laboratory data on the atmospheric heat pump drying of green peas. These experiments contributed to developing a numerical approach to describe the process for many various drying and material conditions. The heat pump system was also examined in terms of capacity, performance, energy efficiency and environmental impact. The main idea of the study was to determine if an AHPD could be a competitive technology to vacuum freeze drying (VFD), which is widely used today.

ACKNOWLEDGEMENT

First of all I want to thank my supervisor, Professor Odilio Alves-Filho, for the opportunity to work with him and on this interesting project: without your patient guidance this thesis would not have developed. I really appreciated the opportunity to study and enjoy working with you and our food engineering research group. I would also like to say thank you to Professor Trygve Magne Eikevik, my co-supervisor, for his advice and the time he has given to help me. Yours doors were always open to me. Again, thanks to both of you for this project!

I want to offer an individual «thank you» to my PhD fellow Ignat Tolstorebrov for his support and help. Also a special thanks to my roommates Per Egil Gullsvåg, Michael Bantle and Zhequan Jin, you have always been so kind and supportive to me.

I would also like to say a special thank you to all the people from the Department of Energy and Process Engineering who helped me over the last four years.

I dedicate this work to my parents Vladimir and Alla and, especially, to my wonderful wife Svetlana, who has gone through all this way with me, encouraging and cheering me up. You are the closest people in my life; thank you for your support, patience, and love.

ABSTRACT

This work has focused on the development of atmospheric freeze and non-freeze drying applying a heat pump system as an environmental friendly and economically preferable technology compare to vacuum freeze drying. The main reason of the research is a lack of knowledge and information in the literature about the atmospheric heat pump drying, while the more common vacuum freeze drying process is widely covered.

The main objective for developing atmospheric heat pump drying as a new drying technology is the desire to reduce the energy consumption compared to that of vacuum freeze drying while maintaining a high product quality.

One technical solution of atmospheric freeze and non-freeze drying is combining with a heat pump system applying a new environmentally friendly natural refrigerant, such as ammonia or R717. Temperature programs make it possible to customize products for desired qualities and properties, such as color retention, instant rehydration and aroma preservation.

Drying is one of the most important industrial processes, and a technology used worldwide for food processing. The vacuum freeze and high temperature drying are both well-known and extensively applied conventional technologies that have the drawback of high energy consumption. This provided the opportunity for heat pump drying development, in order to decrease operational costs while preserving the quality of the products. Heat pump drying is a relatively new technology developed at NTNU. It unifies the drying and heat pump cycles that allows energy recovery for reheating the drying air.

An analysis was made on the technological aspects, product possibilities, physical properties of products, drying kinetics and modeling.

This work covers the drying of green peas, applying a laboratory heat pump dryer. The drying conditions and processing time are the most important parameters for modeling and scaling-up the process. Additionally, the temperature, relative humidity and residence time are essential for understanding changes in product properties, and fundamental for the designing and dimensioning of large-scale drying processes.

Therefore, the various tests were done at many different temperature regimes, from -5°C to 45°C, and at varying levels of relative humidity. Some of the drying tests applied additional equipment, such as an air humidifier, infrared lamps and an oven to get the specific temperature or moisture content of the tested product. All the drying tests were performed, and each run was done in a period of three hours using a fluidized bed mode. The results on kinetics and final moisture content indicated that temperatures and relative humidity levels lead to changes in the moisture removal rates from the material as well as the quality of the product. Studies were also made to investigate the influence of drying conditions and time on product parameters such as color and water activity.

This work also proposes a numerical solution for the moisture content in order to describe the drying kinetics and effective mass diffusivity. The results in this work can be useful since it reduces the number of drying experiments to be tested at a wide range of drying conditions.

The proposed models have been validated by experiments with acceptable deviations. It helps in establishing the temperature and time schedule in a preliminary study on scaling up lab dryers to a pilot or commercial drying plant. This is also a good platform for further research oriented towards the unification of available laboratory data in the heat pump drying of vegetables to the overall simulation program.

The coefficient of performance (COP) and specific moisture extraction rate (SMER) were calculated to characterize the energy efficiency and water removal capacity of the heat pump drying process. Ammonia or R717 was selected as the working fluid due to its thermal properties and for being an environmentally friendly refrigerant. Regarding greenhouse gases (GHGs), ammonia is a natural fluid which has zero ozone depletion potential (ODP) and zero global warming potential (GWP), that makes heat pump drying a competitive and efficient drying technology with a minimum impact on climate change.

LIST OF PAPERS

This thesis is based on the following papers, referred to in the text by Roman numerals.

I. Mukhatov, K., Alves-Filho, O., 2011. Heat pump atmospheric freeze drying: advances in modeling and simulation. In: Proceedings of the 5th Nordic Drying Conference, Helsinki, Finland, 19–21 June 2011.
II. Mukhatov, K., Alves-Filho, O., 2011. Modeling kinetics of heat pump atmospheric freeze drying. In: Proceedings of the 5th International Conference on Advanced Computational Methods in Engineering, Liège, Belgium, 14–17 November 2011.
III. Mukhatov, K., Alves-Filho, O., 2012. Heat pump atmospheric freeze and non-freeze drying: modeling and validation with laboratory data. In: Proceedings of the 18th International Drying Symposium, Xiamen, China, 11-15 November 2012.
IV. Mukhatov, K., Alves-Filho, O., 2013. Study of the effect of drying conditions in atmospheric heat pump drying of green peas. In: Proceedings of the 6th Nordic Drying Conference, Copenhagen, Denmark, 5–7 June 2011.
V. Mukhatov, K., Alves-Filho, O., 2013. Capacity and energetic enhancement in heat pump drying of green peas: characterization of mass diffusion and quality parameters. *Submitted to the Drying Technology: An International Journal.*

Reprints of the papers are provided as Appendices I – V. A short summary of each paper is provided in the "Summary of the papers".

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NOMENCLATURE

D_{eff}	Effective mass diffusivity	m^2/s
r_{sph}	Radius of the sphere	m
R^2	Coefficient of determination	%
χ^2	Chi-squared	dimensionless
t	Drying time	s
T	Temperature	˚C
X	Moisture content db	kg/kg
X_{eq}	Equilibrium moisture content db	kg/kg
X_0	Initial moisture content db	kg/kg
MR	Moisture ratio	dimensionless
DR	Drying rate	kg/s
RH	Relative humidity	%
COP	Coefficient of performance	dimensionless
$SMER$	Specific moisture extraction rate	kg/kWh

SUBSCRIPTS

a_w	Water activity
db	Dry basis
wb	Wet basis
HP	Heat pump
FB	Fluidized bed
AFD	Atmospheric freeze drying
VFD	Vacuum freeze drying or dryer
AHPD	Atmospheric heat pump drying
M1…MN	Modeled curves notation (in the papers)
L	Brightness and darkness of the sample
a	Red-green content of the sample
b	Yellow-blue content of the sample
t_{in}	inlet air temperature
t_{con}	condenser temperature
t_{ev}	evaporator temperature
t_{dp}	dew point temperature

1 INTRODUCTION

1.1 Thesis overview

This thesis is composed of the papers published in the proceedings of international conferences and the paper submitted to an international journal. The first paper describes atmospheric freeze drying technology, and reviews the current development on the kinetics, modeling, simulation, and thermal properties of the fresh materials and dried products. The second paper covers the modeling of kinetics, properties of biological materials, and the evaluation of the performance of a heat pump atmospheric freeze dryer with a fluidized bed. The third paper focuses on tests made in laboratory HP dryer and their modeling and validation. The fourth paper investigates the effect of different drying conditions on product characteristics. The fifth paper proposes and develops a numerical solution to describe drying kinetics and to characterize heat pump system capacity and performance.

1.2 Background

Today's R&D activities in developed countries are directed towards finding and developing alternative new technologies that are environmentally friendly and advantageous to the society. At the same time, these technologies should aim at a high quality and economical competitiveness. This is mostly related to energy efficiency, and the goals to be less vulnerable to the increasing costs of both the energy and resources used in power production and material processing (Alves-Filho, 2011).

Atmospheric heat pump drying (AHPD) is one of the new technologies fulfilling all of these requirements. Drying is one of the oldest ways to preserve foods, and to prevent decay caused by microbial activity. Although conventional vacuum freeze dryers and hot air dryers are the most widely applied processes, they have limitations due to the appearance of new restrictive regulations (Eikevik, 2004; Strømmen, 2003). This creates a trend, and has stimulated the R&D towards the creation of new engineering solutions in the field of energy and process technology. One of the most promising approaches to drying is AHPD technology, which is ready to be used in pilot and industrial applications (Alves-Filho, 2013).

The extensive experiments conducted at NTNU have shown the large potential of AHPD in improving product quality, and have demonstrated the possibilities of controlling several of the drying medium parameters, with high energy efficiency. While this technology resulted in a significant contribution to both profitability and environmental friendliness, there is still a necessity for further studies on the drying kinetics of products, applying both heat pump atmospheric freeze and non-freeze drying in a fluidized bed (FB) (Alves-Filho, 2008).

Strømmen et al. (2005) studied the drying of leeks under different conditions and moisture contents, considering the possible effects on physical properties and quality. The effective mass diffusivity was determined from drying kinetics data and described by a two-dimensional flat plate Fickian model. The result showed increased effective mass diffusivity with the increase of the drying temperature, moisture content and the reduction of the slab size.

In accordance with Alves-Filho and Guzev (2006), the drying kinetics can be predicted by mathematical models representing the mechanisms governing mass transport between the frozen or wet material and the drying medium. Thus, the models require knowledge of the relevant transport properties and the processing conditions. Drying kinetics can be described by the Fick's second law of molecular diffusion using spherical coordinates, since, in the case of green peas, the porous dried particles leaving this stage are nearly round (Alves-Filho, 2010).

A conventional fluidized bed is preferable for atmospheric freeze drying due to the enhanced heat and mass transfer occurring as the drying agent flows through and around each particle. As a consequence, most of the experimental work conducted at NTNU is within atmospheric freeze drying, applying a fluidized bed drying mode (Guzev et al, 2007; Bantle et al, 2011).

Therefore, the advantages of AHPD with a fluidized bed, compared to those of vacuum freeze drying, are the high heat and mass transfer, leading to high drying rates and high thermal efficiency, while manufacturing dried products with uniform or homogeneous moisture content, quality and properties. The additional advantages of AHPD are the smaller component sizes, ease of control and possibility to operate in either a batch or continuous mode (Alves-Filho et al, 2008).

Alves-Filho (1996) studied the use of heat pumps in the drying of fruits and roots. He considered a Fickian diffusion model for the transfer of moisture from the product to the drying air, and developed a simulation program for the heat pump assisted fluidized bed and convective drying. Several key aspects and schedules were simulated for the heat pump assisted atmospheric freeze drying (AFD) of products when the air temperature was below the freezing point of the fresh material. The results included the variability of bed temperature and humidity, and the prediction of the product moisture content, drying rates, components' specifications and energy efficiency.

Alves-Filho et al. (2004) obtained experimental data of the drying of green peas using an AHPD at different drying conditions. The drying curves and other relevant physical properties such as water activity, color, bulk density and rehydration ability were measured and recorded during the experiments. Most of these parameters were affected by the drying conditions, which were also controlled for better quality and properties. However, it was observed that the hardness of the material had no influence on the drying kinetics.

Fick's law is one of the most common equations used to describe mass diffusion, and it has often been used in the AFD of moist porous materials in which the moisture removal process is mainly controlled by internal water vapor transport. It describes the relationship between the mass diffusion flux and a concentration field, meaning that concentration gradients are the main forces responsible for mass transfer in the convective drying process (Claussen et al., 2007).

More comprehensive knowledge is still needed about the changes in the properties of green peas during drying. This would form the basis for a better design of drying processes and methods, to help preserve the desirable characteristics, and minimize or eliminate the undesirable ones. The combination of the heat pump atmospheric freeze and non-freeze drying and the fluidized bed, when properly designed and applied, can be used for achieving a high-quality product (Alves-Filho, 2012).

Atmospheric freeze and non-freeze dried products have superior quality similar to that of vacuum freeze-dried products. However, in addition to the other major advantages of this technology, it is less costly than vacuum freeze dryer. In the AHPD, the ducts and chamber are built to operate in atmospheric pressure instead of in a vacuum (Jovanović, S., Alves-Filho, O., 2013).

The current state of the process requires modeling and simulation that are essential steps for the further improvements and design refinements of this new drying technology, both in pilot and on industrial scales.

1.3 Aims of the study

The main objective for developing atmospheric heat pump drying as a new drying technology is the desire to reduce the energy consumption compared to that of vacuum freeze drying while maintaining a high product quality.

In order to achieve the main objective of the research several key subtasks were made:

1. The relevant information about the atmospheric heat pump drying in fluidized bed has been reviewed,
2. Laboratory experiments have been conducted in order to collect data on the AHPD of green peas,
3. The equations and approaches for modeling AHPD in a fluidized bed have been developed and proposed,
4. The effect of different drying conditions on drying kinetics, effective mass diffusion and product parameters has been studied,
5. The proposed model has been validated with experimental results,
6. The heat pump drying process has been examined and compared in terms of capacity, performance and quality,
7. The AHPD has been proposed as a thermally efficient and environmentally friendly technology.

This PhD thesis covers the experiments and modeling of heat pump drying of green peas. The focus has been on the effect of the heat pump operating conditions, drying temperature, relative humidity on kinetics, and on the characteristics of the dried product.

The experimental analysis of the atmospheric heat pump drying (AHPD) of green peas has provided new information on drying kinetics, effective diffusion and product quality. A sufficient amount of laboratory data made it possible to develop a mathematical approach to describe the AHPD process.

Heat pump system capability and performance were also investigated and described by the coefficient of performance (COP) and specific moisture extraction rate (SMER) values, which are the main parameters to determine if the AHPD could be a competitive technology to vacuum freeze drying (VFD).

2 MATERIALS AND METHODS

2.1 Materials

The existing and commonly used vacuum freeze drying (VFD) is expensive since all the components must be constructed to withstand low pressure, and the drying takes place at very low temperatures. This is the basis and motivation for developing heat pump atmospheric freeze drying (HPAFD) as a new process. The dryer also operates with reduced energy consumption and low costs when compared to VFD, while maintaining the high quality of the products. As a potential technical solution, this new atmospheric freeze dryer combines a heat pump system working with environmentally friendly fluids. Different temperature schedules allow producing dried products with customized quality, properties and higher water removal rates. The final dried product will retain color, aroma, instant hydration properties and nutritional value.

Studies done at the Norwegian University of Science and Technology have shown the potential applications of heat pump fluidized bed drying for fruits and vegetables, with the advantages of high moisture removal rates and enhanced properties that are indicated by the final product color, water activity and particle density. The fluidized bed mode increases the thermal efficiency of the drying process due to the excellent contact and heat exchange between the air and the particles. The benefit of this technology is the possibility to conduct the drying at atmospheric pressure at higher rates even when operating at lower temperature levels that are adequate for sensitive materials.

Developing and applying the drying technologies of the heat pump and fluidized bed are highly important in the production of enhanced quality products. Experiments have been conducted in the laboratory heat pump dryer with a fluidized bed to improve the air and particle contact in the drying chamber. The lab heat pump dryer is designed to allow variable set points in the inlet air velocity and psychometry, leading to an enhanced effect on the quality and kinetics of the product.

It was observed that the drying kinetics depend on the material, process conditions, drying mode and time. This includes the drying temperature, material size and shape, and initial moisture content. The product quality is an essential factor for commercial acceptance, especially in the food and pharmaceutical industries, where sensitive structures and appearance must be preserved during the drying. The demand for a better quality of the final dried product, as indicated by color, density, flavor and nutritional value is high.

As in most convective dehydration processes, atmospheric heat pump drying is done by bringing air of a certain temperature and low relative humidity in contact with the product to be dried. The product is mostly frozen prior to the AHPD in a separate freezing system. Since the air is not saturated with water vapor, a pressure gradient is created between it and the ice surface in the product, forcing the ice to sublimate and diffuse into the air. The sublimation energy needed for the process is provided by the warmer and dryer air, resulting in the development of a temperature and moisture profile between the ice surface and the drying agent.

The green peas drying experiments were conducted in a heat pump drying system with a fluidized bed. Each batch of green peas placed inside the drying chamber had a mass of 1kg. The frozen green peas were dried at six different and constant drying air temperatures of -5, 5, 15, 25, 35 and 45°C, during processing time of 3 hours. Each temperature regime was set with two relative humidity levels (RH) of 20±5% (minimum) and 45±5% (maximum). It was observed that the relative humidity levels which could be reached in the drying chamber have less influence on the final moisture content (X_f) compared to that of the inlet air temperature (Mukhatov and Alves-Filho, 2013). Consequently, this work focuses only on data for the lowest possible RH level. This leads to lower final moisture content which is numerically less than 3% compared to the value for the highest possible RH.

All the green pea samples had the uniform initial moisture content (X_0) of 320%db or 76%wb. The frozen green peas were mixed and homogenized to form a large batch that was divided into six uniform batches of green peas to be dried according to the set drying conditions for the tests. The processing time was 3 hours, and every hour during the tests, the batch was removed from the drying chamber to measure the change in mass. Relatively small samples of product were also extracted every hour to measure color and water activity. The product was dried in the fluidized bed with the air velocity kept constant at approximately 1 m/s.

Heat pump dryer

Figure 1 shows the drawing of the laboratory scale heat pump dryer and its main components, consisting of the drying chamber, blower, compressor, evaporator, condensers, three-way and expansion valves. The dryer has two separate loops, one for the working fluid and another for the drying air flow. The drying air enters the drying chamber with the desired psychometric conditions according to set points established for the experiments. Air flows through the cylindrical chamber with the batch of green peas to be dried. The drying medium flows over the surface of the product, fluidizing the bed and removing moisture from the green peas in the process. The air leaves the drying chamber with a lower temperature and higher relative humidity than that in the chamber inlet. Because of this, the capacity of the air to carry water decreases as it moves upward through the wet bed of material in the chamber. As the air recirculates in the heat pump drying loop there is a need to condense the water vapor and remove it. This is done using the evaporator. The evaporator is a heat exchanger, where the air carrying moisture is cooled down below its dew point and, as a result, the water vapor condenses and is drained 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 in the evaporator, the air flows through the condenser and fan, where it reaches the desired experimental set points for the tests. The heat that the air has received from the condenser is taken away from the refrigerant, which becomes a saturated liquid, and is collect in the liquid receiver. Then, the liquid fluid flows through the expansion valve or throttling device where its pressure is reduced as it re- enters the evaporator in a state of vapor-liquid mixture.

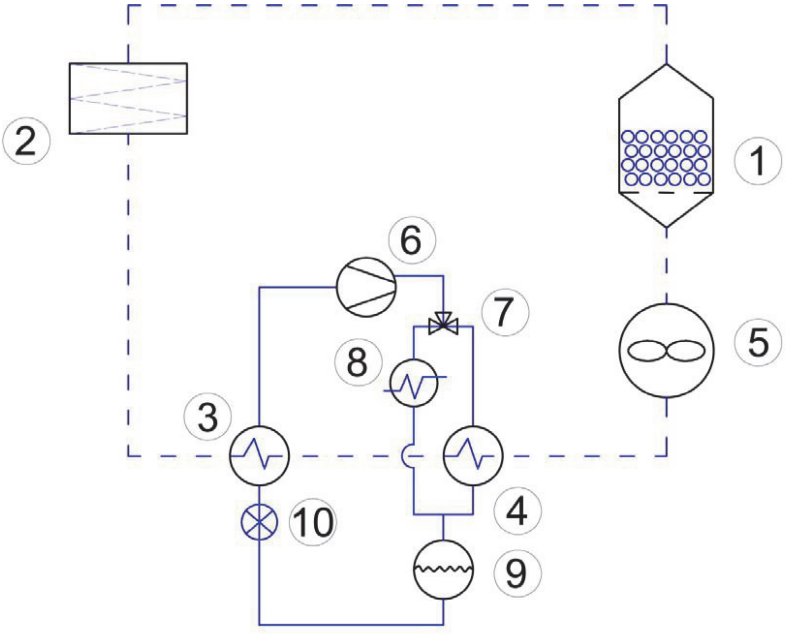

Figure 1. Sketch of the experimental heat pump drying system: 1 - drying chamber, 2 - filter, 3 - air cooler or evaporator, 4 - internal condenser, 5 - blower, 6 - compressor, 7 - three – way valve, 8 - external condenser, 9 - liquid receiver, 10 - throttling valve. [Jovanović, Alves-Filho, 2013]

The drying chamber and particles movement

The drying chamber is placed inside an isolated wooden cabinet made of plywood with a styrofoam insulation. The cabinet's dimensions are 0.8x0.8m in the cross section, with a height of 1.5m. The drying chamber is made of plexiglas, and it is easily locked and unlocked in a central base positioned inside the cabinet, using a three pin lock-rotation mechanism. The chamber is inserted in the drying loop, but separated from the outside 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 batch of 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 are fluidized by controlling the air flow.

The drying air flow was adjusted to the control particle movement, either to achieve a fluidized bed or an onset fluidization. In the case of fluidization, the advantages are rapid vapor removal between the particles, faster drying of the green peas, and a thorough mixing, leading to the uniform moisture content. This method promotes higher rates of heat and mass transfer. Also, the fluidization was gently adjusted to onset the conditions as an alternative to the high intensity bed movement leading to high friction between the particles themselves and between particles and the walls of the drying chamber. This drying mode is used to avoid breaking or mechanically damaging the dried green peas.

Measuring devices

A Mettler Toledo scale (XP 600 2M Delta Range with an accuracy of 0.001 g) was used for measuring the change in mass of the whole drying chamber containing the raw material during each drying test. This was done according to the set time intervals of sampling by periodically taking out the drying chamber and material from the supporting cabinet.

The density was measured based on a standard determination of both mass and volume. The volume was measured, using a graduated cylinder and sample mass weight, by the above-mentioned scale.

Moisture content was measured using a Mettler Toledo HB43-S moisture analyzer, and by an oven set at 104°C, where the samples were kept for 24 hours.

The water activity was determined using an Aqua Lab CX-2 device. A color meter, model X-RITE 948 Spectrometer was used for measuring the color components, expressed as brightness (L), red or green (a), yellow or blue (b), hue (H) and chroma (C) values.

Analysis of data and measurements

The acquired data was recorded in a personal computer using a data logger and sensors. The feedback was received and controlled based on the set points and signals coming from the six sensors installed in the air drying loop. The first and second sensors in the drying loop were for temperature and relative humidity, which were placed at the inlet and outlet of the drying chamber. The third sensor for temperature was located in the connection between the evaporator and air heater of the heat pump. Another sensor was placed in an orifice meter for the measurement of the drying air velocity. The temperature and pressure sensors that were placed in the heat pump circuit were also included.

2.2 Methods

Models that describe a drying process generally predict the moisture loss over time, resulting in drying curves. A model is often validated for a certain product by changing the dependent variable while keeping constant drying conditions. It is difficult to find a general model that is applicable to all products, particularly when the drying process is controlled by water vapor diffusion in the already dried product structure. In this situation, nearly all models use a product specific parameter that is either constant or variable, in order to adjust for the individual characteristics of the product.

Since it is nearly impossible to find a general model for diffusion controlled drying, there are a large number of models reported in the literature. A few models, mainly originated at NTNU, are reported for atmospheric heat pump drying. Recent models are based on the Lewis relation, and depend on a precise knowledge of the thermal properties and external heat transfer rates used in a similar approach in the *computational fluid dynamics* (CFD) modeling of AHPD. Both models have problems with accuracy (deviation of up to 30%, and a coefficient of determination as low as 80%, respectively). This might be caused by the challenging determination of internal heat and mass transfer/diffusion, and the application of a constant drying rate period. All of these approaches depend on the use of correct thermal properties, which change significantly in the AHPD operating temperature range in which AHPD operates, and rely on numerous equations, variables and constants that increase the computational time and efforts. At the same time, these approaches are not generally applicable for AHPD, and depend on a product-specific parameter that requires verification by experiments. Hence, a simple but accurate empirical model would be desirable for this drying technology.

A model for AHPD can therefore be based on an effective diffusion approach, incorporating all drying conditions in one equation. The use of this type of model is useful for comparing the drying behavior for different tests as long as the boundary conditions are analogous. This was the case for the AHPD studies and tests performed for this thesis. The scaling up of a drying process, based on an empirical model of this type, needs to be done carefully with respect to maintaining the boundary conditions.

The empirical model that was found to be suitable for AHPD is the effective mass diffusion approach according to Fick's law of mass diffusion. Based on this, the thesis work includes the evaluation and comparison of the AHPD experimental results with the effective mass diffusion based on Fick's law. This is done because it is desirable to compare drying processes having a single reference parameter.

The Fick's law is commonly used to describe mass diffusion that is associated with drying technologies. It describes a correlation between the diffusive flux and a concentration field, meaning that the concentration gradient is the main force governing mass transfer as occurring in convective drying. In such a case, the molecular diffusion is directly related to the effective mass diffusivity (D_{eff}).

The advantage is that the effective mass diffusion coefficient can be obtained experimentally for a range of drying conditions. The equations are stated based on the assumptions of spherical green peas, uniform initial moisture content, one-dimensional or radial moisture movement, negligible shrinkage and internally controlled moisture transfer.

For the falling rate drying period, the equations for the moisture ratio for the three common geometries are:

$$MR = \frac{6}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{n^2}exp\left[-n^2\frac{\pi^2 D_{eff}t}{r_{sph}^2}\right] \tag{1}$$

$$MR = \sum_{n=1}^{\infty}\frac{4}{Be_n^2}exp\left[-\frac{b_n^2 D_{eff}t}{r_{cyl}^2}\right] \tag{2}$$

$$MR = \frac{8}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{(2n-1)^2}exp\left[-(2n-1)^2\frac{\pi^2 D_{eff}t}{L^2}\right] \tag{3}$$

The drying rate in the atmospheric freeze drying conditions occurs below the initial material freezing point, and is generally low. In order to accelerate the drying of green peas, an investigation was made on the application of different drying conditions, temperatures, and relative humidity levels. The drying rates obtained in AFD and AHPD showed that both processes occur during the falling rate drying period. A modification of the Fick's mass diffusion law was developed and presented for the high accuracy modeling and evaluation of the drying rates in both atmospheric freeze and non-freeze heat pump drying.

The tests performed on the heat pump drying of green peas provided the experimental data used for the modeling kinetics and analysis of effective mass diffusivity (D_{eff}). The drying of green peas, with high initial moisture content, at a low temperature in the AHPD with an FB, mainly takes place during the falling rate drying period. This is because the moisture is initially transported by vapor diffusion from a saturated product surface and later across the dried layers composing the product structure. Hence, under such consideration, the Fick's law applied to AHPD in FB processes leads to the effective moisture diffusion model expressed by:

$$MR = \frac{X_t - X_{eq}}{X_0 - X_{eq}} = K \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} exp\left[-\frac{(2n+1)^2 \pi^2 D_{eff} t}{r_{sph}^2} \right] \quad (4)$$

The experimental data for the nearly spherical green peas was well described by the proposed diffusion model. The mathematical model which produced better results was the moisture ratio equation with a single term, where the pre-exponential coefficient K is equal to 1. Comparison and Figure 2 indicates that this model had a smaller deviation than higher number of terms (n≥1) and with the pre-exponential coefficient K≤1.

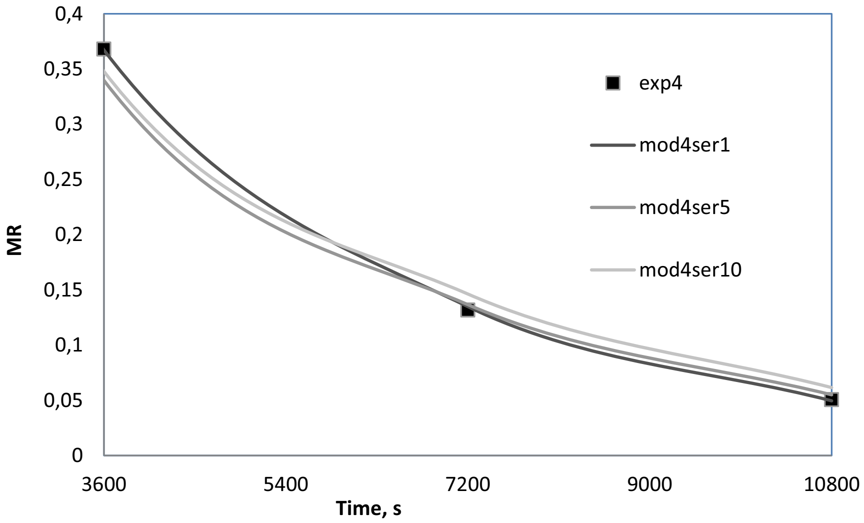

Figure 2. Choice of mathematical approach for MR modeling.

Figure 2 shows the experimental data and the kinetics modeled for test 4 (exp 4), comparing a different number of terms (n=1, 5 and 10). A statistical analysis was used to validate the most appropriate correlation between the data of the drying experiments and the modeled curves. The most suitable equation selected to describe the experimental data points was:

$$MR = \frac{X_t - X_{eq}}{X_0 - X_{eq}} = exp\left[-\frac{\pi^2 * D_{eff} * t}{r_{sph}^2}\right] \quad (5)$$

Considering the drying conditions and the experimental data, Equation (5) was used to model effective mass diffusivity (D_{eff}), moisture ratio (MR) and drying rate (DR).

3 RESULTS AND DISCUSSION

3.1 Modelling diffusion in AHPD

Modeling and simulation are crucial tools in the design and optimization of pilot and industrial drying processes. Models have been proposed for conventional drying, but there is still a lack in the modeling of heat pump atmospheric freeze drying in a fluidized bed. Therefore, this work covers modeling kinetics based on the data obtained in laboratory tests for dried green peas.

The tests were performed under different experimental conditions, including the variable air temperature in the inlet of the drying chamber, bed dynamics, relative humidity and initial moisture content. The modeling results were compared with experimental data as a basis for process validation, refinement and optimization.

The experimental and predicted values for the moisture ratio and effective mass diffusivities are presented in Table 1. The observed and modeled results for the moisture ratio are plotted in Figures 3 to 5. The drying rates are plotted in Figures 6 to 8. The results indicated that the model and procedure are sufficient to predict the experimental data.

Two criteria were used to evaluate the accuracy of the estimates: the coefficient of determination (R^2) and the chi-square between the predicted and experimental values. The chi-square was calculated by an expression, involving the number of experimental data points (N) and having a given number of constants (n).

Advantageously, the drying behavior of the different AHPD experiments were found to be comparable based on single values of effective mass diffusivity (D_{eff}) according to Fick's law.

The effective mass diffusivity for the different drying temperatures increased with temperature as shown in Table 1. This is a result of the temperature-dependent vapor pressure of water/ice that leads to faster drying at higher temperatures.

Table 1. Tests, drying conditions, effective mass diffusivities and accuracy criteria.

Tests	Conditions	Drying time, h	Bed state	D_{eff}, 10^{-10} m^2/s	R^2, %	χ^2
1	-5˚C, high RH	3	fluid	0.75	99.97	0.0001
2	-1˚C, low RH	5	fluid	1.11	99.19	0.0189
3	-1˚C, high RH	5	fluid	1.26	99.07	0.0188
4	-1˚C, high RH, +IR	5	fluid	1.35	99.37	0.0142
5	5˚C, low RH	3	fluid	1.75	99.99	0.0001
6	15˚C, low RH	3/5	fluid	3.33	99.99	0.0001
7	15˚C, high RH	5	fluid	3.58	99.49	0.0154
8	15˚C, high RH, +IR	5	fluid	3.68	99.86	0.0170
9	25˚C, low RH	3	fluid	4.51	99.99	0.0001
10	35˚C, low RH	3	fluid	6.03	99.99	0.0001
11	45˚C, low RH	3	fluid	7.55	99.99	0.0011
12	15˚C, low RH 2.5 kg load	3	stat	2.54	98.85	0.0507
13	15˚C, low RH 2.5 kg load	3	fluid	2.32	98.69	0.0505
14	30˚C, very low RH 2.5 kg load	3	stat	3.80	99.71	0.0451
15	30˚C, very low RH 2.5 kg load	3	fluid	3.55	99.26	0.0687

The graphical representation of the results of the measured data points and predicted drying kinetics curves obtained by the proposed model for the tests #2 to #4, and #6 to #8 are shown at Figure 3, while tests #12 to #15 are presented in Figure 4. The selection of the tests #1, #5, #6, #9, #10, #11 is plotted in Figure 5. The continuous curves are obtained by the model and the points represent the measured values.

Figure 3 shows the modeled drying curves and measured data points for batches of green peas of 8 mm in diameter which were dried at -1˚C /+15˚C, and at low and high relative humidity. Infrared radiation was applied for tests #4 and #8 from Table 1. From the figure we can see that infrared radiation had a smaller effect on the test at 15˚C compared to the test at -1˚C.

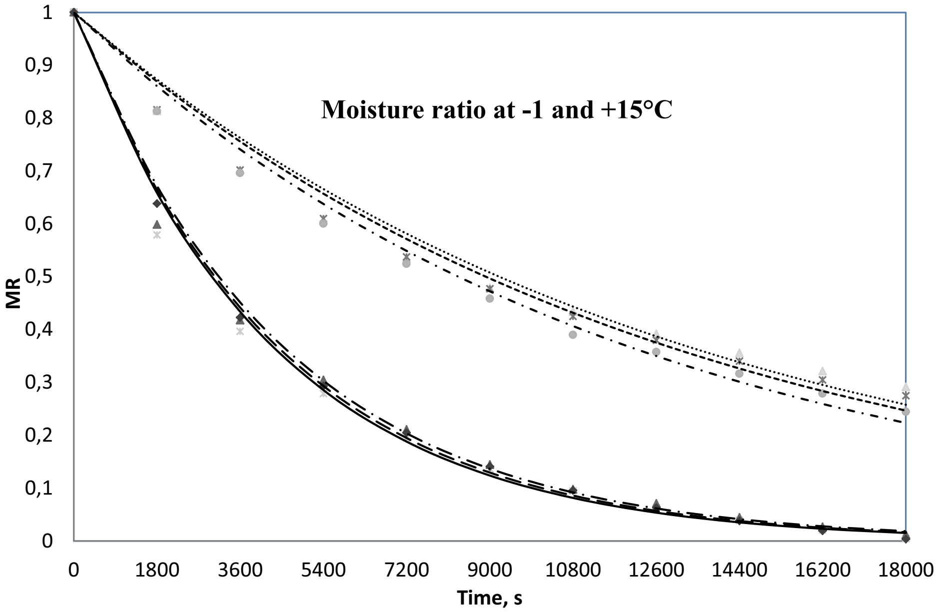

Figure 3. Experimental and predicted moisture ratio for the tests done at temperatures of -1°C and 15°C.

Figure 4 shows the modeled drying curves and measured data points for tests #12 to #15, for batches of green peas of 7 mm in diameter that were dried at +15˚C/+30˚C at low RH conditions applying non-mixed and mixed bed modes. From the figure we can see that stationary or non-mixing bed tests (#12 and #14) had better moisture removal rates compared to the test where the bed was fluidizing or mixing (#13 and #15) during the drying. It has been concluded that smaller fluidization leads to better air-particle interactions in the drying chamber.

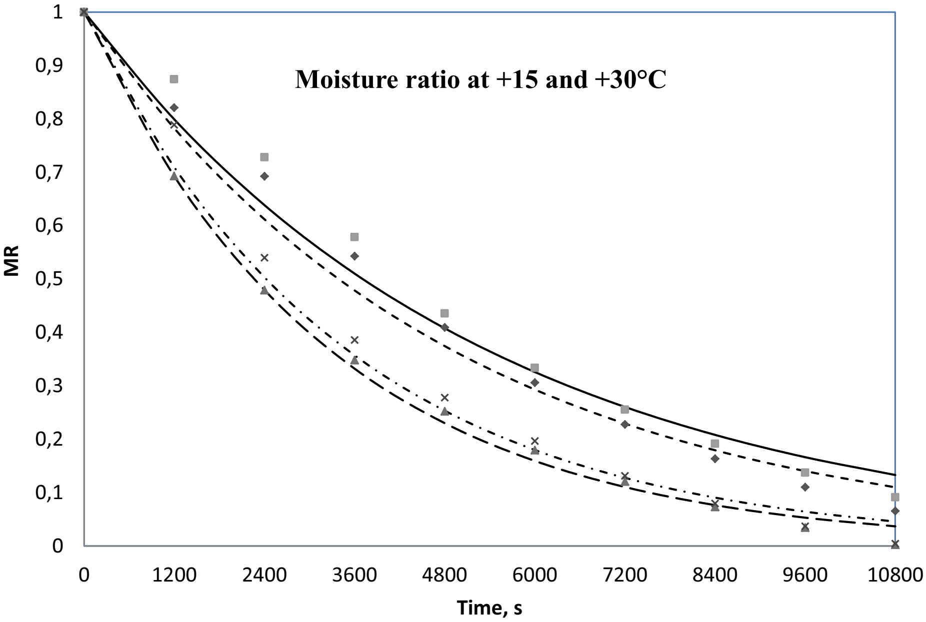

Figure 4. Experimental and predicted moisture ratio for the tests done at temperatures of 15°C and 30°C.

The graphical representation of the results of the measured data points and predicted drying kinetics curves obtained by the proposed model for tests done at temperatures of -5°C, 5°C, 15°C , 25°C , 35°C and 45°C, are shown in Figure 5. The continuous curves are obtained by the model, and the points refer to the measured values of moisture ratio during the drying tests. As expected, it was observed that the drying temperature level has a major effect on mass diffusion, drying kinetics and drying rates.

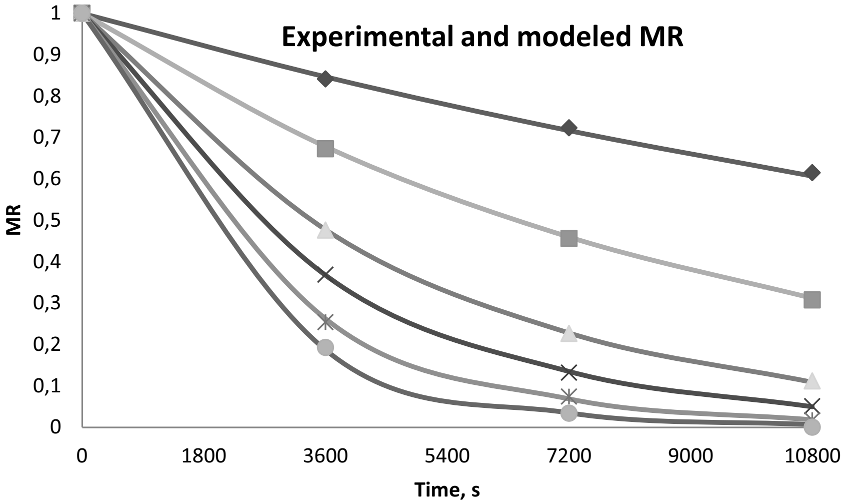

Figure 5. Experimental and predicted moisture ratio for the tests done at temperatures of -5°C to 45°C.

3.2 *Drying rates in AHPD*

The figures show some examples of the drying rates measured for AHPD tests done at varying drying conditions. Similar falling drying rate curves were obtained for all the tests performed. It has been observed that the complete dehydration process for AFD and AHPD occurs during the period when the drying rate is falling. All drying rates decreased continuously with progressing dehydration. This is consistent with the initial assumption that the constant drying rate period was excluded in the physical model for AFD and AHPD. The figures show further that the drying rates obtained for AHPD are generally higher than for AFD due to the strong influence of the temperature level.

The drying rates are defined as the time derivatives of the moisture content as a function of drying time, as follows:

$$\frac{dX}{dt} = \left(X_0 - X_{eq}\right) * \left[-\frac{\pi^2 D_{eff}}{r_{sph}^2}\right] * exp\left[-\frac{\pi^2 D_{eff} t}{r_{sph}^2}\right] \qquad (6)$$

The drying rates in Figure 6 show that the temperature level has a significant influence on the drying rates, while the relative humidity and IR conditions have weaker effects for the tests performed.

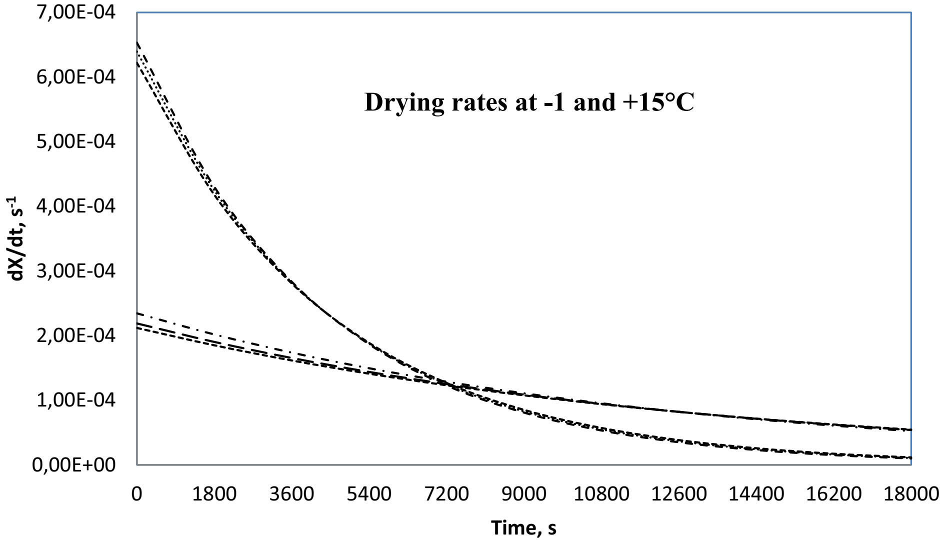

Figure 6. Drying rates versus time at temperatures of -1°C and 15°C.

The drying rates in Figure 7 also indicate that the operating temperature level has a greater influence on the drying rates, while the relative humidity and bed conditions have a minor effect during the tests.

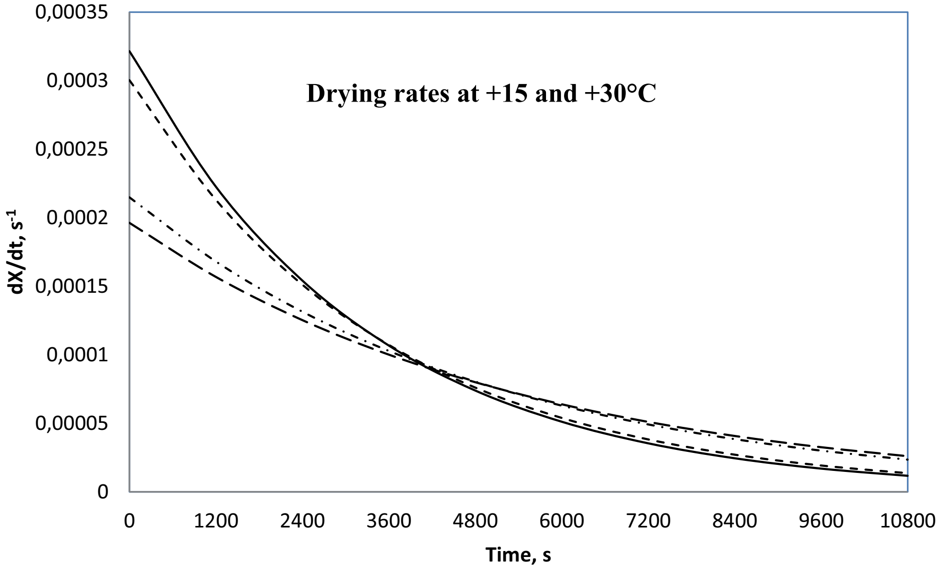

Figure 7. Drying rates versus time at 15°C and 30°C.

The drying rates in Figure 8 indicate that the operating temperature level has a strong influence on the drying rates, and drops dramatically for all the tests where the temperature in the drying chamber was above the initial material freezing point, while the drying rate for the test at -5°C is nearly constant.

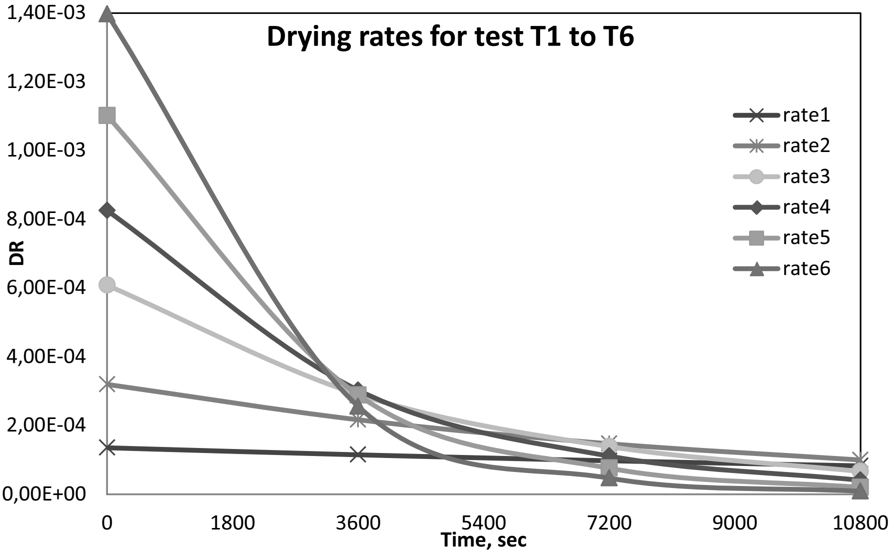

Figure 8. Drying rates versus time at -5°C to 45°C.

3.3 *Product color investigations*

The results of the color measurements for the drying tests (from Paper V) and the frozen green peas, which were used as a reference value, are shown in Table 2, and the results are plotted in Figure 9.

The color change during the AFD process was determined using the Hunter-Scofield equation given by:

$$\Delta E = \sqrt{(L-L_0)^2 + (a-a_0)^2 + (b-b_0)^2} \tag{7}$$

The results indicate that the green peas from tests 1 and 2, dried at temperatures of -5°C and 5°C, had the smaller changes in color compared to the other tests. It was also observed that tests 3 and 4 had approximately the same color change or ΔE value. A possible reason for this is that the temperature levels of 15°C and 25°C are gentler for green peas in respect to color changes (than for tests at 35 and 45°C), maintaining the appropriate level of final moisture content.

Table 2. Green pea samples with color components and drying air conditions.

Test	t, °C	L	a	b	Hue	Chroma	ΔE
Green sample	-	52.17	-26.26	12.46	154.61	29.07	-
Raw peas	-	53.51	-13.81	21.33	113.79	34.24	0
T1	-5	52.95	-12.55	29.23	113.24	31.81	2.51
T2	+5	50.55	-12.17	28.99	112.77	31.44	4.11
T3	+15	48.25	-10.83	26.85	111.97	28.95	7.52
T4	+25	47.89	-10.26	25.98	111.55	27.93	8.53
T5	+35	46.34	-9.48	25.03	110.74	26.77	10.48
T6	+45	45.79	-9.03	24.67	110.10	26.27	11.26

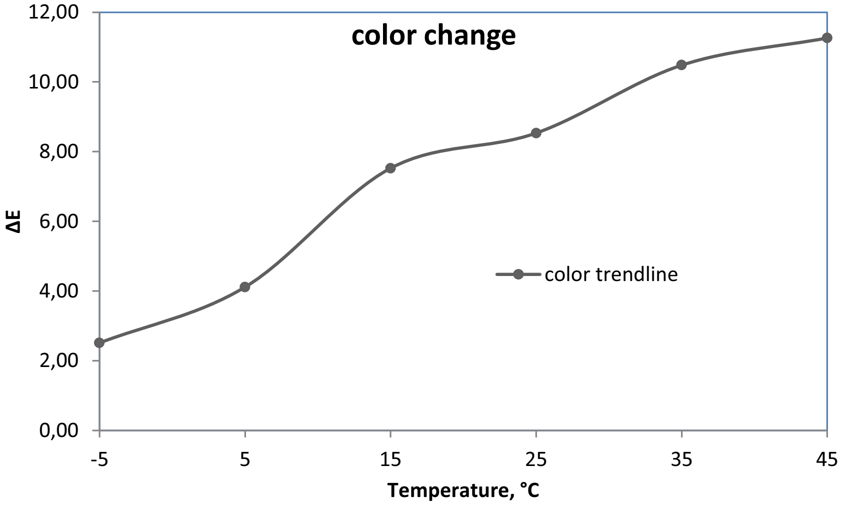

Figure 9. Change in color (ΔE) of green peas from the operating temperature.

The results on color difference (ΔE) for all the tests that plotted in Figure 6 were obtained by Equation 7. The color of the product dried at higher temperature has less green and more yellow color than the other samples. The AHPD in a fluidized bed at -5°C presented a ΔE of approximately 2.5, while higher temperature resulted in a nearly 12-fold increase in the color difference.

3.4 Water activity measurements

The knowledge of moisture content alone is insufficient to predict the stability of foods and vegetables. However, water availability is an important product characteristic since it is related to microbial, enzymatic or chemical activity, and determines the shelf life of the bio material. This availability is associated with the measured water activity (a_w) that depends on equilibrium moisture content, temperature, and the concentration of dissolved solutes, particularly salts and sugars.

The water activity is defined as the ratio of the vapor pressure at the surface of the green peas to the saturated vapor pressure of pure water at the same temperature. The water activity data points for several tests, and for each hour during the drying tests, are presented in Table 3.

Table 3. Initial and progressive water activity for AHPD tests.

Tests	t, °C	a_w	X_{eq}	a_w	X_{eq}	a_w	X_{eq}
Time, h	-	1	1	2	2	3	3
T1	-5°C	0.985	2.74	0.979	2.38	0.971	2.06
T2	+5°C	0.975	2.23	0.956	1.59	0.938	1.15
T3	+15°C	0.959	1.65	0.925	0.91	0.895	0.57
T4	+25°C	0.946	1.33	0.901	0.63	0.861	0.39
T5	+35°C	0.931	1.01	0.867	0.44	0.807	0.29
T6	+45°C	0.914	0.78	0.833	0.34	0.791	0.25

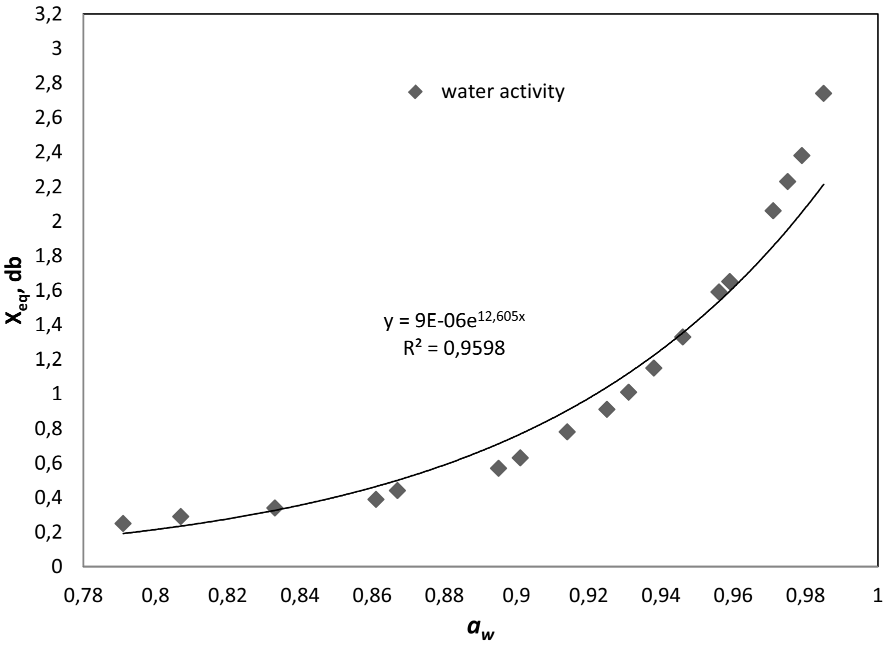

Figure 10. Equilibrium moisture content versus water activity for all tests.

The measurements of the water activity at the different equilibrium moisture content values were taken and the results are shown in Figure 10. The water activity in green peas decreases considerably by increasing the drying air temperature. The graph indicates that the water activity increases exponentially with the equilibrium moisture content.

3.5 Energy and capacity of heat pump drying of green peas

The heat pump dryer performance and energy utilization requires the selection of the type of refrigerant and specification of the operating conditions, particularly the pressure and temperature levels. Ammonia, or R717, was selected as the working fluid due to its thermal properties, and for being an environmentally friendly refrigerant. Regarding greenhouse gases (GHGs), ammonia is a natural fluid that has zero ozone depletion potential (ODP), and zero global warming potential (GWP) (Alves-Filho, 2013).

The energy, capacity, and performances of the heat pump drying of green peas were calculated, and the results are shown in Table 4, along with the conditions inside the heat pump and the drying air loop. The essential parameters, which are the coefficient of performance (COP) and specific moisture extraction ratio (SMER), have been calculated, and are listed in Table 4, where the temperatures are: t_{in} - inlet, t_{con} - condenser, t_{dp} – dew point, and t_{ev} - evaporator. Notice that the COP and SMER are the critical parameters for both evaluating and comparing the energy characteristics of heat pump drying systems at varying operating conditions as well as HP fluids.

Table 4. Energy, capacity, and performances of the heat pump drying of green peas in tests done at temperatures 5°C to 45°C

Tests	5°C	15°C	25°C	35°C	45°C
t_{in}, °C	5	15	25	35	45
t_{con}, °C	15	25	35	45	55
t_{dp}, °C	-10	-7	0	9	17
t_{ev}, °C	-15	-12	-5	4	12
COP	6.7	6.2	5.9	5.7	5.5
SMER, kg/kWh	0.9	1.2	1.5	1.8	2.1

For the test conditions in Table 4, it is observed that the COP drops, while the SMER increases as the drying air temperature rises. This opposite variation is mainly due to changes in the drying air psychometrics, and in the heat pump loop resulting in an improved SMER. Comparing the calculated SMER values, it is noted that the energy use per unit of water removal drops proportionally with an increasing drying temperature. Therefore, the drying tests done at the lowest and highest temperatures are the least and most economical among the drying cases, respectively.

This comparison is relevant since a satisfactory energy performance, drying capacity, and drying temperature must always be considered, computed or specified when thermally sensitive materials are being industrially dried. In the case of green peas, they must be dried based on a high quality and with pre-specified properties.

4 GENERAL CONCLUSIONS

The main idea for developing atmospheric heat pump drying as a new drying technology was the desire to reduce the energy consumption and the running costs compared to that of vacuum freeze drying while maintaining a high product quality. Based on experimental results and their further analysis it is fair to say that this goal has been reached.

An investigation on the combined heat pump fluidized bed atmospheric freeze drying of green peas has been carried out. Studies were also conducted to determine what influence the drying conditions and methods had on the drying kinetics, product quality and characteristics, including the color and water activity of the dried product. Additionally, the COP and SMER were calculated to reveal the energy and water removal capabilities of the drying regimes and to validate the heat pump drying system.

The AHPD tests were conducted at wide range of temperatures and relative humidity levels. The results showed that the temperature of the drying air has a high influence on the products' moisture content, kinetics and drying rates. The relative humidity of the drying air also affects the final product moisture content, but this influence is small compared to the operating temperature of the drying air.

The drying rates obtained in AFD and AHPD showed that both processes take place during the falling drying rate period, and the moisture transfer is controlled by mass diffusion. However, external drying conditions also have an influence on the drying rate, especially at the beginning of the process when the dry layer is relatively thin. The effects of infrared radiation, bed mode and material load on the drying rate have been evaluated, together with the effective mass diffusivity at variable drying conditions.

The drying conditions affect the quality of the final dried green peas. It was observed that higher temperature regimes have a better moisture removal and higher effective mass diffusion, but also a stronger influence on the color change. The largest difference was found for the test at 35°C and 45°C, where the color change is much higher than for the others tests.

The tests for the green pea samples with the lowest water activity were conducted at a higher temperature and lower relative humidity. It was also proposed that the equilibrium moisture content has an exponential dependence on the water activity. This is an important factor for the production, packaging and long-term storing of dried foods.

The empirical model used for AHPD evaluated the effective mass diffusivity for different drying conditions. The model accurately predicted the drying rates, when the drying and boundary conditions are fixed. A model has been developed to describe heat pump drying with air velocity at the onset, and full fluidization. A comparison of the predictions and experimental data of the moisture ratio for all the tests indicated that the proposed equations are satisfactory in describing the drying kinetics of green peas in a fluidized bed atmospheric freeze and non-freeze drying.

In this work, a laboratory scale heat pump system was used for energy recovery and the conditioning of the drying air. In a comparison of the very low temperature and vacuum freeze dryer with a SMER below 0.5 kg/kWh, the proposed heat pump dryer cases have the advantage with a SMER between 0.9 and 2.1 kg/kWh. In addition to this reduced energy consumption, the heat pump drying system operated with significantly shorter drying time.

The dryer performance has been estimated by the model with subroutines, equations and program libraries for determination of the fluid and air-vapor properties in each state point of the heat pump cycle. It was observed that COP drops insignificantly while the SMER increases as the drying temperature rises which is leading to the operating cost increasing. This is an outcome of higher use of energy or electricity per unit of water removal and means that the higher temperature is the least economical operation among the others cases. This could only be justified if this drying temperature would allow manufacturing a product with the highest quality.

Ammonia, or R717, was selected as the working fluid due to its thermal properties and for being known as an environmentally friendly refrigerant. As it relates to greenhouse gases (GHGs), ammonia is a natural fluid which has zero ozone depletion potential (ODP) and zero global warming potential (GWP), that makes heat pump drying a competitive and efficient drying technology with a minimum impact on climate change.

The key advantages of applying heat pump systems in convective drying technologies, compared with those of VFD are:

1. Recovery of the latent heat of the air exhausts in the drying chamber, and a consequent energy savings up to 50%.
2. Heat pump dryers significantly improve product quality by drying at lower temperatures.
3. A wide range of drying conditions, typically temperatures of -20°C to 100°C (with auxiliary heating), and a relative humidity of 15 to 80%, can be generated.
4. Excellent control of the environment, ensuring high quality products, and the simultaneous reduction of the electrical energy consumption.
5. The transition from vacuum conditions to atmospheric pressure precludes the use of expensive and power-intensive vacuum equipment from the technological process, and reduces production costs.
6. The process can be designed to be continuous, resulting in low operational costs with high productivity.

The results in this work are useful in reducing the number of drying experiments to be tested at a wide range of drying conditions, because the proposed models were validated with experiments resulting in acceptable deviations. It helps in establishing the temperature and time schedule in a preliminary study on scaling-up lab dryers to pilot or commercial drying plants.

5 SUGGESTIONS FOR FURTHER WORK

This study provides a good platform for further research oriented towards unification of the available laboratory data in the heat pump drying of vegetables to the overall simulation program. However, the model should include the drying conditions, and more product characteristics, in order to be applicable under variable conditions and for scale-up.

The atmospheric heat pump drying process should be studied further in order to collect more data on the drying of different types of products, in order to achieve a better understanding of the changes which occur during drying. As a consequence, there is still a need in better modeling of the AHPD process, and subsequent simulation and optimization of the whole process, which are the topics for the future journals publications.

New experiments and new heat pump drying design should aim at further energy savings, a lowering of the environmental impact and increasing the drying capacity that is why the technical parts which have to be enhanced are:

- New heat pump fluids for lowering ODP and GWP,
- New controllers and instruments,
- New components, such as highly efficient and compact heat exchangers, and their integration.

AHPD has great potential for industrial freeze drying applications, and should be considered as an alternative for vacuum freeze drying processes. Future heat pump drying research should focus on this potential due to benefits in the drying rates, investment and running costs, as well as the product quality that can be similar or better than that of VFD.

Further energy analysis should include wider drying conditions and variable loads of material. Studies should also be done to determine how faster drying in AHPD influences the overall energy consumption and capacity, particularly when the heat pump dryer is designed for the specific quality of a dried product. The AHPD should be designed to operate at the best drying conditions, taking into consideration a continuous or semi-continuous mode.

6 SUMMARY OF THE PAPERS

Paper I

Mukhatov, K., Alves-Filho, O., 2011. Heat pump atmospheric freeze drying: advances in modeling and simulation. In: Proceedings of the 5th Nordic Drying Conference, Helsinki, Finland, 19–21 June 2011.

This paper describes atmospheric freeze drying technology, and reviews the current development on the modeling, simulation, kinetics and thermal properties of the fresh materials and dried products. The quality and instant properties of different foods and other biotechnological products are very promising, and there is an increased demand for new dried products with desired properties. In combination with heat pump technology, atmospheric freeze drying is an environmentally friendly and economically favorable process compared to vacuum freeze drying. Fluidized bed atmospheric freeze dryers combined with a heat pump system are an alternative to be more competitive in the food and pharmaceutical industry, where vacuum freeze dryers are widely used today. Despite all previous investigations, there is still a need to obtain data on the physical properties of the products, and to develop suitable drying models. The use of heat pump technology, in combination with the drying process, is also attractive because it reduces energy consumption and costs, and is better for the environment.

Paper II

Mukhatov, K., Alves-Filho, O., 2011. Modeling kinetics of heat pump atmospheric freeze drying. In: Proceedings of the 5th International Conference on Advanced Computational Methods in Engineering, Liège, Belgium, 14–17 November 2011.

A new heat pump drying technology has been developed, and a prototype scale dryer has been built and tested at NTNU. The conditions provided by the heat pump dryer can be set according to the sensitivity of the material. It operates in closed loops that contribute to minimize environmental dust discharge, and its heat exchangers recover energy from the moist air to increase the dryer's thermal efficiency, and to decrease operation costs. Several products manufactured in this dryer had improved properties, acceptable quality and quick reconstitution. It is well known that shrinkage, porosity, pore size distribution, water sorption and water diffusion are strongly related drying conditions. Moisture transfer is important to predict the progress of the drying process of a food product, and the effective moisture diffusion is required for describing the drying rates or moisture removal.

Modeling and simulation tools are important in the optimization, design and planning of an industrial drying process. Therefore, this work reviews the modeling of kinetics, properties of biological materials, and the evaluation of performance of a heat pump atmospheric freeze dryer with a fluidized bed. The results of the modeling have been compared with the experimental data as a basis for process validation, refinement and optimization. Suitable drying models have been developed for conventional dryers, but challenges remain for heat pump atmospheric freeze and non-freeze drying in a fluidized bed.

Paper III

Mukhatov, K., Alves-Filho, O., 2012. Heat pump atmospheric freeze and non-freeze drying: modeling and validation with laboratory data. In: Proceedings of the 18th International Drying Symposium, Xiamen, China, 11-15 November 2012.

Atmospheric freeze drying is an innovative and competitive technology for the production of high quality dried foods with desirable properties at lower costs and lower energy consumption. This new drying technology depends on suitable modeling and simulation, which are essential steps in the pilot and industrial design of this new drying process. The most important parameters for modeling are the temperature, relative humidity, processing time, load of material, heat and mass transfer properties. The study of these variables is important for understanding the changes in product properties, and fundamental for designing and dimensioning pilot and large scale drying processes. This work covers kinetics and drying rates modeling, as well as the validation of predictions by comparison with laboratory measurements.

The experimental data of the green peas drying in a laboratory heat pump (HP) dryer were obtained at different drying conditions. The drying curves and other relevant physical properties, such as water activity, color, and bulk density, were monitored and recorded during the tests. The experimental kinetics were well described by the proposed mass diffusion model for spherical materials such as green peas. The drying rates obtained show that dehydration often occurs during the falling drying rate period. It was observed that higher drying rates are caused by a higher temperature, and initial conditions such as the material temperature and initial moisture content. The change in the color was negligible in the atmospheric freeze and non-freeze dried samples. The additional benefit was that these dried green peas kept their original structure.

A comparison of the predictions and experimental data of the moisture ratio for all the tests had a maximum value of a 5% deviation, indicating that the equations and models well describe the drying kinetics of green peas in a fluidized bed atmospheric freeze and non-freeze drying. The number of drying experiments of green peas, tested at a range of drying conditions, is greatly reduced by validated models having negligible deviation between the observed and predicted data. It is useful for establishing a temperature-time schedule, and a preliminary study on an HP drying scale-up to a pilot scale or commercial plant.

Paper IV

Mukhatov, K., Alves-Filho, O., 2013. Study of the effect of drying conditions in atmospheric heat pump drying of green peas. In: Proceedings of the 6th Nordic Drying Conference, Copenhagen, Denmark, 5–7 June 2011.

The development of drying technologies applying a heat pump and fluidized bed are indispensable in the production of enhanced quality products. Experiments have been conducted in the laboratory heat pump dryer operating in a fluidized bed for the improvement of air and particle contact in the drying chamber, resulting in better heat and mass transport. The lab heat pump dryer is designed to allow variable set points in the inlet air velocity and psychometry, leading to an enhanced effect on product quality and kinetics. It was observed that drying kinetics depend mainly on the material and process conditions, such as the drying mode and time, drying temperature, material size and shape and initial moisture content.

The product quality is an essential acceptance factor, especially in the food and pharmaceutical industries, where sensitive structures and appearance must be preserved during and after drying. The current trend is towards better quality of the final dried product that may be indicated by the color, density, flavor and/or nutritional value. Atmospheric freeze and non-freeze dried products have superior quality to products from high temperature dryers, and a similar quality as vacuum freeze dried products. These are the major advantages in this HP drying technology that lead to lower investment costs than VFD. For instance, the ducts and chamber are built to operate in atmospheric pressure instead of a vacuum.

There are challenges in the current state of the process, including modeling and simulation that are useful steps for the further improvements and design refinements of this new drying technology in pilot and industrial scales. This work covers the modeling of the kinetics and drying rates and the validation of predictions by comparisons with laboratory data. The experimental data of the green peas drying in a laboratory HP dryer were obtained at different drying conditions: temperature, relative humidity, infrared radiation and bed mixing state. The drying curves and other relevant physical properties such as water activity, color, and bulk density were measured and recorded during the tests, and the data were analyzed.

The drying kinetics experimental data were well described by the proposed mass diffusion model for green peas, when taking into consideration that the initial shape of the individual material was spherical. The drying rates obtained showed that dehydration occurs during the falling drying rate period. It was observed that higher drying rates are caused by a higher temperature and the initial material conditions, such as the initial moisture content of the green peas. An advantage was that the change in the color was negligible for atmospheric freeze and non-freeze dried samples. Furthermore, the dried green peas preserved their original shape. The comparison of the predictions and the experimental data of the moisture ratio for all tests indicated that the chosen equations suitably described the drying kinetics of green peas in a fluidized and non-agitated bed atmospheric freeze and non-freeze drying.

The relevance of this present work is that the number of drying experiments required in a wider range of drying conditions can be greatly reduced. The models were validated with the experimental data and presented a negligible deviation between the measurements and predictions. It can also be useful for scheduling and establishing the temperature and time under desirable test conditions, and for preliminary studies on scaling-up lab dryers to pilot or commercial plants. An additional relevance of this work is providing a systematic platform for further research focused on the unification of available laboratory data in the heat pump drying of foods to the overall simulating program.

Paper V

Mukhatov K., Alves-Filho O. Capacity and energetic enhancement in heat pump drying of green peas: characterization of mass diffusion and quality parameters. *Manuscript Submitted* *to the Drying Technology: An International Journal, 2014.*

This work covers the drying of green peas applying a laboratory heat pump dryer. The drying process conditions and processing time are the most important parameters for modeling and process scaling-up. Additionally, the temperature, relative humidity and processing time are essential for understanding the changes in product properties, and are fundamental for the designing and dimensioning of large scale drying processes.

Therefore, the tests were done with six temperature regimes, ranging from -5°C to 45°C, and varying levels of relative humidity. All drying tests were performed, and each run was done during a period of three hours using a fluidized bed mode. The results on kinetics indicated that temperatures and relative humidity levels lead to the changes in moisture removal rates from the material, and in the quality of the product. Studies were also made to study the influence of drying conditions and time on product parameters such as the color and water activity.

It was observed that higher temperature regimes have better moisture removal and higher effective mass diffusion, but also a stronger influence on color change. The largest difference was found for the test at 35°C and 45°C, where the color change value is much higher than for the others tests. The tests using green peas samples with the lowest water activity were performed at higher temperature and lower relative humidity. It was also proposed that the water activity has an exponential dependence on the equilibrium moisture content, which is a relevant factor for long-term storage, and very important in dried food production.

This work also proposes the numerical solution for moisture content to describe the drying kinetics and effective mass diffusion. A model has been developed to describe heat pump drying with air velocity at onset and full fluidization. A comparison of the predictions and experimental data of the moisture ratio for all the tests indicated that the proposed equations are satisfactory to describe the drying kinetics of green peas in a fluidized bed atmospheric freeze and non-freeze drying.

The coefficient of performance (COP) and specific moisture extraction rate (SMER) were calculated to characterize the energy efficiency and water removal capacity of the heat pump drying process. For this investigation, a laboratory scale heat pump system was used for the energy recovery and conditioning of the drying air. Comparing the very low temperature used in a vacuum freeze dryer, that has a SMER below 0.5 kg/kWh, the proposed heat pump dryer cases presented the advantage of obtaining a SMER between 0.9 and 2.1 kg/kWh. Further energy analysis should include broader drying conditions and larger loads of materials. Studies should also be done to determine how faster drying influences the overall energy consumption, when the heat pump dryer is designed for a specific quality of dried green peas. Tests should be focused on the best drying conditions and taking into consideration continuous or semi-continuous modes.

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