NTNU – Trondheim
Norwegian University of
Science and Technology

Green heat pump drying technology

Comparison of drying modes based on
kinetics and product characterization

Audun Rostad

Mechanical Engineering
Submission date: June 2015
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-2015-74

MASTER THESIS

for

Student Audun Rostad

Spring 2015

Green heat pump drying technology – Comparison of drying modes based on kinetics and product characterization

Background and objective

New developments are needed on more sustainable, efficient, competitive and improved capacity drying technology than available in the market today. Then, the focus in R&D now is on green technology complying with EU and international policies on climate change, environment, energy use, process capacity, product quality and characterization.

To keep quality and original characteristics of thermal sensitive materials drying is done either at freeze and non-freezing conditions. The common process is the vacuum freeze dryer that is a slow and a costly process. The new proposal is the heat pump dryer that allows setting drying conditions according to the material thermal sensibility.
The challenges for vacuum and atmospheric pressure freeze and nonfreeze drying is that the residence time is relatively long, blower power is high, capacity low leading or high production cost.

These problems can be tackled by applying different drying modes under controlled temperature, relative humidity and other drying air psychrometric conditions.

The heat pump dryer designed in fluidized bed mode has among benefits a high heat and mass transport. However, it has limitation when particles move in non-uniform flow, bed channeling occurs by air bypassing the particles leading to low water removal capacity.

Objectives of this Master thesis are to test drying chambers to study possible reduction residence time, attain uniform particle flow, increase water removal and reduce energy or cost while producing high quality products. Then, the experiments will provide data to compare of potential solutions by applying three different drying modes under controlled air psychrometric conditions and air velocity. The drying experiments will be performed to obtain data on the following drying modes:

- Test under stationary bed
- Test under fluidized bed
- Test under mechanically vibration bed

Measurements and analysis for fresh and dried samples will include:
- Particle size distribution
- Particle density distribution
- Particle density versus characteristic dimension and comparison with standard chart

- Energy use and specific moisture removal ratio in HPD with natural fluid like R717

The following tasks will be made:

1. to pre-test the vibration mechanism and identify batch load for all the 3 modes
2. to review the literature on drying of green peas and vegetables
3. to prepare the batches of green peas for the drying tests
4. to perform tests according to the experimental design
5. to collect and to analyze data on mass change with time, energy and characterization
6. to create models for the different drying modes describing mass transport with time

-- " --

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, 09.06.2015

Olav Bolland

Olav Bolland Department Head	Odilio Alves-Filho Academic Supervisor

Preface

I started this project ten months ago hoping to learn something different, as my field of study had been mechanical engineering with little knowledge of heat and mass transport. The connection between practical lab work and the theoretical made it easier to understand and learn. When all seemed bliss, Odilio would help get my spirt back up through inspiring lectures and answering in such a way that triggered my curiosity. Countless hours has gone into setting the lab up properly, but fiddling with the system gave me great insight in how it worked. Moreover, when it all came together, the satisfaction was great. The same can be said about the struggles of creating a satisfying model.

Big thanks to my supervisor Odilio Alves for helping me with the grammar, pointers and publishing my first scientific article. And to all my fellow students that have silently suffered by my side giving me motivation to sit an extra hour every day in solidarity.

Audun Rostad

Audun Rostad

Abstract

The hypothesis was to study and detect if there is any difference in moisture removal kinetics and drying characteristics by operating in single and combined drying modes. In addition, based on the data from the experiments create a model describing the drying curve, in the temperature range from 25°C to 45°C. The drying modes studied were stationary, fluidizing bed and their effect when combined with mechanical vibration all at 35°C and a bed height of 15 cm.

The fluidized experiments did remove moisture at a faster rate when the limiting factor was what the drying air could evaporate and transport away compared to the static experiments. When internal moisture transfer become the limiting factor, the effect of fluidization disappeared.

The addition of mechanical vibration of green peas at low frequency and low amplitude does not give a notable effect for the drying rate at 35ºC and bed height of 15 cm.

The fluidization characteristics concurred very well with already known research done by Geldart.

A model was created describing the drying curves for stationary and fully fluidized beds with and the model concurred very well with the experiments during the constant and falling rate periods in the temperature range from 25°C to 45°C.

Sammendrag

Hypotesen var å studere og oppdage om det er noen forskjell i fuktighetskinetikk, tørke- og fluidiseringsegenskaper ved forskjellige enkelt- og kombinasjonstørkemetoder. Tørke modusene som ble studerte var stasjonær, fluidisering og deres effekt når det kombineres med mekanisk vibrasjon, alle ved 35°C og en høyde på 15 cm.

De fluidiserte forsøkene fjernet fuktigheten med raskere hastighet når den begrensende faktor var hva tørkeluften klarte å fordampe og transportere bort i forhold til de statiske forsøkene. Når den indre fuktighet overføring blir den begrensende faktoren ble effekten av fluidiseringen neglisjerbar.

Tillegget av mekanisk vibrasjon av grønne erter ved lav frekvens og lav amplitude gir ikke noen merkbar virkning på tørkehastigheten ved 35ºC og sjikthøyde på 15 cm.

Fluidiserings egenskapene til eksperimentene samsvarte svært godt med allerede kjent forskning gjort av Geldart.

En modell som beskriver tørkekurver for stasjonære og fullt fluidiserte sjikt ble framstilt. Denne modellen beskrev de eksperimentelle data i den konstante- og fallende tørkeperiodene i et temperaturområde fra 25°C til 45°C.

Table of contents

Introduction

Energy savings and the EU green guidelines

The European Union through the act “Action plan for Energy efficiency” is aiming for a 20% energy reduction by 2020 compared to the energy usage in 2006. By achieving this goal, they also will reduce the CO_2 emissions by 780 Mt. The manufacturing industry, the food industry also included, has a potential of reducing its energy consumption by 25% by the calculation of the Commission. To encourage the industry to become more energy effective the Commission has set up financial plans for researching and implementing innovative and energy saving technologies. (Commission to the Council and the European Parliament, 2006)

Drying Process

The drying process involves a wet product, a dryer, a drying medium, usually air with lower vapor pressure than the wet product. Then, as the process is carried out, the product gets dryer by means of evaporation until the desired moisture in the product is obtained. To accelerate the process, a heater can be used to warm up the air, bringing down the relative humidity and increasing the drying rate. To move the drying medium and to quick transport the removed moisture, a fan or blower is installed. Specific Moisture Extraction Ratio or SMER is the mass of the moisture removed per kWh of energy used in the drying process. This ratio give an indication on how good the drying process is terms of energy consumption but another important factor is the quality of the product after the drying process.

The reason for drying a food is to preserve nutrients and flavor, and make the product more resilient against microorganisms and spoilage. Research is focused towards cutting down on energy usage but still keeping the quality and shelf life to the product. As of today, the best quality is obtained by vacuum freeze-drying, which has a very high energy consumption up to 115 MJ/kg of product that results in a very low SMER value, which can be as low as 0.08 kg/kWh because of long drying time. (Odilio, 2013)

Shelf life is how long a product can be stored, at shelf standard conditions, and still be safe for consumption while keeping its desired quality. Long shelf life allows transporting the product great distances and storing it over relatively long time when the fresh product is out of season. The shelf life can be roughly predicted by the water content or free water in the product, but other factors do have an effect as well. The amount of free water in the product gives an indication on how microbial, chemical and enzymatic activity will occur or develop on the product surface. Water in a food product can be divided into free water and bound water. Bound water is strongly bound to other non-water molecules. This makes causes difficult for microbial, enzymes and other chemicals to interact with the bound water. Microbial activity from bacteria, yeast and fungi increases with free water content with high values in the water activity range from 0.6 to 1. Undesirable chemical changes such as oxidation happens more rapidly at free water content around 0.3 and lower. (Fellows, 2009) (Valentas, Rostein, & Singh, 1997) (Rahman, 1995)

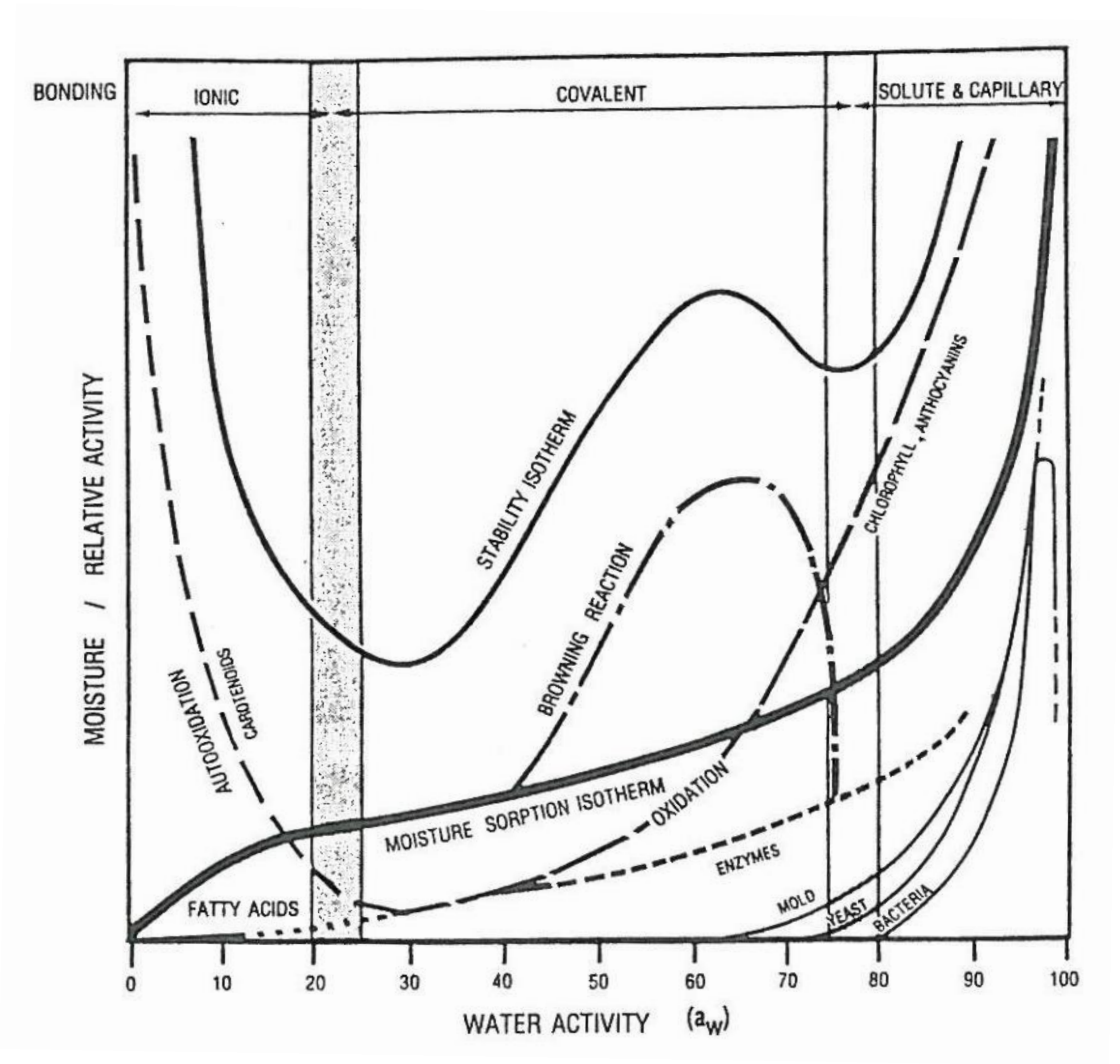


Figure 1: Water Activity
Photo: (Rahman, 1995)

As of today, the most commonly drying methods are vacuum freeze-drying and high temperature drying. With vacuum freeze-drying the benefits are that the technology is well known and it produces a very high quality product. The drawbacks are that vacuum freeze-drying is time consuming and the technology is very energy intensive because of the low temperatures, often down to – 50°C on the condenser surface and very low vacuum pressures. High temperature drying is a fast method with low operation cost but the final product has low quality due to changes in color, structure and effect on nutrients. Another drawback is the high-energy losses or low thermal efficiency of the process. (Odilio, 2013) (Valentas, Rostein, & Singh, 1997)

Heat pump

The application of a heat pump to drying can save energy while operating at very high SMER value. Typical SMER is around 4 relative to a non-recycling energy dryer that has a SMER value of 0.7. The heat pump recovers and utilizes energy through recirculating the drying air and not just venting it to the environment. (Odilio, 2013)

An additional effect is that the relative humidity of the inlet air can be controlled resulting in an optional lower drying temperature and conditions needed to retaining quality and composition of the product. With this effect, a wide range of temperatures can be utilized through the drying giving the process a greater flexibility. The heat pump's evaporator side condenses and removes the moisture from the drying air. This is done by changing the evaporator temperature resulting in control of the air inlet relative humidity. (Odilio, 2013)

Theory

Drying bed characteristics

Figure 2: Gas fluidization
Photo: Audun Rostad

Gas fluidization

Fluidization of a bed of particles requires overcoming the pressure difference between the top and the bottom of the bed. This pressure difference in the air or gas is exerted by particles, chamber perforated plate, tube walls and fittings in the drying loop. Particles that can be fluidized vary in density and size from fine powders to particles up to 8 mm. The level of fluidization depends on other factors such as the particles shape, how round or jagged the surfaces are and how they interlock with each other. There are also effects of static or dynamic friction and stickiness since this prevents the particles movement around in the chamber. Also the size distribution, because smaller particles can act like as lubricant for the bigger particles making it easier to fluidize the bed. The effect of initial conditions includes the packing of the bed. (Geldart, 1986)

There has been done some research on classifying different fluidization or suspension characteristics of powders and particles. Through experience in the industry by using a wide range of different sized particles in the bed, it has shown the possibility to attain a more stable fluidization. This is because less pressure fluctuations will occur due to the lubrication effect created by the smaller particles. This creates smaller bubbles giving a more uniform gas flow through the bed. With similar sized particles, slugging is more likely to occur and will result in higher pressure difference over the bed as needed to create proper fluidization. This implies more energy consumption is needed to maintain the higher pressure difference and higher momentum of the particles increasing the chance of damage by collision. (Geldart, 1986)

Mechanical vibrated bed

In mechanical vibrated bed the fluidization is done by movement of the bed and not by the drying fluid. However, there is still need for some flow through the bed to transport the moisture away for the product. The main fluidization effect is done by transferring momentum energy between the particles how are bumping into each other. This type of fluidization can be more beneficial because of more even particle distribution in the bed if, for example, the product is prone to slugging during gas fluidization. A downside to this type of fluidization is that the transport of momentum energy is focused on a smaller area compared to pressure difference the gas fluidization makes. This causes more stress to the particle and can result in undesirable damage or spoilage. The stress increases with the increase of mass and volume since the structural properties of the particle do not change.

Stationary bed

The product will remain in static mode during a stationary drying process. The drying medium flow is adjusted just for the need to transport the moisture away from the product and this is done by forced or natural convection. Since there is no significant movement, some areas of the particle will be in contact with the drying medium and other areas in contact with other particles next to it. This will cause an uneven dehydration process of the particles. Another effect of the stationary bed is that the layer closest to the inlet of the airflow will dry out first. After crossing the first layer, the drying medium will absorb moisture and as it travels through the upper layers the difference in partial vapor pressure will decrease taking less moisture away from the these layers.

Classifying of fluidization characteristics

Geldart has characterized the fluidization properties of powders and particles based on the average diameter and difference in density compared to the air. All the experiments are located in region D, from the fresh to the dried state, so this region will only be covered.

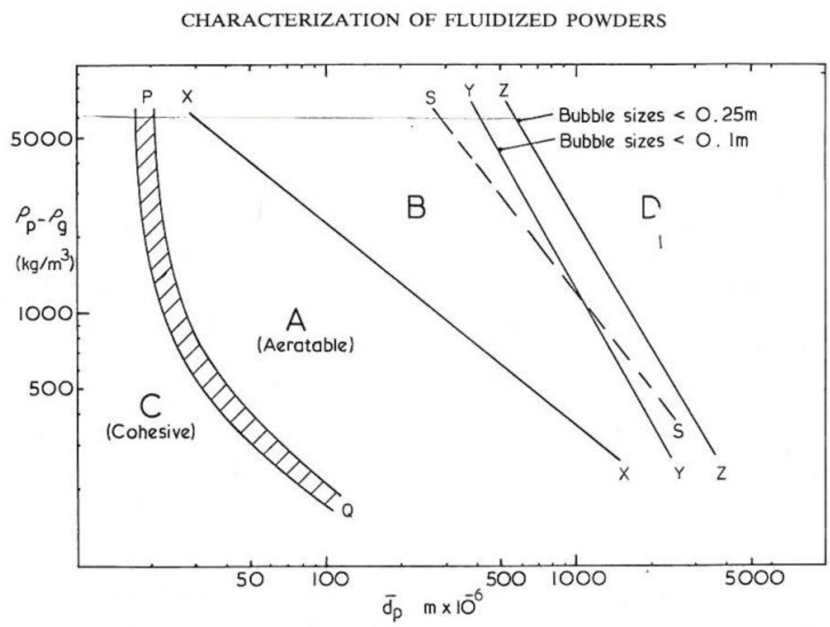


Figure 3: Characterization of Fluidized Powders Diagram: (Geldart, 1986)

Region D, see Figure 3: Characterization of Fluidized Powders Diagram: , do consist of coarse solids ranging from 1 mm and upwards. The relative large size of the particles needs a higher momentum to fluidize, this momentum helps sticky materials to fluidize. However, this can also be undesirable because of the high impact energy between particles that may cause damage. Slugs of gas and particles will be present, and partly break down as the airflow increases into the turbulent flow regime. Making the deaeration fast and good for removing moisture. Mixing of the solids can be increased with spouting by concentrating the airflow to the center of the drying bed. (Geldart, 1986)

Dehydration

Dehydration of a product contains multiple stages with different dominating effects in removing water from the product. The main driving force is pressure differences of water vapor or liquid within the product compared to the partial vapor pressure in the air. This pressure difference can be intensified by heat supplied as radiation, convection and conduction. This leads to higher evaporation of water from the surface of the product. The transport internal of moisture of the product is governed by different mechanisms. These involve capillary transport and internal vapor diffusion and water vapor evaporation from the surface of the product. The dominating effect varies as the product changes from fresh to dry and there will be a point where the periods overlap. (Fellows, 2009)

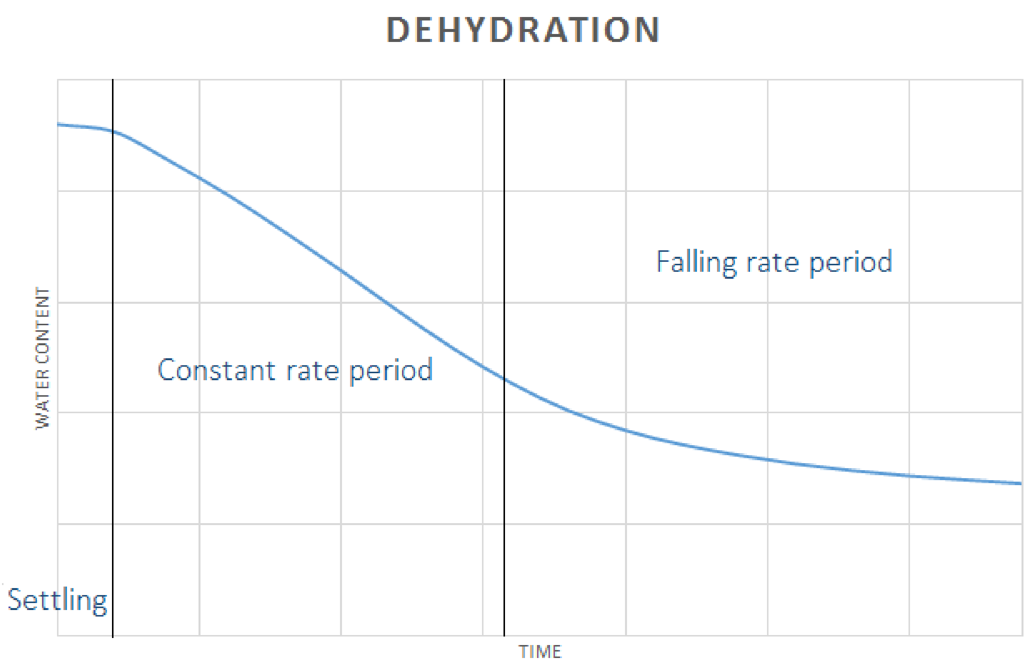


Figure 4: Dehydration periods

Settling period

In this period the material surface is heated up towards the drying air temperature. Evaporation will increase as the temperature of the boundary layer near the surface rises. The air can take up more moisture when there is higher vapor pressure between the water vapor on the surface and the drying air. (Fellows, 2009)

Constant rate period

When the product reaches the drying air wet bulb temperature, the evaporation from the surface is at its maximum and the rate will continue at that level until the surface dries out. This period is limited by how much moisture the drying air can accumulate and how fast the moist air can be replaced by new dry air. This period has a linear evaporation rate. (Fellows, 2009)

Falling rate period

At this point the surface has dried out and other mechanisms limit the evaporation rate. The limiting factor is the transport of moisture from the core of the product towards the surface, effects of capillary forces and diffusion of moisture. The falling rate period will continue until the partial vapor pressure of the drying air equals the water pressure throughout the whole product and, at this point, the product has reached equilibrium with the drying air. (Fellows, 2009)

Psychrometrics

Pysychrometrics is the study of properties of gas-vapor mixtures, and in this sense, of air to water vapor mixture. The psychrometric process can be plotted in the Mollier-diagram for a good overview. There are four interconnected factors determining the rate of moisture removal from the product to the air. These factors are the amount of air traveling over and in contact with the product, pressure of the system, the amount of water vapor already in the air and the temperature of the air. (Fellows, 2009)

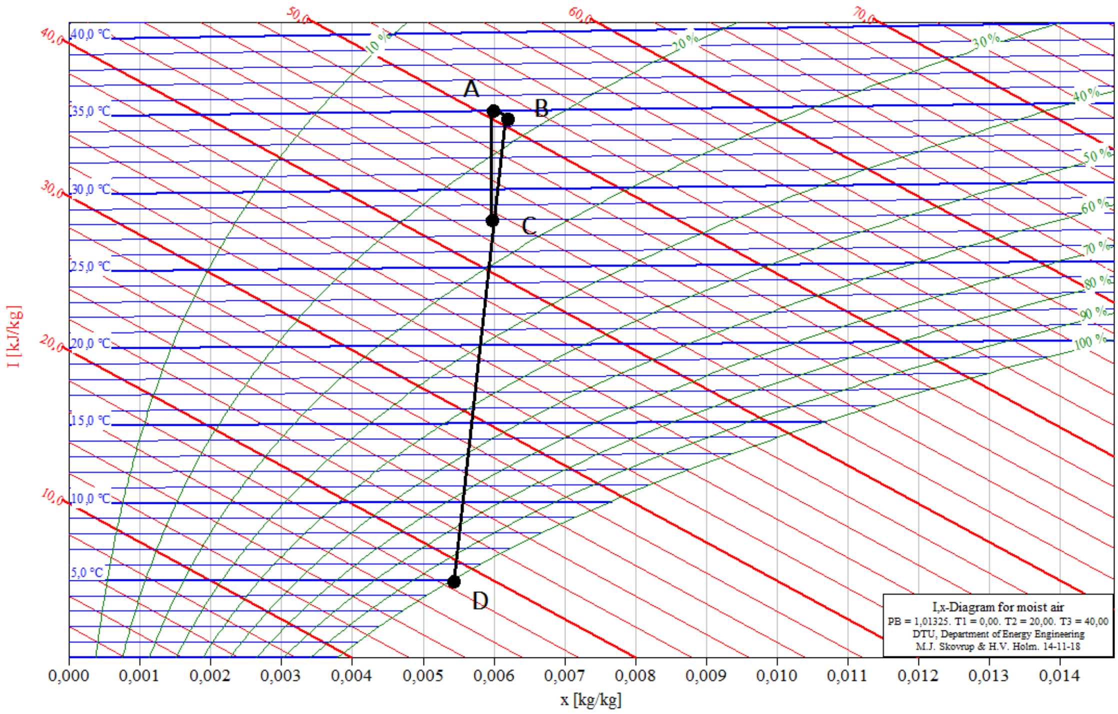


Figure 5: Drying loop psychrometrics

The Mollier-diagram show the drying pyschrometrics for the fluidized bed experiment conducted as an example. See Figure 8: Basic schematics of the drying loop, where the A is the inlet to the drying chamber, B is after and C is after the moisture removal process. D is the surface temperature of the moisture condenser.

SMER

$$SMER = \frac{COP}{\frac{dh}{dx}} \qquad [\frac{kg_{water}}{kWh}]$$

Equation 1: SMER

$$COP = \frac{Q_L}{W}$$

Equation 2: COP

As a reference to other systems, a theoretical heat pump system with R717 ammonia is used with 100% isentropical efficiency. As show in Figure 6: Log p-h diagram for R717 and COP, the COP can be calculated from the diagram.

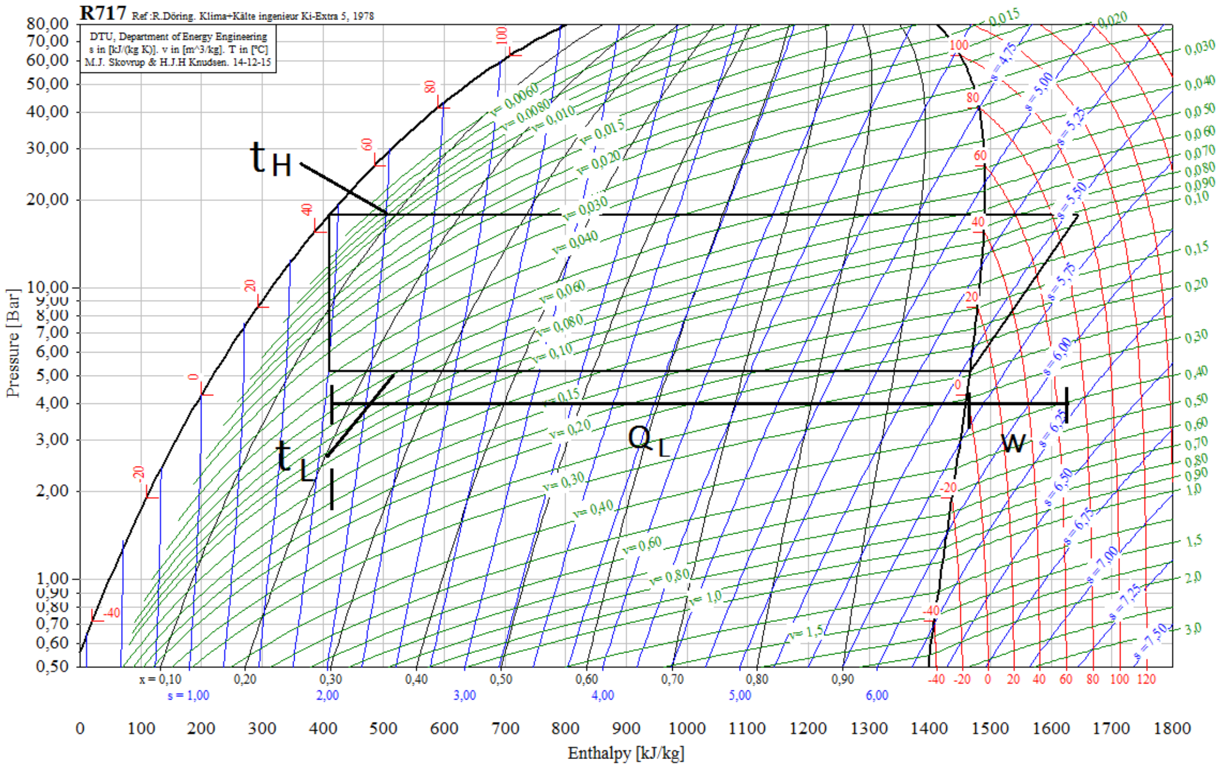


Figure 6: Log p-h diagram for R717 and COP_{is}
Plot: (Skovrup, Jakobsen, Rasmussen, & Andersen, 2012)

t_H [°C]	t_L [°C]	COP_{is}
45	5	5.9

Table 1: Parameter for the heat pump and COP

Mathematical modeling theory

A mathematical model connects the experimental data to heat and mass transportation theory. Another important benefit is the ease to compere if the experimental findings concur with experiments done by others with different variables. Also verifying that the theory and assumptions taken are correct. (Wheeler & Ganji, 2010)

The model used can be derived from the fundamentals of heat and mass transfer. With use of the differential equation know from transient mass transfer with homogenous temperature distribution. Homogenous temperature distribution is assumed since the radius of each pea is small and the difference in temperature is very low where the model is valid. When there is no significant temperature gradient the diffusivity, D_e is constant and the equation can be solved. When the moisture behavior is transient and one-dimensional moisture the general partial equation is

$$\frac{\partial W(r,t)}{\partial t} = D_e \frac{\partial^2 W(r,t)}{\partial r^2}$$

Equation 3: One-dimensional

The moisture ratio depends on dimensionless numbers as follows,

$$\frac{W(r,t) - W(R,t)}{W(r,0) - W(R,t)} = E(Bi_m, Fo_m)$$

$$Bi_m = \frac{h_m L}{D_e}$$

$$Fo_m = \frac{D_e t}{L^2}$$

Equation 4: Derived from the general equation

Giving the Biot (Bi_m) and Fourier (Fo_m) numbers for mass transfer where all the factors are constant except the time variable. All the constant factors construct the constant A in the model, Equation 5: Proposed model. (R.B.Keey, 1972) (White, 2011)

Considering this and that the green peas are made of concentric sphere were the dependent variable is moisture and the independent variables are temperature, time and modes of drying in fluidized and stationary modes. Then, we propose a nonlinear equation as follows,

$$w(t,T) = Ae^{f(T)\times t} + t^{B}$$

Equation 5: Proposed model

Experimental result

Hypothesis

The hypothesis was to study and detect if there is any difference in moisture removal kinetics, drying and fluidization characteristics by operating in single and combined drying modes. The drying modes studied were stationary, fluidizing bed and their effect when combined with mechanical vibration. Second, investigate if a basic model will fit the experiment or if the experiments are too unpredictable to be modeled easily.

Equipment and method

Green peas as experiment carrier

The reason for choosing green peas is based on the current high demand of this vegetable as main component or ingredient in salads, soups, baby foods. The dried green peas can be stored and used all year around instead of only in the harvesting period. Also, there were previously experiments done in the same dryer but further research is still needed. Green peas are easy to handle, simple to clean up, relatively non-sticky, uniform size and shape allowing good fluidization and relatively stable under mechanical stress and thermal stress.

Figure 7: Frozen green peas
Photo: Audun Rostad

In this experiment frozen green peas was used in the drying tests on studying kinetics and drying modes. The fresh green peas were frozen and freeze-stored before tests. During the freezing process part of the green peas had become stuck together forming a solid lump. During the preparation and lump separation about 10% were damaged by cracks or punctures. For keeping sample representation and experimental homogeneity the damaged material was thoroughly mixed with the intact green peas before tests were conducted.

Drying chamber

In this experiment a cylindrical chamber made of acrylic was used to process the green peas. For closing the top and the bottom, perforated screens were used as to prevent the green peas to escape the chamber. The drying chamber was connected at the bottom with an air duct and to the motor-shaft rig that generated vibrations. The air exited the chamber and entered a cabinet with an outlet in the top corner. The cabinet was insolated with Styrofoam boards of 5 cm thickness and air tight to avoid air leakage.

A motor and a reduction gear was mounted on top of the drying chamber outside of the insulation barrier so no additional heat was released from the motor to the drying chamber. From the reduction gear there was a cam shaft to provide linear oscillation movement. To transfer the linear movement to the chamber, three rods were connected to the base of the acrylic chamber.

Dryer setup

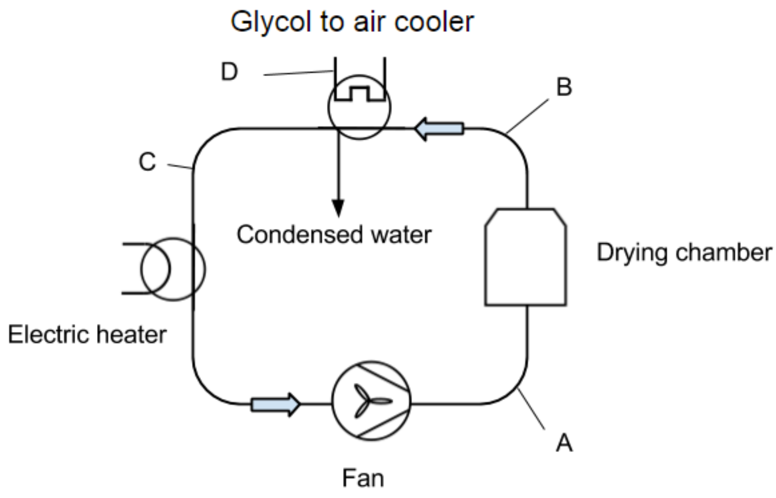


Figure 8: Basic schematics of the drying loop and main components, A, B, C and D is for reference in the Mollier diagram.

The dryer consisted of a closed air loop and a heat pump system instrumented with controllers and sensors placed in key positions such as in the inlet and outlet of each component. The main components were condensers, evaporators, compressors, glycol system, valves, auxiliary heater, fan and drying chamber for holding the green peas.

The heat pump's evaporator was connected to an air-cooler with the task to cool, condense and remove moisture from the air exiting the drying chamber. The cooling medium was glycol and the temperature of the glycol loop was automatically controlled and regulated.

The auxiliary heater consisted of a set of electrical resistors and each element was controlled by a regulator to reach the desired temperature of the air in the inlet of the drying chamber.

Cooling of the drying air

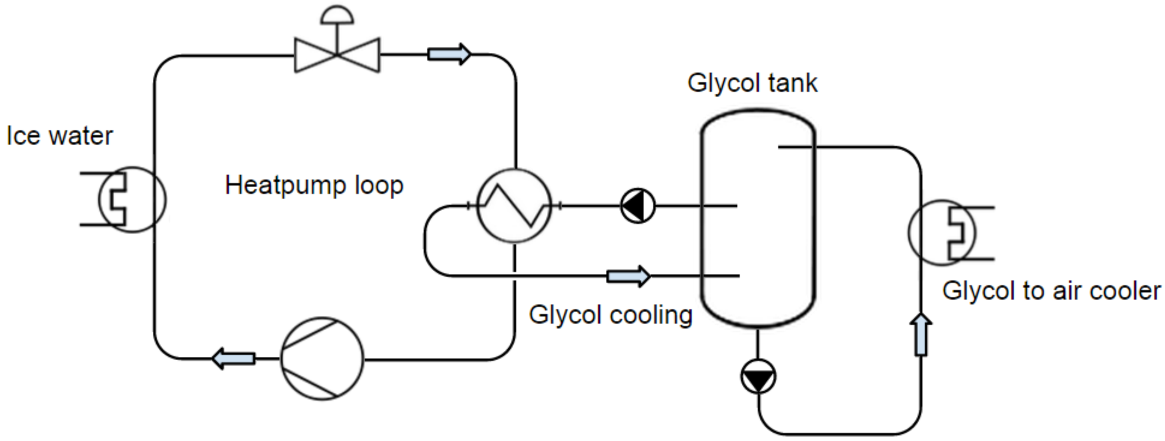


Figure 9: The cooling part of the test rig consist of a heat pump, an auxiliary water loop at 0°C and a glycol loop for cooling the drying air.

The heat pump consist of two compressors running the compression medium R404. After compression of R404, the cooling of R404 is done by an auxiliary ice water loop at 0°C. Then expanded to achieve a lower temperature, which is used to cool the glycol. The regulation of the heat pump system is done by measuring the temperature on the glycol in the tank, which then turns the compressors on and off accordingly.

The glycol loop consists of an insulated tank, the heat pump and drying air heat exchanger. The insulated tank function is the give the system some hysteresis to keep the on and off frequency of the heat pump system low. Cooling of the drying air, which leads to condensing of the moisture in drying air, is done by two rows of multiple pipes acting as a heat exchanger.

Pre-tests

To find the optimum drying load or initial mass of green peas, a pre-test was conducted and bed heights were identified for each experimental mode. Bed heights of 5, 10, 15 and 20 cm were tested to observe easiness of fluidization and consistency in moisture removal between for different runs in the dryer. As lower bed height is easier to fluidize and higher beds give a more consistent drying rate a 15 cm bed height was selected.

Measurements

Mass, relative humidity, temperature and air velocity

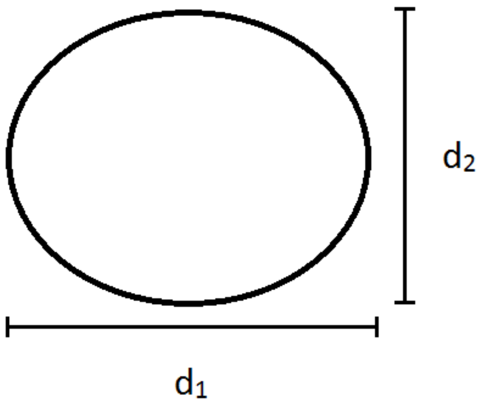
A precision scale was used to measure changes in the sample's mass. With 0.1g accuracy and self-correction for the ambient temperature. The relative humidity and temperature was measured at location A, B and C in the drying loop, see Figure 8: Basic schematics of the drying loop and main components, A, B, C and D is for reference in the Mollier diagram.. The air velocity was recorded at the 1m from the inlet of drying cabinet at location A. The sensor was placed at a strait part of the tubular connection to avoid air turbulence occurring close to bends and other fittings in the drying loop.

Size and density

A representative sample of 100 green peas was taken to measure size and density before and after the drying tests. Caliper with resolution 0.05mm was used to measure the green peas' size. Two measurements of the largest (d_1) and smallest (d_2) diameters were done in each green pea to account for the non-spherical shape of the green peas. The green peas' average diameter and volume were calculated by

$$\frac{d_1 - d_2}{2} = d_{avg} \quad [m]$$

Equation 6: Average diameter



$$V = \frac{\pi {d_{avg}}^3}{4} \quad [m^3]$$

Equation 7: Volume

Based on these values and the individually measured mass, the green peas density was calculated by

$$\rho = \frac{m}{Vn} \quad [\frac{kg}{m^3}]$$

Equation 8: Density

Water content of green peas

The water content of the green peas was measured by standard oven method with removal of all moisture content of the sample. Measuring the mass before and after oven drying provided the water content, were m_0 is the mass of the fresh and m_d is the dried product.

$$X_w = \frac{m_0 - m_d}{m_0}$$

Equation 9: Water content

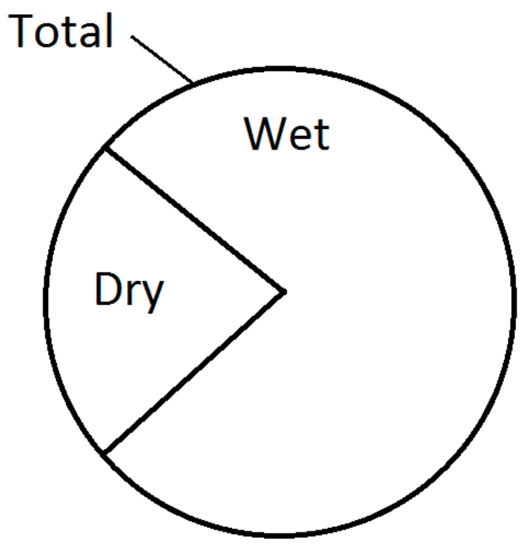


Figure 10: Illustration of Equation 9: Water content and the content dry and wet matter in a green pea.

Procedure

Startup

The drying system was kept empty and running for 20 min to reach steady state temperatures and conditions. About 10 minutes before the test started the green peas was removed from the freezer and loaded into the drying chamber and the initial mass measured and recorded. The frozen green peas had an initial temperature of -18ºC and the laboratory-room temperature was at 21ºC.

After that drying time was set to zero, the test was initiated. The exhaust relative humidity was monitored during the first 20 minutes of drying and afterwards a humidifier was used inside the drying loop to supply a stable load of moisture to the air cooler during the hole drying process. There is continuous decrease in moisture load due to water removal from the batch of green peas during drying.

During process

Every 20 minutes the batch of green peas was weighted in the drying timespan of 5 hours and 40 minutes. During this weighing process the drying chamber with green peas was removed for the drying loop for approximately 0.5 minutes resulting in some exchange between the drying air and the air in the laboratory. Before opening the drying chamber the fan and the motor driving the vibration mechanism were turned off.

Post drying

A sample of 100 green peas was collected randomly to measure volume and mass for each test following the method previously described.

Additionally to the drying in the closed air loop, another test was performed to determine the water content of the green peas. This provides the reference to the data obtained for all experiments. Three fresh and frozen samples, from the same batch used for all the experiments, were placed in the oven for 24h at a temperature of 105ºC. Then, the initial green peas' moisture content was determined after completely oven drying the three samples.

Results and observations

Tests parameters

Appendix 1 contains the heat pump drying test parameters.

The inlet air temperature was set to 35°C and moisture condenser temperature was set to 5°C through all the tests.

Five tests were conducted with different settings regarding the air velocity and mechanical vibration. This allowed to identify or to achieve fluidization through airflow or mechanical vibration. The parameters for the mechanical vibration were amplitude of 5cm and frequency of 0.7 Hz.

Acronyms	Description
STA	Stationary bed, set air speed
STA+MV	Stationary bed + mechanical vibration, airspeed as STA
FB	Fluidized bed
FB+MV	Fluidized bed + mechanical vibration, airspeed as FB
Fully FB	Fully fluidized bed, variable air speed

Table 2: Acronyms for the experiments

Optimization of the model

Optimization of the model was done by using a program in excel called solver, also called goal seeking. This is an easy way and very accessible way to optimize.
The solver has a basic buildup, it uses the formula to seek a target value, minimum, maximum or a given value by altering multiple variables inserted into the formula. To reach this goal it uses a technique where it changes the variables as long as it gets closer to the desired value.

Limitation

If there are multiple local maximums or minimums the solver function will find the nearest one to the given starting variables. So starting variables has to be closest to the global minimum to give the correct result. It is up to the user to make a qualified guess on the variables put into the solver. As can be seen in four. The qualified guess has to be between two and four to find the lowest point four, as indicated be the red arrow.

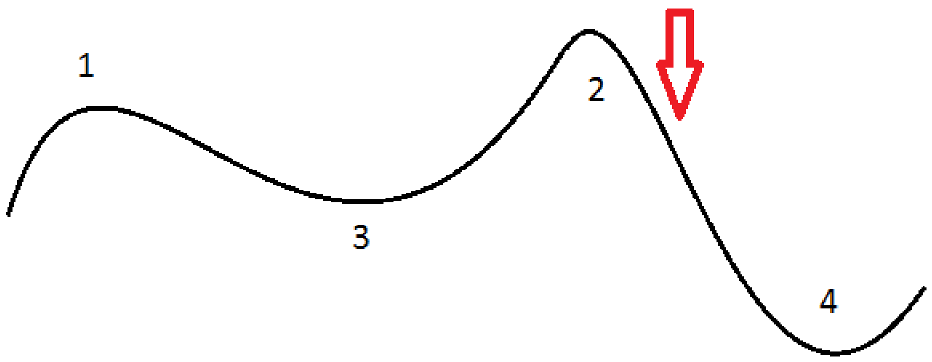


Figure 11: Example of global and local min and max, and a starting point for the solver so it will find the lowest point, four.

Procedure for obtaining the model

To achieve the global desired minimum, some thoughtful guesswork had to be done to get the variables close to the optimum result. First the experimental data and a general form of a nonlinear model was plotted in the graph. The two variables where then guessed to generally fit the experimental data. The summation of all the absolute deviations between the model and the experimental data was used as the goal for the optimizer. And the goal was to have a low as possible summation for the model used. Absolute deviations was used to keep the model simple therefor minimizing computing time. Then the goal seeker function could be used to find the global minimum for the model.

A nonlinear equation was proposed, with different variables, one for fluidized bed drying and one for the stationary bed drying. Also differentiating between temperatures in both cases.

$$w(t,T)$$

$$w(t,T) = Ae^{f(T)\times t} + t^{B}$$

Equation 10: The modeling equation

w	Water content [%]
t	Time [min]
A	Starting variable (when time at 0)
f(T)	Temperature variable
B	Curve variable (to elongate the curvature to fit with the experiments measured)

Table 3: Explication of the variables

To find the best-suiting model, goal seeking in excel was used. As reference the 35C experiments was used to determine the A and f(T) value. Where of the A value indicate the starting value for the formula, and f(T) gives the variation between temperatures in the experiment and is altering the aggressiveness of the sloped curve. The B value retains or pushes the graph to go towards zero as time t moves along.

Model of the temperature function

From the experiments there are only 3 different temperature measured giving little data for producing a temperature model. But a model was produce based on the fact that 3 random points always can be placed on a circle.

$$(X - X_0)^2 + (Y - Y_0)^2 = r^2$$

Equation 11: Circle equation used for the temperature model

Observation

Stickiness and clogging

As the frozen green peas thawed when brought to the drying chamber the batch became sticky due to excess melted water on the surface. Then, fluidization became more difficult to achieve compared to green peas with dried surface. Different fluidization patterns would occur at same setting of air velocity, which ranged from static to full fluidization. High air velocity tended to carry part of the green peas to the top and block the upper mesh while the rest of the product was fluidized.

Mechanical vibration

In the test with mechanical vibration and static bed the airflow was kept equal to the non-vibrating stationary bed. The test with vibration and fluidization the air velocity was kept equal to non-vibrated fluidized bed.

Visual characterization

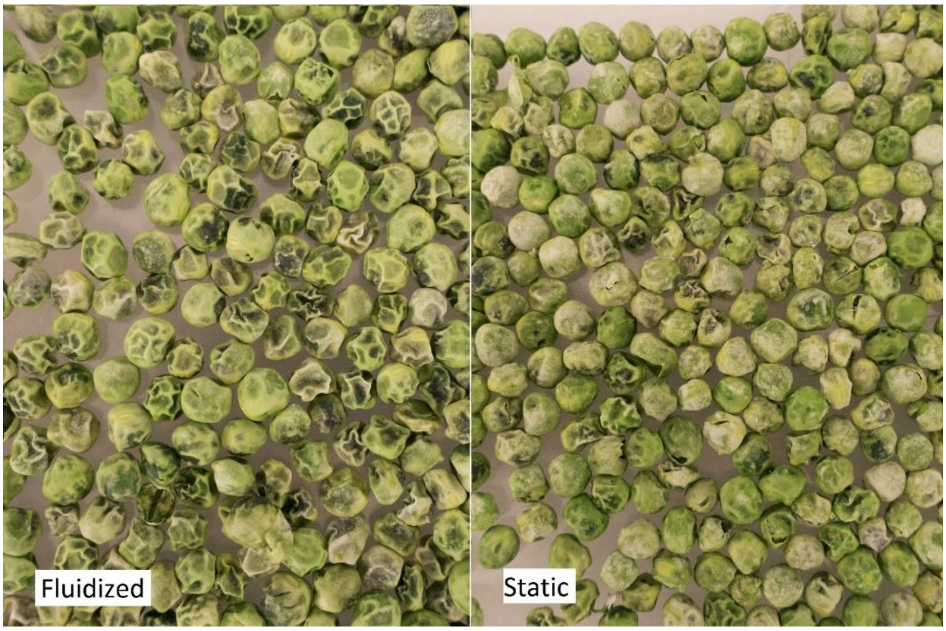


Figure 12: Surface quality comparison
Photo: Audun Rostad

Minor damage was observed on the surface of some green peas after finishing the drying process. This damage was mostly cracks and punctures and the frozen samples also had some cracks. There was not a clear visual difference of damage in the batches dried in the fluidized or the static beds. Surface wrinkles were more noticeable in green peas dried in fluidized bed compared peas dried in static bed.

Drying curves

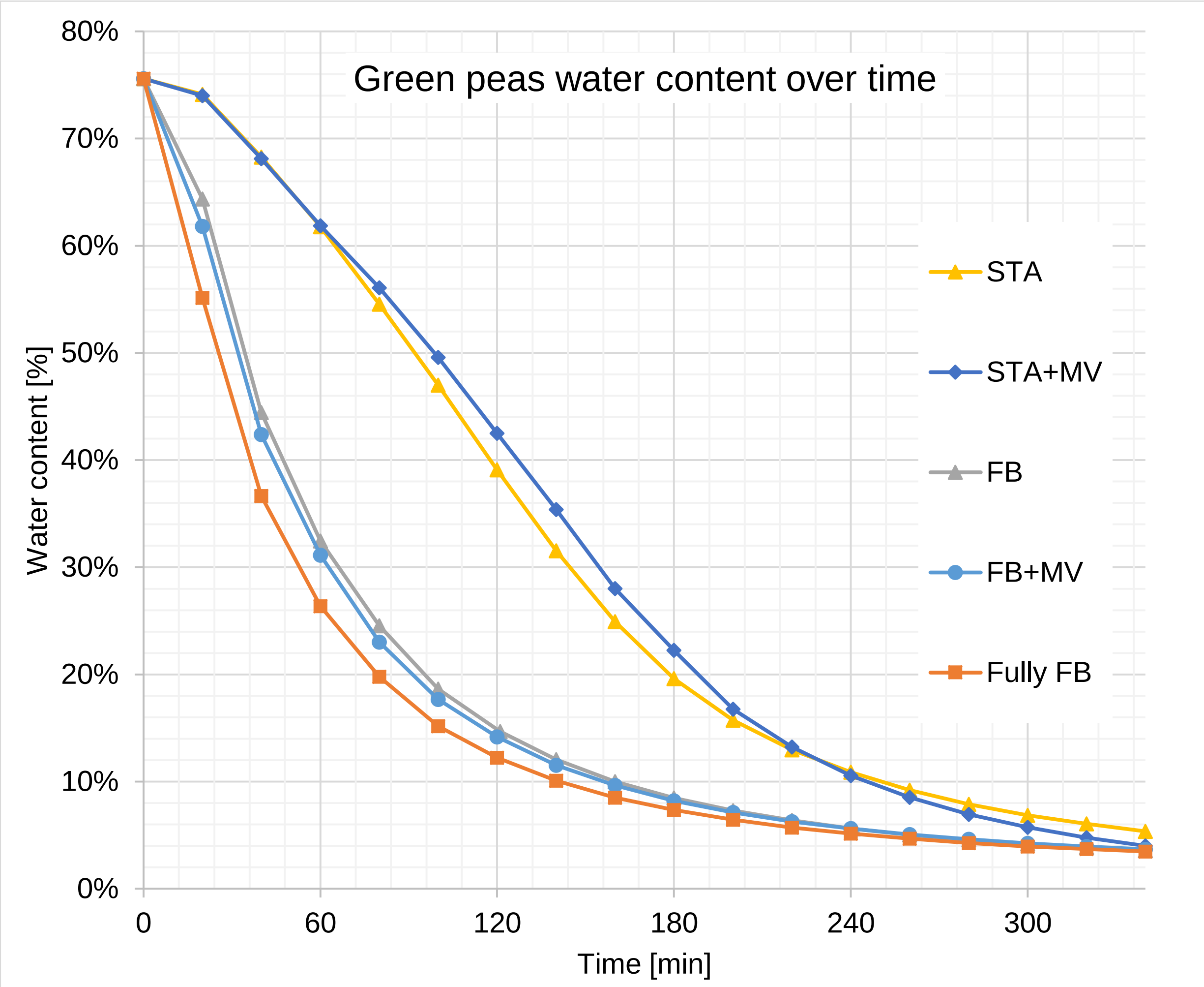


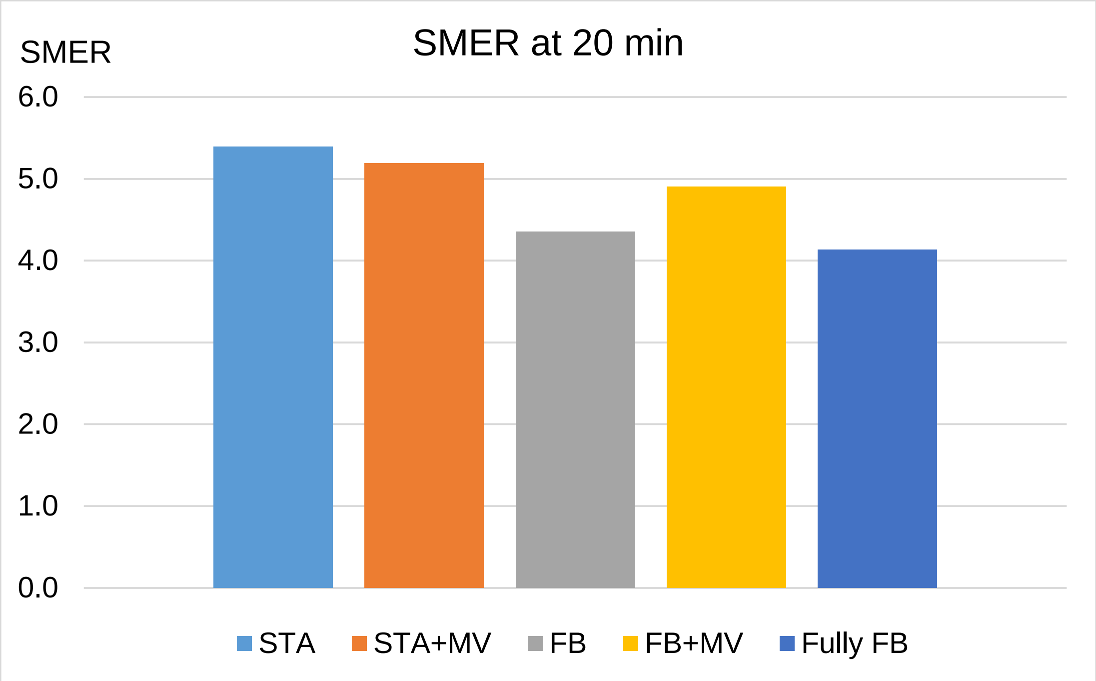
Figure 13: Water content

A major difference between fluidized and static drying can be observed in the settling period. With the fluidized bed the settling period is over before the first measurement at 20 minutes. By analyzing the slope between 0 min and 20 min, it is clear that the settling period for fluidized bed is very short, around 5 min. As for the static bed the settling period is around 30 min. Also there is no notable effect of using mechanical vibration on the settling period.

In the constant rate period, the fluidized bed has a faster evaporation rate compared to the static bed. There was a small notable effect of using mechanical vibration in the constant rate period. It is observed that STA removes more moisture than STA+MV but this is opposite to fluidization where the FB+MV removed more moisture than FB alone.

After 180 minutes in the fluidized bed tests the water evaporation curve enters the falling rate zone and the effect of fluidizing is no longer perceptible. The same is observed for the static bed at 240 minutes. After entering the falling rate period both the fluidized bed and the static bed perform drying at the same rate implying that fluidization has no effect after that time. It is observed that, at these settings, fluidized bed drying gives 60 minutes shorter total drying period. There is no notable increase in effect of using fluidization in the falling rate period compared to the static experiments. In the static experiments the STA+MV surpasses the STA in moisture removal and, at the end of drying, it approaches the fluidization experiments.

Psychometrics



t_H [°C]	t_L [°C]	COP
45	5	5.9

Figure 14: SMER and COP for heat pump using R717

Chart of the drying chamber psychometrics measured at the 20 minutes drying intervals. This is obtained from the enthalpy change and moisture removed before and after the chamber. It shows the difference in moisture removal from the drying chamber between all experiments. This occurs at the point of highest moisture removal within the constant drying rate period. The measured values are presented in appendix 4.

Water content

The initial water contents of all tests of green peas were measured in triplicate samples by the previously described oven method. The average initial moisture content was 76.0% wb (wet basis).

Density, size distribution and fluidization characteristics

	Density [kg/m^3]
Fresh	785
STA	524
STA+MV	453
FB	565
FB+MV	477
Fully FB	501

Table 4: Density, see appendix 2 for measurements

Green peas, diameter		
	Max [mm]	Min [mm]
Fresh	9.7	6.2
Dried	8.4	3.8

Table 5: Diameter of the green peas

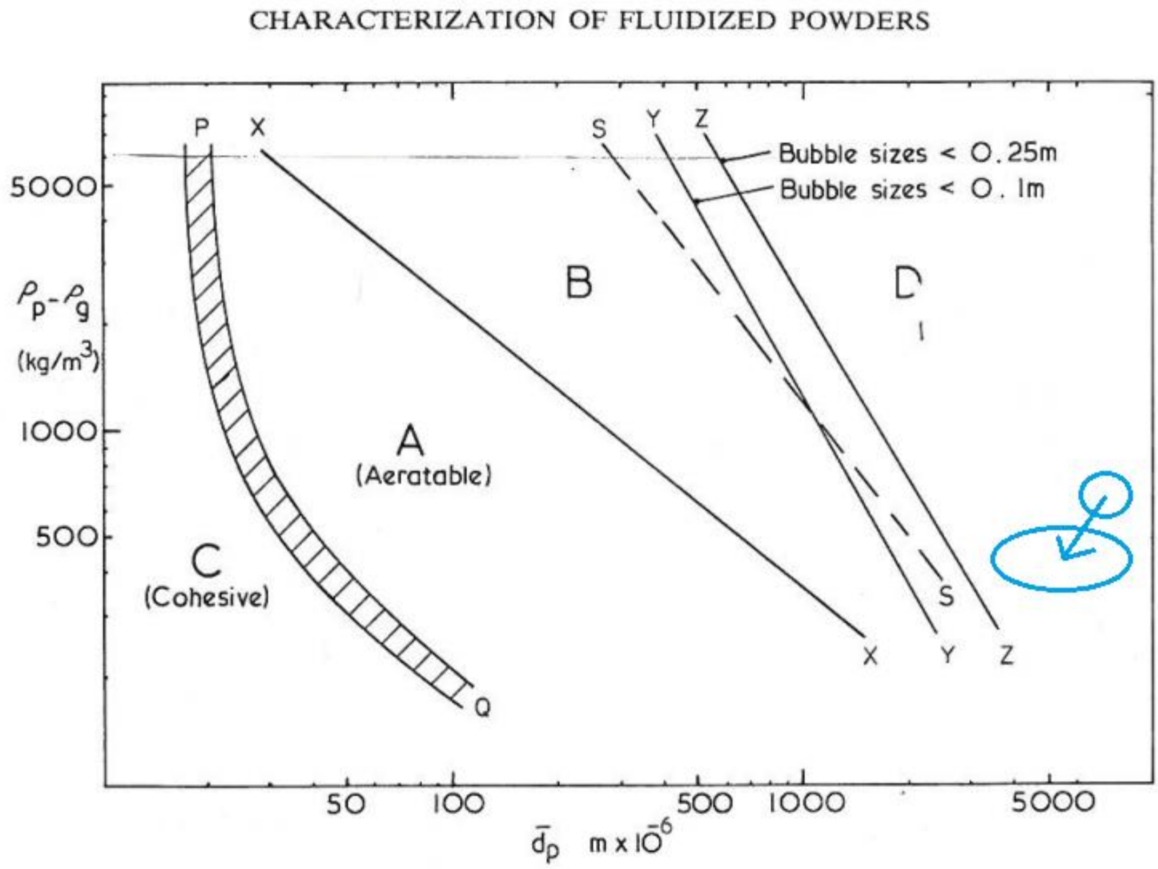


Figure 15: Characterization of fluidized green peas from fresh to dried Diagram: (Geldart, 1986)

The green peas fluidization characteristics are inside region D at all time during the drying process. A chaotic fluidization was observed, and slug of gas and particles was present during the experiments with FB, FB+MV and Fully FB. The photo in Figure 2: Gas fluidization
Photo: Audun Rostad is taken during FB and give an indication of the chaotic behavior of this fluidization.

Model

To keep the simplicity of the model the settling period and the lager uncertainty of the initial measured values compared to the constant and falling rate periods was excluded.

Fluidized bed

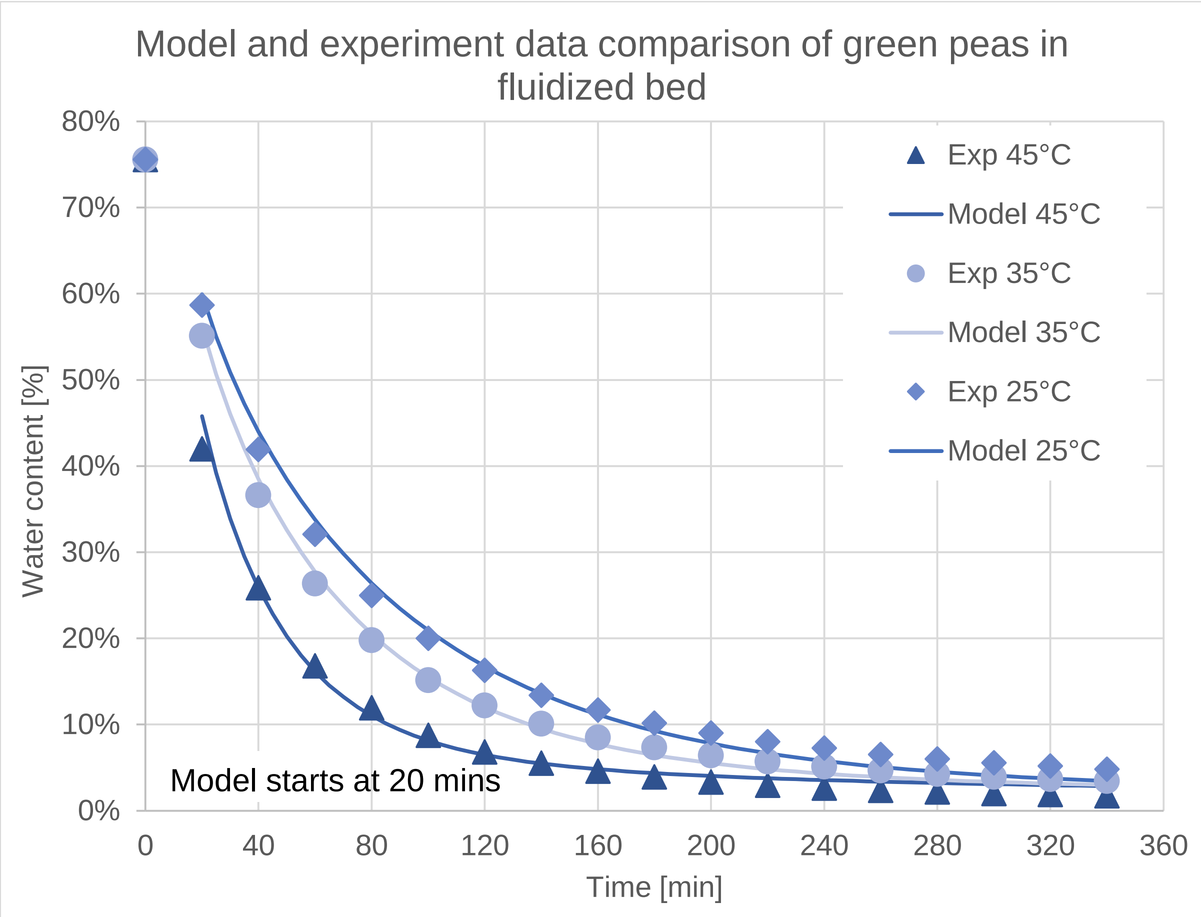


Figure 16: Model of product moisture in fluidized bed

As seen in the graph the model is only accurate for time values between 20 and 340, indicating that the model only is valid within the constant rate and falling rate period. The settling period is not included in the model.

		Model 45	**Model 35**	**Model 25**
Start variable	A	0.57457	0.57457	0.57457
Temperature variable	T	-0.0330	-0.0180	-0.01350
Curve variable	B	-0.610	-0.610	-0.610

Table 6: Variables for stationary bed

Static bed

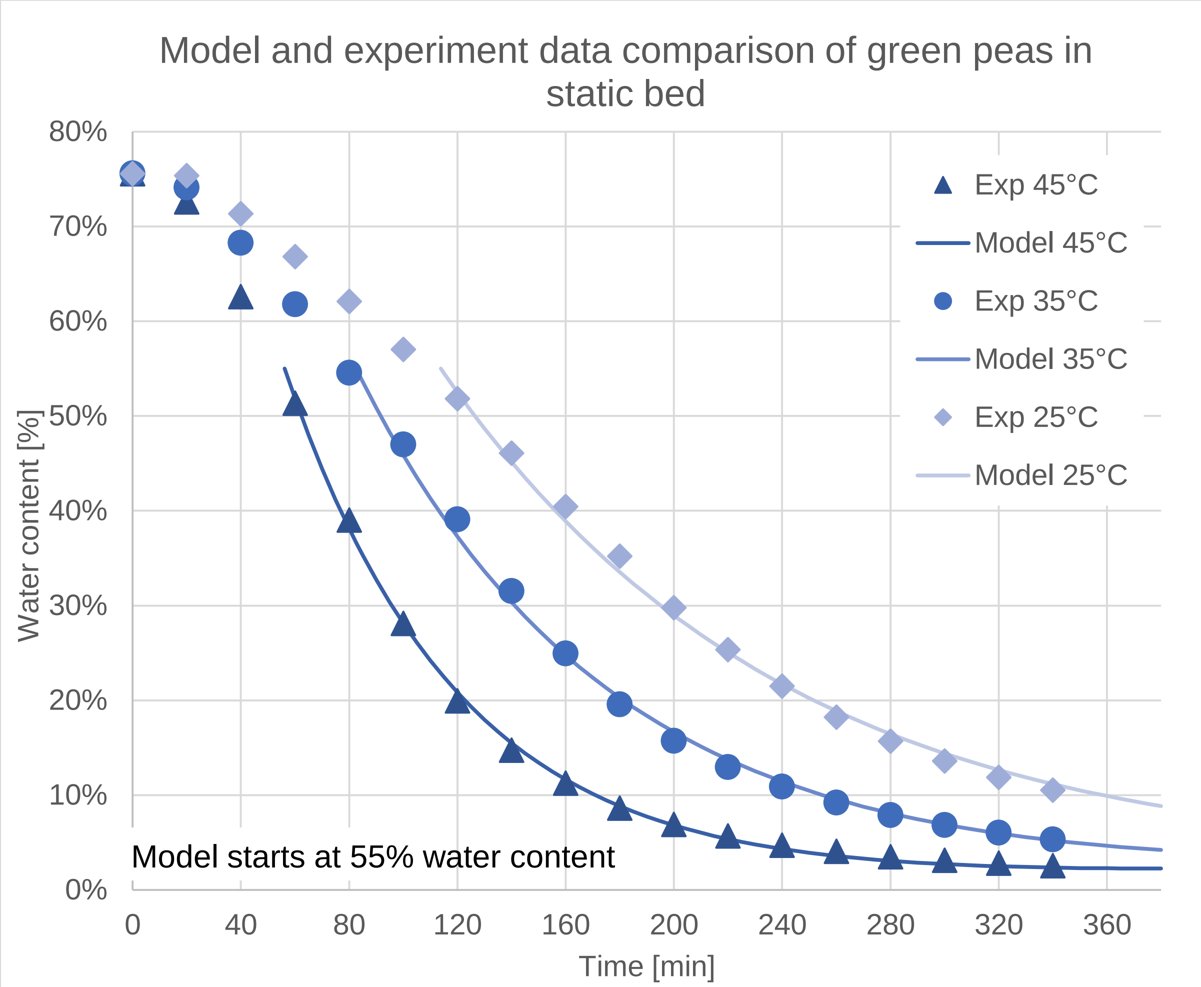


Figure 17: Model of product moisture in stationary bed

The model is valid from 55% water content in the green peas, and concludes the constant- and falling rate periods.

		Model 45	**Model 35**	**Model 25**
Start variable	A	1.312617	1.312617	1.312617
Temperature variable	T	-0.015583	-0.010629	-0.007733
Curve variable	B	0.000050	0.000050	0.000050

Table 7: Variables for stationary bed

Temperature model

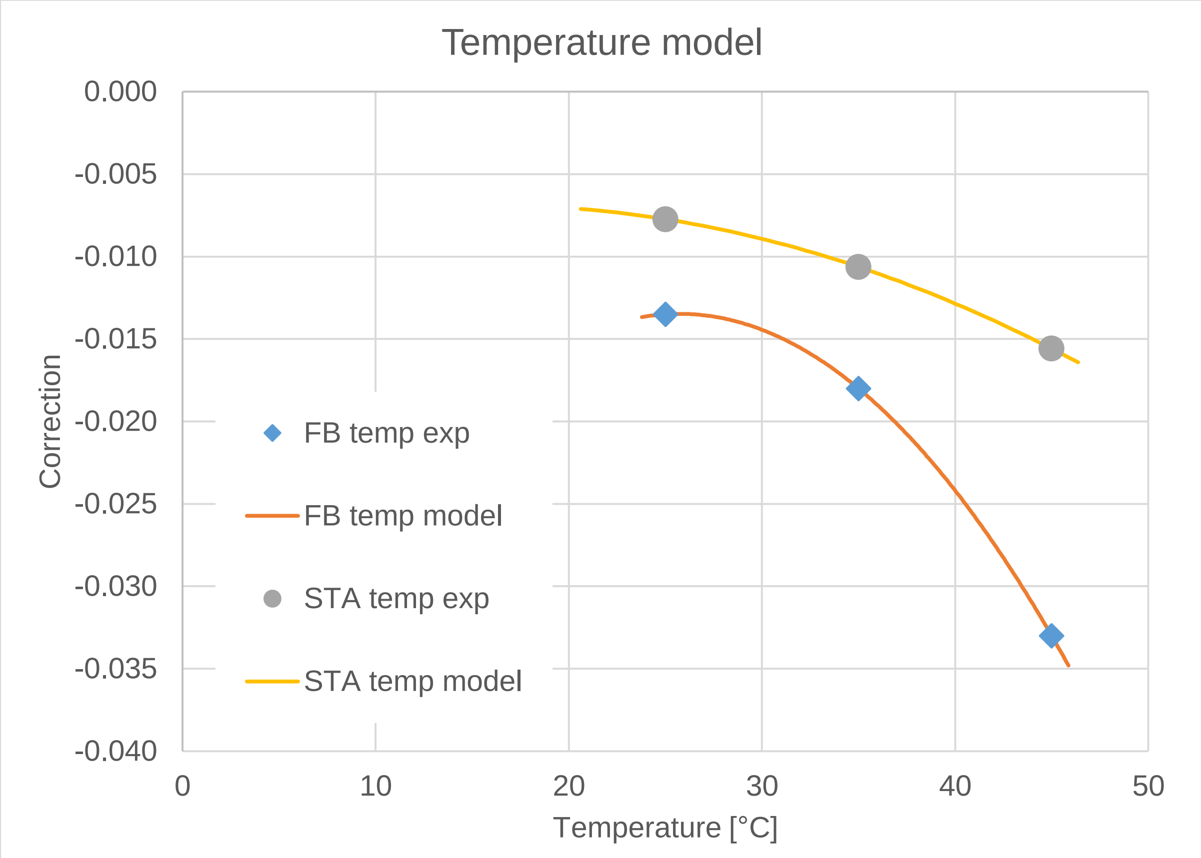


Figure 18: Temperature correlation factors

The temperature function base on the temperature value for static- and fludidized beds.

	Circle radius	**Circle center: X_0**	**Circle center: Y_0**
Static bed	48594.28	15.92	-48594.29
Fluidized bed	9523.79	25.71	-9523.83

Table 8: Variables for the temperature function

Analysis and Discussion

Drying efficiency

The drying curves show clearly that fluidization of the bed is a faster way in drying the green peas compared to static bed. The specific moisture extraction ratio (SMER) values at the 20 minutes reference mark indicates that static bed is an energy efficient way of extracting moisture.

An interesting observation in the static bed tests is that mechanical vibration gives a lower moisture extraction rate in the continuous drying period compared to static bed. An explanation to this result is that vibration compresses the bed slightly, lowering the exposed surface area of green peas in contact with the drying air contacts. When combined with fluidization, the vibration helps amplifying the effect of fluidization or bringing more energy into the system giving the green peas a higher surface temperature due to improved heat transport. This may indicate that mechanical vibration can be counter effective in some setups.

Mechanical induced vibration does not show any significant increased drying rates worthy to justify the additional energy consumption of the vibrating shaft-motor in this frequency and amplitude. The reason can be the low frequency of the mechanical vibration unable to fluidize the bed by itself.

The drying rate in the settling and following up periods are significant different for the fluidized and static bed while in the falling rate period there is no significant difference. The result is that the fluidization in this period is ineffective to improve the drying rate.

Sensible quality

The higher count of wrinkled surface of green peas in fluidized bed may be due to the higher drying rate in the following up drying periods.

Density, size and fluidization characteristics

The fluidization characteristics observed for the green peas in the experiments correspond very well to what is described for region D in Figure 3: Characterization of Fluidized Powders
Diagram:

The measurements of the size distribution by caliper, even though with a precision of 0.1 mm, do not give accurate readings since the green peas' surfaces and shape were irregular. This influenced the measurements and resulted in uncertain particle density.

Mathematical model

The two models give a description of two out of three drying periods, the constant rate period and the falling rate period. The reason not to include the settling period involves different factors. Since the settling period can be very short, from 1 min to 40 min, the sample rate of 20 min is too low to collect enough data to give an accurate description of the change of water content. The sample rate could have been increased, but due to the way of measuring the mass transport by interrupting the drying process, this was not desirable.

The temperature model is not very accurate outside of the temperature range since it is based on 3 recorded data points, and the model is based on a function of a circle.

Conclusion

The fluidized experiments did remove moisture at a faster rate when the limiting factor was what the drying air could evaporate and transport away compared to the static experiments. When internal moisture transfer become the limiting factor, the effect of fluidization disappeared.

The addition of mechanical vibration of green peas at low frequency and low amplitude does not give a notable effect for the drying rate

The fluidization characteristics concurred very well with already known research done by Geldart.

The moisture mass transfer over time concurred to the mass transfer theory, and could be modelled with a basic equation for the constant- and falling rate periods for both static- and fluidized beds.

Further studies

A recommendation is to further vary the bed height for comparison of mechanical vibration and fluidization. This would allow studying what changes in height will result in improved performance or work better or worse at the same amplitude and frequency. It is also possible to keep the bed height and vary the amplitude and frequency.

Do further research in the effect of mechanical vibration, and see if it is counterproductive for some setups.

It would be interesting to look into the resonant frequency of the bed and amplify this frequency with mechanical vibration. Then, verify if it is easier to fluidize with a lower air velocity through bed with the resonant frequency. Since the mass of the bed changes during drying the resonant frequency will also change and therefore some feedback loop has to be implemented to keep the resonant active during the drying process.

Fabricate an accurate scale connected to the drying camber to measure the change in mass in real time, making the data more accurate, thereby making the modeling more accurate.

References

Commission to the Council and the European Parliament. (2006). *The Global Energy Efficiency and Renewable Energy Fund*. Retrieved 11 18, 2014, from http://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1411032196058&uri=URISERV:l27063

Fellows, P. (2009). *Food processing technology Principles and practice* (3. ed.). CRC Press LLC.

Geldart, D. (1986). *Gas fluidization technology.* John Wiley & Sons.

Honarvar, B., Mowla, D., & Safekori, A. A. (2011). *Physical Properties of Green Pea in an Inert Medium FBD Dryer Assisted by IR Heating.* Retrieved 11 19, 2014, from http://www.sid.ir/en/vewssid/j_pdf/84320115713.pdf

Li, Z., Ye, J., Wang, H., & Wang, R. (2006). *DRYING CHARACTERISTICS OF GREEN PEAS.* Tianjin: College of Mechanical Engineering, Tianjin University of Science and Technology, .

Odilio, A.-F. (2013). *Heat Pump Drying: Theory, Design and Industrial Application.* Trondheim, Norway: Newdrytech.

R.B.Keey. (1972). *Drying Principles and Practice.* Pergamon Press.

Rahman, S. (1995). *Food properties handbook.* CRC Press. Retrieved 12 9, 2014, from http://www.aqualab.com/education/measurement-of-water-activity-for-product-quality/

Skovrup, M. J., Jakobsen, A., Rasmussen, B. D., & Andersen, S. E. (2012). CoolPack v.1.50. Kongens Lyngby: IPU & Deparment of Mechanical Engineering Technical University of Denmark.

Valentas, K., Rostein, E., & Singh, R. (1997). *Handbook of Food Enginerring Practice* (1. ed.). CRC Press LLC.

Wheeler, A., & Ganji, A. R. (2010). *Indroduction to Engineering Experimentation.* New Jersey: Pearson Education.

White, F. (2011). *Fluid Mechanics.* New York: McGraw-Hill.

Appendix 1: Experiment setup

Test #	Description	Fluidized bed	Inlet air temperature [ºC]	Inlet air relative humidity @ 20 min	Condensing temperature [ºC]	Air speed [m/s]	Test duration [min]	Bed frequency [hz]	Bed amplitude [mm]	Start mass [g]
1	STA	NO	35	13.5 %	5	7.55	340	0	0	2299.9
2	STA+MV	NO	35	13.8 %	5	7.48	340	0.7	50	2300.2
3	FB	YES	35	17.5 %	5	10.04	340	0	0	2299.9
4	FB+MV	YES	35	18.4 %	5	10.09	340	0.7	50	2300.2
5	Fully FB	YES	35	19.4 %	5	10.18	340	0	0	2300.0

Acronyms	Description
STA	Stationary bed, set airspeed
STA+MV	Stationary bed + mechanical vibration, airspeed as STA
FB	Fluidized bed
FB+MV	Fluidized bed + mechanical vibration, airspeed as FB
Fully FB	Fully fluidized bed

Appendix 2: Green peas dimensions and density

Green peas dimensions and density											
Fresh		Dried									
		STA		FB+MV		FB		Fully FB		STA+MV	
Max [mm]	Min [mm]	Max [mm]	Min [mm]	Max [mm]	Min [mm]	Max [mm]	Min [mm]	Max [mm]	Min [mm]	Max [mm]	Min [mm]
9.7	6.2	8.4	4.5	8.3	4	8	3.8	8.1	3.9	8.4	4.5
Average diameter [mm]		Average diameter [mm]		Average diameter [mm]		Average diameter [mm]		Average diameter [mm]		Average diameter [mm]	
8.03 mm		6.2435 mm		6.34875 mm		5.918 mm		6.1855 mm		6.3975 mm	
Mass [g]		Mass [g]		Mass [g]		Mass [g]		Mass [g]		Mass [g]	
31.93 g		10.02 g		9.59 g		9.2 g		9.31 g		9.31 g	
Volume [m^3]		Volume [m^3]		Volume [m^3]		Volume [m^3]		Volume [m^3]		Volume [m^3]	
4.0666E-07 m^3		1.9115E-07 m^3		2.0098E-07 m^3		1.6279E-07 m^3		1.8587E-07 m^3		2.0565E-07 m^3	
Density [kg/m^3]		Density [kg/m^3]		Density [kg/m^3]		Density [kg/m^3]		Density [kg/m^3]		Density [kg/m^3]	
785.17 kg/m^3		524.20 kg/m^3		477.16 kg/m^3		565.16 kg/m^3		500.88 kg/m^3		452.72 kg/m^3	

Density of drying air at 35°C
1.15 kg/m^3

	Density [kg/m3]	Difference in density [kg/m3]
Fresh	785	784
STA	524	523
STA+MV	453	452
FB	565	564
FB+MV	477	476
Fully FB	501	500

Green peas, diameter

	Max [mm]	Min [mm]
Fresh	9.7	6.2
Dried	8.4	3.8

Appendix 3: Data for SMER calculations

See appendix 4 for actual measurements

Calculated at the 20 min mark

	STA		STA+MV		FB		FB+MV		Fully FB	
	Enthalpy	Humidity ratio	Enthalpy	Humidity ratio	Enthalpy	Humidity ratio	Enthalpy	Humidity ratio	Enthalpy	Humidity ratio
A	47.48	0.004857	46.68	0.004629	50.86	0.006137	51.51	0.006389	51.92	0.00661
B	44.14	0.005666	43.41	0.005568	48.22	0.007463	49.13	0.007628	49.16	0.0079
C	41.99	0.005012	40.63	0.00469	44.62	0.006108	44.61	0.006118	45.83	0.00658
delta	-3.34	0.000809	-3.27	0.000939	-2.64	0.001326	-2.38	0.001239	-2.76	0.00129
SMER	5.4		5.2		4.4		4.9		4.1	

COP derived from the log p-h diagram for R717

R717	temp low [°C]	temp high [°C]	COP
	5	45	5.9

Appendix 4: Data measured for psychometric analyses

	Relative humidity and temp at A		Relative humidity and temp at B		Relative humidity and temp at C		Air velocity at A
	Ch 101 'RH1'	Ch 102 'T1'	Ch 103 'RH2'	Ch 104 'T2'	Ch 105 'RH3'	Ch 106 'T3'	Ch 107 'V1'
STA	14.074342	34.844	20.158498	28.969616	22.154233	29.468138	7.275859
STA+MV	13.649771	34.591	19.545796	28.471864	22.417111	28.998058	7.489466
FB	17.692298	34.886625	24.770861	28.836639	30.005462	28.966126	11.67895
FB+MV	18.411433	34.90065	24.932527	28.798001	29.828762	29.445768	11.679191
Fully FB	19.243483	34.74445	26.674261	28.84197	32.059537	28.797314	8.917093

All measurements take at the 20 min mark

Appendix 5: Fluidized bed model

Calculation

Water content in % of the total weight of green peas at a specific time

	Model 45	Model 35	Model 25
Start variable A	0.57457	0.57457	0.57457
Temperature T	-0.0330	-0.0180	-0.01350
Curve variab B	-0.610	-0.610	-0.610

Experiments

				w = Ae^(f(T)*t)+tB		w = Ae^(f(T)*t)+tB		w = Ae^(f(T)*t)+tB		
					(w(real)-w(model))		(w(real)-w(model))		(w(real)-w(model))	
Exp 45°C	Exp 35°C	Exp 25°C	t (time)	Model 45°C	Deviation	Model 35°C	Deviation	Model 25°C	Deviation	
75.57 %	75.57 %	75.57 %	0	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	Description:
42.00 %	55.12 %	58.70 %	20	45.8 %	3.8 %	56.2 %	1.1 %	59.9 %	1.2 %	Not shown
25.87 %	36.63 %	41.91 %	40	25.9 %	0.0 %	38.5 %	1.9 %	44.0 %	2.1 %	in the graph
16.83 %	26.35 %	32.09 %	60	16.2 %	0.7 %	27.7 %	1.4 %	33.8 %	1.7 %	
11.96 %	19.78 %	25.00 %	80	11.0 %	1.0 %	20.5 %	0.7 %	26.4 %	1.4 %	
8.74 %	15.14 %	20.00 %	100	8.1 %	0.6 %	15.5 %	0.4 %	20.9 %	0.9 %	
6.83 %	12.20 %	16.30 %	120	6.5 %	0.3 %	12.0 %	0.2 %	16.8 %	0.5 %	
5.52 %	10.08 %	13.39 %	140	5.5 %	0.0 %	9.5 %	0.5 %	13.6 %	0.2 %	
4.61 %	8.49 %	11.70 %	160	4.8 %	0.2 %	7.7 %	0.7 %	11.1 %	0.5 %	
3.91 %	7.35 %	10.17 %	180	4.4 %	0.4 %	6.5 %	0.9 %	9.3 %	0.9 %	
3.35 %	6.42 %	9.00 %	200	4.0 %	0.7 %	5.5 %	0.9 %	7.8 %	1.2 %	
2.96 %	5.69 %	8.00 %	220	3.8 %	0.8 %	4.8 %	0.9 %	6.7 %	1.3 %	
2.61 %	5.12 %	7.26 %	240	3.6 %	0.9 %	4.3 %	0.8 %	5.8 %	1.5 %	
2.35 %	4.67 %	6.52 %	260	3.4 %	1.0 %	3.9 %	0.8 %	5.1 %	1.4 %	
2.17 %	4.25 %	6.00 %	280	3.2 %	1.0 %	3.6 %	0.7 %	4.5 %	1.5 %	
2.00 %	3.94 %	5.57 %	300	3.1 %	1.1 %	3.3 %	0.6 %	4.1 %	1.5 %	
1.87 %	3.68 %	5.17 %	320	3.0 %	1.1 %	3.1 %	0.5 %	3.7 %	1.4 %	
1.74 %	3.46 %	4.83 %	340	2.9 %	1.1 %	3.0 %	0.5 %	3.4 %	1.4 %	

Sum	14.86 %	Sum	13.44 %	Sum	20.72 %
	Sum of sums				
Optimization	49.016 %	Value not to be mistaken as accuracy			

Appendix 6: Static bed model

Calculation

Water content in % of the total weight of green peas at a spesific time

		Model 45	Model 35	Model 25
Start variable	A	1.312617	1.312617	1.312617
Temperature variab	T	-0.015583	-0.010629	-0.007733
Curve variable	B	0.000050	0.000050	0.000050

Experiments				w = Ae^(f(T)*t)+tB	(w(real)-w(model))	w = Ae^(f(T)*t)+tB	(w(real)-w(model))	w = Ae^(f(T)*t)+tB	(w(real)-w(model))	
t Time [min]	Exp 45°C	Exp 35°C	Exp 25°C	Model 45°C	Deviation	Model 35°C	Deviation	Model 25°C	Deviation	
0	76 %	76 %	76 %	1.312617055	56 %	1.31261706	56 %	1.31261706	56 %	Discription:
20	73 %	74 %	75 %	0.962142822	24 %	1.06224104	32 %	1.12551652	37 %	the graph
40	63 %	68 %	71 %	0.705781442	8 %	0.86000542	18 %	0.96537115	25 %	
60	51 %	62 %	67 %	0.518332692	0 %	0.69669095	8 %	0.82831823	16 %	
80	39 %	55 %	62 %	0.381344112	1 %	0.56484392	2 %	0.71104855	9 %	
100	28 %	47 %	57 %	0.281304184	0 %	0.45843811	1 %	0.61072714	4 %	
120	20 %	39 %	52 %	0.208319315	1 %	0.37260131	2 %	0.52492528	1 %	
140	15 %	32 %	46 %	0.155145079	1 %	0.30339441	1 %	0.4515623	1 %	
160	11 %	25 %	40 %	0.116476862	0 %	0.24763265	0 %	0.38885567	2 %	
180	9 %	20 %	35 %	0.088430445	0 %	0.2027412	1 %	0.33527832	2 %	
200	7 %	16 %	30 %	0.068161672	0 %	0.16663831	1 %	0.28952202	1 %	
220	6 %	13 %	25 %	0.053587953	0 %	0.1376409	1 %	0.25046598	0 %	
240	5 %	11 %	22 %	0.043184347	0 %	0.11438822	1 %	0.21715004	0 %	
260	4 %	9 %	18 %	0.035834238	1 %	0.0957801	0 %	0.18875165	1 %	
280	4 %	8 %	16 %	0.030720006	0 %	0.08092709	0 %	0.1645661	1 %	
300	3 %	7 %	14 %	0.027242956	0 %	0.06911005	0 %	0.14398969	1 %	
320	3 %	6 %	12 %	0.024964709	0 %	0.05974757	0 %	0.12650522	1 %	
340	3 %	5 %	11 %	0.023564264	0 %	0.05236958	0 %	0.11166961	1 %	

Sum	6 %	10 %	10 %
	Sum of sums		
Optimization -> Min	26.241 %	Value not to be mistaken as accuracy	

Appendix 7: Temperature model

Static bed

Determinant method
Laplace expasion
C(x^2+y^2) + Dx + Ey + F =0
STA temp exp

	points	x^2 + y^2	x	y
Known:	P	2025.00024	45	-0.0155828
	Q	1225.00011	35	-0.0106292
	R	625.00006	25	-0.0077335
	C	45	-0.0155828	1
	0.02057856	35	-0.0106292	1
		25	-0.0077335	1
	-D	2025.00024	-0.0155828	1
	-0.6555716	1225.00011	-0.0106292	1
		625.00006	-0.0077335	1
	E	2025.00024	45	1
	2000.00077	1225.00011	35	1
		625.00006	25	1
	-F	2025.00024	45	-0.0155828
	18.9946683	1225.00011	35	-0.0106292
		625.00006	25	-0.0077335

Circle radius	r	48594.2849
Cirlce center	x0	15.9285129
	y0	-48594.292

Fluidized bed model

Determinant method
Laplace expansion
C(x^2+y^2) + Dx + Ey + F =0
FB temp exp

	points	x^2 + y^2	x	y
Known:	P	2025.00109	45	-0.033
	Q	1225.00032	35	-0.018
	R	625.000182	25	-0.0135
	C	45	-0.033	1
	0.105	35	-0.018	1
		25	-0.0135	1
	-D	2025.00109	-0.033	1
	-5.3999987	1225.00032	-0.018	1
		625.000182	-0.0135	1
	E	2025.00109	45	1
	2000.00623	1225.00032	35	1
		625.000182	25	1
	-F	2025.00109	45	-0.033
	96.3750321	1225.00032	35	-0.018
		625.000182	25	-0.0135

Circle radius	r	9523.792546
Cirlce center	x0	25.71427945
	y0	-9523.839202