A brief introduction to drying of plant-based materials

Summary

This report explains the theory behind the drying process, the key parameters such as product moisture content and air humidity and the effect these parameters have on the process. Different evaporative drying methods, convective; radiation and vacuum, and their implementations is summarized. Two general ways, recirculation and heat pump, to improve the energy efficiency of a dryer is explained. The main conclusion is that an economic evaluation is needed for each case to determine what type of dryer is the best option. Duration of the drying season, product quality requirements and the scale of the operation will all effect the economics.

Interreg Pohjoinen, Euroopan aluekehitysrahasto, EUROOPAN UNIONI, KAUSTISEN seutukunta, REGION NORRBOTTEN, LAPIN LIITTO, Centria AMMATTIKORKEAKOULU, OAMK OULUN AMMATTIKORKEAKOULU, LULEÅ TEKNISKA UNIVERSITET, Hushållningssällskapet

Author: Hampus Lundholm Ljungkvist, Lulea University of Technology

Table of Contents

1 How?

The drying process is a complex fluid mechanics problem that incorporates phase change. Several different parameters affect the process. They can be summed in three categories: the drying method, the properties of the drying medium and the properties of the product being dried. Key parameters will be defined in this section to better understand the process.

1.1 The product

Moisture content in agricultural products is usually expressed as wet basis [1], the water weight per unit of wet product:

$$X_{wb} = \frac{m_w}{m_w + m_d} \tag{1}$$

were m_w is the mass of water in the product and m_d is the mass of dry product.
For example, if we have a product with 70%wb moisture content and want 1 kg of dried product with 10%wb moisture content we would need to remove 2.2 kg of water.

The moisture content can also be expressed as dry basis [1], the water weight per unit of dry product:

$$X_{db} = \frac{m_w}{m_d} \tag{2}$$

which is not as common.

An important parameter when storing dried product is the Equilibrium Moisture Content, EMC, described by [1] as: *"The products moisture content when the moisture exchange is zero between the product and ambient air"*. In other words, the moisture content is stable. Different air properties, humidity and temperature, and products reach EMC at different moisture contents. Therefore, to keep the moisture content stable, either the storage humidity and the temperature are adjusted to fit products desired moisture content or the other way around. The product can also be stored in an airtight container.

Some of the moisture in plant materials is bound, for example trapped in capillaries, and the rest is "loosely" held or free. Because of this, the drying rate will go through two periods [2]. At first, the constant drying rate and then the falling drying rate period as shown in Figure 1.

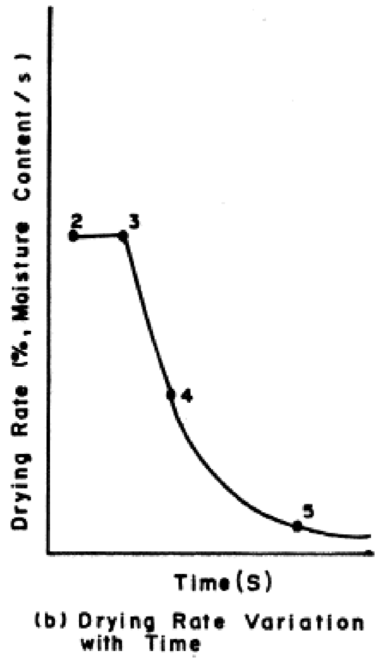

Figure 1. The two different periods of drying. Constant drying rate 2->3. Falling drying rate3->5 [2].

At first, the product surface is saturated with moisture, free water. The water will evaporate from the product during steady-state conditions until the diffusion or moisture transport from within the product cannot keep up with the drying rate. This is the products critical moisture content and is the start of the falling drying rate period. The drying rate of the first period were mainly determined by the ambient conditions since the water was free. Now, during the second period, the internal diffusion of the product becomes the determining factor making the drying rate to decrease. The diffusion rate varies with different products meaning that the critical moisture content also varies. Not all agricultural product is going through the constant drying rate period, for example rice, since their initial moisture content is below the critical moisture content.

1.2 Air properties

The theory in this section is summarized from [3].
Atmospheric air is a mixture of dry air and water vapour which both at lower temperatures and atmospheric pressures behaves as ideal gases. This means that atmospheric air will be an ideal gas mixture obeying Daltons ‘s law:

$$P = P_a + P_v \tag{3}$$

where P_a is the partial pressure of dry air and P_v is the partial pressure of vapour. Partial pressure is the pressure from the gas alone when occupying the same volume as the mixture at the same temperature. The ideal gas law,

$$PV = nRT \tag{4}$$

where V is the volume, n the amount of the gas, R the specific gas constant and T the temperature, says that the pressure is interrelated with the amount of gas at a fixed volume and temperature. This means that the maximum vapour content in atmospheric air is when the partial pressure equals the vapour saturation pressure. The saturation pressure is the maximum pressure a gas can have at a certain temperature before it starts to condense. Atmospheric air with vapour at saturation pressure is called saturated air.

The amount of water vapour or moisture content in atmospheric air is expressed in absolute terms or relative to saturated air. Absolute humidity in atmospheric air is expressed as the vapour weight per unit of dry air:

$$\omega = \frac{m_v}{m_a} \tag{5}$$

where m_v is the mass of water vapour and m_a is the mass of dry air.

Relative humidity can be expressed as the ratio of vapour partial pressure (P_v) and saturated conditions (P_s) at the same temperature:

$$\phi = \frac{P_v}{P_s} \tag{6}$$

The condition of air used as a drying medium is important if the drying process is going to be controlled. A normal question could be: What drying effect does ambient air at 5 °C and $\phi = 80\%$ that is heated to 35°C have? This can be answered by looking at a Mollier diagram, Figure 2, which shows the relation between temperature, moisture content and enthalpy of air.
The amount of moisture that can be removed with the heated ambient air equals the difference in absolute humidity which is 6,5 g of water per kg of air. The Mollier diagram should not be used directly for calculation of drying processes, because of reading errors, only to visualise the process. There are formulas behind the Mollier diagram that can be used instead. This process is called adiabatic saturation [3]. The air will evaporate the moisture from the product and lower the temperature. The enthalpy for the gas mixture can be assumed to be almost constant since the evaporated water is added to the air. To be exact, the water vapour added to the air is initially water at the same temperature as the product. This means that the specific enthalpy of the air will slightly increase since it doesn't have to supply heat to bring the water from 0°C to product temperature.

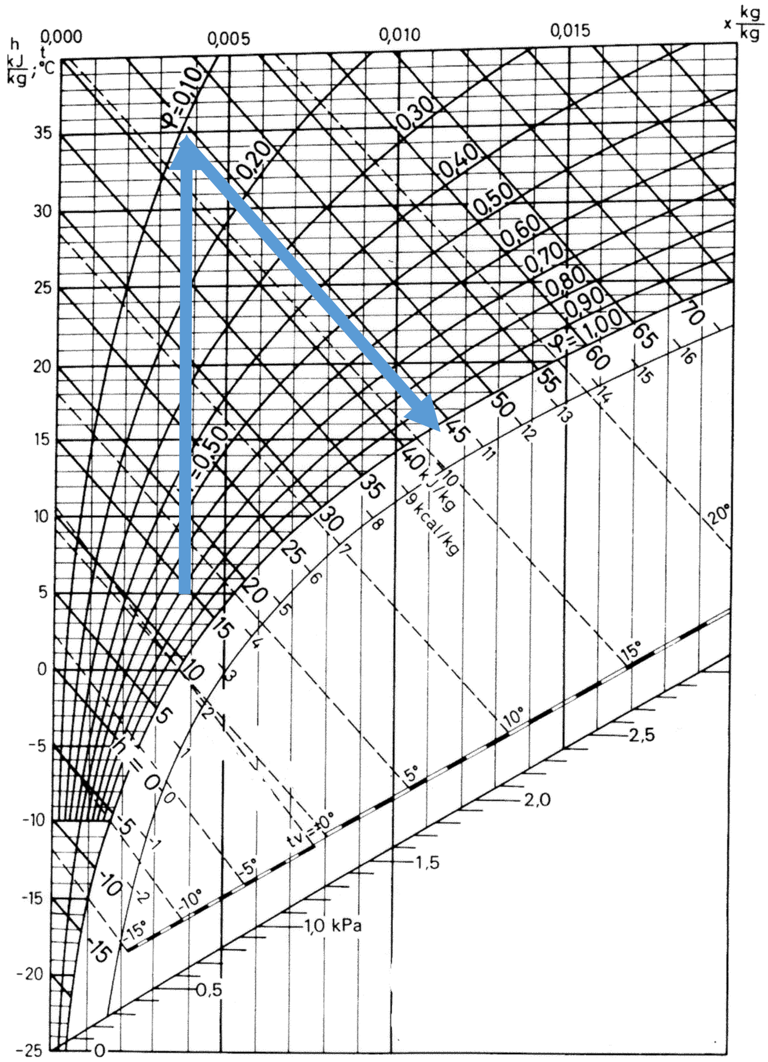

Figure 2. The Mollier diagram shows air properties. The blue lines show the way air is heated and then saturated [4].

The main principle of drying is supplying heat to the product to evaporate the moisture. The heat can be supplied in different ways: conductive, convective by a medium like air or by radiation like solar or microwave. Forced air is often used as transport medium to remove the vapour. Air closest to the product will get saturated resulting in higher vapour partial pressure compared to the ambient air which will drive the vapour to the circulating air through the dryer because of the equilibrium principle [5]. A larger vapour partial pressure difference gives a faster moisture transport.

2 Drying methods

Moisture in products can be removed in several ways. Agricultural products are usually dried with evaporative methods. Non evaporative methods exist and are used for other purposes, for example spin drying when washing clothes. There are different ways to improve the energy efficiency of driers, for example with heat pumps or recirculating the air.

2.1 Convective drying

Convective drying uses a heated medium in gas phase to both evaporate and transport the moisture. It is often called conventional drying in the literature when air is the medium since it is one the most frequently used drying methods.

2.1.1 Flat-bed dryer

A flat-bed dryer, FBD, is a type of batch dryer that is made up of a heater, a fan and a drying bin with a raised perforated floor. The product is placed on the floor. Air is normally heated to 40-45C°, with a heat pump, an electrical heater or fuel as heat source. For example, furnaces burning rice husks is often used in Asia where FBD is a common way to dry rice [6]. The heated air is forced through the layer of product and released to the surroundings. FBD is easy to operate and maintain but occupies a large surface area. Other disadvantages are nonuniform drying, low energy efficiency, time consuming loading and unloading and non-continues drying [7]. The bottom layer gets dryer than the top layer. Therefore, the drier air at the bottom has a higher drying rate. Mixing of the product during drying is therefore needed to get a uniformly dry product. Some improved dryer models can reverse the flow and will get a more uniform drying without mixing needs [7]. The residual heat in the air can be recovered by recirculating the air and by doing so improving the energy efficiency of the dryer. More on this in section 2.3.1. A non-continues dryer can cause longer breaks in the production line, both before and after the dryer, since some sensitive products have a short time window after harvest before product quality will start to deteriorate. The harvest may need to be paused after one batch is loaded in the dryer and resumed when the batch is almost dry. Otherwise would the non-dry product be stored for too long. This can be improved if several dryers are installed that starts in intervals resulting in higher investment costs but increased capacity.

2.1.2 Conveyor dryer

A conveyor dryer, also called a belt dryer, consists of one to several conveyor belts that moves the product while air is forced through or over the product. This means that the drying process will be continuous. Different air velocities and temperatures can be applied for each belt to optimise the process [1]. For example, using a higher temperature on the first belts to improve the drying rate during the constant drying rate period. A higher temperature will not harm the product since more evaporation generates a larger cooling effect. Conveyor driers will have shorter drying time and increased drying rate compared to FBD [1]. The drying process is less labour intense since the product is mixed when falling to the next belt and can be mechanically loaded and unloaded. The disadvantages are that it requires constant control, a lot of moving parts resulting in higher maintenance costs and require higher technical knowledge. Less suitable for small scale operations because of higher investment costs.

2.1.3 Tray dryers

A tray dryer resembles the convectional ovens found in households. The product is spread out on trays which are stacked in an insulated container. The air can be distributed parallel sideways over/through each tray or in series through each tray bottom-up. Sideway distribution will give a more uniformly dry product if the design distributes the air equally. A dryer with perforated trays will work similar to the FBD resulting in a more non-uniform drying. It is easier to design since equal air distribution does not have to be considered. Advantages are space efficient, small scale friendly and a simple construction. Disadvantages is the non-continues drying.

2.1.4 Fluidised bed dryer

A fluidised bed can be achieved by forcing a gas through the product at high velocities making it behave as a fluid. This type of drying for agricultural products is mostly done with different type of granular products like rice and other seeds [8]. Fluidisation increases the surface area of the product that are in contact with the drying medium which gives high thermal efficiency and high drying rates. It is less suited for material that are very wet, sticky or not in a granular shape and the dryer design is product specific [8].

2.2 Radiation drying

Drying by exposing the material for solar radiation has been around since ancient times. Today we have access to and can control different types of radiation like microwaves and infrared but solar radiation is still used for many products like sundried tomatoes and raisins.

2.2.1 Solar drying

Summarized from [9]:
The product is placed outdoors on a large surface, often concrete floors, in direct exposure of the sun. It is spread out as a thin layer which is turned over regularly to disband moist nests. The solar radiation heats the product and evaporates the water. No fan is used to move the air and transport the moisture. It is moved by natural convection and by the wind (which itself is caused by natural convection). This happens when the warm product, heated by the sun, heats the air closest to the product and therefore lower its density. The heated air will start to rise and due to density differences to the ambient air. Ambient air will take its place making the air circulate

Direct solar drying is an unsteady state process since it is affected by parameters out of our control such as solar radiation intensity and wind velocity. This means that the drying times varies and the weather conditions of the location can be more or less suitable for direct solar drying. Unsteady drying conditions makes it hard to perform scientific quality controls. An experienced based control is used instead. Direct solar drying has low investment and operation costs but the variable drying process, lack of quality control and exposure to weather changes makes it less good for more sensitive products.

2.2.2 Microwave drying

Microwaves causes polar molecules, like water, to rotate which will selectively heat those in the product promoting a faster moisture transport to the surface [10].
A combination of microwave and convective drying is often applied when drying plant material because of the temperature that may arise from microwaves. It is also more economical to apply microwaves in the latter part of the drying process when the drying rate for convective drying drops [1]. The reference reviews several studies on microwave drying for medicinal and aromatic plants that shows a reduced drying time and energy use. A problem with microwave drying besides the technical nature and high investment cost [10] is that water molecules is not the only polar molecules in plants. Some essential oils are polar and will evaporate which lowers the quality of the product [10]. However, [11] concluded that microwave combined with vacuum where the best way to preserve the essential oils of oregano. The color of the product seems to do well with microwave

drying. For example, [12] showed that microwaves could reduce the drying time of spinach without deteriorate the colour.

2.3 Vacuum drying

Vacuum drying can be used alone, in combination with radiation or conductive drying and is applied when freeze drying. Combining another method with vacuum will improve the drying rate and therefore decrease the drying duration. It is therefore possible to dry with lower temperatures. The absence of oxygen will improve the colour of the product and the low temperature increase the quality but large operational costs make vacuum drying less preferable than other methods [13].

2.3.1 Freeze drying

Freeze drying is considered one of the best ways to produce a dried high-quality product [10] but is for agricultural products mainly used at laboratory scale today. The moisture content of the product is removed through sublimation. Sublimation is when a substance transitions directly from solid to gas and skips the liquid phase [3]. Water does this if the partial pressure is lower than 611 Pa and the temperature below 0,01C°. This is called the triple point. The procedure for freeze drying is to freeze the product, lower the pressure below the triple point and supply the heat needed for sublimation [14]. Freeze dried products have a much higher rehydration ratio than air-dried products meaning that they are well suited to be used in instant meals [14]. The high operational costs compared to convective drying is the biggest disadvantage.

2.4 Dryer improvement

Two general ways to improve the efficiency of a dryer is to recirculate the air and/or install a heat pump.

2.4.1 Recirculation

Recirculation means that some of the air that leaves dryers is redirected back to the dryer again instead of being exhausted. The relative humidity of the outlet air will decrease, and the temperature will go up when the drying process enters the falling drying rate period showed in figure 1. This means that heated air with potential to transport more moisture is exhausted. A way to prevent this is by recirculation. Recirculating some of the dryer outlet air means that less ambient air is used and therefore less heat is needed which improves the energy efficiency. However, the drying rate will decrease since the pressure drop is smaller due to higher moisture content in the air which will prolong the drying process. The energy savings from recirculation can be substantial but also negative [15]. It all depends on the momentary drying rate of the product, the ambient air conditions and the drying temperature. In general, recirculation is not used in the beginning of the drying process when the drying rate is high, and the moisture more loosely held. Instead, it is used later on when the drying rate has dropped because the moisture in the product is more tightly bound and less humid air comes out of the dryer. An easy way to estimate the drying rate without measuring the moisture content of the air is to measure the temperature difference between dryer inlet and outlet. High temperature difference mean high drying rate and low temperature difference means low drying rate. This is due to the heat needed to evaporate the moisture is taken from the air, explained in section Air properties1.2.

2.4.2 Heat pump

Utilizing heat pumps to improve the efficiency of the drying process is a common way. The clever thing with a heat pump is that it exploits the large amounts of heat, latent heat, supplied/released when a medium evaporates/condensate. As a comparison, increasing the temperature of 1 kg of water with 1°C requires 4.2 kJ of heat while evaporating it requires 2260 kJ [3]. This is done by changing the pressure between evaporation and condensation making the working medium evaporate at a lower temperature and condensate at a higher temperature. The main advantage of using a heat pump dryer is energy efficient heating and dehumidification of the air. A review of several studies [16] that showed that heat pump dryers could reduce the power use with 20-40% compared to an electrical heater. There is several different heat pump dryer setups and this review will only explain the basic implementation.

The refrigerant cycle

A heat pump consists of four components: a compressor, a condenser, an expansion valve and an evaporator. The working medium, called a refrigerant, circulates between the components. A heat pump schedule is shown in Figure 3. The refrigerant is evaporated (6->7) at a low pressure and low temperature. The refrigerant is then compressed (7->8) in the compressor which increases the temperature and raises the phase change point of the refrigerant. The refrigerant condensates in the condenser (9->10) at a high temperature and the pressure is then decreased in the expansion valve (10->6). Some of the refrigerant will evaporate after the expansion but most will stay as liquid.

Heat pump dryer

Ambient air is heated by the condensing refrigerant in the heat pump condenser (1->2) and enters the dryer (2->3). Moisture from the product being dried humidifies the air and cools it (2->3) as described in Sec. 1.2. The humid air goes through the evaporator and supplies the heat needed to evaporate the refrigerant before it is exhausted (3->4). This lowers the air temperature below saturation temperature causing the water in the air to condensate. Condensate water (5) is diverted out of the dryer. Not shown in Figure 3 is fans to move the air around.

Heat pump drying is very energy efficient since the latent heat bound in the air moisture is also recovered when condensing it and expelling it as liquid instead of vapour.

There is several ways to improve the efficiency of the heat pump dryer, for example, [17] compares partially mixing the recirculated air with ambient air and recirculating all the air. The air cycle of the study is also modified with a heat exchanger making the heat pump even more efficient.

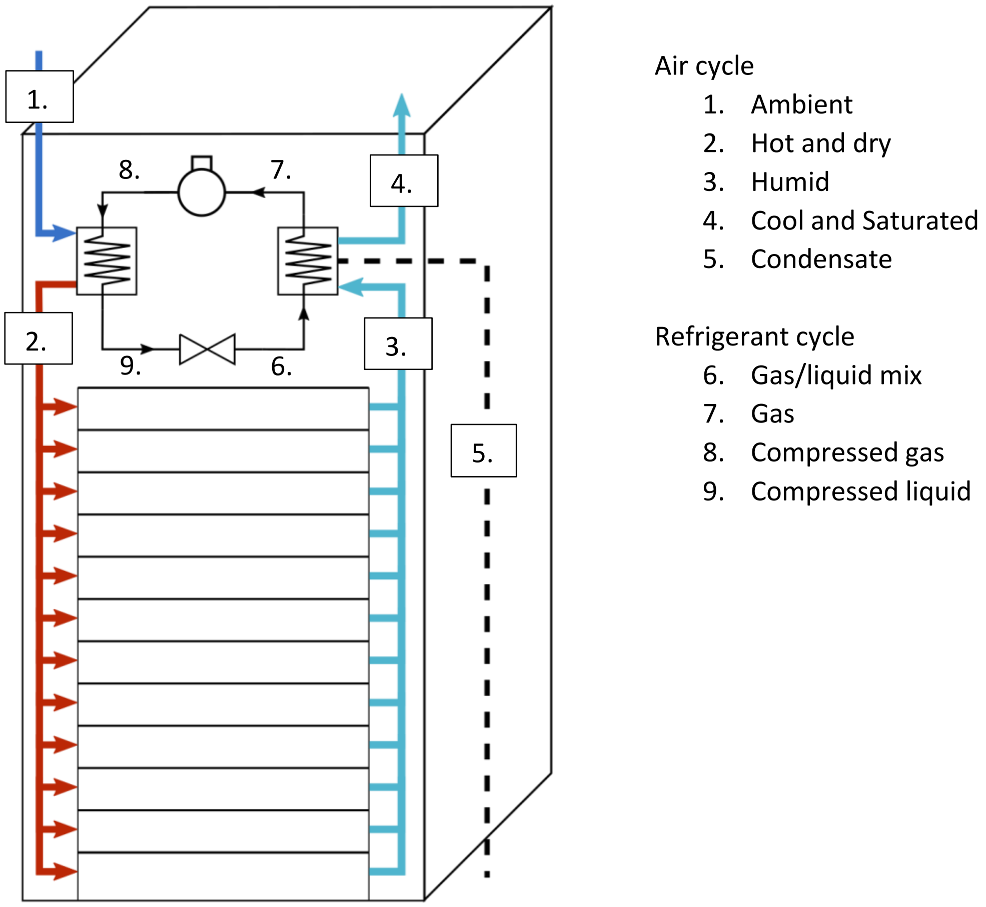

Figure 3. A heat pump tray dryer.

3 Discussion/conclusion

All the different drying methods have their advantages and disadvantages. It is the needs of the producer of agricultural products that will decide what method is most suitable.

A small-scale operation that only runs shorter periods per year will have a hard time to justify a large investment cost even if it comes with small operational costs. Therefore, several of the methods is less suited for small-scale operations: conveyor, microwave, vacuum, freeze and fluidised bed dryer. Solar dryer is not a good option for high quality products because of weather uncertainties and lack of quality control. Out of the two quite similar options left, tray dryer and flat-bed dryer, is the tray dryer more space efficient. Therefore, the conclusion is that tray dryers is most suitable for small scale operations. Recirculation should be used as long as short drying time is not prioritized. A dryer equipped with a heat pump improves the energy efficiency but comes with a larger investment cost. This means that a dryer equipped with a heat pump are more suitable for long drying seasons. A life-cycle cost analysis must be performed to know if a heat pump is economical for each individual case.

Predrying with unheated ambient air may be useful mostly to protect the product from damage by the self-heating caused by enzymatic activity. There is some support that it could improve the energy efficiency of the dryer but that is highly dependent on the air velocity, ambient air conditions, temperature and humidity, and how the moisture in the product is bound.

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