AN INTERMEDIATE COURSE IN FOOD DEHYDRATION AND DRYING

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CHAPTER 1: GETTING STARTED

1.1 Learning Objectives

During this "Intermediate Course in Food Dehydration and Drying", we will examine the following topics:

- thermal properties of food materials
- calculating the heat to dry a product
- drying mechanisms
- drying curves
- types of dryers

Before beginning this work, there will be a short review to refresh the material and concepts from the "Introduction to Food Dehydration and Drying" course. A thorough understanding of this introductory material is essential, since the Intermediate Course will build on it. We will continue to use the dimensional analysis approach to problem solving, as well as the organizational techniques described in the Introductory Course.

The purpose of this manual to provide instruction pertaining to the overall mechanisms of food drying and to demonstrate how these principles can be applied to actual food drying situations. Many of the most serious problems encountered in industrial food drying are a direct result of a failure to understand how food products dry. A general disregard, or lack of respect, for the "kinetics" of drying is the primary cause of improperly dried products.

As part of the drying process, it is also necessary to have some knowledge of the thermal properties of food products. While the thermal properties of food will be covered in other courses such as "Thermal Processing", they should also be considered in a drying course such as this. A knowledge of the specific heat capacities of food products and the latent heat of vaporization of water at various temperatures can be used to calculate the theoretical amount of heat necessary to dry a food material.

Water removal from food materials is generally controlled by two factors - the amount of heat applied to a product and the time during which the product is exposed to this heat. Time is a key factor in any drying process. During the drying process, there will be several changes that take place in the way in which the actual water removal takes place - this is called the "drying mechanism". Knowing how a specific food behaves under various drying conditions is essential for good drying and for the design of the dryers themselves.

Small-scale drying trials can greatly assist food processors in understanding the mechanisms by which their products dry. Through a series of drying trials, sets of drying curves can be obtained that will provide insight into the drying process. Development of drying curves will be discussed in this course.

A number of different types of dryers will be described. These dryers offer a range of attributes to address the needs of processors who are drying a wide range of food and other products. A common mistake amongst food processors is to assume that one dryer is suitable for all
their drying needs. Again, this is primarily due to a lack of understanding of the drying kinetics of their products, and a failure to match the conditions within their dryers to the drying mechanisms of their products.

Throughout this course, sample problems will be used to illustrate the various concepts.

After completing the “Intermediate Course in Food Dehydration and Drying”, you should:

- be able to calculate the theoretical amount of heat required to dry a variety of food materials.
- be able to identify the various drying mechanisms for a given material from basic drying data.
- be able to prepare drying curves for a food product from basic drying data.
- be able to perform necessary calculations involved in the various aspects of food drying.
- be able to communicate with dryer suppliers to describe the drying needs and mechanism of your product.
- be able to establish a suitable set of drying conditions for a particular product from basic drying data.
- be able to determine the problems associated with a drying process that does not appear to be functioning properly.

1.2 Review of Introductory Course

The following is a brief review of the major topics discussed in the Introductory Course. A detailed description of each point will not be given since it is assumed that those taking an intermediate course in food drying should already be familiar with these concepts.

1.2.1 Reasons for Drying Foods

The basic reasons for drying food are:

- to reduce spoilage
- to enhance storage life
- to alter food storage conditions
- to reduce weight and volume
- to increase convenience
- to change food properties

1.2.2 Factors Influencing Drying

Attributes of the food products that affect drying include:

- particle size
- particle shape
- composition, structure, and porosity
- moisture content
- surface characteristics
- specific surface area
- specific heat capacity
- seasonal and cultivar product variation

Attributes of the drying equipment that affect food drying include:

- type of dryer / dryer design
- air temperature
- retention time in dryer
- relative humidity of the drying air
- volumetric air flowrate
- linear air velocity
- air flow patterns
- seasonal and daily variations
1.2.3 Effects of Drying on Products

Improper drying of a food product can result in the following effects:

- degradation of nutrients
- loss of structural integrity
- reduction of product functionality
- flavour and aroma changes
- colour changes
- case hardening
- leaching of soluble constituents

1.2.4 Wet and Dry Basis Moistures

Wet Basis Moisture =
\[
\frac{\text{Weight of Water}}{\text{Total Weight of Wet Material}} \times 100\%
\]

\[= \% \text{ Moisture (wet basis)} \quad \text{Eqn. 1-1}\]

Dry Basis Moisture =
\[
\frac{\text{Weight of Water}}{\text{Weight of Dry Material}}
\]

\[= \frac{\text{g water}}{\text{g dry solids}} \quad \text{Eq'n 1-2}\]

(or: \[\frac{\text{kg water}}{\text{kg dry solids}}, \text{etc.}\])

A series of examples is presented to illustrate these calculations.

1.2.4.1 Wet Basis Moisture Sample Calculations

1. What is the percent moisture of 75 grams of onions containing 66 grams of water?

Solution: From equation 1-1

\[
\% \text{ moisture} = \frac{\text{Weight of Water}}{\text{Total Weight of Wet Material}} \times 100\%
\]

\[= \frac{66 \text{ g water}}{75 \text{ g total weight}} \times 100\%
\]

\[= 88\%
\]

Therefore, the onions contain 88% moisture on a wet basis.

2. What is the percent moisture of a mixture prepared by adding 150 grams of water to 200 grams of dry solids.

Solution:

Weight of wet material = 150 g + 200 g = 350 g

From Equation 1-1:

\[
\% \text{ moisture} = \frac{\text{Weight of Water}}{\text{Total Weight of Wet Material}} \times 100\%
\]

\[= \frac{150 \text{ g water}}{350 \text{ g total weight}} \times 100\%
\]

\[= 42.9\% \quad \text{(to one decimal place)}
\]

Therefore, the wet basis moisture is 42.9%.
3. What is the percent moisture of a mixture prepared by adding 600 grams of water to 200 grams of dry solids?

Solution:

Weight of wet material = 600 g + 200 g
= 800 g

From Equation 1-1:

\[
\text{% moisture} = \frac{\text{Weight of Water}}{\text{Total Weight of Wet Material}} \times 100\%
\]

\[
= \frac{600 \text{ g water}}{800 \text{ g total weight}} \times 100\%
\]

= 75.0 % (to one decimal place)

Therefore, the wet basis moisture is 75.0%.

4. A sample of potatoes has a dry basis moisture content of 4.26 grams of water per gram of dry solids. What is its wet basis moisture content?

Solution:

No weight of the sample is specified, and we really do not need an exact weight. It is sufficient to know that each gram of dry solids is combined 4.26 grams of water.

The definition of wet basis moisture requires that we know how much water is present in a given weight of material. The weight of the material is the combined weight of the water and the solids. Therefore, in a total weight of 5.26 grams of potatoes (1 gram of solids + 4.26 grams of water), we have 4.26 grams of water.

From Equation 1-1:

\[
\text{% moisture} = \frac{\text{Weight of Water}}{\text{Total Weight of Wet Material}} \times 100\%
\]

\[
= \frac{4.26 \text{ g water}}{5.26 \text{ g total weight}} \times 100\%
\]

= 81.0 % (to one decimal place)

Therefore, the wet basis moisture of the potatoes is 81.0%.

1.2.4.2 Dry Basis Moisture Sample Calculations

1. What is the dry basis moisture of 75 grams of onions containing 66 grams of water?

Solution:

Wt of solids = 75 g onions - 66 g water
= 9 g dry solids

From equation 1-2

Dry Basis Moisture =

\[
\frac{\text{Weight of Water}}{\text{Weight of Dry Material}}
\]

\[
= \frac{66 \text{ g water}}{9 \text{ g dry solids}}
\]

= 7.3 g water / g dry solids

Therefore, the dry basis moisture of the onions is 7.3 g water / g dry solids.
2. What is the dry basis moisture of a mixture prepared by adding 150 grams of water to 200 grams of dry solids.

Solution: From equation 1-2

Dry Basis Moisture = \[
\frac{\text{Weight of Water}}{\text{Weight of Dry Material}}
\]

\[
= \frac{150 \text{ g water}}{200 \text{ g dry solids}}
\]

\[
= 0.75 \text{ g water / g dry solids}
\]

Therefore, the dry basis moisture of the mixture is 0.75 g water / g dry solids.

3. What is the percent moisture of a mixture prepared by adding 600 grams of water to 200 grams of dry solids.

Solution:

From equation 1-2

Dry Basis Moisture = \[
\frac{\text{Weight of Water}}{\text{Weight of Dry Material}}
\]

\[
= \frac{600 \text{ g water}}{200 \text{ g dry solids}}
\]

\[
= 3.0 \text{ g water / g dry solids}
\]

Therefore, the dry basis moisture of the mixture is 3.0 g water / g dry solids.

4. Tomatoes may contain over 90% water. What is the dry basis moisture content of a tomato that has a 92% wet basis moisture content?

Solution:

Since no weight is given for the tomato, any initial weight may be used for the purpose of this calculation. For ease of calculation, 100 grams will be used here.

If 92% of the weight of the tomato is water, then the remaining 8% can be considered as being “solids”. This means that in 100 grams of tomato, we have 92 grams of water and 8 grams of solids.

From equation 1-2

Dry Basis Moisture = \[
\frac{\text{Weight of Water}}{\text{Weight of Dry Material}}
\]

\[
= \frac{92 \text{ g water}}{8 \text{ g dry solids}}
\]

\[
= 11.5 \text{ g water / g dry solids}
\]

Therefore, the dry basis moisture of the tomatoes is 11.5 g water / g dry solids.
1.2.4.3 Additional Drying Calculations

Calculate the wet basis moisture and dry basis moisture of the following mixture. 3.0 kg of sugar solution (65% by weight solids) plus 500 grams of powdered starch (10% moisture by weight) mixed with 2.0 litres of water.

Solution:

Recognizing that these three components (i.e., the sugar solution, the starch, and the water) will all be mixed together, the first thing that we need to do is determine the weight of solids and water that each one is contributing to the final mixture.

Sugar solution:

Weight of solids = 3.0 kg x 0.65
= 1.95 kg

Weight of water = 3.0 kg x 0.35
= 1.05 kg

Starch powder:

If the starch contains 10% water, it also contains 90% solids by weight.

Weight of solids = 500 g x 0.90
= 450 g

Weight of water = 500 g x 0.10
= 50 g

Water:

Based on the density of water being 1.0 kg per litre, we can convert the volume of water to its weight.

Weight of water = \( \frac{2.0 \text{ L} \times 1.0 \text{ kg}}{1 \text{ L}} \)
= 2.0 kg

The dissolved mineral content of water is generally at the parts per million, which is not significant to our calculations here. Therefore we will assume there are no solids present in the water.

From the calculations we have just done, the total weights of solids and water can be determined.

Total solids weight = 1.95 kg + 450 g
= 1.95 kg + 0.45 kg
= 2.40 kg

Total water weight = 1.05 kg + 0.05 kg + 2.0 kg = 3.10 kg

Total weight of mixture = Weight of solids + weight of water
= 2.40 kg + 3.1 kg
= 5.5 kg

% moisture = \( \frac{\text{Weight of Water}}{\text{Total Weight of Wet Material}} \times 100\% \)
= \( \frac{3.1 \text{ kg water}}{5.5 \text{ kg total weight}} \times 100\% \)
= 56.4 % (to one decimal place)

Dry Basis Moisture = \( \frac{\text{Weight of Water}}{\text{Weight of Dry Material}} \)
= \( \frac{3.1 \text{ kg water}}{2.40 \text{ kg dry solids}} \)
= 1.3 kg water / kg dry solids

Therefore, the wet basis moisture of the mixture is 56.4% by weight, and its dry basis moisture is 1.3 kg water / kg dry solids.
1.2.5 Dimensional Analysis

Dimensional analysis involves the use of dimensions or “units” with all numbers in a mathematical relationship. It is a valuable tool in preventing errors that can occur when you are uncertain as to whether to multiply two numbers together, or to divide one number by the other. By paying attention to the units associated with a number, you can tell how to arrange various values in an equation. Dimensional analysis can be set up using a horizontal line with quantities arranged above and below it to indicate whether they should be multiplied or divided. Examples of correctly and incorrectly solving a problem will be used to illustrate this point.

1. Calculate the number of minutes in one day.

Solution:

There are 24 hours in a day and 60 minutes in one hour.

\[
1 \text{ day} = \frac{1 \text{ day}}{\text{day}} \times \frac{24 \text{ hours}}{\text{hour}} \times \frac{60 \text{ minutes}}{\text{minute}} = 1,440 \text{ minutes}
\]

In this example, the “days” above and below the line cancel each other out, as do the “hours”, which leaves us with the desired units of “minutes”. The values are then multiplied by each other to give 1,440 (i.e., \(1 \times 24 \times 60\)). This gives a final answer of 1,440 minutes being equal to one day.

2. Example 1 will be repeated with an error in the calculation. Although this is a trivial example, it shows how dimensional analysis can be used to detect errors in a calculation.

Solution:

As stated above, there are 24 hours in a day and 60 minutes in one hour.

\[
1 \text{ day} = \frac{1 \text{ day}}{\text{day}} \times \frac{24 \text{ hours}}{\text{hour}} \times \frac{60 \text{ minutes}}{\text{minute}} = 0.4 \text{ hours}^2 / \text{minute} \quad (WRONG !!!)
\]

In this example, the conversion from hours to minutes was used incorrectly. Instead of multiplying by 60 minutes per hour, we incorrectly divided by 60 minutes per hour. If the numerical portion of the answer does not indicate that there are some problems, the units that we obtained should definitely cause some alarm. We were looking for a final answer expressed in “minutes” and we ended up getting units of “hours\(^2\) per minute”, which is totally wrong. Recognizing that we have an error in our calculations, we can then go back and use the units of each value to find the source of our error.
1.2.6 Process Flow Diagrams

A process flow diagram (or PFD) is a simple yet effective way of representing a food process (or any other process, for that matter). It consists of a series of “blocks” or “boxes” drawn on paper. Each box represents an important step, or unit operation in the complete process. Arrows pointing into each box show materials entering that unit operation and arrows pointing out of each box show materials leaving that particular unit operation.

Process flow diagrams are particularly helpful in following the flows of mass and heat within a process. They can assist in identifying problems associated with losses of product or heat, and can also provide information on where streams leaving a process may be re-used or where heat recovery might be beneficial.

Figure 1-1 shows an example of a hypothetical flour-making process. Although this is greatly simplified, it does show the basic principles involved in a PFD. Product flow rates and other relevant information could be added, if desired.
1.3 Practice Review Problems
(with answers)

Use the “dimensional analysis” approach to answer the following questions. Be sure to show each individual step involved in your solution in order to develop good problem solving skills. Even though these questions may not appear to be very difficult, they are designed to provide practice in the use of dimensional analysis, which will become useful when more difficult problems are encountered.

Question 1:
Calculate the dry basis moisture of a sample of okra having a wet basis moisture of 87%.
(Answer: 6.7 g water / g dry solids)

Question 2:
What is the wet basis moisture (to the nearest tenth of a percent) of a sample of sweet maize containing 2.85 grams of water per gram of dry solids.
(Answer: 74.0%)

Question 3:
How many cm are in a mile? There are 5,280 feet in a mile; 12 inches in a foot; and 2.54 cm in an inch.
(Answer: approximately 160,934 cm)

Question 4:
Convert 475.9 pounds to kilograms. There are 2.2046 pounds in one kilogram.
(Answer: approximately 215.9 kg)
CHAPTER 2: THERMAL PROPERTIES OF FOOD MATERIALS

2.1 Introduction

It is not the purpose of this module to provide detailed instruction regarding the thermal properties of various food materials. That is a topic to be covered in an entirely separate course. However, it is necessary to have an understanding of the basic thermal properties associated with the foods you will be drying.

For those of you who are already familiar with the topic, please consider this chapter as a review of thermal properties. Anyone working on this chapter who has not had previous training in “thermal properties of food materials” should get enough background instruction from the information presented here to understand the concepts and to be able to perform the required calculations.

Once the appropriate topics have been introduced, we will use a “Case Study” to put these principles into application.

We will begin by looking at the properties of water and building our knowledge from there.

2.2 Thermal Properties of Water

2.2.1 Importance

Water is one of the primary components of almost all food products. As such, its effects on the thermal properties of food materials are very significant. In order to understand how various foods behave during processing, we need to be aware of the behaviour of water under those processing conditions. For this reason, we will look at some of the properties of pure water.

2.2.2 Freezing Point

Pure water consists of hydrogen and oxygen molecules combined in a two to one ratio to form H₂O. If we look at water at temperatures around 20°C, we will see it in its liquid form. However, if we start removing heat from the water, its temperature will drop and eventually a temperature will be reached at which the structure of the water changes from a liquid to a crystalline solid which we call “ice”. The point at which the water solidifies to form ice is referred to as the “freezing point”. For pure water, the freezing point occurs at 0°C on the Celsius temperature scale.

If we have water present as ice at a temperature below 0°C, and raise the temperature by adding heat, the ice will change its state at 0°C and form liquid water. When we convert ice to water, we often refer to the temperature at which this occurs as being the “melting point”.

Regardless of the direction from which we approach it, the melting point or freezing point of pure water is 0°C. The freezing point of pure water is not dependent on atmospheric pressure which is the case with the boiling point of water.

If we dissolve substances such as salt in the water, its freezing point is lowered. Sugar also has the effect of lowering the freezing point of water. The actual change in the freezing point can be
calculated, but that is not important for our discussion here.

2.2.3 Boiling Point

If we were to take pure water as a liquid at 20°C and add heat to it, the temperature of the water would increase to a point where the water molecules would be converted from their liquid form to a vapour (or gas, if you prefer). The temperature at which water changes from a liquid to a vapour is called its “boiling point”. The boiling point of water should not be confused with the fact that water can be converted to its vapour form at temperatures well below its boiling point.

The boiling point of water is quite dependent on atmospheric pressure and can actually change with changes in weather conditions and altitude above sea level. However, for most purposes, it is sufficiently correct for us to say that pure water will boil at 100°C. To be truly correct, pure water boils at 100°C when the atmospheric pressure is equal to one atmosphere or 101.325 kiloPascals (i.e., 101.325 kPa).

If you live in a location that is significantly high above sea level, the boiling point of water will be lower than 100°C.

If we dissolve substances such as salt in the water, its boiling point would be increase or raised. Sugar also has the effect of raising the boiling point of water. Just as in the case of the freezing point, mathematical equations exist that enable us to calculate the boiling point elevation, but they are outside of the scope of what we want to accomplish here.

2.2.4 Specific Heat Capacity:

Once again, let’s take a sample of pure water at 20°C. If we were to add heat to it and increase its temperature, or if we were to remove heat from it and lower its temperature, we would find that we had to add or remove 4.187 kiloJoules (i.e., kJ) of heat to change the temperature of one kilogram of pure water by 1 Celsius degree. We refer to this as the “specific heat capacity” of the water. It is abbreviated to \( C_p \) for convenience.

\[
\text{Specific Heat Capacity of Water} = C_p = 4.187 \text{ kJ/kg } \text{C°}
\]

\[
\text{Specific Heat Capacity of Ice} = C_p = 2.050 \text{ kJ/kg } \text{C°}
\]

2.2.5 Latent Heat of Fusion

When we take a sample of pure water and lower its temperature by removing heat, we may notice a rather interesting phenomenon taking place at the freezing point. As we remove heat from the water, its temperature goes down until it reaches the freezing point. If we continue to remove heat, the temperature will stay constant for a period of time. Once the liquid water freezes to form “ice”, the temperature of the ice will continue to go down. This indicates that something is happening at the freezing point which requires heat to be removed without giving a change in temperature. Since we do not see the effects of this heat removal in the form of a temperature change, we call this the “latent heat of fusion” of water.

Latent heat is hidden from us because we do not see a temperature change happening as we remove or add this heat. However, what is really taking place
is that the water molecules at the freezing point are being re-organized into ice crystals. This structural change requires the removal of heat which we say is “latent heat”.

If we have a sample of ice and heat it to its freezing point of 0°C, we will notice a similar situation as we did with the freezing of the water. At 0°C, we have to add some heat to break the bonds of attraction between the water molecules in the ice and convert the water from its solid to its liquid form. Once again, we will see no temperature change when this latent heat is being added.

It takes the same amount of heat removal to convert one kilogram of water to ice at the freezing point as must be added to convert one kilogram of ice to liquid water at the freezing point.

The latent heat of fusion of water is 333.3 kJ / kg.

### 2.2.6 Latent Heat of Vaporization

When we heat water, we see a temperature change until the temperature of the water indicates we have reached its boiling point. If we keep adding heat, there will be no temperature rise, and we will see that the amount of water we have begins to decrease. This is due to the fact that liquid water is being converted into a vapour and is leaving the container in which it is being held.

The reason that the temperature stopped rising even though we were still adding heat is due to heat being required to break the molecular bonds holding the water together. Once these bonds are broken, the water is in its gaseous vapour form. We refer to this input of heat energy as the “latent heat of vaporization” of water.

For pure water at its boiling point of 100°C, the latent heat of vaporization is: 2,257.1 kJ / kg.

If one kilogram of water as a vapour is condensed, it will release 2,257.1 kiloJoules of heat energy.

### 2.2.7 Summary of Properties of Water:

Freezing Point = 0°C  
Boiling Point = 100°C  

$C_p$ of Water = 4.187 kJ / kg °C  
$C_p$ of Ice = 2.050 kJ / kg °C  

Latent Heats:  
of Fusion = 333.3 kJ / kg  
of Vaporization = 2,257.1 kJ/kg
2.3 Sensible Heat and Latent Heat

In the discussions above, we mentioned that in some cases we get a temperature change when we add or remove heat and in other cases there is no temperature change when heat is added or removed.

We refer to heat that gives a temperature change when it is added or removed as “sensible heat”. This is because we can feel it or sense it by the temperature change of the material.

When heat is added or removed and there is no temperature change, we call this “latent heat”, because it is essentially hidden from us.

“Latent heats" occur when there is a change of state of a material involved.

2.4 Thermal Properties of Foods

2.4.1 Background

Food materials have the same type of thermal properties as water. However, the combination of different types of solids and water makes them somewhat more complex than the thermal properties of pure water.

Some of the water molecules in food materials may be chemically bound to the food, while other water molecules may be “free” water that is present in an unbound state.

2.4.2 Freezing Point:

The freezing point of a food material is considered to be the temperature at which the unbound water that is present solidifies or turns to ice crystals.

It is not the solid dry matter in the food that actually freezes; it is just the unbound water that changes state to form ice crystals.

Because there are usually things dissolved in the water in the food material, the freezing point of the food is often below that of pure water. We see this in the case of apples which freeze at temperatures around -1.1 °C because of the sugars that are naturally present in them.

Freezing points of foods are best determined experimentally due to the complex nature of the food itself.
2.4.3 Boiling Point

Food materials are not considered to have a “boiling point” unless they are a liquid, in which case they are basically a solution with water as the solvent and other materials dissolved or dispersed in the water.

We do not speak about the boiling point of an apple, for example. However, we can look at apple juice which is a solution of sugars and other compounds in water, and we can determine its boiling point.

For our purposes, we will not consider that food materials other than solutions have a boiling point.

When we do consider the removal of water in the drying process, it will be on the basis of pure water being evaporated from the food.

2.4.4 Specific Heat Capacity

You will recall that it took the addition or removal of 4.187 kJ of heat to raise or lower the temperature of one kilogram of water by one degree on the Celsius scale. Food materials also have their own characteristic specific heat capacities. Since most solids have specific heat capacities less than water, the specific heat capacities of food materials will be less than that of water.

To determine the specific heat capacity of a food material, you can do actual experiments where you add or remove known quantities of heat to accurately weighed samples of the food and measure the corresponding change in temperature. Another way to determine the specific heat capacity of a food material is to apply the following equation:

\[
C_p = 1.424 m_c + 1.549 m_p + 1.675 m_f \\
+ 0.837 m_a + 4.187 m_w + 2.050 m_i
\]

Eq'n. 2-1

where:

- \( m_c \) = mass fraction of carbohydrate
- \( m_p \) = mass fraction of protein
- \( m_f \) = mass fraction of fat
- \( m_a \) = mass fraction of ash
- \( m_w \) = mass fraction of water
- \( m_i \) = mass fraction of ice

The mass fraction is the percentage of each component present expressed as a decimal fraction. For example if an apple contains 84% water by weight, its mass fraction of water is 0.84.

One caution that should be made is in the case of materials containing sugars. While sugars are “carbohydrates” in the chemical sense, they are classified as “ash” for the purpose of this calculation.

Sample Calculation:

Calculate the specific heat capacity (above its freezing point) of an apple having 84% moisture.

If 84% of the apple is water, then 16% of it will be solids. These solids are primarily sugars and fibrous material which will be treated as ash.

Mass fraction of water = 0.84
Mass fraction of ash = 0.16

\[
C_p = 0.837 m_a + 4.187 m_w \\
= 0.837 \times 0.16 + 4.187 \times 0.84 \\
= 0.134 + 3.517 \\
= 3.651 \text{ kJ} / \text{kg C}^\circ
\]

A similar calculation could be performed for frozen apples. However, in this case,
the water would be present as ice and the mass fraction of ice, \( m_i \), would be equal to 0.84 while the mass fraction of water, \( m_w \), would be zero.

When doing a calculation such as this, the sum of all of the mass fractions should equal 1.00, since the total composition of the material must add up to 100%.

### 2.4.5 Changes of State

When we examined the thermal properties of water, we saw that water could exist as a solid (i.e., ice), a liquid, and a vapour. Food materials can exist in a frozen or unfrozen state. We usually never see food materials in a vapour form. I sometimes joke with my students and tell them that the only time you will see food being vaporized is when it is on fire.

In addition to foods being frozen or thawed (i.e., unfrozen), we may also see other changes of state. With foods containing a high level of starches (e.g., potatoes or rice), the raw starch is present in an ungelatinized form. When sufficient heat is added to get the temperature of the starchy material up to about 60°C or slightly higher, the structure of the starch is changed in a process known as “gelatinization”. Gelatinization requires the input of heat to create the changes in the starch, but there is no apparent change in temperature. Therefore, we have a “\textit{latent heat of gelatinization}” to consider at these temperatures. Gelatinization is generally not a reversible process. Once starch has been gelatinized, it will stay gelatinized even when the temperature is reduced below its gelatinization temperature.

#### 2.4.5.1 Latent Heat of Fusion

The latent heat of fusion is a measure of how much heat must be removed or added to a kilogram of a food material at its freezing point to convert the water in it to ice or the ice in it to water. Remember, it is only the water present in the food that actually freezes, any solids present remain unchanged.

The latent heat of fusion of pure water is 333.3 kJ / kg. From the literature, the latent heat of fusion of an apple with 84% moisture content is 280.18 kJ / kg (presented in Table 2-1, later in this chapter).

If we were to take the latent heat of fusion of pure water and multiply it by the 84% water content of the apples we are considering, we would get a result of 279.97 kJ / kg.

i.e., \[ 333.3 \text{ kJ} / \text{kg} \times 0.84 = 279.97 \text{ kJ/kg} \]

As can be seen from this calculation, the latent heat of fusion can be approximated by taking the water content of the food material and multiplying it by its water content expressed as a decimal fraction. This indicates that it is really only the water present that contributes to the latent heat of fusion.
2.4.5.2 Latent Heat of Vaporization:

While we are not vaporizing the solid portion of the food materials we are drying, we are certainly vaporizing water from these solids.

If the food material is being heated up to 100°C (i.e., the boiling point of pure water at atmospheric pressure), we know that it takes about 2,257.1 kiloJoules of heat to evaporate one kilogram of water.

If the drying process is being conducted at a lower temperature, then we can calculate the latent heat of vaporization of water at that temperature based on information provided in steam tables. Steam tables will not be discussed here but are covered in a separate course.

To do this, you take the heat content of water as a vapour at the given temperature and the heat content of water as a liquid at that same temperature. The difference between these two values is the amount of heat that must be added to a kilogram of water to convert it to a vapour at that temperature. In steam tables, these values are designated as $h_v$ and $h_c$ for heat content of the vapour and heat content of the condensate liquid, respectively.

Heat of vaporization $= h_v - h_c$

Eq'n. 2-2

2.4.5.3 Example Thermal Properties

Thermal properties of some food products are listed in Table 2-1. These include specific heat capacities above and below the freezing points of the products, and latent heats of fusion. They have been calculated based on the relationships presented here using representative moisture levels (see reference source below Table 2-1).
Table 2-1: Examples of Thermal Properties of Food Products

<table>
<thead>
<tr>
<th>Material</th>
<th>Moisture Content (by weight)</th>
<th>Specific Heat Above Freezing (kJ/kg K)</th>
<th>Specific Heat Below Freezing (kJ/kg K)</th>
<th>Freezing Point (°C)</th>
<th>Latent Heat of Fusion (kJ/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apples</td>
<td>84%</td>
<td>3.651</td>
<td>1.892</td>
<td>-1.1</td>
<td>280.18</td>
</tr>
<tr>
<td>Dried Apple</td>
<td>24%</td>
<td>1.641</td>
<td>1.139</td>
<td>not available</td>
<td>not available</td>
</tr>
<tr>
<td>Bananas</td>
<td>75%</td>
<td>3.349</td>
<td>1.779</td>
<td>-0.8</td>
<td>250.16</td>
</tr>
<tr>
<td>Grapes</td>
<td>82%</td>
<td>3.584</td>
<td>1.867</td>
<td>-1.6</td>
<td>273.51</td>
</tr>
<tr>
<td>Peaches</td>
<td>89%</td>
<td>3.818</td>
<td>1.955</td>
<td>-0.9</td>
<td>296.86</td>
</tr>
<tr>
<td>Dried Peach</td>
<td>25%</td>
<td>1.675</td>
<td>1.151</td>
<td>not available</td>
<td>not available</td>
</tr>
<tr>
<td>Bread</td>
<td>34%</td>
<td>1.993</td>
<td>1.271</td>
<td>-2.2</td>
<td>106.74</td>
</tr>
<tr>
<td>Water</td>
<td>100%</td>
<td>4.187</td>
<td>2.050</td>
<td>0</td>
<td>333</td>
</tr>
</tbody>
</table>

Based on information from the American Society of Heating, Refrigerating, and Air-Conditioning Engineers from the 1986 ASHRAE Handbook - Refrigeration

2.5 Heat Transfer Mechanisms

The main methods of heat transfer in food products are through conduction and/or convection. Heat may also be transferred by radiation.

While an understanding of these heat transfer mechanisms is not essential to understanding the thermal properties of foods, they do play an important role in heating and cooling of food materials.

Additional information regarding these three heat transfer mechanisms is presented in Chapter 4.

2.6 Impact on Food Drying

Each of the thermal properties we have examined so far has some effect or impact on food drying.

While it may seem somewhat repetitive, the following points will briefly summarize these impacts, and will review some points already made on how to estimate or calculate the values of these factors.
### 2.6.1 Specific Heat Capacities

Specific heat capacities indicate how much heat is required to change the temperature of one kilogram of material by one Celsius degree. Specific heat capacities differ depending upon whether the material is in a frozen or unfrozen state.

One of the things we must do in drying is get the temperature of the wet material entering the dryer up to the desired temperature at which we will remove the moisture. The specific heat capacity will enable us to calculate the theoretical amount of heat we need to obtain this temperature, based on the initial temperature of the material and the temperature increase we require to get to the desired drying temperature.

To do this, the following equation is used:

\[ \text{Heat added} = m \cdot C_p \cdot \Delta T \]  
\[ \text{Eq'n. 2-3} \]

where:

- \( m \) = mass (in kg)
- \( C_p \) = heat capacity (in kJ / kg °C)
- \( \Delta T \) = temperature change (in °C)

The heat capacity itself can be calculated as indicated from equation 2-2 presented earlier in this chapter, or by experimentation. Literature sources often do not have complete list of food products, or the physical characteristics of the food material you are drying may be different than that listed in the literature.

### 2.6.2 Latent Heat of Fusion

While most drying is done at temperatures above the freezing point of a food material, some drying is done with the food in its frozen state to protect the quality of it. If the food must be frozen first, you may need to know its latent heat of fusion to determine how much heat must be removed to get it down to the desired frozen temperature. For this calculation, you need the latent heat of fusion.

Similarly, you may have a frozen wet product that is to be dried in its unfrozen form. In order to determine the heat required to thaw the product, you need to know its latent heat of fusion.

Limited values for latent heats of fusion appear in the literature. A good approximation of the latent heat of fusion of a food material can be obtained by taking the latent heat of fusion of pure water (i.e., 333.3 kJ / kg) and multiplying it by the percentage of water in the food (expressed as a decimal fraction).

**Sample Calculation:** For peaches with a moisture content of 89%:

\[ \text{Latent Heat of Fusion} = \frac{\text{Latent Heat of Fusion of Water}}{\text{Fraction of Water in Peaches}} \]

\[ = \frac{333 \text{ kJ/kg}}{0.89} = 296.37 \text{ kJ/kg} \]

This conveniently calculated compares favourably with the value reported in Table 2-1, and would be suitable for use in many calculations where the utmost accuracy is not essential.
2.6.3 Latent Heat of Vaporization

As stated above the latent heat of vaporization is important in order to determine how much heat is needed to evaporate water at a given temperature.

It can be calculated from information presented in steam tables, based on the equation:

\[
\text{Heat of vaporization} = h_v - h_c
\]

If we have a food material at 60°C in a dryer and water is being removed, we can find out how much heat is required to evaporate one kilogram of water in the following manner.

From steam tables for a temperature of 60°C:

Heat content of water as a vapour:

\[
h_v = 2,609.6 \text{ kJ/kg}
\]

\[
h_c = 251.13 \text{ kJ/kg}
\]

In order to convert the water from a liquid to a vapour, we need to add enough heat to raise the heat content of the water from 251.13 kJ/kg to 2,609.6 kJ/kg. This is the difference between the two values.

\[
\text{Heat of vaporization} = h_v - h_c
\]

\[
= 2,609.6 \text{ kJ/kg} - 251.13 \text{ kJ/kg}
\]

\[
= 2,358.47 \text{ kJ/kg}
\]

Therefore, we must add approximately 2,358.5 kJ of heat to every kilogram of water at 60°C to convert it to vapour at that temperature.

While we are discussing this topic, you may want to compare the heat required to vaporize one kilogram of water at 60°C (i.e., 2,358.5 kJ/kg) with the heat required to vaporize a kilogram of water at 100°C (i.e., 2,257.1 kJ/kg). You can see that as the temperature is reduced, it takes more heat to convert water from a liquid to a vapour at that temperature than it did at the higher temperature.

Once the amount of water to be removed has been calculated, this mass can be multiplied by the heat required to vaporize one kilogram of water to determine the total heat required to vaporize the complete amount of water.

In order to enhance the drying process, some dryers are operated under vacuum. This lowers the boiling point of water and in turn lowers the heat required for the drying process. Even though the heat required to vaporize water at lower temperatures is greater than that required at lower temperatures, there is an energy savings due to the fact that not as much heat is required to raise the temperature of wet material to the higher temperatures. Another major advantage of vacuum drying is that the lower temperatures do not cause heat damage to sensitive products.
2.7 Case Study #1: Heat Calculations Associated with Food Drying

The two column page format will be discontinued for this case study.

2.7.1 Background

The following case study brings together a series of factors that you may encounter into one problem. While it may not be something that you would find in a “real-life” situation, each of the elements involved do have application to actual processing conditions.

2.7.2 Case Study Scenario

A food processor has a factory that dries berries for use in dried food products. One year, during the harvest season, many berries ripen at the same time. After picking, they are brought to the factory for drying. The dryer can only handle so many berries per day, and there are many more berries than can possibly be dried in the time available. The process manager realizes that unless something is done quickly, the berries will spoil and have to be thrown away. Rather than waste the expensive berries, the manager decides to freeze the extra berries and then dry them later when there is time to use the dryer.

Using the information given below, calculate the following:

1. The heat required to thaw and warm the berries up to their drying temperature.
2. The amount of water that must be removed in the drying process.
3. The amount of final product (i.e., dried berries) that will be obtained
4. The heat required to remove the water during drying.
5. The total amount of heat required in the process.

2.7.3 Given Information

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight of frozen berries</td>
<td>750 kg</td>
</tr>
<tr>
<td>Moisture content of berries</td>
<td>82% (wet basis)</td>
</tr>
<tr>
<td>Moisture content of dried berries</td>
<td>12% (wet basis)</td>
</tr>
<tr>
<td>Specific heat capacity above freezing point</td>
<td>3.584 kJ / kg C°</td>
</tr>
<tr>
<td>Specific heat capacity below freezing point</td>
<td>1.867 kJ / kg C°</td>
</tr>
<tr>
<td>Latent heat of fusion of berries</td>
<td>273.51 kJ / kg</td>
</tr>
<tr>
<td>Freezing point of berries</td>
<td>-1.6°C</td>
</tr>
<tr>
<td>Temperature of frozen berries</td>
<td>-18°C</td>
</tr>
<tr>
<td>Drying temperature used for berries</td>
<td>60°C</td>
</tr>
</tbody>
</table>
2.7.4 Solution

Step 1:

We should begin by drawing a diagram to summarize all that we know about the process. In actual fact, we have two events happening here. One is the heating of the berries from their frozen state to the temperature at which they will be dried. The other is the removal of water in the dryer. We will begin by looking at the heating of the berries and then we will look at the drying process.

Figure 2-1 shows the heating process on what I call a “thermometer diagram”. All available information is summarized here and important values such as the temperature change (i.e., $\Delta T$, or “Delta T”) are identified and calculated.
Step 2: Heat Calculations to thaw and warm frozen berries:

From Figure 2-1, it can be seen that the heating process has three distinct parts.

Part 1: Warming of frozen berries from -18°C to their freezing point.
Part 2: Thawing of frozen berries at their freezing point (-1.6°C).
Part 3: Warming of unfrozen berries from their freezing point to 60°C.

We will do each of these three calculations and then add up the heats required to find the total heat requirement for this part of the process.

Part 1: Heat required to warm frozen berries to their freezing point:

This is also the temperature at which the berries thaw, or become “unfrozen”. Note that the freezing point of the berries is -1.6°C. It is not the same as the freezing point of pure water which has been included in Figure 2-1 as a reference point and to aid in the calculation of the temperature changes.

\[
\text{Heat added to warm} = Q_1 = m \cdot C_p \cdot \Delta T = \frac{750 \text{ kg}}{\text{kg}} \cdot \frac{1.867 \text{ kJ}}{\text{kg C}} \cdot \frac{16.4 \text{ C}}{\text{C}}
\]

\[
= 22,964.1 \text{ kJ}
\]

Part 2: Heat required to thaw frozen berries at their freezing point (-1.6°C):

This is a latent heat calculation. There is no temperature change associated with it. The structured frozen water molecules in the berries require heat energy to break the bonds of attraction and become liquid water.

\[
\text{Heat added to thaw} = Q_2 = \text{mass} \times \text{latent heat of fusion}
\]

\[
= \frac{750 \text{ kg}}{\text{kg}} \times \frac{273.51 \text{ kJ}}{\text{kg}}
\]

\[
= 205,132.5 \text{ kJ}
\]

Part 3: Heat required to warm berries to final temperature (60°C)

\[
\text{Heat added to warm} = Q_3 = m \cdot C_p \cdot \Delta T = \frac{750 \text{ kg}}{\text{kg}} \cdot \frac{3.584 \text{ kJ}}{\text{kg C}} \cdot \frac{61.6 \text{ C}}{\text{C}}
\]

\[
= 165,580.8 \text{ kJ}
\]
Calculation of Total Heat Added to Berries:

Total heat added to berries \( = Q_1 + Q_2 + Q_3 \)

\[ = 22,964.1 \text{ kJ} + 205,132.5 \text{ kJ} + 165,580.8 \text{ kJ} \]

\[ = 393,677.4 \text{ kJ} \]

Therefore, 393,677.4 kJ of heat must be added to the berries.

This is the result required for the first question we were asked to answer.

At this point, it would seem appropriate to round-off this value to 393,700 kJ, or even 394,000 kJ; both of which will be sufficient for our remaining calculations. Some purists may wish to round-off the answer based on significant digits. Others may find that based on experience it is quite acceptable to do calculations to the nearest thousand kiloJoules when dealing with quantities of heat of this size.

Step 3: Calculation of water to be removed in the drying process:

We will begin this step of our Case Study by drawing a diagram of the drying operation, as shown in Figure 2-2. While this diagram is very simple, it does allow us to organize the available information and the time we spend in preparing it forces us to organize our thoughts about what is happening in the drying process.
Now, you should calculate the weights of water and solids present in the berries entering the dryer. You can then do a “mass balance” to follow where the water and solids go in the process.

Water in berries entering dryer = 750 kg x 0.82 = 615.0 kg
Solids in berries entering dryer = 750 kg x (1.0 - 0.82) = 135.0 kg
Or: Solids = 750 kg - 615.0 kg water = 135.0 kg

Since we are not told about any losses of material in the dryer other than the removal of water, we will assume that no solids are lost in the dryer.

The finished product moisture is 12% (wet basis), which means that the final product will have a solids content of 88% by weight

Solids leaving dryer = 135.0 kg (assuming no losses)

Let weight of dried product = X kg

0.88 X = 135 kg
X = \frac{135 kg}{0.88} = 153.4 kg

Water in dried product = weight of product - solids in product
= 153.4 kg - 135.0 kg
= 18.4 kg

Therefore, 18.4 kg of water and 135.0 kg of solids would be in the finished product produced leaving the dryer each hour.

153.4 kg of finished product would be produced.

Water removed in dryer = Water in berries going into dryer - Water in berries coming out of dryer
= 615.0 kg - 18.4 kg
= 596.6 kg

This means that the dryer must remove 596.6 kg from the berries to give the desired final product.
Step 4: Calculation of heat to evaporate water:

We need to evaporate 596.6 kg of water at 60°C. This requires a value for the latent heat of vaporization of water, which we calculated previously in this module based on steam table information. The calculation involved was:

Heat content of water as a vapour:
(Values are from Steam Tables that are covered in another course)

\[ h_v = 2,609.6 \text{ kJ/kg} \]
\[ h_c = 251.13 \text{ kJ/kg} \]

Heat of vaporization = \( h_v - h_c \)
\[ = 2,609.6 \text{ kJ/kg} - 251.13 \text{ kJ/kg} \]
\[ = 2,358.47 \text{ kJ/kg} \]

Heat required for evaporating water = mass of water \( \times \) heat of vaporization
\[ = 596.6 \text{ kg} \times 2,358.47 \text{ kJ/kg} \]
\[ = 1,407,063.2 \text{ kJ} \]

Therefore, 1,407,063.2 kJ of heat are required to evaporate the water during drying. This could be rounded off to approximately 1,407,100 kJ.

Step 5: Calculation of total heat required in the overall process:

Total heat required = Heat required for heating berries + Heat required to evaporate water

\[ = 393,677.4 \text{ kJ} + 1,407,063.2 \text{ kJ} \]
\[ = 1,800,740.6 \text{ kJ} \]

Therefore, we require 1,800,740.6 kJ of heat for the entire process.

We could round this off and say that we required 1,800,100 kJ

or: 1,800,000 kJ

or: 1.8 million kiloJoules

We would certainly not report our answer to one decimal place since that would be stretching the limits of accuracy of the numbers we have available.

2.7.5 Summary of Answers
We were asked to calculate the following values. The answers shown are given to one decimal place. As stated above, in an actual production environment, reporting values to this degree would not be appropriate.

1. The heat required to thaw and warm the berries up to their drying temperature.  
   Answer: 393,677.4 kJ

2. The amount of water that must be removed in the drying process.  
   Answer: 596.6 kg

3. The amount of final product (i.e., dried berries) that will be obtained.  
   Answer: 153.4 kg

4. The heat required to remove the water during drying.  
   Answer: 1,407,063.2 kJ

5. The total amount of heat required in the process.  
   Answer: 1,800,740.6 kJ (or 1.8 million kJ)
2.8 Practice Problems (with answers)

Question 1:

How much heat must be added to 25 kg of artichokes to raise their temperature from 20°C to 75°C? The specific heat capacity of artichokes is 3.517 kJ/kg °C.

Answer: 4,835.8 kJ, which could be rounded off to 4,836 kJ

Question 2:

1,500 kg of milk is stored at 4°C and must be pasteurized at 73°C for 15 to 30 seconds. How much heat would be used to pasteurize the milk if the specific heat capacity of the milk is 3.751 kJ / kg °C?

Answer: 388,228.5 kJ which would be rounded off to 388,229 kJ or possibly to 388,000 kJ. (The pasteurization time is not used in this calculation. It is just extra information).

Question 3:

A grower picks 75 kg of ripe cherries from his orchard on a day when the temperature is 29°C. In order to reduce the risk of spoilage, he needs to cool the cherries as quickly as possible. If the cherries are cooled to 10°C, how much heat must be removed? The C_p for cherries is 3.651 kJ / kg °C.

Answer: 5,202.6 kJ of heat must be removed. (The answer could be rounded off to 5,200 kJ).

Question 4:

Using the appropriate equation, determine the specific heat capacity of okra which has a water content of 90% by weight.

Answer: 3.852 kJ / kg °C. (Assume that the solids are present as “ash”).

Question 5:

How much heat must be added to 1.5 kg of ice at -18°C to melt it and warm the water to 25°C? You will need to use the properties of water as listed in Table 2-1. Draw a thermometer diagram to assist you with this problem.

Answer: 712.29 kJ (or approximately 712 kJ) of heat must be added.

Question 6:

What is the latent heat of fusion of guava, if it takes the addition of 693.8 kJ of heat to thaw 2.5 kg of frozen guava at its freezing point.

Answer: 277.5 kJ / kg.

Question 7:

What would the final temperature be if 500 kJ of heat were added to 5.3 kg of sweet peppers (C_p = 3.919 kJ / kg °C) having an initial temperature of 10°C?

Answer: approximately 30.1°C (Hint: You need to find the temperature increase due to the addition of heat as a first step).
CHAPTER 3: CALCULATING THE HEAT TO DRY A PRODUCT

3.1 Introduction

In the previous chapter, we examined various thermal properties of food materials and performed a number of related calculations, including a Case Study to calculate the amount of heat required in a drying process. This module also presents a similar Case Study.

Although it may seem to duplicate the work presented in Chapter 2, I am including this as a separate chapter to build on the previous work. It will also benefit those who are already familiar with the thermal properties of food materials to have a chapter that focusses solely on the heat calculations.

Basically, most conventional drying involves taking materials with a relatively high moisture content and a low initial temperature; heating them to an appropriate temperature; and evaporating water from them. As we shall see in Chapter 4 (Drying Mechanisms), this is a somewhat overly simplified treatment, but it will enable us to gain some insight into how much heat is required for the drying task.

A key factor in approaching any problem is to divide it up into a series of manageable steps that follow a logical sequence. In our calculations, we will begin by gathering the necessary background information concerning the drying process and doing some preliminary calculations regarding how much water must be removed from the material we are drying. After this, we can calculate the amount of heat to raise the temperature of the material, and then we can calculate the amount of heat needed to evaporate the water from it.

Case Study #2 follows some general instructions on calculating the amount of heat required to dry a product.

3.2 Data Organization and Preliminary Calculations

3.2.1 Diagrams

The one thing that separates successful problem solvers from those who are unsuccessful is “organization”. While a person may be able to solve some problems without any apparent level of organization, he or she will not be as fortunate when facing a more difficult or more complex problem. Without a disciplined and structured approach, it is often not possible to develop the relationships necessary to solve the problem.

The first thing we should do is draw a set of simple diagrams for each part of the problem we are facing.

If there is a temperature change due to the addition or removal of heat, then draw a “thermometer” diagram showing the initial and final temperatures, as well as temperatures where there is a change of state (e.g., freezing point, or boiling point). You may also wish to indicate the heat capacities of the material on the thermometer diagram, along with the
mass of material.

I personally draw a diagram of the dryer. This is just a rectangle on a sheet of paper with arrows pointing into it to indicate materials entering the dryer. Arrows pointing out of the rectangle indicate product streams leaving the dryer. Each arrow should be labelled with as much information as there is available. It is then possible to identify the “unknowns” in the process and establish any relationships between these and some of the “known” quantities.

Before proceeding too far, it is also a good idea, whenever possible, to calculate the weights of water and dry solids present in each one of the product streams entering and leaving the dryer. Doing this will enable you to calculate the amount of water that must be removed in the dryer.

3.2.2 Calculating Heat to Raise the Temperature of a Product

One of the first things that happens when a material enters a dryer is that its temperature begins to rise.

With all of your information organized and the preliminary calculations done, it is usually a straightforward process to calculate the heat required to warm the material from its initial temperature to the temperature at which it will be dried. Along the way, we may have to make some simplifying assumptions, but these are not that unreasonable. For example, we will assume that none of the water starts to evaporate until the product reaches the drying temperature. We can then calculate the heat needed to warm the product by means of the equation:

\[
\text{Heat Required} = Q_1 = m C_p \Delta T
\]

Often the most difficult thing about applying this equation is finding an appropriate value for the specific heat capacity term.

3.2.3 Calculating Heat to Remove Moisture from a Product

After the product has warmed up to the drying temperature, water begins to be evaporated. The heat required to evaporate this water can be calculated by means of the following equation:

\[
\text{Heat Required} = Q_2 = \text{mass} \times \text{latent heat of vaporization of water}
\]

Latent heats of vaporization for water can be determined by taking the difference between the enthalpy of water as a vapour (i.e., \( h_v \)) and the enthalphy of water as a liquid (i.e., \( h_c \)) at the temperature at which the drying is taking place. In mathematical terms, this would be:

\[
\text{Latent Heat of Vaporization} = h_v - h_c
\]

3.2.4 Total Heat Requirement

The total heat required for drying the product would then be the total of the heat needed to raise the temperature of the incoming material (i.e., \( Q_1 \)) and the heat needed to evaporate the water (i.e., \( Q_2 \)).

\[
\text{Total Heat Required} = Q_1 + Q_2
\]
3.3 Theoretical Values versus Production Values

We should recognize that the amounts of heat required for drying that we calculate based on the methods discussed here are theoretical values.

Our calculated values do not take into account heat lost though the walls of the dryer or heat leaving the dryer in the exhaust air. Our calculations assume that every single kilojoule of energy put into the dryer is used in the drying task. This is seldom the case in real life situations.

Hot air entering the dryer does not transfer all of its heat to the material being dried, since the drying process is not something that is 100% efficient. There is normally a great deal of heat left in the air coming out of the dryer. We also need to determine how much heat is being put into the dryer under actual running conditions to dry our product. In this way, a comparison can be made between the actual heat used and the theoretical heat calculation to determine an overall efficiency for the process:

\[
\text{Heat Use Efficiency} = \frac{\text{Theoretical heat requirement}}{\text{Actual amount of heat used}} \times 100\%
\]

The heat use efficiency can then be used as a basis for improving the operation of the dryer and possibly as a guideline for energy consumption calculations needed if the size of the dryer is to be changed or the throughput rate of the dryer is to be altered.

3.4 Role of Time in Drying

You may have noticed that “time” was not a factor in any of the calculations we have discussed so far in this module. The time it takes to dry a material is usually determined through experimentation and is quite dependent on the nature of the material being dried and a host of other factors (see Chapter 1, Section 1.2.2: Factors Influencing Drying).

It must always be kept in mind that drying is a “kinetic process”. This means that it is highly dependent on time. Drying cannot normally be rushed. It takes time for moisture to diffuse from the inside of a particle to the outer surface where it can evaporate. There are only limited things that we can do to speed up the diffusion process. The application of heat must be matched to the drying characteristics of the material in the dryer. This is something that can only be done by trial and error, coupled with experience.

Never, ever, lose sight of the important role that time plays in the drying process.
3.5 Case Study #2: Calculation of the Heat Required to Dry a Product

3.5.1 Problem Statement

1,000 kg of green beans with an initial moisture content of 89% wet basis are stored under refrigerated conditions (4°C). How much heat would be required to dry this material to a 12% final moisture if the temperature of the drying air was 65°C?

3.5.2 Solution

1. Organization of Data and Preliminary Calculations:

Begin by drawing a set of diagrams appropriate for the drying process. Figure 3-1 shows a “thermometer diagram” for the heating of the green beans. Figure 3-2 shows the water removal portion of the process in the dryer.

For heating the beans, we need to know the mass, specific heat capacity, and temperature change. From the given data, we know the mass of the beans and can easily calculate the temperature change. However, we need to find the specific heat capacity.

From tables of food properties, the specific heat for green beans is 3.818 kJ/(kg°C).

Any water that evaporates in the dryer will leave the beans at a temperature of 65°C. This means that we need to determine how much heat is required to remove one kilogram of water at this temperature.

From steam tables: at 65°C:

\[
\begin{align*}
\text{heat content of water as a vapour} & = 2,618.3 \text{ kJ/kg} \quad \text{(i.e., } h_v) \\
\text{heat content of water as a liquid} & = 272.06 \text{ kJ/kg} \quad \text{(i.e., } h_c) \\
\text{latent heat of vaporization} & = h_v - h_c \\
& = 2,618.3 \text{ kJ/kg} - 272.06 \text{ kJ/kg} \\
& = 2,346.24 \text{ kJ/kg}
\end{align*}
\]

Therefore, it takes 2,346.24 kJ of heat to vaporize 1 kg of water at 65°C.

Next, we need to know how much water is being removed in the dryer:
Delta T = 61 deg.

65 deg. C

Cp = 3.818 kJ / kg C

mass = 1,000 kg

4 deg. C

**FIGURE 3-1**
THERMOMETER DIAGRAM FOR HEATING OF GREEN BEANS IN CASE STUDY #2

**FIGURE 3-2:**
DIAGRAM OF DRYER FOR WATER REMOVAL FOR CASE STUDY #2
The solids content of the starting material = 100% - 89% moisture = 11%

Solids present in the starting material = \( \frac{1000 \text{ kg}}{1.0 \text{ kg}} \times 0.11 \text{ kg solids} = 110 \text{ kg solids} \)

Water present at start = weight of starting material - weight of dry solids

= 1000 kg - 110 kg solids

= 890 kg water

Since no solids are reported as being lost in the drying process, we can safely assume that:

Weight of dry solids at start = Weight of dry solids in dried product

Let X kg be weight of final product with 12% moisture content. This means there are 88% solids.

0.88 X = weight of solids in final product = 110 kg solids

X = \( \frac{110 \text{ kg solids}}{0.88} \) = 125 kg product

Weight of water in final product = Weight of final product - Weight of dry solids

= 125 kg product - 110 kg solids = 15 kg

Weight of water removed = Weight of water at start - Weight of water in final product

= 890 kg - 15 kg

= 875 kg water
2. Heat to raise temperature of green beans up to drying temperature:

Heat for green beans = mass of green beans x heat capacity x temperature rise

\[ m \cdot C_p \cdot \Delta T \]

\[ = 1,000 \text{ kg} \cdot 3.818 \text{ kJ/kgC} \cdot (65 - 4) \text{ C} \]

\[ = 232,898 \text{ kJ} \]

3. Heat Required to Evaporate Water:

Heat for vaporization = mass of water x latent heat of vaporization

\[ = 875 \text{ kg water} \cdot 2,346 \text{ kJ/kg} \]

\[ = 2,052,750 \text{ kJ} \]

4. Total Heat Requirement:

Total heat required = heat for temperature increase + heat for vaporization

\[ = 232,898 \text{ kJ} + 2,052,750 \text{ kJ} \]

\[ = 2,285,648 \text{ kJ} \]

This mathematical treatment could be streamlined somewhat by combining many of the multiple steps into single steps. However, for the purpose of this example, it is best to show each step.

**CAUTION:** The procedure outlined above provides an indication of how much heat is required to do the actual drying. It assumes that every kilojoule of heat energy goes to the product (i.e., 100% efficiency).

In a “real-world” situation, there would be heat losses to the surroundings and other inefficiencies that must be considered.

Let’s consider a calculation involving the efficiency of the process.
5. Calculation of Heat Use Efficiency:

For this example, let us imagine that 1,250 kg of steam were used to heat the beans and warm the air for drying. The steam pressure was 270 kiloPascals (kPa). Calculate the heat use efficiency of the process.

From steam tables (not taught in this drying course), we find that steam at 270 kPa has a temperature of 130°C. The heat content of the vapour is 2,720.5 kJ / kg and the heat content of the condensate is 546.31 kJ / kg. This means:

\[ h_v = 2,720.5 \text{ kJ/kg} \quad \text{and} \quad h_c = 546.31 \text{ kJ/kg} \]

The heat released when the steam condenses is:

\[ h = h_v - h_c = 2,720.5 \text{ kJ/kg} - 546.31 \text{ kJ/kg} = 2,174.19 \text{ kJ/kg} \]

Heat released from 1,250 kg of steam:

\[ \text{Heat released} = \text{mass of steam} \times \text{heat released per kg steam} \]

\[ = 1,250 \text{ kg} \times 2,174.19 \frac{\text{kJ}}{\text{kg}} \]

\[ = 2,717,737.5 \text{ kJ} \quad (\text{or approximately} \: 2,717,738 \text{ kJ}) \]

Heat Use Efficiency = \( \frac{\text{Theoretical heat requirement}}{\text{Actual amount of heat used}} \times 100\% \)

\[ = \frac{2,285,648 \text{ kJ}}{2,717,738 \text{ kJ}} \times 100\% \]

\[ = 84.1\% \]

Therefore, the process heat use efficiency is approximately 84%, based on these calculations. This may be rather high compared to many drying processes. However, the values used here are for example purposes only.
### 3.6 Practice Problems (with answers)

**Question 1:**

How much heat is required to vaporize 824 kg of water at its boiling point? (Latent heat of vaporization of water = \(2,257.1 \text{ kJ/kg}\)).

**Answer:** 1,859,850 kJ

**Question 2:**

How much heat is required to raise the temperature of 37 kg of tomatoes from 12°C to 65°C and then evaporate 30 kg of water at that temperature?

The \(C_p\) of tomatoes = 3.952 kJ/kg°C. The latent heat of vaporization of water at 65°C is 2,346.24 kJ/kg.

**Answer:** 78,137 kJ (7,750 kJ to heat the tomatoes and 70,387 kJ to evaporate the water).

**Question 3:**

How much water must be removed from 15.0 kg of apple slices to dry them from 84% moisture to 13% moisture? What weight of dried apple slices would you get?

**Answer:** 12.24 kg of water would have to be removed. The final product weight would be 2.76 kg.

**Question 4:**

How much heat must be added to heat the apple slices in Question 3 from 8°C to 100°C and remove the water. This is not recommended since the quality of the apples would be destroyed. However, it does serve as a sample calculation.

\(C_p\) for apples = 3.651 kJ/kg°C

Latent heat of vaporization for water at 100°C = 2,257.1 kJ/kg

**Answer:** 32,665.3 kJ

**Question 5:**

If we added exactly the same amount of heat to exactly the same weights of fresh green peas \((C_p = 3.316 \text{ kJ/kg°C})\) and beets \((C_p = 3.785 \text{ kJ/kg°C})\), which would have the higher final temperature?

**Answer:** Since the peas have the lower specific heat capacity, it takes less heat to raise the temperature of 1.0 kg by 1 degree on the Celsius scale. This means that we would get a bigger temperature increase with the peas if we added the same amount of heat to the same weight as we did to the beets.

**Proof:** For example purposes, consider 1 kg of beets and peas at 20°C. Add 100 kJ of heat to each sample and calculate the final temperature. From the equation \(Q = m \cdot C_p \cdot \Delta T\), we can find that \(\Delta T = Q / m \cdot C_p\). Substituting the values for peas and beets, the \(\Delta T\) for the peas is 30.2 Celsius degrees, and the \(\Delta T\) for the beets is 26.4 Celsius degrees. The final temperatures would be 50.2°C for the peas and 46.4°C for the beets.
CHAPTER 4: DRYING MECHANISMS

4.1 Heat Transfer Mechanisms

There are three basic methods by which heat can be transferred from one material to another, or through materials. These are:

- Conduction
- Convection
- Radiation

We will briefly explain each of these in terms of everyday events and occurrences. Then we will examine the role they have to play in drying.

Conduction is a method of heat transfer that is very familiar to most of us. Some of you may have had the misfortune to grasp one end of a metal rod that was sticking out of a fire. Heat from the fire would be conducted through the metal rod and you could suffer a serious burn if you were to pick it up without protecting your hand somehow.

As an additional example, have you ever used your bare hand to pick up a pot with a metal handle? If the pot was just sitting on a shelf, there is no problem; but if the pot was on a stove and is full of boiling water, you would probably have felt tremendous discomfort, or even burned your hand. You can easily visualize the process by which heat from the hot stove was transferred to the metal pot and then was transferred into the metal handle. When you grasped the hot handle of the pot, the heat was transferred to your hand. This process is known as “conduction”.

With conduction, heat is transferred from one particle or material to another particle or material that is touching it. The first particle heats up and then begins to pass heat to other particles that are touching it. These particles, in turn, pass heat to other particles that are touching them, and eventually heat is distributed throughout the entire mass of the material that is being heated.

Continuing with our examination of the pot on the stove, let’s look inside the pot at the water that it contains. When the pot was put on the stove, the metal bottom of the pot became hot, and this heat was then conducted through the metal. Water that was in contact with the metal bottom of the pot became heated through conduction. However, when this water was heated, it began to circulate in the pot and during its circulation, it transferred some of its heat to other water molecules in the pot. As the water circulated through convection, more and more water molecules contacted the bottom of the pot where they picked up heat and then transferred this heat to other water molecules as they continued to circulate or flow around in the pot. This heat transfer process is called “convective heat transfer” and involves the motion of fluids such as liquids or gases. Most often these fluids are water and air.

Radiation is the third method of heat transfer. If we were to take a block of steel and place it in a fire, it would become heated through the process of conduction. If we were to then remove
the block of metal from the fire and place it safely on a stand, it would emit heat to the air around it through the process of radiation. Many homes are heated by means of radiant heating devices. In some cases, hot water is pumped through pipes which radiate their heat to the air and warm the home. In other cases, hot water in pipes transfers its heat by conduction to metal “radiators” or concrete slabs which then radiate the heat to the air in the home.

All three of these heating mechanisms may have a role to play in drying, especially in the case where air is used as the drying medium.

Let us consider for example purposes a food dryer that uses hot air as the heating medium. The air can be heated by passing it through flames from a natural gas burner or by passing it over metal surfaces heated internally by steam. When using steam pipes to heat the air, the heat is radiated from the hot metal pipes and is picked up by the air passing these radiating surfaces. Heat is then distributed through the air by convection.

As the hot air comes into contact with the product to be dried, heat is transferred to the surface of the food material and is then transferred by conduction to the inner portions of the material. As it travels to the centre of the food material, the heat warms both the solids and water that are present. In addition, the heat evaporates water from the surface of the food and reduces its overall moisture content in the drying process.

In some drying process, the product is heated by contacting a hot metal surface, as in the case of drum drying, which we will discuss later. Heat is transferred by conduction from the hot metal surface to the food material and then is conducted through the food material. In this case, convection and radiation are not active heat transfer mechanisms.

While these are extremely oversimplified explanations of the drying process, they do illustrate the heat transfer mechanisms involved.
4.2 Stages of Drying

In the preceding section, we examined how heat may be transferred in a drying process. Now, we will look at the actual removal of water from the material being dried. In doing so, we will assume that we have sufficient heat delivery and air circulation in the dryer to adequately dry our product.

Once again, let's focus our discussion on the use of heated air to dry a product. We may wish to consider a product like sliced tomatoes that are positioned on a wire mesh with hot air blowing upwards or downwards through the mesh to dry the tomatoes.

When a wet or moist product (such as our tomato slices) is introduced into a drying operation, there are generally three distinct phases involved in the drying process.

At first, the product may go through a **warm-up period**. Typically, a product will enter a dryer at ambient (i.e., room temperature or the temperature of the surroundings) or perhaps at a chilled temperature. It will then need to be heated to a temperature at which evaporation of the moisture from the product can begin. The duration of this period is highly variable and depends on a number of factors including the moisture content of the product and the product's specific heat capacity. In most cases, it is relatively short, lasting only a few minutes. Conditions within the dryer also play a key role in determining the warm-up period.

The second stage is the **constant rate period**. During this period, drying proceeds by loss of water vapour from the saturated surface of the material into the surrounding air. To visualize this, consider that there is a "pool" of water on the surface of the material being dried. As the moisture at the surface is removed from this pool, moisture from within the material travels to the surface to maintain the saturated state there. This period of drying is controlled by the rate of heat transfer to the surface of the material being dried. If drying conditions remain uniform, the rate at which the water is removed will remain constant, hence the term, **constant rate period**. The mechanism of drying here is very similar to evaporation from a body of water and does not really depend on the properties of the material being dried. It is essentially a surface phenomenon. Because of the evaporation at the surface, the temperature of the material being dried remains relatively constant throughout this period.

A point will be reached during the drying process when the surface is no longer saturated. There is no longer a "pool" or layer of moisture at the surface of the material. The drying mechanism now enters the **falling rate period**. There can actually be two zones of drying within this period. The first "zone" of drying begins after the constant rate period ends and moisture continues to diffuse from the inside of the material to its surface. However, the rate of diffusion is not sufficient to maintain saturated conditions at the surface. As moisture continues to be removed during this **unsaturated surface drying**, the rate of moisture removal slows or "falls". Eventually, the rate of evaporation exceeds the rate of diffusion and water can no longer diffuse to the surface rapidly enough to keep the zone of drying at the material surface. The drying front then moves inwards towards the centre of the material; this then becomes the **internal moisture**
movement control zone. During this time, capillary action and diffusion are the controlling forces. Because the moisture front is moving into the material being dried, the material will begin to heat up.

While we are restricting our focus on drying to water removal, we should be mindful of the fact that other liquids such as organic solvents may require removal by drying. However, these are special cases and will not be discussed here.

In drying of any food product, it is absolutely essential to understand the drying mechanism in order to match the drying conditions to the appropriate drying period. Failure to recognize the periods of drying can have disastrous results. From another perspective, a thorough understanding of the drying mechanism can allow the processor to enhance the drying of a product to maintain quality and product functionality. Gaining the required understanding of a product cannot be done solely through testing on a laboratory bench or in small scale processes. Often the only way to determine the manner in which to dry a particular product is to do actual large-scale trials. Many dryer manufacturers offer such services to clients prior to the design and purchase of a production scale dryer for their processing facility.

Figure 4-1 shows how the dry basis moisture of a product may change during a typical drying process. From Point A to Point B, the product and the moisture it contains are warming up. There may be little or no moisture loss during this period. The portion of the curve between points B and C is linear which means that the rate of drying is uniform over this "constant rate" period. Here, moisture is being removed from the saturated surface of the product. Once the surface is no longer saturated, the rate of water removal slows down as diffusion of water from the inside of the product to the surface begins to control the rate of drying. This portion of the curve in Figure 4-1 from Point C to Point D is referred to as the "falling rate" period. Note that the slope is decreasing at positions along the curve from Point C to Point D.
Figure 4-2 shows the moisture content expressed on a dry basis and plotted against time for a sample of tomato slices. This graph is based on drying trials conducted using a laboratory-scale dryer. The shape of this curve is quite useful in determining the actual drying mechanism of the tomatoes under the conditions to which they were subjected in the dryer. Notice that there is no warm-up period. It appears that as soon as the tomatoes were placed in the dryer, they began losing moisture. For approximately the first three hours of drying, the curve in Figure 4-2 is quite linear, indicating that moisture is being lost by the tomatoes at a relatively constant rate. After the constant rate drying period has ended, the rate of moisture removal begins to decrease or “fall” which is from a time of three hours onwards in Figure 4-2. During the final stages of drying, there is less and less removable moisture left in the tomatoes and the rate of water removal slows noticeably. Ultimately, water removal ceases altogether as indicated by the horizontal portion of the curve after about 14 hours of drying.
4.3 Critical Moisture Content

The critical moisture content of a material is the moisture content at which the drying mechanism changes from the constant rate drying period to the falling rate drying period. This is where the surface of the material is no longer saturated with moisture and diffusion of moisture from inside the material to the surface begins to control the rate of drying.

The critical moisture content of a food material is generally difficult to predict. Most often, it needs to be determined by experimental means. The importance of the critical moisture level should not be underestimated. As the name implies, this is a “critical” piece of information in designing a drying process and in optimizing the quality of the finished product.

If we agree that the constant rate drying period for the tomatoes in Figure 4-2 ends at approximately 3 hours into the drying run, the dry basis moisture at this point will be about 7 g of water per gram of dry solids, which corresponds to a wet basis moisture of approximately 87.5%. This, in turn, would give us an estimate of the critical moisture content of these tomatoes under the drying conditions used in this test.

Once the water content of the food material falls below its critical value, and diffusion of water to the surface becomes the controlling factor, the food material will begin to heat up. If excessive heat is applied, the product will become heated to the point where nutrients will be damaged and quality attributes such as flavour, colour, texture, structure, and functionality may be affected in a negative manner.

If the critical moisture content of the product is known, then care can be taken to alter the drying conditions once the surface drying during the constant drying rate period has ended. By lowering the drying temperature, thermal damage to the product can be reduced appreciably.

We will examine the critical moisture content in a case study in Chapter 5 (Drying Curves).

4.4 Calculation of Water Removal Rates

There is really no way to reliably determine how fast water is removed from a material during drying other than to do a series of actual drying tests. These tests may be done in small bench-scale dryers or larger laboratory-scale or pilot-scale dryers. Regardless of the size of dryer used, care must be taken when you consider increasing the size of the dryer to a commercial production-scale dryer.

In spite of this limitation, small-scale tests are very important in gaining the knowledge necessary to design a dryer or to set up a drying process on an existing commercial dryer. One obvious advantage of a bench-top dryer over a large commercial dryer is the amount of material used for the drying tests. Compare the waste material generated from a dryer that uses several kilograms of product per test run to one that may use several thousand kilograms per trial run. In addition, small-scale dryers offer increased control of drying conditions over their large-scale counterparts.

The actual drying tests are not overly complicated. If you are using a small bench-top dryer, you establish the air temperatures and flowrates that you wish...
to have over the course of the drying trial. Once you have the dryer operating at the desired initial conditions, you then place an accurately weighed sample of known moisture in the dryer and record its weight at regular intervals during the drying test run. Some test dryers are equipped with apparatus to monitor the weight of the sample inside the dryer without removing it. In other dryers, you may have to remove a tray on which the material is placed and weigh the combined tray and product weight over the course of the test run. Since the weight of the tray is constant, any weight differences can be attributed to a loss in moisture from the product being dried. The problem with this approach is that removing the material from the dryer at regular intervals can disrupt its rate of water loss and give incorrect test results. Opening the dryer can also upset conditions within the dryer and alter the drying process. For these reasons, it is best to equip the dryer with a method for obtaining product weights during the entire drying trial without having to open the dryer. This can be done by suspending the tray of materials from a balance mounted on top of the dryer.

By plotting the dry basis moisture content of the product (grams of water per gram of dry solids) versus its time in the dryer, a curve can be obtained that shows how rapidly water was removed over time. By taking the slope of this curve at various points, the water removal rate, usually expressed in grams of water per gram of dry solids per minute can be determined. It should also be evident as to when the constant rate drying period and falling rate drying period occur.

The use of a computer spreadsheet program will assist greatly in doing the required calculations and in preparing the graphs you wish to obtain.

It is somewhat difficult and confusing to try to describe what is happening without the use of an actual example. Since this is an important topic that involves the use of a series of drying curves, a complete module has been devoted to it. In Chapter 5, a case study is presented to illustrate the concepts involved.