INTERMEDIATE COURSE IN FOOD DEHYDRATION AND DRYING

CHAPTER 5: DRYING CURVES

5.1 Introduction

We have now familiarized ourselves with a number of aspects involved in the drying of food products. We have examined the basics of drying, wet and dry basis moistures, drying mechanisms, and the thermal properties of food materials being dried. Using this knowledge, we have performed calculations of the amount of heat that would be required to dry a specific weight of product under a given set of drying conditions.

Before we proceed to look at the various types of dryers that are available, I would like to examine methods of handling information obtained from drying tests. This information will provide you with an understanding of how a material dries and will assist you in determining how you might want to approach the commercial scale drying of that material. Once the information from a drying test run has been gathered, it can be organized and used to compile a series of graphs which we refer to as “drying curves”.

Drying curves are very useful in understanding the “kinetics” of how a particular product dries under a specific set of conditions. Basically what this means is that you will know how the drying process changes over the time the material is being dried. Very wet product will certainly dry differently than the same material when it has a lower water content. Drying curves will alert you to the changes that are taking place and will allow you to adjust the drying process accordingly.

A personal observation that I have made in the field of food product drying is that most dryer operators want to treat the product as if it were something like wet chunks of broken stone, or some other equally as indestructible material. They fail to realize that most food products are rather delicate and require a great deal of care when reducing their moisture content. These operators use the approach that all you have to do is get as much heat into the product as rapidly as possible and you can keep pushing product through the dryer. The result of this fallacy is that they end up with product toasted or burnt on the outside and wet in the middle. However, the average moisture most frequently meets their target specifications.

Keep in mind that you cannot speed up the drying process of many food products without doing serious harm to their quality and appearance. Knowing how your product responds to the input of heat over the course of the drying process is critical for achieving the desired quality and finished product performance.

5.2 What Are Drying Curves?

Drying curves are generally graphs of the moisture of a food product versus time, or plots of the rate of water removal versus time. However, there are some ways of manipulating the drying information which you have that are more informative and enlightening than others.

Perhaps the best way to study this topic is through the use of a Case Study.

5.3 Case Study #3: Drying Curve Exercise

5.3.1 Drying Scenario

A food processor wanted to dry apple slices for use in a snack product. Fearing that improper drying of the apple slices in an actual production dryer would result in large amounts of wasted product, the processor decided to do a some small pilot-scale or bench-scale tests.

For these tests, a small cabinet dryer was used as shown in Figure 5-1. Cabinet dryers offer a great degree of flexibility and require only a small amount of product.

After a few failed attempts, the processor finally obtained the desired quality in the dried apple slices. Data from the successful pilot-scale run were then analysed to determine how the product was behaving under these drying conditions.

It should be noted here that by using only small amounts of the apple slices in the small cabinet dryer rather than doing the tests on a large production-scale dryer, a great deal of expense was avoided. The large dryers require much greater quantities of raw materials and a large amounts of waste product can be produced while trying to identify the best drying conditions.

When doing drying tests such as these, you may often learn more from your “failures” than you do from your “successes”. In designing a set of test runs, you may need to push the limits of your drying to determine the conditions under which the final dried product fails to meet your finished product specifications. By knowing the drying conditions under which your tests fail, you can set up a dryer operating strategy that avoids these undesirable conditions and stays within what you consider to be a safe range of drying conditions.

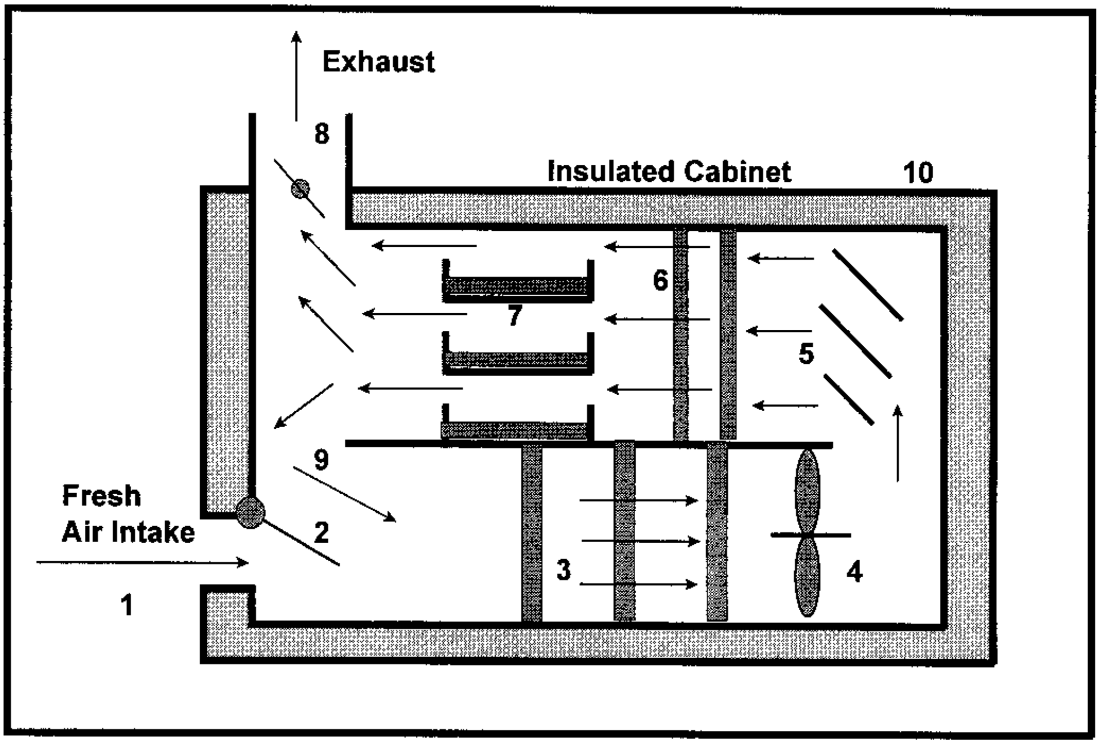


FIGURE 5-1: SCHEMATIC SIDE VIEW OF A CABINET DRYER

1. Fresh air enters cabinet dryer
2. Adjustable damper allows fresh air and recirculated air to be balanced
3. Heaters warm the air stream to the desired temperature
4. Adjustable fan conveys air and controls volumetric air flowrate
5. Air distribution plates "even out" flow pattern of air
6. Screens "filter" particulates from air and create back-pressure
7. Product is contained in trays with heated air passing over them
8. Air is exhausted from cabinet dryer after removing moisture from product
9. Heated air with some drying capacity may be recirculated
10. Cabinet is insulated to prevent excessive heat loss.

Arrows in schematic diagram indicate air flow

5.3.2 Dryer Operating Data

We will only concern ourselves here with a portion of the data obtained. We will not worry about air velocities and relative humidities etc.

In our exercise, 450 g of apple slices with an initial moisture content of 84.4% (wet basis) were placed in the dryer .

The air was heated to 65°C in the dryer and then blown through the drying chamber containing the apple slices. The apple slices were placed on a small wire mesh rack suspended from a balance mounted on top of the dryer for weighing the sample. The weight of the wire mesh rack was determined to be 85 grams before the apple slices were placed on it.

The weight of the apple slices and the wire mesh rack were recorded every 15 minutes throughout the course of the trial. By subtracting the weight of the rack (85 g) from the total weight, the weight of the apple slices could be found. In addition, the temperature of the exit air leaving the dryer was recorded. This information is presented in Table 5-1. I have personally done numerous test runs with different types of small dryers (including solar dryers which take the energy of the sun as their heat source) and have used this basic approach each time.

Table 5-1: Drying Data for Apple Case Study

Time (minutes)	Exit Air Temperature (°C)	Weight of Apple Slices + Tray (grams)	Weight of Apple Slices (grams)
0	—	535	450
15	51	513	428
30	51	487	402
45	51.5	460	375
60	51	433	348
75	51.5	407	322
90	52	380	295
105	52	354	269
120	53	328	243
135	54.5	305	220
150	56	285	200
165	58.5	266	181
180	59.5	251	166
195	60.5	237	152
210	61	225	140
225	62	214	129
240	62.5	205	120
255	63	195	110
270	63.5	187	102
285	63.5	179	94
300	64	174	89
315	64	169	84
330	64	165	80
345	64	163	78
360	64	160	75
375	64	159	74
390	64	158	73
405	64	158	73
420	64	158	73

5.3.3 Working with the Data

One of the first things that you may want to do with the raw data in Table 5-1 is prepare plots to show how the weight of the apple slices changes over time and how the temperature of the exit air changes over the same time period. These plots are presented as Figures 5-2 and 5-3, respectively.

From Figure 5-2, we can see that there is not a great deal of scatter in the data and that the shape of the curve of weight versus time follows a trend that we would typically expect to see. We also see that the weight of the dried apple slices "levels off" at about 73 grams. In spite of additional exposure to drying conditions, its weight does not change. In addition, it is evident that the weight of the apple slices decreases at a relatively uniform or constant rate during the first 120 minutes to 150 minutes (i.e., 2 to 2.5 hours) of the test run. After this, the line in Figure 5-2 begins to decrease its slope. This observation will become significant as we examine the data more thoroughly. Right now, we should suspect that there is something causing a change in the rate of drying at a time around 120 minutes.

Figure 5-3 shows us that the temperature of the exit air increases over time. We can compare this to the weight change due to moisture loss in Figure 5-2. It appears as if the temperature of the air is increasing as more and more of the water in the apple slices is removed. Once the apple slices stop losing weight, the exit air temperature remains constant at 64°C. This is not surprising, since the temperature of the air going into the dryer is being controlled at 65°C and there is usually some small loss of heat through the walls of the dryer, even though they are insulated. Once again, we notice that there is something happening in our dryer at approximately the 120 minute mark of our test run. From the start of the test until 120 minutes, the exit air temperature is relatively low, being about 51°C to 52°C prior to this time. After 120 minutes, the air temperature begins to rise. We will come back to this observation shortly.

For the food processor, the first manipulation that could be performed on the data would be to determine the moisture content of the apple slices from the weight data gathered during the trial run. We know that we have 450 grams of apple slices at the start with 84.4% moisture. This translates to a solids content of 70.2 grams, and a moisture content of 379.2 grams at the start of the drying test. As the drying proceeds, the weight of solids will remain constant, assuming no losses due to such things as air blowing pieces away etc. The only thing that will change is the weight of the water.

As stated previously, the weight of the apple slices can be found at each sampling time by subtracting the weight of the wire mesh tray (85 grams) from the combined tray and apple slice weights which were taken at 15 minute intervals. Table 5-2 shows the data used for Figures 5-2 through 5-7 inclusive. An explanation of how the various values were calculated is included for clarity and understanding of the procedures involved. Spreadsheet programs are ideal for organizing raw data and calculating derived data as shown here.

FIGURE 5-2:
WEIGHT OF APPLE vs TIME

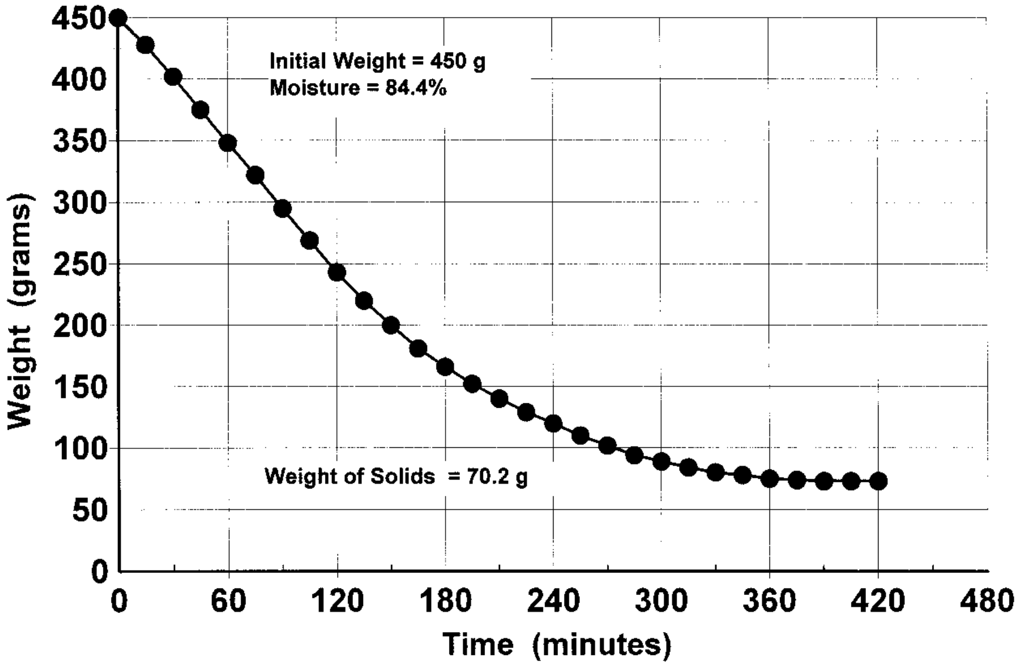


FIGURE 5-3:
EXIT AIR TEMPERATURE vs TIME

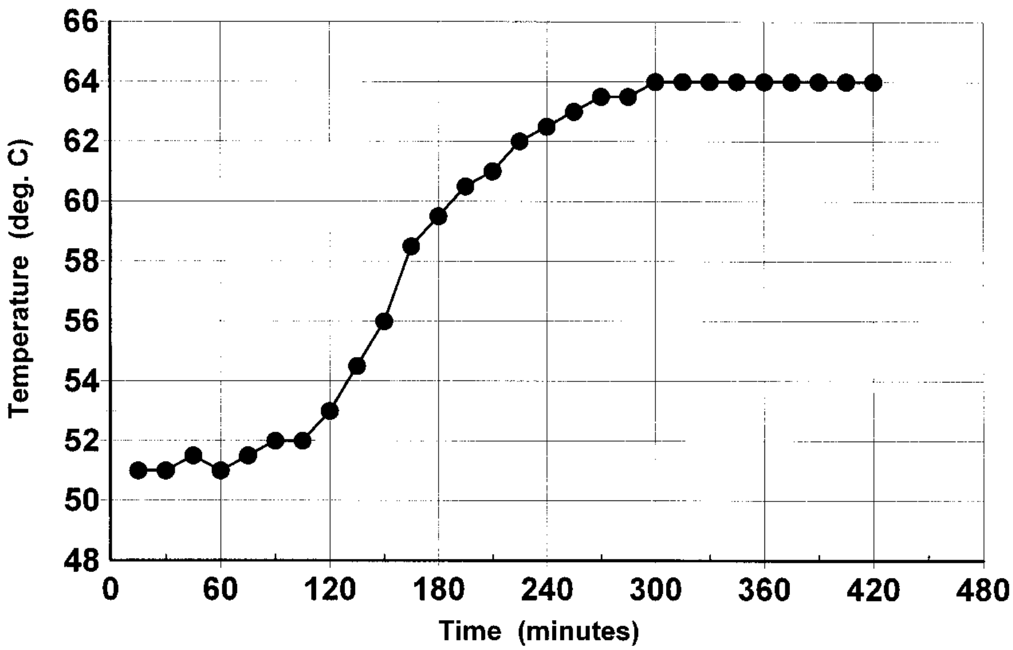


TABLE 5-2: APPLE DRYING CASE STUDY - VALUES USED IN GRAPHS

Time (min)	Exit Air Temp (°C)	Apple Slice Weight (g)	Solids Weight (g)	Moisture Weight (g)	Wet Basis Moisture (%)	Dry Basis Moisture (g H_2O/g solids)	Water Removed (g)	Water Removal Rate (g/g solids/min)
0		450	70.2	379.8	84.4	5.41		
15	51	428	70.2	357.8	83.6	5.10	22	0.0209
30	51	402	70.2	331.8	82.5	4.73	48	0.0247
45	51.5	375	70.2	304.8	81.3	4.34	75	0.0256
60	51	348	70.2	277.8	79.8	3.96	102	0.0256
75	51.5	322	70.2	251.8	78.2	3.59	128	0.0247
90	52	295	70.2	224.8	76.2	3.20	155	0.0256
105	52	269	70.2	198.8	73.9	2.83	181	0.0247
120	53	243	70.2	172.8	71.1	2.46	207	0.0247
135	54.5	220	70.2	149.8	68.1	2.13	230	0.0218
150	56	200	70.2	129.8	64.9	1.85	250	0.0190
165	58.5	181	70.2	110.8	61.2	1.58	269	0.0180
180	59.5	166	70.2	95.8	57.7	1.36	284	0.0142
195	60.5	152	70.2	81.8	53.8	1.17	298	0.0133
210	61	140	70.2	69.8	49.9	0.99	310	0.0114
225	62	129	70.2	58.8	45.6	0.84	321	0.0104
240	62.5	120	70.2	49.8	41.5	0.71	330	0.0085
255	63	110	70.2	39.8	36.2	0.57	340	0.0095
270	63.5	102	70.2	31.8	31.2	0.45	348	0.0076
285	63.5	94	70.2	23.8	25.3	0.34	356	0.0076
300	64	89	70.2	18.8	21.1	0.27	361	0.0047
315	64	84	70.2	13.8	16.4	0.20	366	0.0047
330	64	80	70.2	9.8	12.2	0.14	370	0.0038
345	64	78	70.2	7.8	10.0	0.11	372	0.0019
360	64	75	70.2	4.8	6.4	0.07	375	0.0028
375	64	74	70.2	3.8	5.1	0.05	376	0.0009
390	64	73	70.2	2.8	3.8	0.04	377	0.0009
405	64	73	70.2	2.8	3.8	0.04	377	0.0000
420	64	73	70.2	2.8	3.8	0.04	377	0.0000

By definition, the **Wet Basis Moisture** of a product is:

$$\frac{\text{Weight of water}}{\text{Total weight of material}} \times 100\%$$

Dividing the weight of water in the apple slices at each sampling time by the weight of the wet apple slices at that time will give us the wet basis moisture.

We can find the weight of water present in the apple slices at each sampling point by subtracting the weight of solids (i.e., 70.2 grams) from the total weight of the sample at that time.

Wet basis moistures are plotted against time in Figure 5-4. However, there is nothing that really stands out and grabs our attention in this graph.

Even though we have calculated the wet basis moisture, it is the dry basis moisture which tends to be more informative.

By definition, the **Dry Basis Moisture** of a product is:

$$\frac{\text{Weight of water}}{\text{Weight of dry solids present}}$$

= grams water / gram dry solid
(or other appropriate weight units)

We have already determined the weight of water present in the apples at each 15 minute interval. We can divide it by the weight of solids (i.e., 70.2 grams) present in the sample at that time to get the dry basis moisture.

Dry basis moistures are plotted against time in Figure 5-5.

Figure 5-5 is remarkably similar in shape to Figure 5-2. This is due to the fact that they are both based on a constant weight of dry solids. We can observe the same trends in Figure 5-5 as we did in Figure 5-2 with respect to the slope of the curve being constant or linear up until about 120 to 150 minutes in the trial run and then becoming less and less as time goes on after that.

The most revealing information for the processor will be obtained by determining how fast the water is removed from the apple as the drying progresses. To determine the rate of water removal, we could take the slope of tangents to the curve of dry basis moisture versus time (Figure 5-5), or we could use the raw data and do some calculations.

The dimensions associated with the rate of water removal will be:

> "grams of water per gram of dry material per minute"

Other appropriate dimensions of weight and time could also be used.

To calculate the water removal rate from the observed data, we will first determine how much water is removed in each 15 minute period between sample weighings. For example, 22 grams of water were calculated to have been removed during the first 15 minutes of the drying process. Dividing this value by the number of grams of solids present (i.e., 70.2 g) as well as the number of minutes that it took to remove this amount of water (i.e., 15 minutes), will give the following:

FIGURE 5-4:
WET BASIS MOISTURE vs TIME

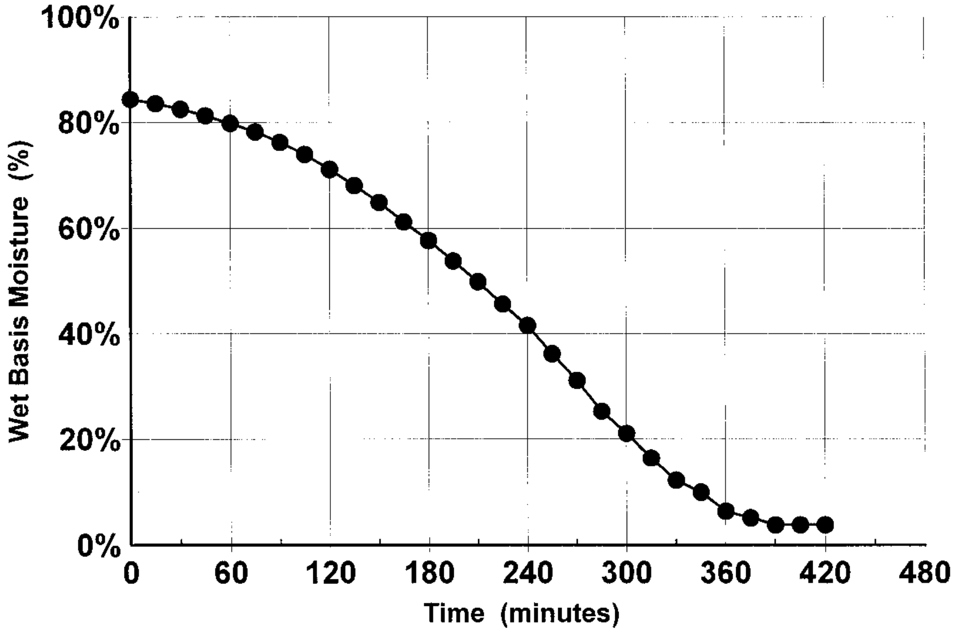
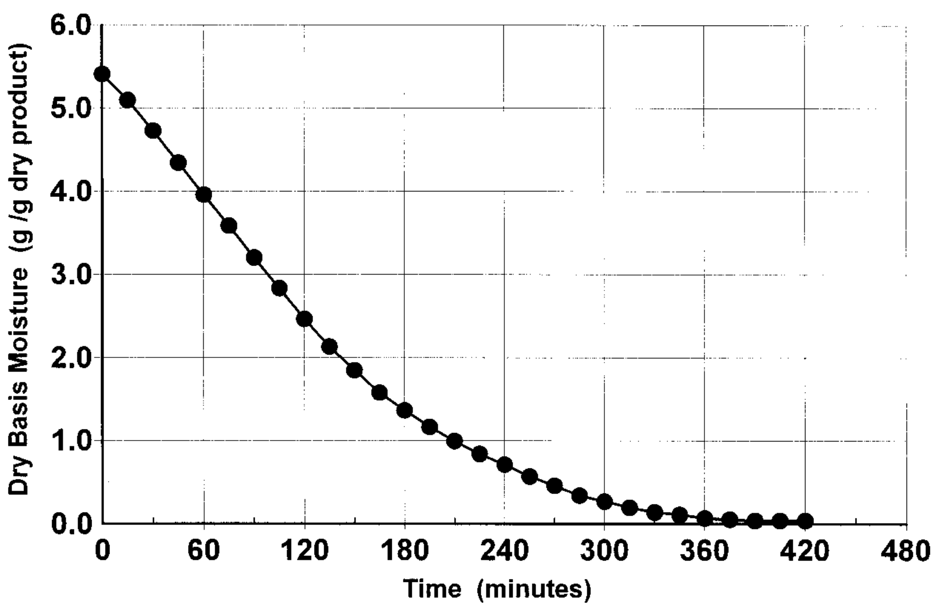


FIGURE 5-5:
DRY BASIS MOISTURE vs TIME



Water removal rate =

$$\frac{22 \text{ g water removed}}{} \left| \frac{}{70.2 \text{ g solids}} \right| \frac{}{15 \text{ min}}$$

= 0.0209 g water / g solid / minute

or: 0.0209 grams of water are removed from each gram of dry solid material per minute

In the time interval from 15 minutes to 30 minutes, an additional 26 grams of water were removed (i.e., 48 g water loss at 30 minutes minus the 22 gram water loss at 15 minutes). Dividing this water loss by the weight of dry solids and the 15 minutes time that it took to evaporate the 26 grams of water gives us a water removal rate of 0.0247 grams of water removed per gram of dry solids per minute.

A plot of "Water Removal Rate vs Time" appears as Figure 5-6.

From Figure 5-6, we can see that the rate of water removal remains relatively constant for the first 120 minutes or so. This corresponds to the **constant rate** drying period where the water that is evaporating is on the surface of the product or is just at the surface in crevices and larger capillaries in the product (i.e., free water).

The water removal rate then begins to decrease or "fall" until it levels off at about 375 minutes. Drying from about 120 minutes to about 375 minutes is in the **falling rate** drying period. Here, water is being brought to the surface through the pores and capillaries in the product. Some of this water is physically trapped in the product capillaries while other water is loosely bound by the product. In either case, it takes time for this moisture to work its way to the surface of the apple, where it can then be removed by the drying air. During the falling rate period, the rate at which water is removed follows a gently decreasing slope downwards and to the right in Figure 5-6. This shows how diffusion of moisture to the surface of the apple slices is becoming more and more controlling in the drying process.

Finally, all of the free water, loosely bound water, and physically trapped water is removed from the apple slices. At this stage, only the more tightly bound water in the water "monolayer" is left. Since it is tightly bound, it will not be removed by the gentle drying conditions to which the apple is exposed. A vacuum oven and much higher temperatures are required to remove it, as would be done in a moisture determination test.

The moisture of the product at the point at which the drying mechanism changes from the constant rate drying period to the falling rate period is known as the **critical moisture content**. In Figure 5-6, we can clearly see that the water removal rate changes from a relatively constant value of approximately 0.025 grams of water per gram of dry solids per minute to continuously decreasing lower values after 120 minutes of drying. From Figure 5-4, we can estimate that the moisture content of the apple slices 120 minutes into the drying test was just over 70% on a wet basis. From Figure 5-3, we can see that the dry basis moisture content was about 2.5 grams of water per gram of dry solids.

FIGURE 5-6:
WATER REMOVAL RATE vs TIME

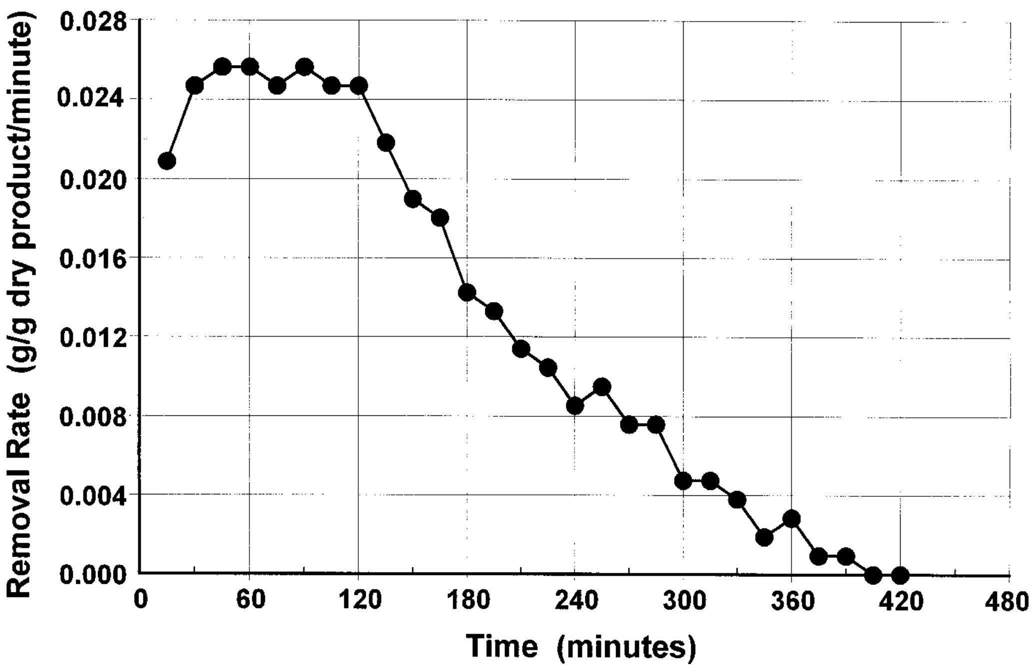
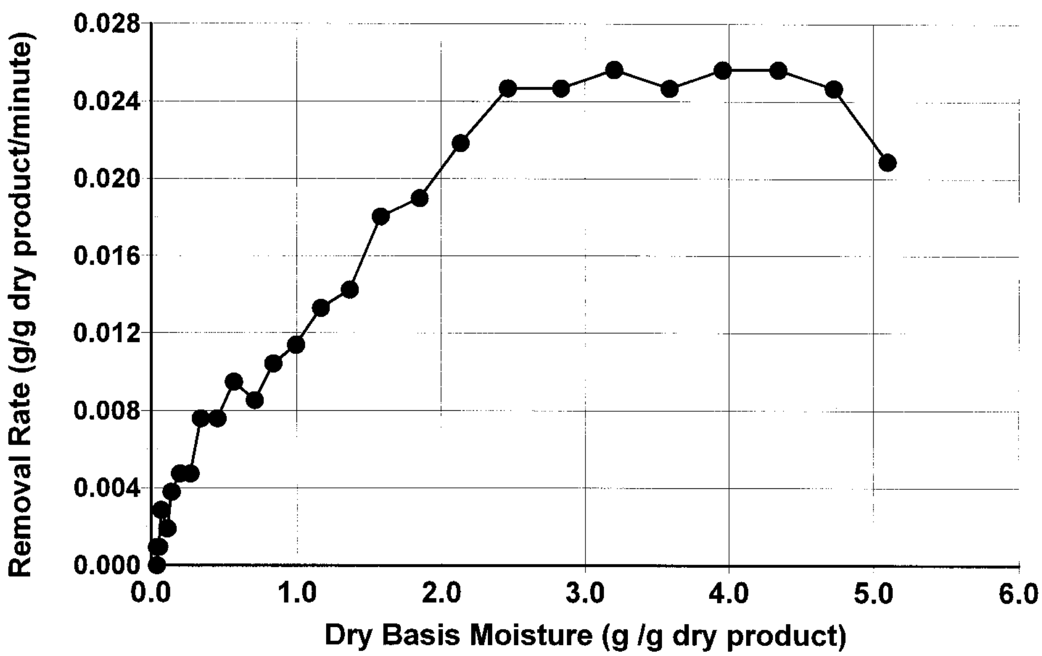


FIGURE 5-7: WATER REMOVAL RATE
vs DRY BASIS MOISTURE



The change from constant rate drying to falling rate drying was what gave us the temperature change in the air leaving the dryer as shown in Figure 5-3. Since evaporation of water was not as rapid after the constant rate drying period ended, there was not as much evaporative cooling of the air in the dryer because not as much heat was required per unit time to remove the moisture from the product. This change in the drying mechanism is also what is responsible for the change in the rate of weight change noticed in Figure 5-2. You can see how the slope of the curve in Figure 5-2 changes at approximately 120 minutes of drying time, which is when we have the change to the falling rate drying period from the constant rate drying period.

In Figure 5-7, we have plotted the water removal rate against the dry basis moisture of the product. This is an interesting, although at times somewhat confusing curve. The easiest way to read it is to start at the right side and work your way towards the left. In this way, we can see that when the water content is at its highest, the water removal rate is constant. At a certain point (i.e., about 2.4 or 2.5 g water per g dry product) the water removal rate begins to fall. It drops until the moisture content is extremely low. This clearly shows us the **critical moisture content** as a dry basis moisture value.

In summary, Figure 5-6 and Figure 5-7 are the two drying curves that allow us to most clearly understand the apple drying operation. From Figure 5-6, we can see that after 120 minutes drying shifts from its constant rate period to its falling rate period. From Figure 5-7, we can tell that the constant rate period ends when the moisture content of the apple slices hits about 2.5 g water per g dry product.

We then know that during the initial 120 minutes of drying, water removal is primarily from the surface of the apple slices. However, after 120 minutes, moisture is being pulled from inside the apple slices. If we heat the apple too harshly during the falling rate period, the apple material could be damaged severely. Therefore, we must tailor our drying process to address the drying mechanism that is occurring within the apple itself. This could be done with a multiple zone continuous belt dryer that has higher temperatures in the first zone and lower temperatures in subsequent zones (more on this later). We could also design a dryer that had different zone lengths to accommodate the various drying periods.

We can see in Table 5-2, that the water content of the apple slices at 120 minutes was 71.1% wet basis moisture or 2.46 grams of water per gram of dry solids dry basis moisture.

Therefore, in our drying work, we would need to be aware of the critical moisture content of the apple slices being about 71% wet basis moisture and we would have to control our drying and the application of heat accordingly.

From Figures 5-4 , 5-5, and 5-6, we can also see that drying the product beyond 375 or 390 minutes will not give us any additional advantages. Therefore, we could stop the drying process at this point. Figures 5-4 and 5-5 show no change in the wet or dry basis moisture content of the apples after this time; and Figure 5-6 indicates that the water removal rate is essentially “zero” beyond this time.

5.4 Caveats in Scaling up

BEWARE: Every caution must be taken in “scaling up” the apple dryer based on the data generated in the cabinet dryer tests.

Even though tests have been done to determine the drying characteristics of the product being dried, there are other factors that play a major role in drying. Many of these factors can change as you scale up a dryer from a small unit to a larger size.

The following factors must be considered:

- bed loading characteristics
  - thickness
  - uniformity
  - permeability
  - changes during drying
  - throughput rates
  - etc.

- air distribution patterns

- product attributes
  - uniformity
  - seasonal variation
  - apple varietal differences
  - etc.

Once the conditions from the cabinet dryer have been established that best meet the needs of the processor, expanded testing should be considered before committing to a larger dryer. Such tests might be done on a small-scale belt dryer at a dryer manufacturer’s testing facility. The dryer manufacturer would then be able to offer advice on the final scale-up to a production-scale unit.

Do not think that just because you know how your product behaves in a small dryer that you will know how it behaves in a larger dryer. If you do fall into this trap, you may be setting yourself up for a nasty or unpleasant surprise later when you attempt to go into commercial production.

5.5 Practice Problems (with answers)

Question 1:

If a sample contains 10.5 grams of water per gram of dry solids at the start of a drying process and after 3 hours of drying, its moisture content is down to 2.7 grams of water per gram of dry solids, what is its rate of water loss? Express your answer in units of grams of water per gram of dry solids per minute.

Answer: 0.043 grams of water per gram of dry solids per minute.

Question 2:

A sample of apple starts out at 84% moisture. Two hours later its moisture is 75%. What is the rate of moisture removal? Express your answer in units of grams of water per gram of dry solids per minute and grams of water per gram of dry solids per hour.

Answer: 0.0188 grams of water per gram of dry solids per minute; or 1.125 grams of water per gram of dry solids per hour.

Be sure to convert the percent moistures to a dry basis as the first steps in your calculations. Then take the differences in the water content and divide by the time in the appropriate units.

Question 3:

2.5 kg of tomatoes with a moisture content of 93% by weight are dried in the sun. After 6 hours, they weigh 0.70 kg. What is the final moisture content on a wet basis, and on a dry basis? How fast was the moisture removed ? Express the answer to the last part of the question as "grams of water per gram of dry solids per hour".

Answer: After six hours, the wet basis moisture content = 75%, and the dry basis moisture content = 3.0 g water per gram of dry solids.

Water removal rates:
0.0286 grams of water per gram of dry solids per minute or 1.714 grams of water per gram of dry solids per hour.

In your calculations, you need to determine the weights of solids and water at the start of the drying (0.175 kg solids and 2.325 kg water). After drying, 0.175 kg of solids would still be present. Of the 0.70 kg of dried tomatoes, 0.525 kg would be water (i.e., 0.70 kg - weight of the dry solids). The percent moisture on a wet basis would be the weight of the water (i.e., 0.525 kg) divided by the total weight (i.e., 0.70 kg) times 100%. For the water removal rates, you remove 1.800 kg of water (i.e., weight of water at the start - weight of water at the end) from 0.175 kg of solids in 6 hours.

CHAPTER 6: TYPES OF DRYERS

6.1 Introduction:

Drying is an incredibly diverse activity covering a wide variety of applications and products. As a result, many different types of dryers are now available for food processing and other applications. In addition, there are several new concepts being developed that address highly specific needs for specialized drying applications.

The purpose of this chapter is to introduce a number of these dryers to you and give you a brief overview of how they operate as well as their areas of application. It is certainly beyond the scope of a course such as this to provide detailed information regarding any individual type of dryer.

We will begin by looking at various methods of applying heat to food materials, and sources of heat commonly used. Then we will look at batch and continuous methods of drying. Following this, we will discuss airflow in dryers, before we begin to look at individual types of dryers. While we are examining the types of dryers, please keep in mind that developments are always happening in the areas of design and operation. We cannot possibly provide a in-depth examination of each type of dryer. For this reason, you should consult other sources, such as the Internet and especially dryer suppliers, for any details that you may require for your particular applications.

6.2 Direct and Indirect Heating

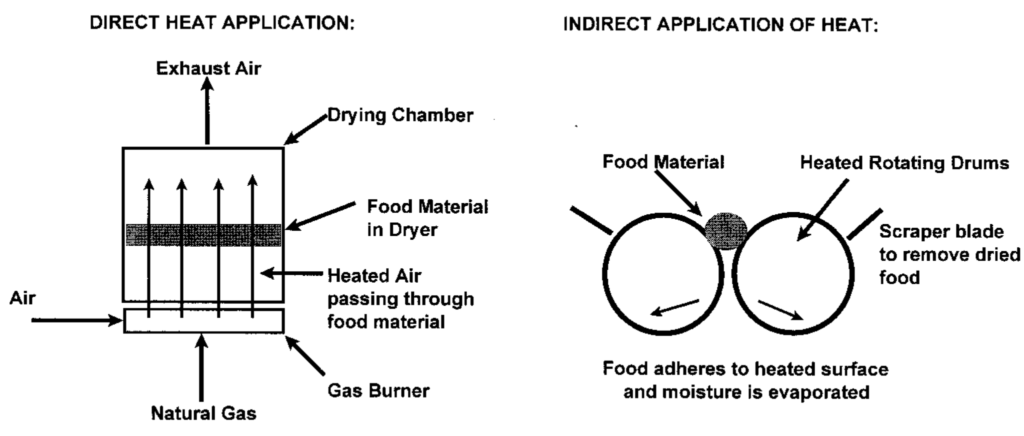
A key feature that separates one classification of dryers from another is the method by which heat is delivered to the product being dried. Even freeze dryers utilize some heat in combination with a vacuum at low temperatures to dry products.

The most common method of delivering heat to materials in a dryer is referred to as “direct” heating. Here, the drying medium is air which has been heated prior to entering the drying chamber. It may be heated by passing it through the flames of a burner (such as a natural gas burner, etc.), or by passing it across heated metal surfaces where it picks up heat which it then carries and transfers to the material being dried.

There may be cases where it is not suitable to dry materials with the direct application of heat from hot air. In these instances, the product may be brought into contact with heated surfaces and the heat can then be transferred to the material in this manner. Hot surfaces such as those on the outside of rotating metal “drums” with steam circulating through them are one method of indirect heating that may be used.

Figure 6-1 shows diagrams of direct and indirect heating for a food material in two types of dryers.

FIGURE 6-1: DIRECT AND INDIRECT HEAT APPLICATION METHODS



6.3 Batch and Continuous Dryers

Another way in which we can classify dryers is through the manner in which they are used.

Consider the example of when we dry small quantities of materials in the laboratory (or even in our kitchen). We often put the material inside a bench-top dryer (or our kitchen oven); start the dryer to remove moisture; and finally, we take the dried material out of the dryer once the desired final moisture has been reached. This process is referred to as "batch drying". The dryers are called "batch dryers" since we have dried the material in small batches.

Figure 5-1 in the previous chapter shows a cabinet dryer which is a type of batch drying apparatus.

Small food dehydrators that function as batch dryers are available commercially. They allow the user to place several kilograms of material on trays inside the dehydrator and remove the moisture by blowing hot air through the unit.

For larger, commercial scale drying applications, it is not really practical or efficient to use a batch dryer. You cannot keep putting in small amounts of material and removing them after they are dry. This is much too labour-intensive; far too slow; and just not practical. In cases where you may have many kilograms of material to dry and you will be working at it for long periods of time, "continuous dryers" are best suited for the task.

Consider a farmer who has large quantities of grain to dry. The drying could be done by spreading the grain in a thin layer on a wire mesh conveyor belt and passing it through a drying chamber where hot air removes the excess moisture from the grain. After travelling through the drying chamber, the grain falls off the end of the conveyor belt and is collected in storage bins or sent to storage silos for later use. Many industries use continuous dryers in their processes due to their convenience, reliability, and water removing capabilities.

Figure 6-2 shows a diagram of a continuous belt dryer.

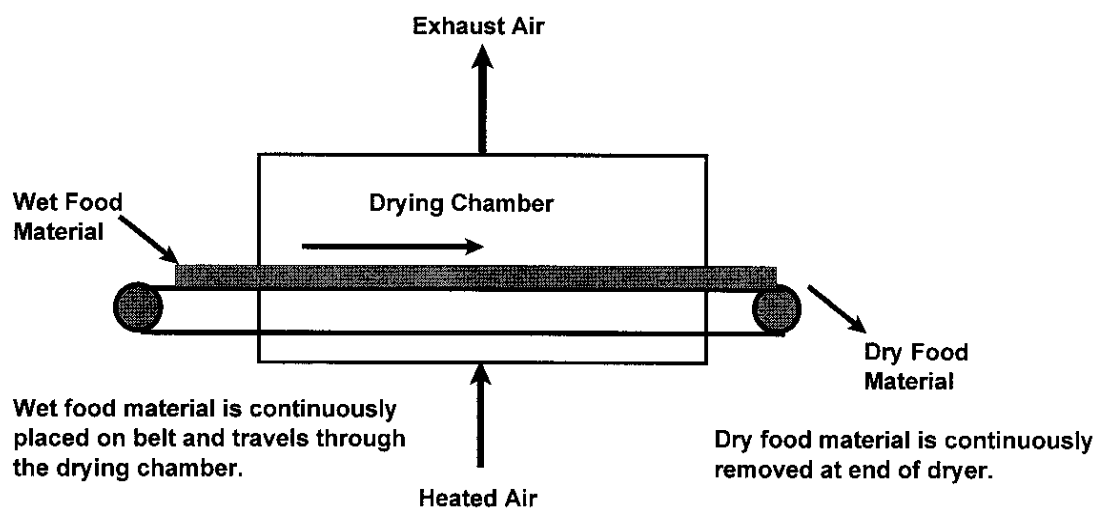


FIGURE 6-2: CONTINUOUS BELT DRYER

6.4 Airflow in Dryers

Air is probably the most commonly used drying medium in the food processing industry.

Before we begin to examine the different types of dryers available for various applications, it would be a good idea to look at the ways in which air can be introduced into the dryers.

If you look at the continuous belt dryer shown in Figure 6-2, you can see that the heated air is being introduced into the bottom of the dryer and travels upwards through the bed of material being dried. This is referred to as "**updraft**". The air then exits through the top of the dryer. The exhaust air is cooler and contains more moisture than the air entering the dryer because it has given up some of its heat to evaporate the moisture from the material in the dryer. Having air flowing upwards through the bed of material is a good way of avoiding problems encountered with soft wet products. If the air was flowing downwards through the material, it could literally push the soft material into the wire mesh of the conveyor belt where it would dry and harden. In a very short time, the belt would become plugged and no air could flow through it to dry the product. With air travelling in the upward direction, the wet material is dried on the bottom of the bed which may harden it slightly and prevent it from being mashed into the wire mesh of the conveyor belt.

Once the bottom portion of the material has been dried somewhat, the flow of air can be directed downwards to dry the top portion of the product bed. This "**downdraft**" can be accomplished by having the conveyor belt pass through various "zones" in a dryer. The zones are separated by walls or partitions in the dryer. More information regarding dryer zones will be presented later in this chapter.

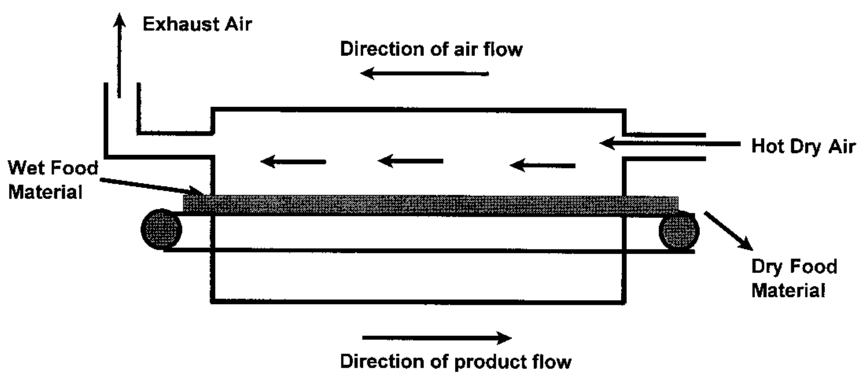
In cases where very light fluffy products are being dried, it might not be desirable to have air flowing in the upward direction since this may blow the product around inside the dryer. Care must be taken to match the direction of air flow to the material being dried.

There may also be cases when it is not desirable to have updraft or downdraft flow of air in a dryer. You may want to have the air flowing along or across the surface of the material in the dryer. There are several different options available that may be used. We will look at each one of these options in turn.

Counter-current air flow is the term used to describe the situation where product is introduced into one end of the dryer and heated air is introduced into the opposite end, as shown in Figure 6-3 on the next page. In Figure 6-3, the wet material is entering the dryer from the left and leaves the dryer at the right-hand side of the diagram. Heated air is blown into the dryer from the right and leaves the dryer on the left side of the diagram. This is a very good way to maximize the efficiency of the drying operation.

The air entering the dryer in Figure 6-3 is at its highest temperature just as it enters the dryer. It also has its lowest water content at this point. The combination of being at its highest temperature and lowest water content means that the air has its highest capacity to remove water.

FIGURE 6-3: COUNTER-CURRENT AIR FLOW



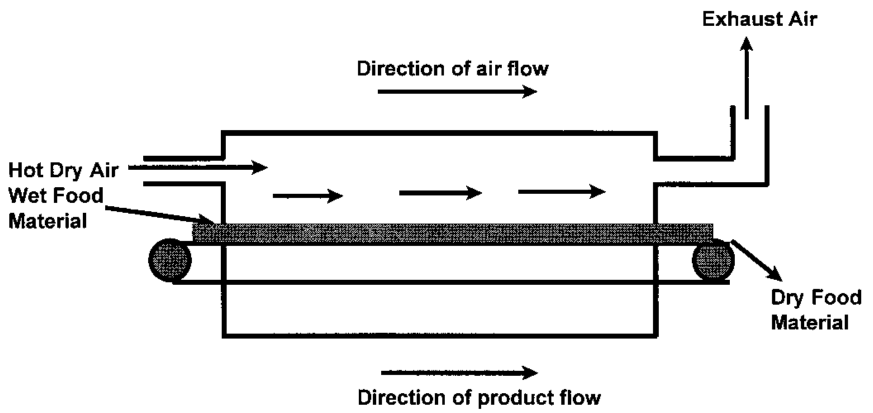
This is also the point where it is most difficult to remove moisture from the product which is almost finished being dried, but is in its falling rate drying period where diffusion is slow .

As the air travels to the left of the dryer in Figure 6-3, it continues to lose heat as it evaporates moisture. As it is leaving the dryer at the left-hand side of the diagram, it still has sufficient heat to warm the incoming cool wet material. At this point, the air has its lowest water removal capacity, but since it is in contact with very wet product, it may still be able to pick up some moisture before it leaves the dryer.

While counter-current air flow maximizes the driving forces of temperature and moisture difference between the air and the material being dried, it may pose a problem in some applications. For this reason, we should consider co-current air flow.

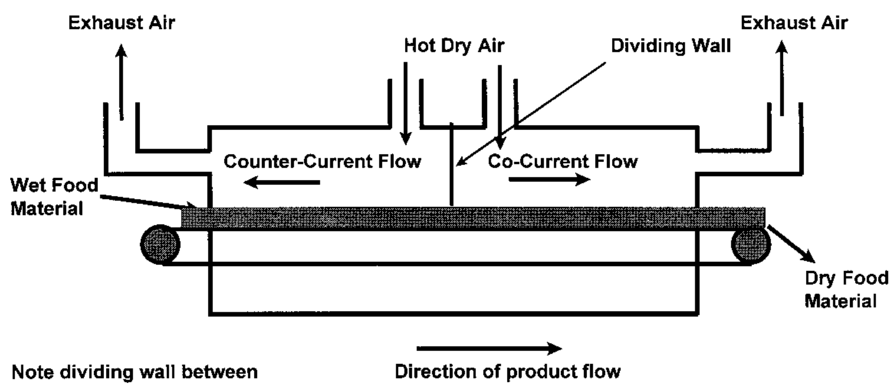
Co-current air flow describes the situation where the heated air for drying and the material to be dried are both introduced into the dryer and flow through the dryer in the same direction. Looking at Figure 6-4, we can see how this takes place. With co-current airflow, we are bringing the hottest, driest air into contact with the wettest, coolest material. This avoids the danger of over-heating the product before it leaves the dryer, which can happen with counter-current airflow. Excessive heat may damage delicate products and it should be avoided if there is a danger of doing harm to the product quality by exposing it to excessive heat. While there are not the most optimum differences in temperature and moisture content helping to dry the product, the effects may be more gentle on the product itself.

FIGURE 6-4: CO-CURRENT AIR FLOW



Some drying applications may use a combination of counter-current air flow and co-current air flow by having them in two separate sections of the dryer as shown in Figure 6-5.

FIGURE 6-5: COMBINED COUNTER-CURRENT and CO-CURRENT AIR FLOW



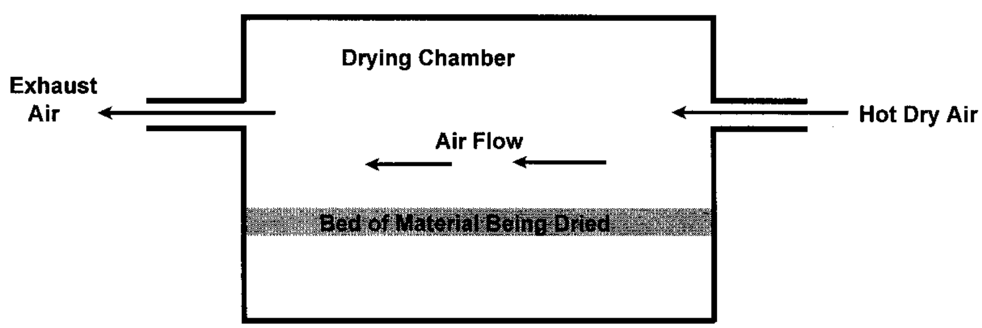
Note dividing wall between two sections of the dryer.

Another option for the direction of air flow is across the surface of the material being dried from one side of the dryer to the other. This would be referred to as **"cross-current air flow"** and is shown in Figure 6-6. One potential danger here is having material on one side of the drying bed becoming dryer than material on the other side of the bed. This would be similar to the flow of air in a batch dryer where the bed of material is not moving. The air is simply blown across the bed of material from one side of the dryer to the other.

Special Note:

Whatever direction we have for the airflow in a dryer, having a uniform distribution of the air is absolutely essential in order to get a uniformly dried final product. We will come back to this topic when we discuss continuous belt dryers.

FIGURE 6-6: CROSS-CURRENT AIR FLOW



Bed of material is moving out of the page towards you while the air is travelling from one side of the drying chamber to the other.

6.5 Types of Dryers

Now that we have had a look at how we get the heat to the product in dryers using hot air, we should examine several of the different types of dryers that are available to the food processor. These dryers may be divided into two main groups: "traditional" dryers and "emerging technology" dryers. Even though we may only be able to take a quick look at just a few different types of dryers, there are many variations of dryer types that have been designed to meet various needs in food drying. You should consult a drying specialist for a dryer to meet your specific drying requirements. We will consider the "traditional dryers first.

6.5.1 Traditional Dryers

6.5.1.1 Continuous Through-Circulation Dryers

This type of dryer is often called by names such as a "continuous belt dryer" or "conveyor belt dryer" etc. It is similar to the dryers shown in Figures 6-2 through 6-5. Basically, the material to be dried is spread evenly on a wire mesh belt which travels through the drying chamber. The time that the material spends in the dryer is controlled by the speed of the belt. The amount of heat delivered to the dryer is determined by the temperature of the heated air, and the volume of air blown into the dryer in a given period of time.

Figure 6-7 shows a side view of a continuous through-circulation dryer with four zones for drying the product. Zones 1 and 3 have updraft and zones 2 and 4 are downdraft zones. In some belt dryers, the final zone may be used for cooling the product before it leaves the dryer as is the case in Figure 6-7. This helps to "set up" the product. If the product happens to be starchy in nature, cooling it will make the starch become more solid rather than being soft and pliable. This can be very important if the starchy product is going to be held in a bulk storage bin prior to being packaged. Hot or warm products may "sweat" during storage and give off moisture which collects on surfaces of the storage bin. Later this moisture may cause mold growth to occur. Hot products also tend to be somewhat soft, which can cause them to alter their shape or change their structure as they cool.

Each zone in the continuous through circulation dryer can have its air flow and air temperature controlled independently from the other zones. Care must be taken in each drying zone to match the application of heat to the drying needs of the product.

In zone 1, the material may be in its constant rate drying period, so moisture is being evaporated from the surface. This means that it may be possible to use higher air temperatures without damaging the product. The updraft direction of air flow prevents the air from pushing the moist material into the mesh belt. Having material pushed into the belt can cause the wire mesh to become plugged and not allow air to pass through it during the drying process.

In zone 2, a lower temperature might be used since the material may be in its falling rate drying period where moisture must diffuse to the surface before it can be removed by the drying air. If high air temperatures were used, the material could heat up and become damaged by the heat. Even if the product was still undergoing constant rate drying, it may be considered to be a good idea to change the direction of the airflow so that the top of the drying bed becomes dry and the bottom does not become overly dry.

Zone 3 is a second updraft zone. It would generally have a much lower air flow than zone 1 because the product is lighter than it was when it contained a lot of water as it did in zone 1. If high air flows were used, the speed of the air could be sufficient to lift pieces of material off the drying belt and blow them around inside the dryer. This would create uneven drying and could also result in product being blown out of the dryer.

Continuous through-circulation dryers can have any number of zones. The actual number depends on the nature of the product being dried and other such considerations including air temperatures during drying and the air flowrates.

These dryers are used in many drying applications where the particles of material are easily handled and can be spread on a belt for drying. They may be used for drying grain and cereal products, animal feed, etc.

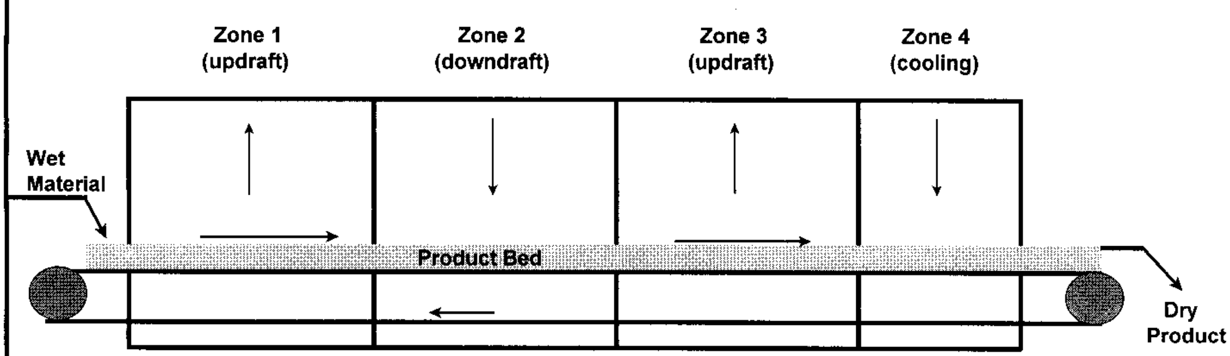


FIGURE 6-7: Schematic Side View of a Continuous Through Circulation Dryer

6.5.1.2 Tunnel Dryers

Tunnel dryers are similar in many respects to continuous through-circulation dryers. The big difference is that the material is not placed on a moving conveyor belt. Instead, the material to be dried is placed on trays or racks that are then placed on carts which are pulled through long tunnels where heated air is blown across the material. Figure 6-8 shows such a dryer.

The carts are manually loaded and pushed into the "front end" of the dryer. They can either be fastened to a chain that will pull them through the tunnel, or the wheels of the cart may be grabbed in an assembly that will pull them through the tunnel. The speed at which they are pulled determines the time the material spends in the dryer. Once the carts reach the end of the dryer, they are pushed out and unloaded. The empty carts are then returned to the start of the dryer to be reloaded and sent through the dryer with a fresh load of wet product.

These dryers require much more labour to operate than a continuous belt dryer and are not as commonly used as they once were.

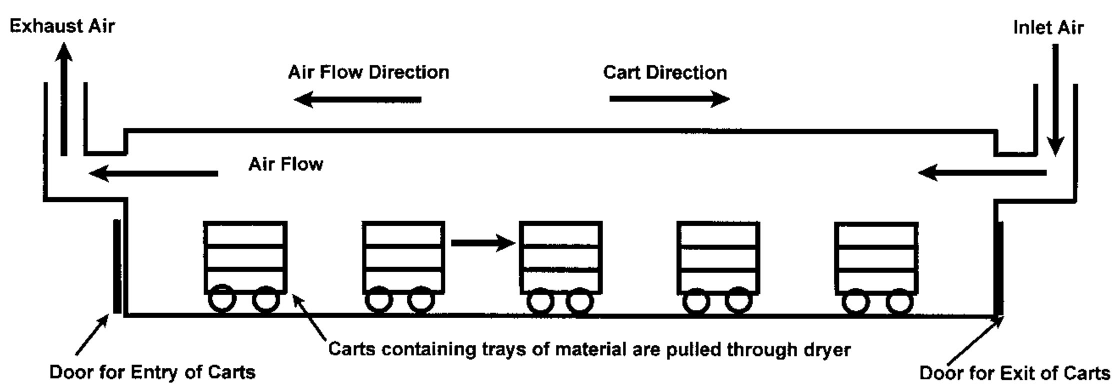


FIGURE 6-8: DIAGRAM OF TUNNEL DRYER

6.5.1.3 Cabinet Dryers

Cabinet dryers represent a basic type of batch style dryer. We have already seen a cabinet dryer in Figure 5-1. It is reproduced here as Figure 6-9 for the sake of completeness.

Cabinet dryers are useful in drying small quantities of food material or for laboratory-scale drying studies.

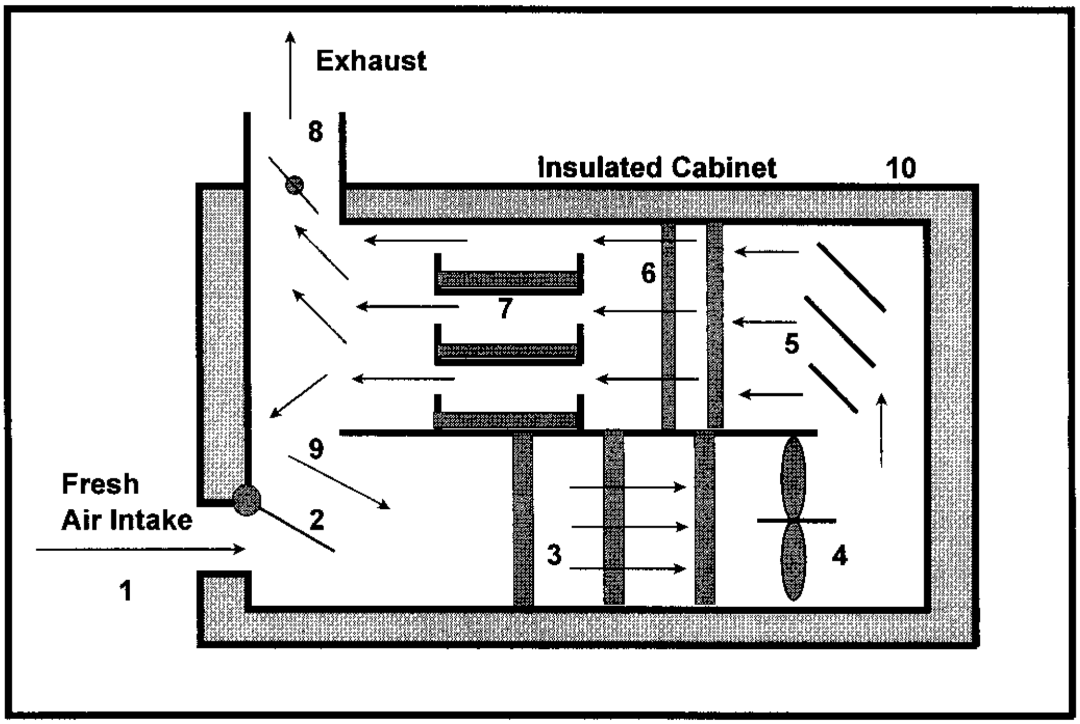


FIGURE 6-9: SCHEMATIC SIDE VIEW OF A CABINET DRYER

1. Fresh air enters cabinet dryer
2. Adjustable damper allows fresh air and recirculated air to be balanced
3. Heaters warm the air stream to the desired temperature
4. Adjustable fan conveys air and controls volumetric air flowrate
5. Air distribution plates "even out" flow pattern of air
6. Screens "filter" particulates from air and create back-pressure
7. Product is contained in trays with heated air passing over them
8. Air is exhausted from cabinet dryer after removing moisture from product
9. Heated air with some drying capacity may be recirculated
10. Cabinet is insulated to prevent excessive heat loss.

Arrows in schematic diagram indicate air flow

6.5.1.4 Tray Dryers

Tray dryers are another type of batch dryer that is often used in small to moderate scale food drying operations. In many respects, they resemble cabinet dryers.

In a tray dryer, the material to be dried (e.g., sliced fruit or vegetables) is placed on large trays, generally made of metal, or wire mesh. The tray itself can be a solid sheet of metal, or it may have slots or holes in it to allow drying air to pass through the material being dried.

Once they are loaded, the trays are placed on supports inside a large drying cabinet or compartment. The trays look like shelves inside a large box that is actually the dryer. After all the trays have been loaded, the drying chamber is closed and air is blown through the drying compartment.

By monitoring the humidity of the air leaving the tray dryer, the progress of the drying process can be followed. Once the drying is completed, the air flow is stoped; the dryer is opened; and the trays are removed. The dried contents of the trays are then dumped and the trays are reloaded for the next load of product that is to go into the dryer.

Figure 6-10 shows a diagram of a tray dryer.

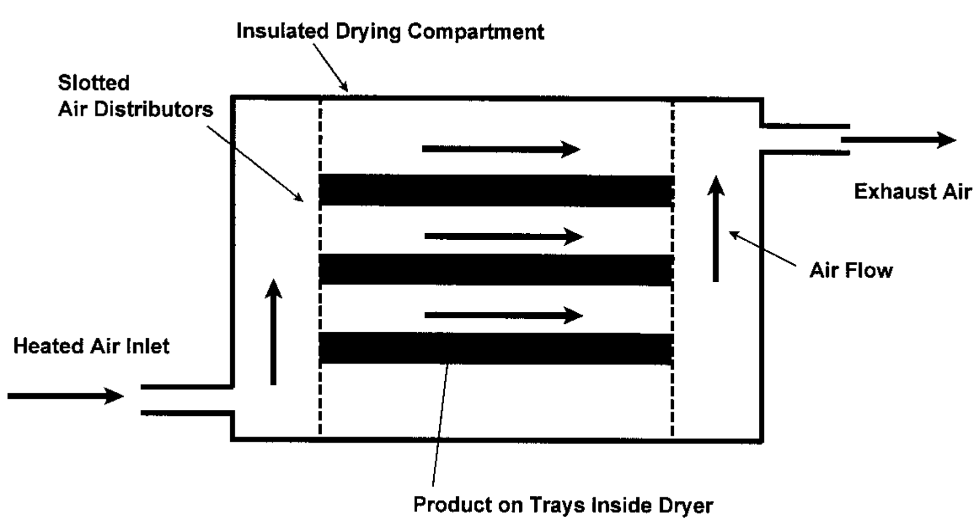


FIGURE 6-10: Schematic Diagram of a Tray Dryer

6.5.1.5 Fluidized Bed Dryers

Fluidized bed dryers recognize the fact that drying can be done much more efficiently if all surfaces of the product being dried are in contact with the drying medium, which is usually heated air. Such dryers can be either batch or continuous in their design and operation. For our example purposes, we will examine a batch fluidized bed dryer.

Consider a chamber with small openings in its bottom and top. The openings are large enough to permit air to pass through them but do not allow particles of material being dried to escape.

Figure 6-11 is a schematic representation of such a dryer.

Heated air is blown into the drying chamber through the openings in the bottom. By using a sufficient volumetric flowrate of air, a velocity can be achieved that is sufficient to lift the wet product pieces and keep them suspended in the air that is drying them. While in their fluidized state, it appears as if the particles are “dancing” in the air that is drying them. As the process continues, the product particles lose moisture and become less dense. This means that the air flowrate must be reduced so as not to lift the particles too much and pack them against the openings in the top of the drying chamber. When drying is completed, the batch of product can be removed from the drying chamber and a fresh batch of wet product can be inserted for drying.

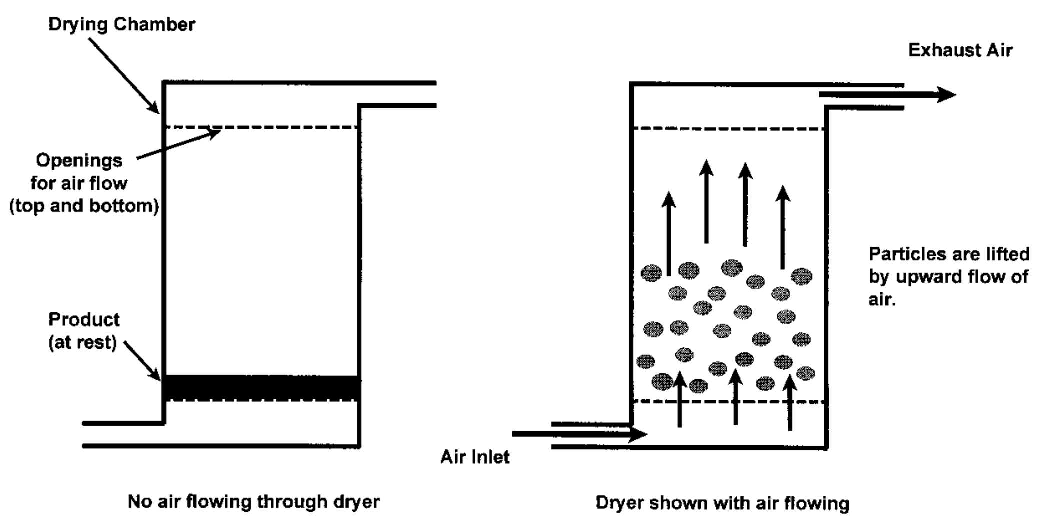


FIGURE 6-11: DIAGRAM SHOWING FLUIDIZED BED DRYER (with and without air flowing through it)

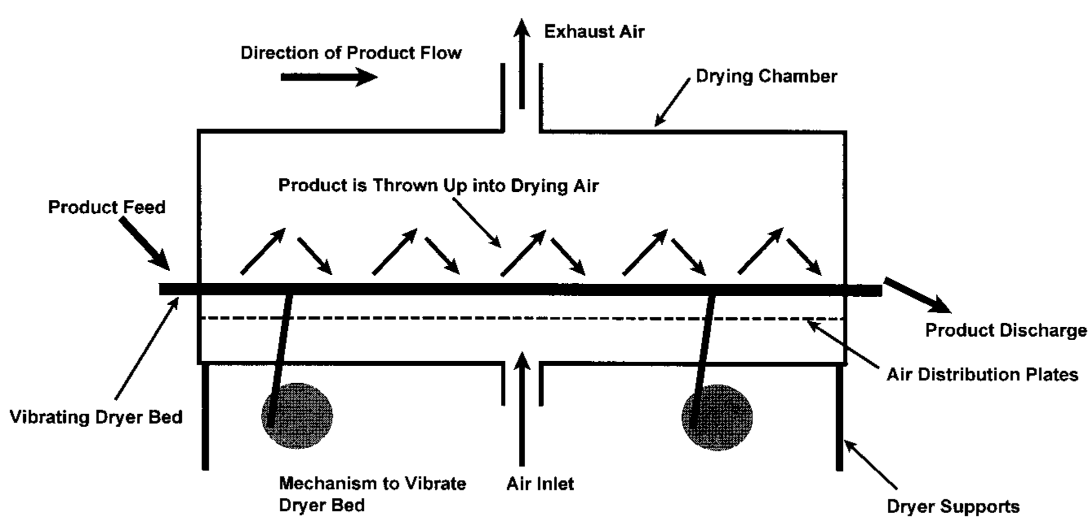
6.5.1.6 Vibrating Bed Dryers

Vibrating bed dryers also recognize that it is important to expose as much of the surface of a product to the drying medium. When dealing with starchy products that can have a sticky surface, these dryers may be used in series with another dryer, such as a conveyor belt dryer. In the conveyor belt dryer, the surface of the product is dried to the point where the product is no longer sticky. Essentially, this will be at the end of the constant drying rate period. If the material is left on the conveyor dryer, the points where each particle touches another particle will experience slower drying than fully exposed surface areas.

Figure 6-12 is a schematic representation of a vibrating bed dryer.

The bed of partially dried material leaving the conveyor belt dryer can be broken up and fed into a second dryer which has a vibrating surface onto which the product particles are spread. Air is introduced through small openings in the vibrating bed, or is blown into the dryer from above or from the sides. As the particles are thrown a short distance upwards, they are in full contact with the heated air. As soon as they come back down onto the dryer bed or “deck”, they are once again thrown upwards into the drying air. This procedure is repeated many times as the particles travel from the feed end of the dryer to the discharge end where they go on to further processing, storage, or packaging, etc.

FIGURE 6-12: DIAGRAM OF A VIBRATING BED DRYER



6.5.1.7 Spray Dryers

Spray dryers are typically used in cases where solids are required to be recovered by drying liquid streams. An example of this would be in the recovery of whey solids from liquid whey in a cheese-making operation. See Figure 6-13 for a diagram of a spray dryer. There are many different designs and configurations. However, their basic operation is quite similar.

In spray drying, the liquid is pumped through an atomizing nozzle that creates small droplets which are then distributed uniformly into a large drying chamber, or tower, where they are allowed to fall through heated air that is circulating in an upwards direction. As the droplets fall through the heated air, they lose moisture. By adjusting conditions such as droplet size, air temperature, and air velocity, etc., the desired degree of drying can be achieved so that by the time they reach the bottom of the dryer, the droplets have become small particles of powder. This powder can be collected at the bottom of the spray drying tower. Any powder being carried out of the spray dryer in the exhaust air can be recovered through the use of one or several cyclone separators.

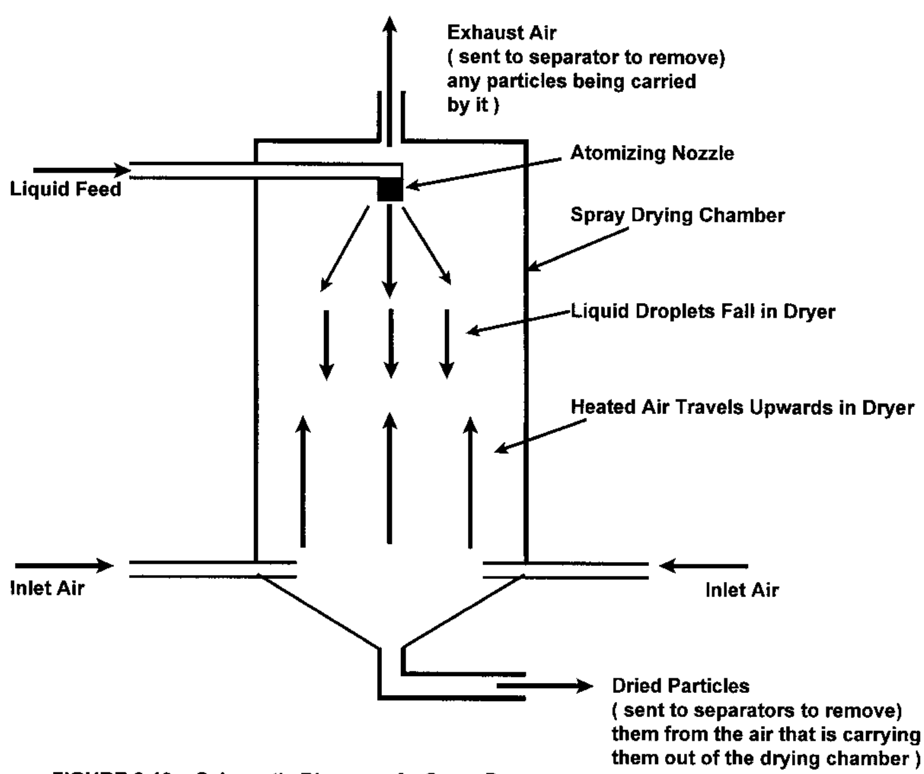


FIGURE 6-13: Schematic Diagram of a Spray Dryer

6.5.1.8 Drum Dryers

Drum dryers use heat to warm a set of metal drums to the desired temperature. The drums rotate in opposite directions (as shown in Figure 6-14). The material to be dried is introduced into the narrow gap, or "nip" between the drums. This material can be a viscous liquid or a "mushy" solid. An example of a solid being dried on a drum dryer would be the conversion of mashed potatoes into dried flakes for use as instant mashed potatoes. After it goes through the "nip", the material sticks to the surface of the rotating heated drum and moisture evaporates from it.

Just before it travels back to the top of the dryer, the dried material is removed from the drum using a "doctor blade" that continuously scrapes the drum surface. As it falls, the dried product is caught in a hopper and is removed for further processing.

There are numerous variations in the operation of drum dryers. Each method is designed to suit a particular drying need or product characteristic. Some dryers have only one of the drums heated instead of both of them, and others have different ways of getting the wet material onto the drum for drying. Figures 6-15 and 6-16 show two additional drum dryer configurations. Such variations demonstrate how adaptable certain dryers are, and how creative dryer manufacturers can be at meeting specific drying needs.

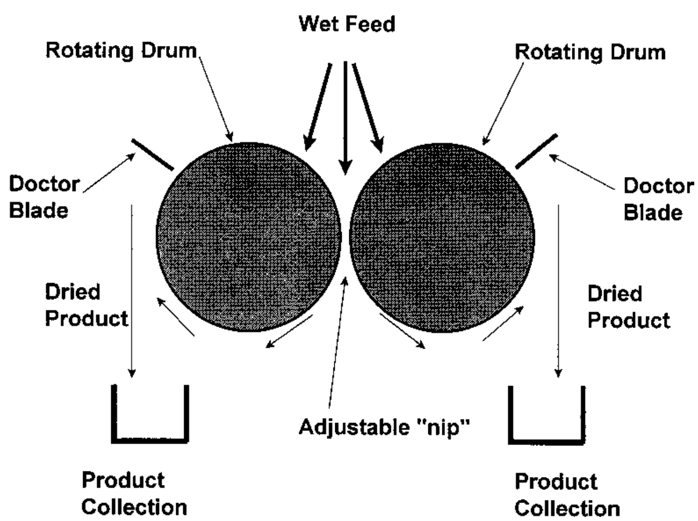
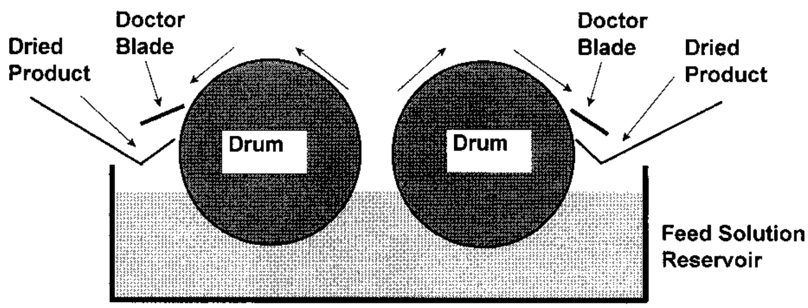


FIGURE 6-14: SCHEMATIC REPRESENTATION OF A DRUM DRYING OPERATION



Drums operate independently of each other

Drums are not closely spaced

Solution adheres to drums and dries upon leaving reservoir

FIGURE 6-15: SCHEMATIC REPRESENTATION OF A DRUM DRYING OPERATION USING A TWIN DRUM DIP FEED MECHANISM

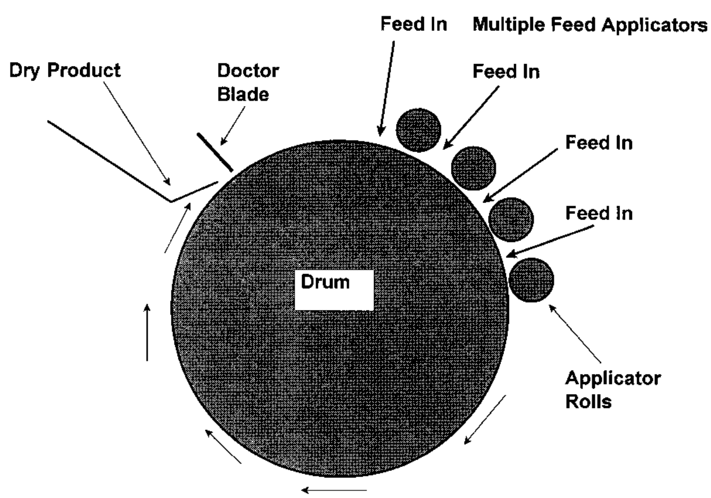


FIGURE 6-16: SCHEMATIC REPRESENTATION OF A DRUM DRYING OPERATION USING A SINGLE DRUM WITH MULTIPLE APPLICATOR ROLLS

Typically 4 to 6 applicator rolls

6.5.1.9 Other Types of Traditional Dryers

It is basically impossible to discuss in any great detail the full range of dryers that are available to food processors today. Not only is it beyond the scope of a work such as this, but there are far too many specific applications of dryers that would have to be considered to do justice to the treatment of each dryer type. Complete textbooks have been written on the subject of dryers. New styles of dyers are being developed continuously to meet new drying demands.

In addition to those dryers described above, the following types of dryers are also available for consideration in food processing applications.

- Freeze dryers
- Flash dryers
- Plate dryers
- Rotary dryers
- Vacuum dryers
- Solar dryers
- Roto-louvre dryers
- etc.

Should you wish to study any of these additional types of dryers, you may find the Internet to be of particular assistance.

Before deciding upon a specific dryer for a processing task, care should be taken to investigate all suitable types of dryers and to pick the one most appropriate fro the product. You should work with a dryer specialist or drying company and recognize the needs to match the dryer to the product being dried. The purchase of a dryer is often a major capital expense. Mistakes made in the selection of a dryer cannot be easily corrected in most cases.

6.5.2 Emerging Technologies

In a chapter of the book "Food Science and Food Biotechnology" (edited by G.F. Gutierrez-Lopez and G.V. Barbosa-Canovas; Food Preservation Technology Series, by CRC Press, 2003), Dr. Arun Mujumdar, discusses a number of new developments in the field of drying technology.

He lists the following new dryer designs:

- Heat pump dryers
- Intermittent batch dryers
- Vacuum fluid-bed dryers
- Sorption dryers
- Pulse combustion dryers
- Cyclic pressure / vacuum dryers
- High electric field dryers
- Superheated steam at low pressure dryers

Each one of these dryers addresses a special concern in the drying of a particular product.

While it is not possible to examine each one of these dryers here, it is important to mention them in order to show how new dryers are being developed to meet the needs of various processors.

CHAPTER 7: DRYER OPERATION - CASE STUDY

7.1 Introduction

Setting up a food drying process is not a matter of simply running a few small-scale tests and having a supplier design a dryer that meets your requirements. Once the dryer is installed and operating, conditions must be maintained to keep the dryer functioning properly.

In order to illustrate some of the situations that can arise during a food drying process, a case study example involving a continuous through-circulation dryer will be used.

7.2 Case Study: Continuous Through-circulation Dryers

7.2.1 Mode of Operation

The continuous through-circulation dryer is used in this chapter as a means of introducing drying or dehydration on an industrial scale and to provide material for a "Case Study". As previously stated, there are many types of dryers available and each application must be assessed on an individual basis to optimize the drying process.

7.2.2 Design Features

To ensure the best possible performance for any type of dryer, it is essential to have a uniform bed of material on the dryer belt. The material being dried must then be exposed to a uniform, controlled drying environment.

7.2.2.1 Creating a Uniform Product Bed

Methods of establishing a uniform product bed are varied and often imaginative. They are dependent upon the properties of the material being dried, and on the nature of the discharge stream from the previous unit operation in the process sequence. Some materials may be conveyed in a water slurry and spread on the dryer belt by dams or weirs, and drained prior to entering the dryer itself. Other materials may be "airveyed" (i.e., blown in a stream of high-velocity air) and blown onto the belt through tubes that sweep from side-to-side across the dryer belt.

7.2.2.2 Creating Uniform Air Flow

Delivering the drying medium (usually heated air) to the product is a major challenge. "Air distribution plates" are the most commonly used method in continuous through-circulation dryers. These plates are simply large sheet-metal panels with small holes (typically 1 to 2 cm) spaced at regular intervals to give an appropriate open area (perhaps 25% to 50%). A schematic diagram of an air distribution plate appears as Figure 7-1. Sufficient back pressure must be created by the air distribution plates to establish a uniform flow of air through the holes in

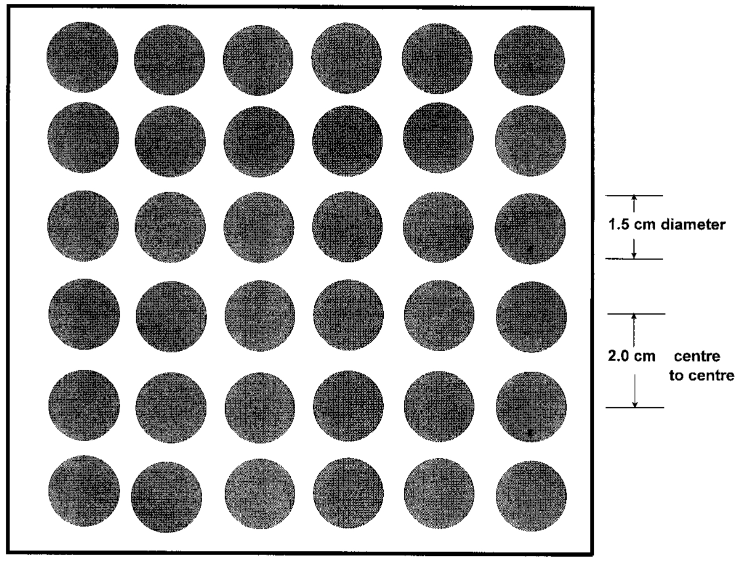


FIGURE 7-1: AIR DISTRIBUTION PLATE

1.5 cm diameter circles on 2.0 cm centres have open area of 44.2% (as seen here)

2.0 cm diameter circles on 2.5 cm centres have open area of 50.2%

2.5 cm diameter circles on 3.0 cm centres have open area of 54.5%

the plate. The flow must be uniform both across the product bed, and along the total length of the dryer zone. Non-uniform air patterns will result in non-uniform drying.

Figures 7-2a and 7-2b show the positioning of air distribution plates in updraft and downdraft zones of a dryer, respectively.

In the case of airflow in an updraft zone (Figure 7-2a), air enters the drying chamber below the product bed. Due to the large open volume and the high velocity of the air, the air flow patterns are very chaotic. Air from the fan may be blown across to the far side of the dryer and be deflected in a random manner from the wall of the dryer. If nothing was present to even out the air flow, there would quite probably be a highly non-uniform distribution of air going upwards through the product bed. However, with the air distribution plates in place, the chaotic flow of air is essentially trapped below the distribution plates and cannot reach the product bed until the air flow pattern is made more uniform. The air distribution plates create a back-pressure by allowing only a portion of the air to pass through the small holes. This creates a uniform flow at all locations beneath the product bed so that when the air does travel upwards, all product spread on the dryer belt receives the same degree of exposure to the drying air.

In the downdraft zones of the dryer (Figure 7-2b), the same arrangement is used for the air distribution plates. The plates are placed between the source of the air (i.e., the fans) and the product bed

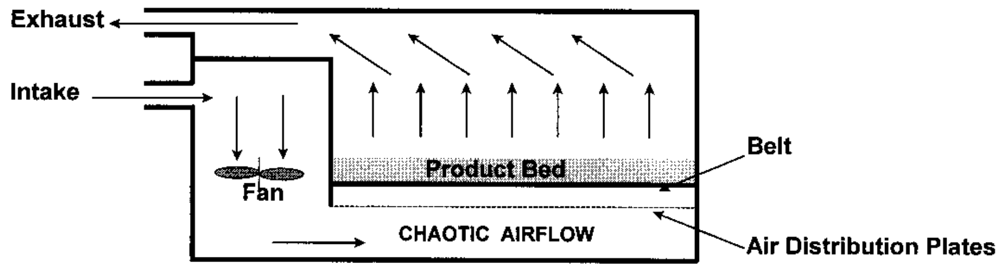


FIGURE 7-2a: SCHEMATIC END VIEW OF AN UPDRAFT ZONE

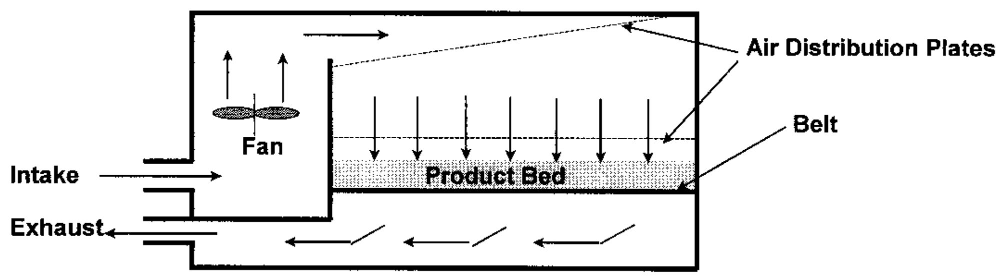


FIGURE 7-2b: SCHEMATIC END VIEW OF A DOWNDRAFT ZONE

to prevent chaotic air flow from reaching the product bed. As can be seen, the air distribution plates are located above the product bed in this case. The air travels down through the holes in the plates before it strikes the product bed. In some cases a second set of distribution plates or air deflectors could be used to further ensure the uniform distribution of air in the downdraft zones. This might be necessary due to the large volume of space above the product bed in most dryers of this type.

7.2.2.3 Volume of Air to the Dryer

The volume of air being sent to the dryer may be controlled in several different ways. If the dryer is so equipped, variable-speed drives can be used to adjust the speed of the fans. The faster the fan is spinning, the more air that will be delivered to the dryer. The specifications of the manufacturer and the appropriate fan curves (i.e., curves defining the air delivery of a fan under a set of given conditions such as speed, temperature of the air, back-pressure, etc.) must be used to determine the actual delivery rates. In addition, tests to determine air velocities should be conducted to verify results. This is a topic best left for other courses, or hands-on training.

A second way to control the amount of air delivered by a fan is through the use of louvres or dampers to control the open cross-sectional area of the plenum through which the air is flowing.

A third way to adjust the air delivered by a fan is by using volume control disks mounted on the central shaft of the fan. These disks can be moved along the shaft to control the percentage of the blades of the fan available to blow air into the dryer. This concept is somewhat more complex than the other two and is also more difficult to use since the fans must be shut off and the dryer cooled down to enable crews to go in and physically adjust the volume control disk positions.

7.2.3 Assessing Dryer Performance

7.2.3.1 Drying Uniformity

How well a dryer does its job is determined by a wide variety of factors. In general, however, the success of drying a product comes down to how well you as a processor understand the behaviour of your product while it is being dried, and how well you match the operation of the dryer to your product's drying needs.

The first thing that you must realize is that **there is a limit to how much water can be removed from a particular type of material by a given dryer in a specified period of time**.

Suppose you buy a dryer that is designed to dry grain and remove a certain amount of water from it on an hourly basis. Let's assume the dryer can remove 1,500 kg of water per hour from a specified input rate. You should not expect to dry more grain which requires that you remove 2,000 kg of water per hour. Some operators try to do this by turning the temperature controllers up to their maximum settings to get the air as hot as possible. They also turn the fans up to their maximum settings to deliver as much air as possible. In spite of these measures, they still fail to get an acceptable product, since they have not taken into account the time it takes for the moisture inside the kernels of grain to diffuse out to the surface and be removed. Even if the conveyor belt is slowed down to allow the grain to spend more time in the dryer, the results are usually not encouraging because the thickness of the drying bed increases and the air cannot penetrate through it and remove the desired moisture.

Consider the following factors:

- Time:
  Kinetic factors (such as diffusion) control the removal of moisture. It is not simply matter of blasting the material with abundant amounts of hot air.

- Nature of the Product:
  This is critical. Not all products dry in the same way. You cannot expect to have grain dry in the same manner as flakes of parsley or other leafy plant material.

- Temperature:
  Excessive temperatures can damage your product. You cannot keep increasing the heat to drive off moisture without scorching or burning your product or without decreasing its nutritional or functional properties.

- Air Flow:
  The air entering a dryer must be distributed uniformly to all product in a particular drying zone. Its rate of delivery (linear and volumetric) must be such that it does not disrupt the product bed. The air must also have a relatively low moisture content to maximize its ability to remove moisture from the product in the dryer.

- Material Bed Characteristics:
  The product must be distributed evenly from side-to-side and along the dryer belt. Its thickness must be sufficient to ensure that it is not disrupted by the air passing through it and it cannot be so thick as to be impenetrable to the air.

- Other Factors:
  Other factors exist that are specific to each dryer that impact its operation. The operator of the dryer must identify and understand how these factors relate to the drying of his or her specific product.

All of these factors are usually taken into account by the dryer manufacturer. It is rather amazing that dryer manufacturers are often blamed for problems when the dryer is not used in the manner in which it was designed to be run. Processors may be running a product that the dryer was not designed to dry; and they may be using improper drying conditions.

No dryer can be expected to operate properly if it is not run under its appropriate design conditions.

7.2.3.2 Aspects to Consider

In operating a commercial-scale dryer such as a continuous through-circulation dryer, keep in mind the following points:

- No matter what you do to try to duplicate drying on a small scale, nothing can be done to reproduce actual conditions during commercial production.

- Small scale trials in lab units impose wall effects and fail to duplicate air flow patterns (Note: some dryer types are scaleable).

- Lab tests can give very good information about the drying properties of the material itself on an individual "chunk" or particle basis.

  e.g.: TGA - thermal gravimetric

analysis can detail how moisture loss proceeds with temperature and time

DSC - differential scanning calorimetry can show how properties of a material change over time as heat is applied

- To assess the true operating capacity of a dryer, you need to have a test sequence that includes overall water removal and water removal uniformity across and along the dryer bed.

- Single or even multiple grab samples of product cannot provide sufficient data as to a dryer's overall operation. We will discuss this more in the "Advanced Course in Food Dehydration and Drying".

We will look at a relatively simple method of determining the uniformity of drying together with the water removal capacity of a dryer later in this case study.

7.2.4 An Approach to Water Removal Capacity Determination

7.2.4.1 Definition

We can define "water removal capacity" as:

The amount of water a dryer is capable of removing from a given product in a given period of time (usually per hour).

It is highly dependent on a number of factors which are listed below.

7.2.4.2 Factors Influencing Water Removal

Factors influencing the water removal capacity of a dryer include:

- characteristics of the product to be dried
- characteristics of the product bed (on the dryer belt)
- condition of the dryer
- age of the dryer
- characteristics of the drying air
- etc.

You cannot always rely on the manufacturer's rated capacity of the dryer.

Manufacturers of dryers build their equipment to deliver a certain level of performance that can be demonstrated when the dryer is newly installed. With age and other factors, the performance of the dryer can change. Insulation in the dryer can deteriorate and more heat can be lost when the dryer is old than when it was new. Burner performance can deteriorate over time and processors can even change things on their own without the manufacturer's knowledge.

7.2.4.3 Water Removal Capacity Testing

One method of determining how much water the dryer is actually capable of removing and to determine how uniform the drying is, is to do a series of simple tests.

Imagine yourself standing at the discharge end of a conveyor belt dryer with the dried product coming towards you. The bed of dried product may be two or three metres wide and will fall off the belt into a collection hopper of some description just in front of you. What you want to do is determine the uniformity of moisture across the dryer bed. If you do this at a series of time intervals, you can also determine the uniformity in moisture over time.

A procedure that I have used is to take a set of six samples across the end of the dryer at a particular time. Two other helpers are needed to get the samples at the same time. Each sample is placed into a labelled plastic bag and tied for future testing. The time of these samples will be "Time t = 0". Five minutes later, a second set of samples is taken at the same six locations and are labelled "Time t = 5 minutes". Five minutes later, a third set of samples labelled "Time t = 10 minutes" is taken; and five minutes after that, a fourth set of samples labelled "Time t = 15 minutes" is taken. Each sample is then tested for moisture using a recognized moisture determination method. Figure 7-3 shows how the sampling pattern would look.

The results of the 24 moisture tests, in what is referred to as "Scenario 1", are then arranged in a table format such as that shown in Table 7-1. The first set of samples is in the bottom row to duplicate the view of the dryer bed as if seen from above. Averages of moistures are calculated across each row of six samples and along each group of four samples taken at each sample site. The overall average for the 24 samples is also calculated.

In order to get some idea of the variation or spread of the moisture results, standard deviations are also taken for each row of six samples, each set of four moistures from each sample location and for the entire 24 samples. While it is recognized that a standard deviation based on four samples may not be statistically valid, the objective is to have the standard deviation as small as possible to indicate a low degree of variability among any set of sample results. The standard deviation is essentially used for qualitative purposes.

In Table 7-1, we can see the individual moisture values and the calculated averages and standard deviations. It appears as if the product along the left side of the dryer (average moisture = 7.2%) is much dryer than that along the right hand side of the dryer (average moisture in position 5 = 21.6% and in position 6, average moisture = 21.3%). The degree of variation in the moistures is also lower on the left hand side of the dryer than it is on the right hand side.

The average moisture across the dryer is reasonably uniform over time. It ranges from an average of 14.2% to 16.3%. The overall average moisture for the 24 samples was found to be 14.97%, or

FIGURE 7-3

SAMPLING PATTERN FOR DRYER STUDY

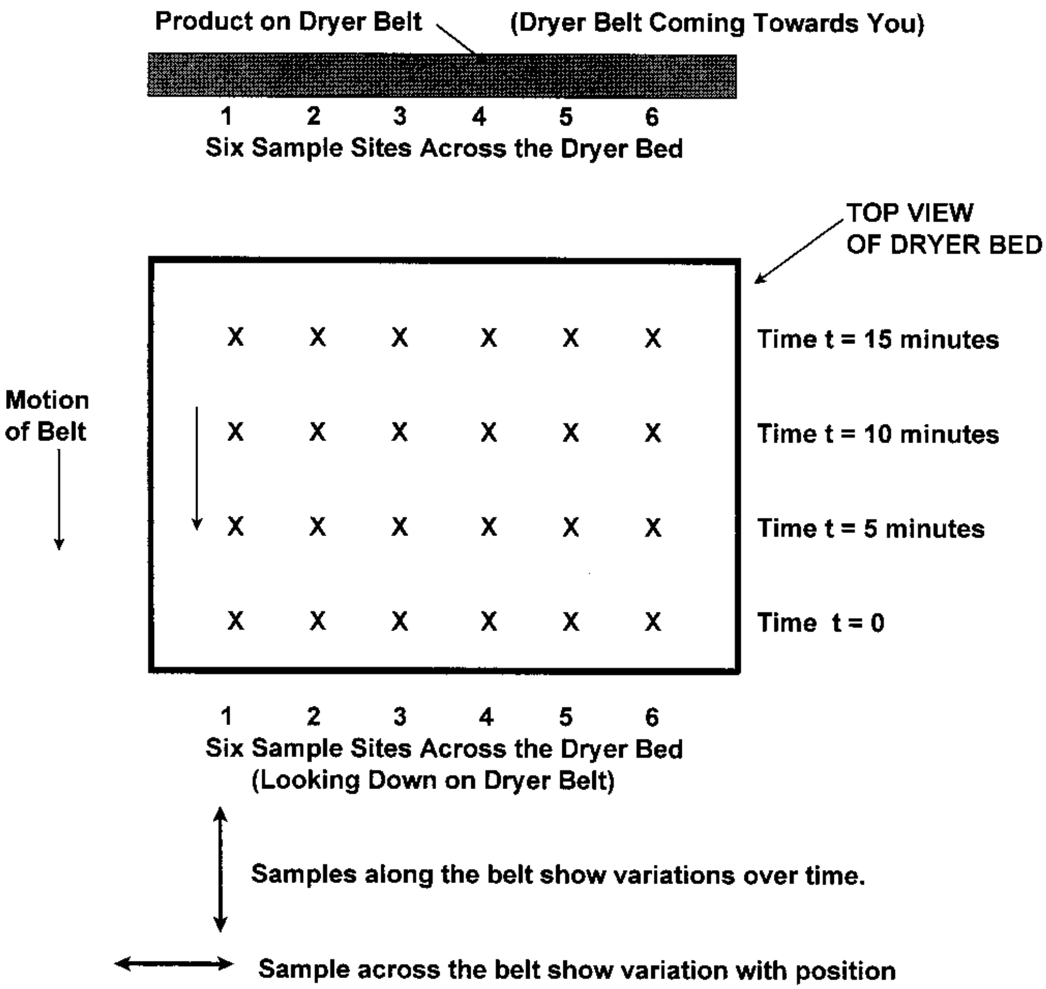


TABLE 7-1: **Scenario #1: Initial Moisture Profile Along and Across the Dryer**

Time	Position 1	Position 2	Position 3	Position 4	Position 5	Position 6	Average and Std. Dev.
15 min.	7.6	11.4	14.3	16.7	18.3	21.3	14.9 4.93
10 min.	5.9	10.9	13.7	16.1	21.2	17.4	14.2 5.35
5 min.	7.1	6.3	13.9	14.1	27.4	29.2	16.3 9.85
0 min.	8.0	12.2	14.0	15.6	19.5	17.2	14.4 4.03
Average Std. Dev.	7.2 0.91	10.2 2.65	14.0 0.25	15.6 1.11	21.6 4.05	21.3 5.61	14.97 6.07

Confidence Limits	Standard Deviations	Average Moisture	Range
68.3%	± 1.0	14.97%	8.90% to 21.04%
95.5%	± 2.0	14.97%	2.83% to 27.11%
99.7%	± 3.0	14.97%	-3.24% to 33.18%

Note: Target moisture = 14.0% ± 1.5%

The use of standard deviations with only four data points may be considered to have some statistical deficiencies. They are used here to show directional or qualitative trends and aid in the assessment of overall dryer performance.

Large standard deviation values indicate a wide scatter of the data. Low standard deviations show a small degree of scatter in the data.

15.0% when rounded off to one decimal place. If our target moisture is 14% and we have an acceptable range of ±1.5%, a moisture value between 12.5% and 15.5% would be considered acceptable. On the basis of these results, the average moisture of 15.0% would be acceptable, but this does not tell the whole story. There are individual moistures as low as 5.9% and as high as 29.2%. These are certainly outside the range of acceptability. From experience, we may know that mold can grow on our product if moisture levels rise beyond a certain threshold level. For this example, let's consider that value to be 20% moisture.

A chart of confidence limits has also been included as part of Table 7-1. With an overall standard deviation of 6.07% and 99.7% confidence limits, we know that the moisture will lie in a range of three standard deviations below the mean to three standard deviations above the mean. This tells us that moisture levels will lie between -3.24% (this is impossible, so we'd call this 0%) and 33.18%.

Basically, Table 7-1 is telling us that we have a widely fluctuating moisture content in our product and our dryer is not functioning very uniformly at all.

Now let us suppose that we do major modifications to our dryer. Perhaps we find that there are no air distribution plates in it; so we install some, etc.

We now repeat our set of tests under similar operating conditions and tabulate the results. Table 7-2 shows the data from the tests done in Scenario #2 after the dryer modifications were made.

We can see that average moistures for the six positions across the product bed range from 13.4% to 14.7%, with very low standard deviations (0.13% to 0.28%). Average moistures over time range from 13.9% to 14.1% and the standard deviations range from 0.47% to 0.56%. This shows a great improvement over the first test results.

Now, if we take the mean of 13.98% plus or minus three standard deviations, we can say with 99.7% confidence that the moisture of any sample taken from the dryer will lie between 12.54% moisture and 15.43% moisture. Since this moisture range is within our allowable moisture range of 12.5% to 15.5% moisture and our average moisture value (i.e., 13.98%) is basically right on the target value of 14%; we can say that the dryer is operating well and moisture fluctuations are acceptable. We may still want to work on the dryer to improve its operation, but we are certainly in much better shape now than we were originally.

In order to determine the water removal capacity of the dryer, we should do a series of similar tests using different water loadings for the dryer. We could increase the moisture content of the wet product entering the dryer and determine the moisture of the product leaving the dryer. Once the dryer is no longer able to remove the necessary amount of water to give us an average moisture that is within our specifications, we can say that the dryer has exceeded its water removal capacity.

TABLE 7-2: **Scenario #2: Second Moisture Profile Along and Across the Dryer**

Time	Position 1	Position 2	Position 3	Position 4	Position 5	Position 6	Average and Std. Dev.
15 min.	13.2	13.8	14.3	14.2	14.6	14.2	14.1 0.49
10 min.	13.4	13.6	13.9	14.1	15.0	13.9	14.0 0.56
5 min.	13.3	13.4	14.1	14.1	14.7	13.7	13.9 0.52
0 min.	13.5	13.4	14.0	14.4	14.5	14.3	14.0 0.47
Average Std. Dev.	13.4 0.13	13.6 0.19	14.1 0.17	14.2 0.14	14.7 0.22	14.0 0.28	13.98 0.48

Confidence Limits	Standard Deviations	Average Moisture	Range
68.3%	± 1.0	13.98%	13.50% to 14.46%
95.5%	± 2.0	13.98%	13.02% to 14.94%
99.7%	± 3.0	13.98%	12.54% to 15.43%

Note: Target moisture = 14.0% ± 1.5%

The use of standard deviations with only four data points may be considered to have some statistical deficiencies. They are used here to show directional or qualitative trends and aid in the assessment of overall dryer performance.

Large standard deviation values indicate a wide scatter of the data. Low standard deviations show a small degree of scatter in the data.

7.2.4.4 Summary of Points for Water Removal Capacity Determination

You should begin by conducting a series of tests similar to those outlined in Table 7-1 to determine a bench-mark for how the dryer is operating under current conditions. You can run this procedure under increasing moisture loads and determine at what point the dryer fails to meet the desired target moisture and uniformity.

The maximum dryer capacity is the point at which the dryer last meets the performance criteria.

To establish an operating strategy for a dryer, you may want to operate at about 90% of the maximum water removal which you determined. This will allow some extra capacity in the event of an emergency and does give an added range of control.

In actual fact, many processors seem to operate a dryer at 110% (or more) of its rated or designed maximum water removal capacity. In spite of demanding that the dryer perform above its design capacity, the operators still want the dryer to function perfectly and to still be capable of handling any "spikes" of high moisture in the incoming product.

As stated previously, the typical approach is to turn up the burners and maximize the volumetric air flowrate. The dryer belt can then be sped up to make a thinner bed of material or slowed down to make a thicker bed but give the material more exposure time. Regardless of the approach, the results are always the same - catastrophic. To make matters worse, the dryer manufacturer usually bears the major portion of the unjustified blame for this.

7.2.5 Typical Problems

If a dryer is not operated properly, the following problems can be expected:

- wet pockets of material (mold growth may occur in the product later).
- toasting / browning of product.
- case hardening + wet centres of particles. This means that the outside of the product is dried to form a hard crusty shell around a moist wet centre of the material. Water cannot readily escape and is caught inside the case-hardened particle.
- stress cracking due to uneven moisture or temperature profiles in a product particle.
- holes in the dryer bed due to air lifting the product.
- dry top and bottom surfaces of the material bed but wet centre layer.
- non-uniformity of drying between product on one side of the dryer and the other.
- poor final product performance due to changes in product properties and functionality.
- economic losses (fuel and product waste).

7.2.6 Changes in Moisture After Drying:

If poorly dried product is packaged, the following problems may arise. The actual packaging material will certainly have an impact on how the product is affected during storage.

- Establishment of equilibrium with ambient atmosphere. You want the product to be dried to a level of moisture that is as close as possible to the moisture at which it will be stored. In this way, the product will not experience excessive moisture losses or gains that can alter its properties and performance.

- Moisture equilibrium of stored or packaged product. You do not want to have excessively wet and dry product in the same package. Moisture changes during storage will affect the product in a negative manner.

- Structural collapse (if improperly processed). Moist product may be soft and collapse in on itself as it dries in the package.

- Spoilage. Mold growth can result if moisture levels are excessive.

- Product shrinkage. Some products actually begin to “shrivel up” if they dry slowly under uncontrolled conditions.

- Nutritional degradation. Nutrients can be lost during storage due to excessive moisture levels.

7.2.7 Factors to Remember About Product Drying:

Once you have established a dryer's water removal capacity and have optimized its performance, there are still some things to keep in mind:

- Every product has its own drying characteristics.

- In the case of agricultural crops, there will be crop to crop variation and seasonal changes based on fresh versus stored material:

  There may be years when kernels of grain are quite large and plump. In other years the kernels may not be as plump. This difference in diameter can affect how fast the grains take up water in a hydration process and how fast they lose water in a drying process.

  You must always be aware of the characteristics in your product to be successful in any drying operation.

CHAPTER 8: SOURCES OF INFORMATION

8.1 Introduction

The Internet / World-Wide-Web is a valuable source of information and should definitely be considered as a primary resource.

When looking for detailed information on drying a particular product, dryer manufacturers and equipment suppliers are a valuable source of information. They often have useful websites with details on how to contact them for further information. Since website addresses are constantly changing while new ones appear and others may disappear, no specific website addresses are given here.

Scientific journals also offer in-depth studies of food drying. These papers are often highly specific and complex in their mathematical treatment of a particular drying phenomenon. For these reasons, scientific journal articles are not listed here.

The following is a list of general reference books relating to food drying and food processing in general. It is not intended to be an exhaustive listing of available textbooks, etc. Once again, the Internet can provide up-to-date information on new publications and journal articles about drying.

8.2 General References:

"**Dehydration of Foods**"; Gustavo V. Barbosa-Canovas and Humberto Vega-Mercado; Chapman and Hall; New York, 1996. (ISBN 0-412-06421-9)

"**Food Preservation and Safety - Principles and Practice**"; Shirley J. VanGarde and Margy Woodburn; Iowa State University Press, Ames, Iowa, 1994. (ISBN 0-8138-2133-9)

"**Food Science - Fifth Edition**"; Norman N. Potter and Joseph H. Hotchkiss; Chapman and Hall; New York, 1995. (ISBN 0-412-06451-0)

"**Food Science and Food Biotechnology**"; Gustavo F. Gutierrez-Lopez and Gustavo V. Barbosa-Canovas, editors; CRC Press; New York, 2003. (ISBN 1-56676-892-6)

"**Food Process Engineering - Theory and Laboratory Experiments**"; Shri K. Sharma, Steven J. Mulvaney, and Syed S. H. Rizvi; Wiley-Interscience; New York, 2000. (ISBN 0-471-32241-5)

"**Food Processing Technology: Principles and Practice**"; P.J. Fellows; Taylor and Francis, New York, 2000. (ISBN 0-8493-0887-9)

"**Fruit and Vegetable Processing**"; W Jongen; Taylor and Francis; New York, 2002. (ISBN 0-8493-1541-7)

"**How to Dry Foods**"; Deanna DeLong; HP Books, Division of Berkley Publishing Group; New York, 1992. (ISBN 1-55788-050-6)

"**Introduction to Food Engineering - Second Edition**"; R. Paul Singh and Dennis R. Heldman; Academic Press; New York, 1993. (ISBN 0-12-646381-6)

"**Perry's Chemical Engineers' Handbook - Seventh Edition**"; Robert H. Perry and Don W. Green editors; McGraw-Hill, New York, 1997.
(ISBN 0-07-049841-5, International Edition ISBN 0-07-115448-5)

"**Principles of Food Processing**"; Dennis R. Heldman and Richard W. Hartel; Chapman and Hall, New York, 1997. (ISBN 0-412-99451-8)