Chapter 6– Boiling, Steam And Humidity

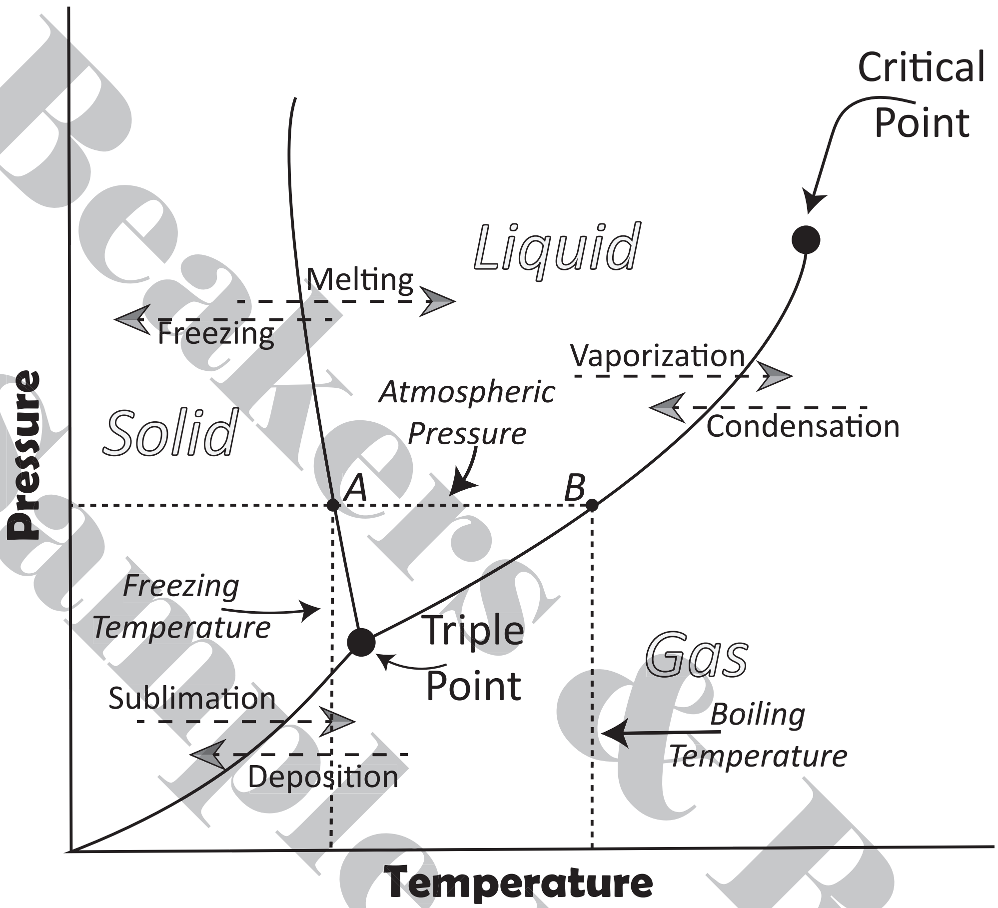
We have evaluated many aspects of water, including when we add other components to it, and the effect those components have on some of the normally observed properties. In this chapter, we will specifically discuss the boiling of water, and then some of the properties of steam.

Boiling Defined and Phase Transitions

What is "boiling"? Merriam-Webster defines the boiling point as "the temperature at which liquid boils". That isn't a very helpful definition for scientific purposes. More specifically, scientists define the boiling point of a substance as being the temperature at which the vapor pressure of the liquid equals the pressure surrounding the liquid. It is at this point that the liquid will break free from the rest of the liquid and phase transition into a gas.

> **Phase Diagram**
>
> **A diagram that shows how a material's phases (solid, liquid, gas) behave in relation to temperature and pressure.**

We have discussed phase transitions quite often in this workbook. At this point, we can evaluate them in more detail. A *phase diagram* is shown below.



There is a large amount of information packed into this chart. First, you will notice there are three lines that connect at a point called the *Triple Point*. These lines represent the demarcation between phases. There is the solid-gas, solid-liquid, and liquid-gas lines. At the triple point, all three phases exist together, at the same time. If you travel on the diagram to any side of that point, you lose two of the other phases. For example, if the temperature increases but pressure remains the same, the solid and liquid present become a gas. If the temperature remains the same but pressure increases, everything becomes liquid. Another point of interest is the *critical point*, which is the point at which water can no longer exist as a liquid, regardless of the pressure. The diagram shows what occurs as you move across any phase transition line. For example, traveling from left to right across the solid-liquid line, water melts. If you travel from right to left across the line, it freezes.

The horizontal dotted line represents atmospheric pressure, or the pressure of the atmosphere at the surface of the planet Earth. The vertical lines represent the freezing and boiling temperatures of water at atmospheric pressure at sea level (on the surface of the planet). Points A and B represent the freezing and boiling points of water, respectively. A is 0ºC (32ºF) and B is 100ºC (212ºF) at 1 atmosphere. Previously mentioned is the unique quality of water. It exists in all three phases, at temperatures commonly found on the surface of our planet. You can see this directly now in this chart.

We will refer to this phase diagram throughout this chapter.

Other terms from the Phase Diagram, as described for water:

Melting: Solid to Liquid. Example, Ice melting to liquid water

Freezing: Liquid to Solid. Liquid water in an ice cube tray in the freezer becoming solid.

Vaporization: Liquid evaporating into a gas. Think of the vapor evaporating from a pot of hot water on the stove.

Condensation: Water vapor becoming a liquid. Think of dew on the grass or your car in the morning, or water condensing on the outside of a cold beverage glass on a warm summer day.

Sublimation: Ice skipping the liquid step and moving directly to a gas. If you have lived in a cold climate and the temperature stays below freezing for several days, you may notice ice reducing in size over time, as water sublimates from a solid to a gas.

Deposition: Water vapor skipping the liquid step and moving directly to a solid. If you have lived in a cold climate, you have experienced this as frost on your car windshield on a below freezing morning.

Hydrogen Bonding

We have previously talked about hydrogen bonding and the unique characteristics that type of bonding gives water. This is also important in considerations regarding phase change. Hydrogen bonding allows water to have such high surface tension, be such a great solvent, and have the relatively low freezing temperature and higher boiling temperature than would be expected by observing other materials in nature. It is truly a miraculous compound.

Phase Changes

We previously examined and evaluated the temperature of pure water as it is warmed to boiling. We saw that it levels off as it approaches the boiling point, then stays constant as the water continues to boil. We discussed how this temperature will remain constant, until there is no water left.

Referring to the phase diagram, let's assume that we are at sea level and have a temperature probe inserted in a block of ice. We then begin to warm the environment while we monitor the temperature. As we measure the temperature while the ice warms, we move along the dotted line towards the solid-liquid phase transition line. Once we get there and continue to add energy (heat) to the *system*, something interesting is noted: the temperature will stop moving until all of the ice is gone. Once the ice is gone, the temperature will again rise until the liquid-gas line is reached. At that point, the temperature will again stop moving, until all of the water has evaporated.

> **System:**
>
> **In this case, a fixed *mass* of water in a fixed volume of space.**

These observations agree exactly with what we have discussed earlier and have also seen through experimentation. These "pauses" in the rise of temperature, while energy continues to go into the system, represent a very large amount of energy.

Latent Heat of Fusion

When you put a cube of ice on your hand, the energy that converts the solid to a liquid is called the *latent heat of fusion*. You can literally feel the energy being taken out of your hand and transferred to the ice as it melts. For this transition, 334 *Joules* per gram of ice is required to convert it to water. This is exactly how an ice chest works, keeping the contents cool. The ice takes energy (heat) out of the environment, as it changes to a liquid. It will continue to do this, until the ice is gone.

> **1 Calorie = 4.19 Joules**

Latent Heat of Vaporization

When water is boiled and vaporizes into steam, the energy required to convert one gram of water to steam at 212F (100C) is 2258 Joules. This is the *latent heat of vaporization*. This is extremely high relative to other common materials found on earth and is also part of the wonder of hydrogen bonding.

You may not have heard of a joule before, or even a BTU, or British Thermal Unit. A calorie is another measure of energy. It is equal to 4.19 Joules. This means that to convert one gram (approximately one cubic centimeter) of water to steam, it would take about 539 calories, or roughly the equivalent of the energy in two candy bars.

If you have ever accidently been burned by steam, you know that it can burn instantly. This can be explained by the latent heat of vaporization. Steam condenses on your skin, releasing much of that energy into your hand. Steam will burn you much more severely than boiling water under similar conditions, although both will be severe burns. I would advise not trying this at home!

Moderation of Temperatures

The phase changing tends to keep temperature changes moderate at certain times. As water falls from the sky and changes into snow, this transition releases heat, moderating the temperature. As snow melts from the ground, it absorbs heat, keeping the ground and air immediately above the ground relatively cool. It is worthwhile noting that these transitions also take time. Water doesn't instantly vaporize as soon as it hits the boiling temperature. The energy must continue to be supplied. Why is this? As water leaves as a gas, it takes energy with it. More energy is required to convert additional water into steam.

Steam Quality

All steam is not equal. I know, it sounds strange, but it is true. *Steam quality* refers to different factors associated with steam, such as whether it is wet or dry, or contains contaminants. Wet steam has condensate in it, or water that has condensed from a gas back to a liquid. Wet steam behaves differently in use than dry steam. It is important to keep a consistent steam quality for a finely tuned, efficient production process. A more thorough discussion of steam quality is beyond the scope of this introductory workbook.

Humidity

What happens to the energy in steam as it enters the room? The water vapor rapidly cools to room temperature., shouldn't it condense and fall out of the air again? The answer is: it depends. It depends on other variables, a big one being the amount of water already in the air, or the relative humidity. Consider the outdoor environment. Water is continually moving between phases. When conditions are right, it rains. The energy is not lost, but remains in the system of this planet, with some escaping into space.

In our kitchen, the same happens. If too much water is in the air, water will start to condense on other objects. Energy from the steam is lost into the room as the temperature of the water vapor drops from boiling to the temperature of the room. However, a significant amount of energy remains with the water vapor in the air and will have to be removed if we want that water vapor to become liquid again.

When we talk about the amount of water in the air, an objective measure is the *percent humidity*, or simply the *humidity*. Very simply, as temperatures increase air can hold more water. When the air is saturated, water will begin to fall out of the air. This can happen in many ways, including rain, dew, frost, and snow.

You may have noticed weather reports that will say it is 85ºF, but it *feels* like 90ºF, because it is humid. What does that mean, and how does it happen? When there is more water in the air, evaporative cooling, such as through your sweat, doesn't work as well. Heat is also transferred to your body much more readily through moist air than through dry air.

In the United States, the reported humidity measurement is usually the percent relative humidity:

% Relative Humidity = (partial pressure of water vapor at temperature X)/(the equilibrium vapor pressure of water at temperature X).

The “at temperature X” part is what makes % Relative Humidity somewhat confusing, at least to me. It is all *relative* to the temperature. What is more useful, in my opinion, is the dew point, which is the saturation point of air. It depends only on the absolute amount of water in the air. The National Weather Service describes it as follows:

> The dew point is the temperature the air needs to be cooled to (at constant pressure) in order to achieve a relative humidity (RH) of 100%. At this point the air cannot hold any more water in the gas form. If the air were to be cooled even more, water vapor would have to come out of the atmosphere in the liquid form, usually as fog or precipitation.
>
> The higher the dew point rises, the greater the amount of moisture in the air. This directly effects how "comfortable" it will feel outside. Many times, relative humidity can be misleading. For example, a temperature of 30ºF and a dew point of 30ºF will give you a relative humidity of 100%, but a temperature of 80ºF and a dew point of 60ºF produces a relative humidity of 50%. It would feel much more "humid" at 80ºF with 50% relative humidity than on a 30ºF day with a 100% relative humidity. This is because of the higher dew point.[6]
>
> So, if you want a real judge of just how "dry" or "humid" it will feel outside, look at the dew point instead of the RH. The higher the dew point, the muggier it will feel.

Dew point is a better, more comparable measure. This terminology is what is typically used in science.

Summary and Application

We have had considerable discussion in this chapter regarding heating water, the resulting steam, and the related humidity. You may be wondering why as a food scientist

[6] https://www.weather.gov/arx/why_dewpoint_vs_humidity; accessed 28 March 2018

you would need to be concerned about these things. Surprisingly, it is integral to what you will do every day. Here are some examples:

- Humidity of the air when drying a sugar-coated cereal. It is critical to the efficient operation of the dryer, especially the humidity inside of the dryer.
- Humidity of the room where sugar or crystalline acid, such as citric acid, is applied to a product. If it is too high, the sugar or acid will clump and not flow, causing production problems.
- The overall humidity in a production area. If it is too high, the water activity of organic material on the side of a production line may remain high enough to allow for mold growth, resulting in unsanitary conditions.
- Poor steam quality, such as wet steam, will unexpectedly and variably increase cook times for grains, vegetables, or anything else you are trying to process.
- Understanding the boiling point of a mixture is important to prevent boil-overs, or where the product bubbles excessively and overflows the container. In a process, steps will be taken to design it such that temperatures are not too close to the boiling temperature. This reduces the risk of a dangerous boil-over.
- The overall humidity of the environment must be considered for the type of package of a product. The package must prevent any moisture migration that is not desired, whether inside or outside of the package. A food scientist will work with a packaging engineer to ensure that this is known and controlled.

These are just some examples of considerations regarding the boiling of water, steam, and humidity in food science. It gives you a little taste of the multi-disciplinary nature of food science. Most food science curricula include a course on Food Engineering, where many of these considerations are taught. A food scientist must understand this, so the proper questions can be asked during product and process design, and quality control.

Experiments: Let's Make a Mess!

Boiling #1: Boiling Point and Water Solutions

Items Needed

- Candy thermometer with pan clip
- 1 cup sucrose (normal white table sugar)
- Corn Starch
- Water
- Small sauce pan
- Spoon
- Ice

Procedures

Note: If you completed Stuff in Water #2 in Chapter 4, you can use your data for Parts A and B from that experiment, and skip to Part C.

Part A

1. Add one cup of water to the sauce pan.
2. Clip the candy thermometer to the side of the pan.
3. Record the beginning temperature of the water.
4. Place the pan on the stove and begin heating on medium heat.
5. Record the temperature every 60 seconds.
6. Once the water begins to boil, continue to record the temperature every 30 seconds for an additional four minutes.
7. Turn off the heat and let it stand until the water is cool enough to safely dump down the drain, around 100^{0}F.
8. Discard the water and run cold water over the pan to cool it, in preparation for Part B.
9. Record any observations you have not already.

10. Create a graph with temperature on the y-axis, and time on the x-axis.

Part B

1. Add sugar and water to the sauce pan.
2. Clip the candy thermometer to the side of the pan.
3. Record the beginning temperature of the blend.
4. Place the pan on the stove and begin heating on medium heat.
5. While heating, record the temperature every 60 seconds.
6. Make a note on your data sheet when the mixture begins to boil.
7. Continue recording the temperature until it reaches 250^{o}F.
8. Turn off the heat and let cool to 150^{o}F. At this point you can wash what is left down the sink or use it as a syrup. To make the candy, you will need to continue heating and evaporating off more water.
9. Record any observations you have not already.

10. Create a graph with temperature on the y-axis, and time on the x-axis.

Part C

1. Add two cups cold water in the saucepan.
2. Stir in two tablespoons of corn starch.
3. Clip the thermometer to the side of the pan.
4. Record the temperature, and begin heating on medium heat, recording approximately every 60

seconds.

5. Be extremely careful! As the mixture beings to boil, it will tend to foam and want to boil over the side of the pan!
6. Continue heating and recording for three minutes, after the mixture begins to boil.
7. Remove from heat and let cool while you record your observations.

8. Create a graph with temperature on the y-axis, and time on the x-axis.

Boiling #1 Discussion: Boiling Point and Water Solutions #2

Part A

Your graph for water should have shown the temperature rising steadily until it approaches boiling (at or near 212^{o}F depending on your altitude), at which point the temperature levels off and no longer rises. This will remain the case until all the water has been boiled off, which we did not do in this experiment. This is an example of a phase change of water.

Part B

The graph will be very different than the one created in A, with boiling not occurring until higher than 212, and then rising steadily as water is flashed off through evaporation. This is additional evidence of the boiling point elevation rule. Note: from the observed boiling point, you can calculate the concentration of the sucrose syrup.

Part C

This graph should have been similar to Part A, but then might become variable once the product began to boil. You may have seen temperatures fluctuating between hot and not so hot. This is because as the starch gelatinizes and causes the dispersion to become thick convection currents are hindered, creating hot and cold spots in the mixture. Since corn starch in water is a colloidal dispersion and not a true solution, the colligative properties, including the boiling point, are not affected.

Convection Currents:

Natural currents in substances associated with gravity and density, where portions of the same substance that are warmer than other portions will be less dense and will tend to rise if conditions allow it, promoting mixing.

Boiling #2: Steam vs. boiling water

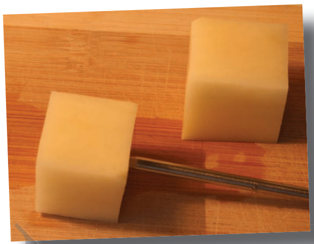
Items Needed

- Pot/steamer combination with lid
- 1 or 2 medium sized potatoes
- Temperature probe
- Knife
- Cutting Board

Procedures

Part A

Important Note: Cut the potato so that you end up with at least two identically sized cubes, approximately 1" on a side. Note: Immediately after cutting the potato cubes, place both in a tightly fitting plastic bag to prevent evaporative cooling (a phase change!). When I first tested these procedures, I did not use a plastic bag. The second potato cooled off 6 degrees due to evaporative cooling while I was working with the first potato, which confounded the results of the test.



1. Fill the pot to a depth that will allow the potato to be held submerged while on the temperature probe.
2. Before adding the potato and probe, bring to a full rolling boil, then reduce the heat to a point where the water is still boiling, but not vigorously.
3. Remove one cube from the bag, reseal the bag. Insert the temperature probe such that is about ¼" from the other side of the cube. Let the temperature stabilize, then record. The temperature should be very close to room temperature.
4. Carefully place the prepared potato cube and probe into the water. Start the

stopwatch. Don't splash on yourself! You will want to hold the probe and potato in place so that they remain submerged.

5. Monitor and record the temperature every 30 seconds until it reaches 200ºF, then stop the stopwatch. Record the amount of time it took for the temperature to get to that temperature, including seconds.
6. Create a graph with time on the x-axis and temperature on the y-axis.

Part B

1. Fill the pot with approximately 2 inches of water, place the steamer lid on the pot.
2. On medium to high heat, bring to a full rolling boil where the steam is escaping freely from beneath the lid.
3. Remove the second cube from the bag and insert the temperature probe, again such that the tip is approximately ¼" from the opposite side of the cube. Record the temperature, it should be the same as the first potato.

4. Carefully place the prepared potato cube and probe into the steamer pot and close the lid and immediately start the stopwatch. **<u>Be careful, the steam can burn you instantly!</u>**
5. Monitor and record the temperature until it reaches 200ºF, then stop the stopwatch. Record the amount of time it took for the temperature to get to that temperature, including seconds.
6. Plot your data on the same chart created for part piece of graph paper used for Part A.

Boiling #2 Discussion: Steam vs. Boiling Water

As discussed in this chapter, steam has a very large heat of vaporization that is exerted on whatever the steam condenses on. In this case, it is the potato. Heating the potato using steam is faster than submerging it in boiling water!

Boiling #3: Boil Egg in Wax Paper Cup

Items Needed

- Paper cup, NOT plastic or Styrofoam. It can be a waxed paper cup.
- Water
- Raw egg
- Oven baking pan, such as for cookies
- Oven cooking sheet with sides, approximately ¾" inch in height
- Oven
- Aluminum foil

Procedures

1. Place the raw egg carefully in the cup and fill it with water so that there is about ¾ inch water above the egg if it were completely submerged.   There should still be at least ½ inch of space above the water, before you reach the top of the cup.
2. Place the oven rack in the middle of the oven.
3. Place aluminum foil on the baking pan and place the cup with water and egg in the center. Place all in the oven on the rack. **Note: I did not use aluminum foil when developing the experiment, which resulted in a wax ring burned into the baking pan which is almost impossible to remove.**
4. Turn on the oven and set it to 350ºF.
5. Monitor the cup with the oven light, or occasionally opening the door briefly. Note what is happening to the cup.

6. Leave in the oven for 30 minutes, then turn the oven off.
7. ***DO NOT ATTEMPT TO MOVE THE CUP OR TRAY UNTIL IT HAS COOLED DOWN. THE CUP WILL BE VERY FLEXIBLE AND COULD SPILL BOILING WATER AND BURN YOU!***

8. Peel and evaluate the boiled egg.
9. Record your observations of the egg and the cup.

Boiling #3 Discussion: Boil an Egg in a Paper Cup

Because of the same phase transition phenomena, we have been investigating, since the paper cup is in direct contact with the water inside the cup, the temperature of the paper cup will not exceed the temperature of boiling water, until all of the water is gone. This allows you to boil an egg in a paper cup! Depending on the cup used, you may have noticed browning of the outside of the cup in the area above the water line. I did when developing this experiment. My cup was one with textured plastic on the outside, which melted and became smooth above the water line.

An even more impressive example of this experiment is to prepare a bed of red-hot coals and then place the cup with the egg directly on the coals. The portion of the cup above the water line will burn away, but the part in direct contact with the water will not be affected, until the water has evaporated!

Journaling Idea:
Describe what your life would be like without refrigeration or freezers. Include air conditioning in vehicles and your home. Did you know that these technologies are new inventions in our history?

Mid-Course Review:

Write short essay responses to each of the following questions:

1. **Refrigerators, freezers, and air conditioners make use of phase changes from a liquid to a gas to move heat around. A compressor converts a gas into a liquid, which is then converted to a gas as it exchanges heat with the interior of the refrigerator, freezer, etc. Use the phase diagram from earlier in this chapter to describe what is happening . You might want to include a basic graph showing the path of the refrigerant.**
2. **When eating a vegetable, do you prefer them fresh and steamed, fresh and boiled, canned, or frozen and then boiled? There are, of course, many other ways to prepare vegetables. They will all result in a different flavor and texture. For example, my favorite vegetable is the sweet pea. However, I love them blanched, then frozen, then reconstituted. I will tolerate them canned, and I am just learning how to even like them fresh. Write about what is happening to your favorite vegetable and preparation method.**