Have you ever placed a soda in the fridge to cool?

Ever wonder what is happening inside the bottle as it cools?

A Brief Summary of How Confined Water Cools

Investigation of the Vertical Movement of an Isothermal Line at the Density Maximum in H_2O and D_2O

William R. Gorman, Gregory J. Parks, and James D. Brownridge
(wgorman1@binghamton.edu, gparks1@binghamton.edu, jdbjdb@binghamton.edu)

When you place a container of water in the fridge to cool it, do you ever think about what is going on inside the container? Well, we were kind of curious, so we decided to take a look to see if anything unique happened. Our initial measuring device was a single thermocouple and it was placed in the water to measure the temperature as the water cooled. We expected to see a cooling curve that followed Newton's Law of Cooling; a smooth curve in the form of an exponential decay. However, we found under certain conditions that there is an inflection or abrupt change in the cooling curve as the water is cooled. Looking at Fig. 1, we can see the difference between the cooling curves of water that is stirred as it cools and water that is not stirred as it cools.

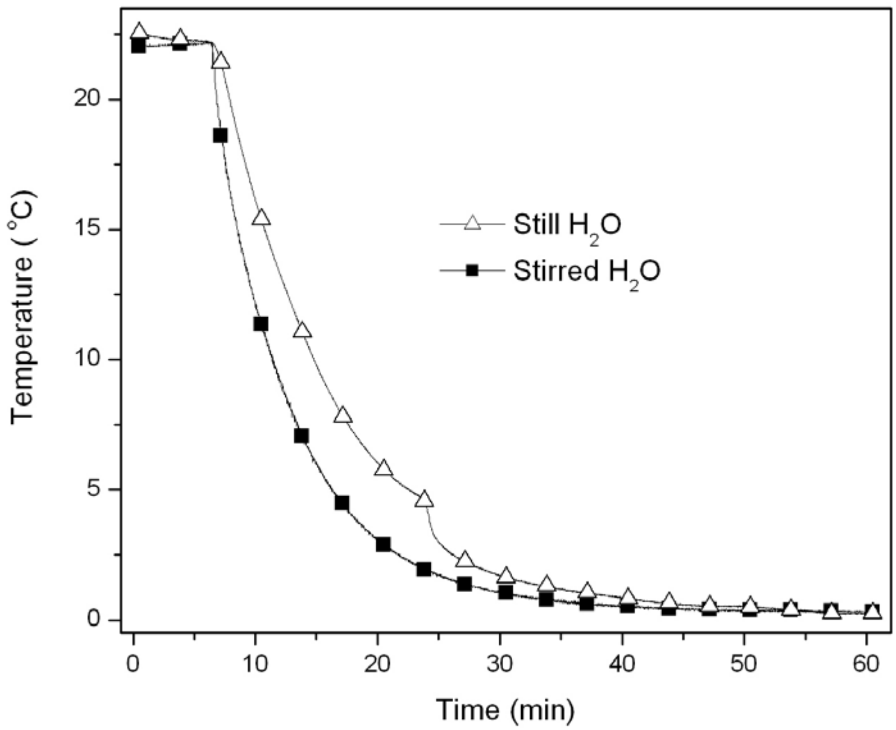

FIG. 1. Temperature versus time showing the difference between stirred and non-stirred water. The thermocouple is at the same location for each curve and the error bars are smaller than the symbols.

For the stirred water, a slowly rotating rotor was placed in the water as it cooled. (Note to the reader: the symbols in most of the figures do not represent actual data points but are used to clearly indicate each curve. The actual data was collected at 1 sample per second).

To try to further understand what is going on, we placed two thermocouples (one top, one bottom) in the container of water. For these tests, the container was 20 cm tall with varying diameters. If we just look at 3 different size diameter containers (4 mm, 16 mm, and 40 mm), as shown in Fig. 2, we see that this disturbance becomes more prevalent with increasing diameter.

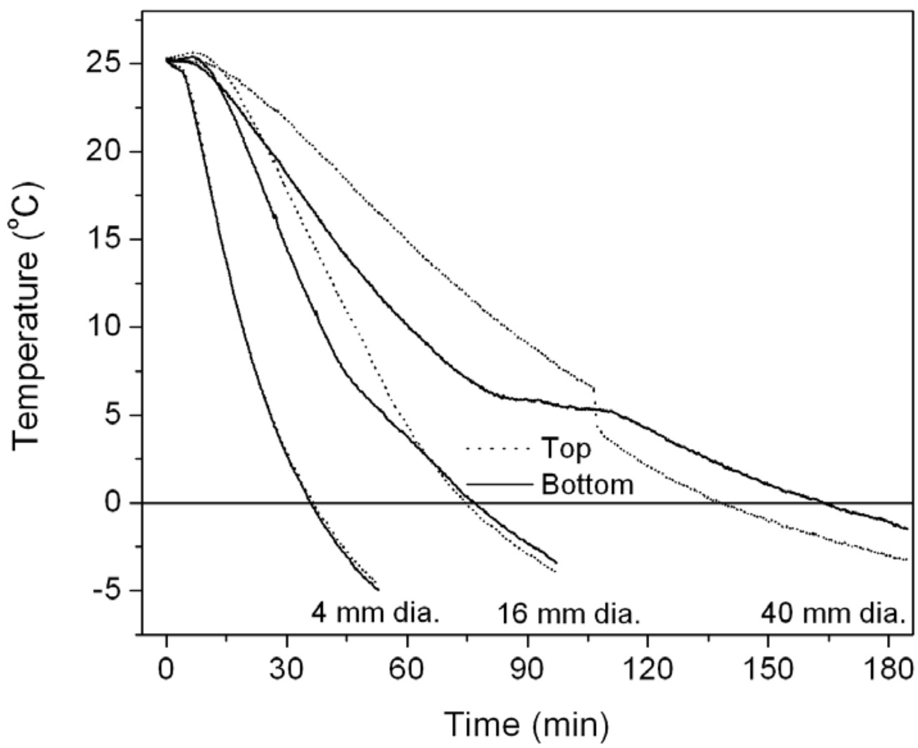

FIG. 2. Temperature versus time of a 4 mm, 16 mm, and 40 mm diameter cylinder with thermocouples placed at the top and bottom.

From this we learn that whatever is causing this disturbance is a function of the diameter of the container. Later we will find out that it is more a function of the cooling rate which can be related to the diameter.

Now that we know roughly the diameter that this disturbance should occur, we decided to evenly space 7 thermocouples up the center of a 60 mm diameter container that was 15 cm tall. This will tell us what happened between the bottom and top thermocouples of the 40 mm diameter curve that we saw in Fig. 2. The results of the 60 mm diameter container are shown in Fig. 3 and warm water was used to show that the effect can still be seen.

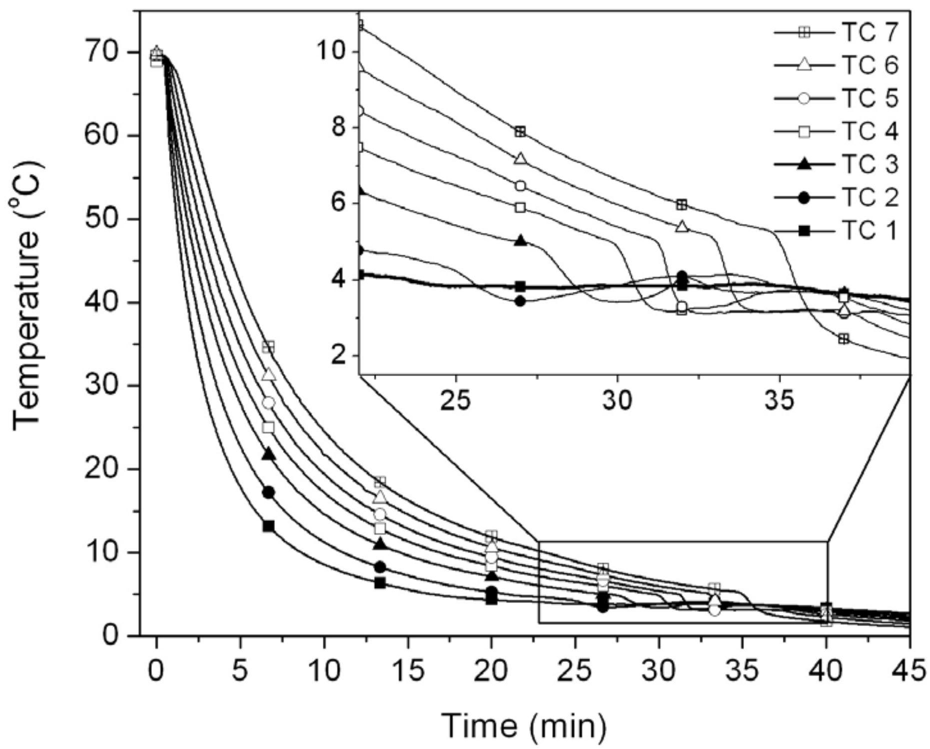

FIG. 3. Temperature versus time of warm water cooled in an ice bath in a container with a 60 mm diameter and 15 cm length. **Inset:** Close up of the movement of the cold front from that same run. TC 1 is at ~0.3 cm from the bottom of the container and TC 7 is at ~0.3 cm from the top of the container.

We describe this disturbance as a cold front or isothermal line moving up the column of water. The cause for this cold front is the result of water having a maximum density of 0.99995 g/mL at $3.984°C$. As the water cools from say $20°C$, it becomes denser and thus starts to sink. This causes the water towards the bottom to cool faster because in addition to loosing heat from the side walls of the container, heat is being removed by denser colder water moving down from the top of the cylinder. As the water at the bottom cools to less than $\sim 4°C$, it starts to become less dense and therefore begins to rise. However, as it rises it comes in thermal contact with slightly warmer water causing it to heat up and become denser, thus sinking. This cycle continues and a cold front moves up the container until there is not enough water warmer than $\sim 4°C$ to keep the process going.

If we place thermocouples vertically very close together (1 cm apart) at the top of the container, we can see the sudden drop in temperature very clearly as in Fig. 4.

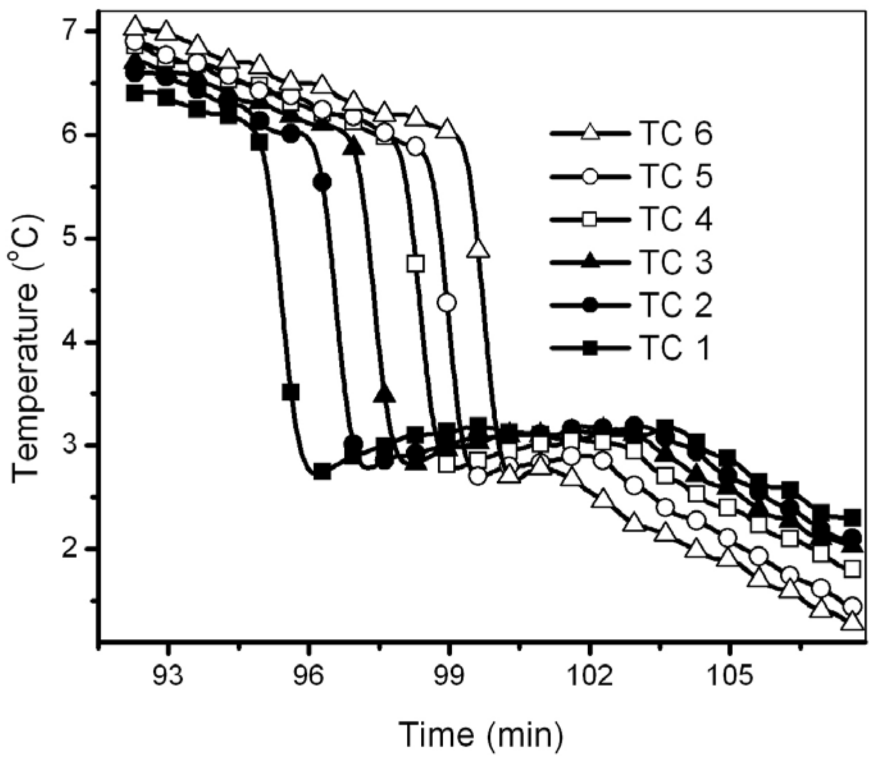

FIG 4. Movement of cold front monitored by 6 thermocouples in a 60 mm diameter cylinder, 21 cm long, with thermocouples 2 cm from the top and spaced 1 cm apart. TC 1 was 14 cm from the bottom.

Knowing the distance between the thermocouples and the time between each one registering the temperature drop, we are able to calculate the speed that the cold front is moving up the column of water. The velocity of the cold front was measured for various diameter containers and is shown in Fig. 5.

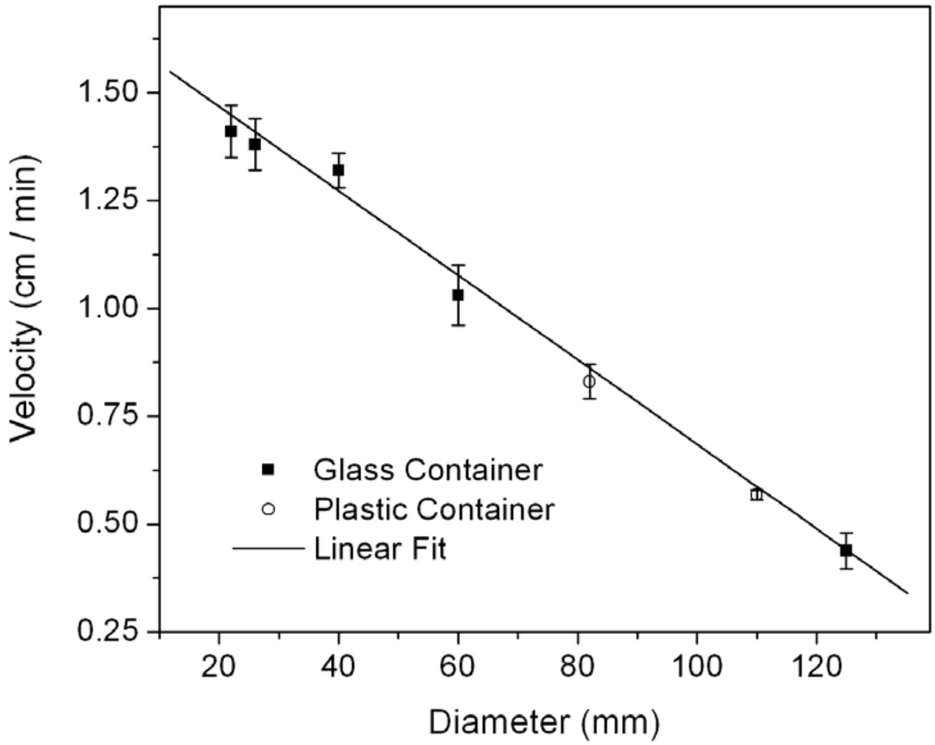

FIG. 5. Velocity versus diameter from the cooling of DI H_20 in the freezer.

This effect can also be seen in D2O since it has similar density properties as H2O, as seen in Fig. 6.

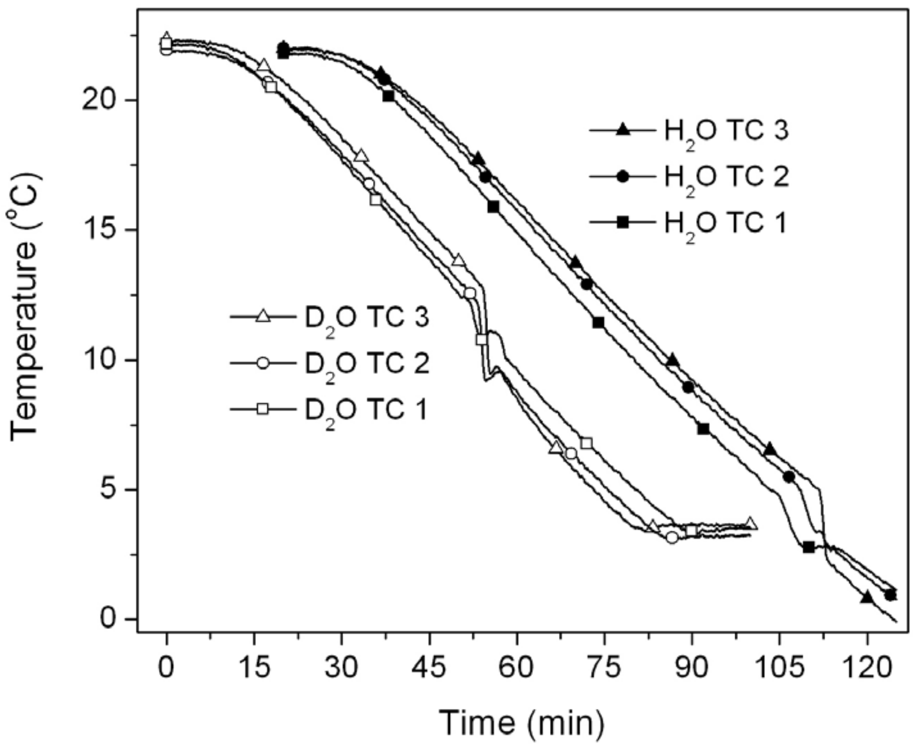

FIG. 6. Temperature versus time for H_2O and D_2O placed in identical containers. The starting times were offset by 20 minutes for graphing purposes. TC 1 is 4.5 cm from the bottom of a 10 cm container.

Supplemental Information

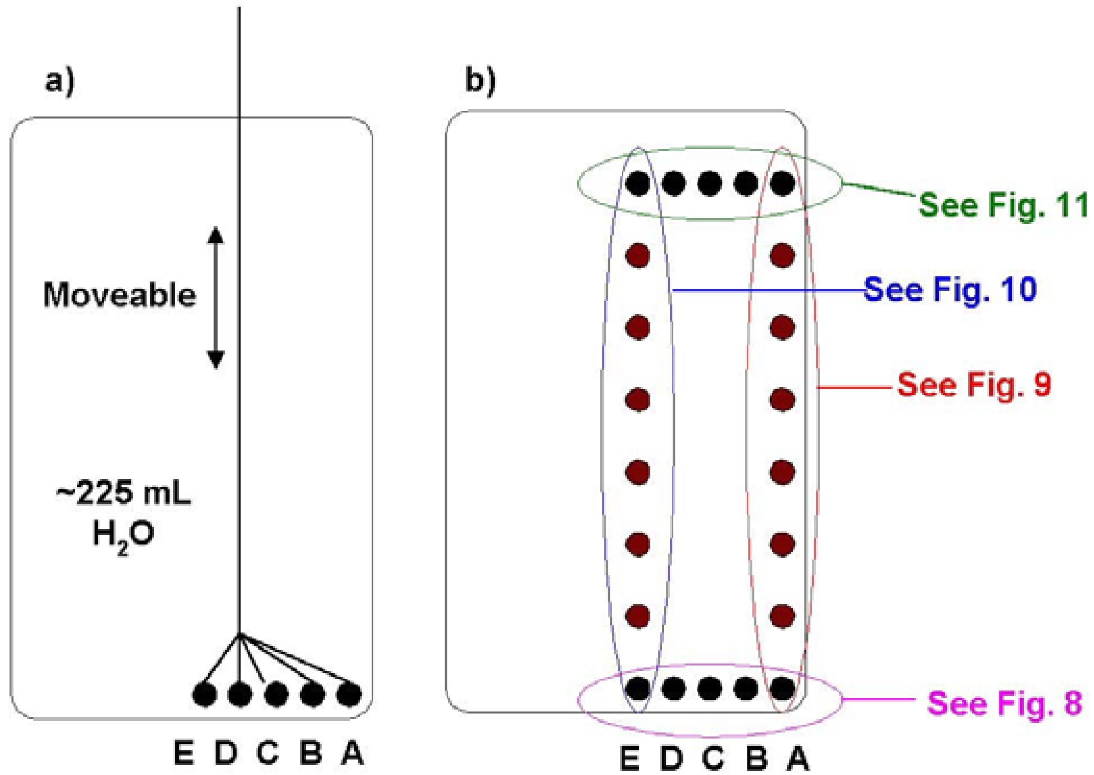

FIG. 7. This is the setup of an experiment that was conducted. Five thermocouples were placed on a moveable rod **(a)** and data was collected at 8 different positions **(b)**. Thermocouple A is 2 mm from the wall with B through E are 8, 14, 21, and 25 mm, respectively. Position 0 is essentially directly on the bottom of the container and the thermocouples are moved up in increments of 1 cm to record the temperature as the water cools at that location. Each position represents an individual run where all 5 thermocouples were collecting temperature data during that run.

Refer to Figures 8-11 to see how the water cooled at the different thermocouple and position combinations. Figure 12 shows the difference in cooling between Coke, Diet Coke, and Water. Figure 13 shows the how the cold front effect does not occur with a small enough volume.

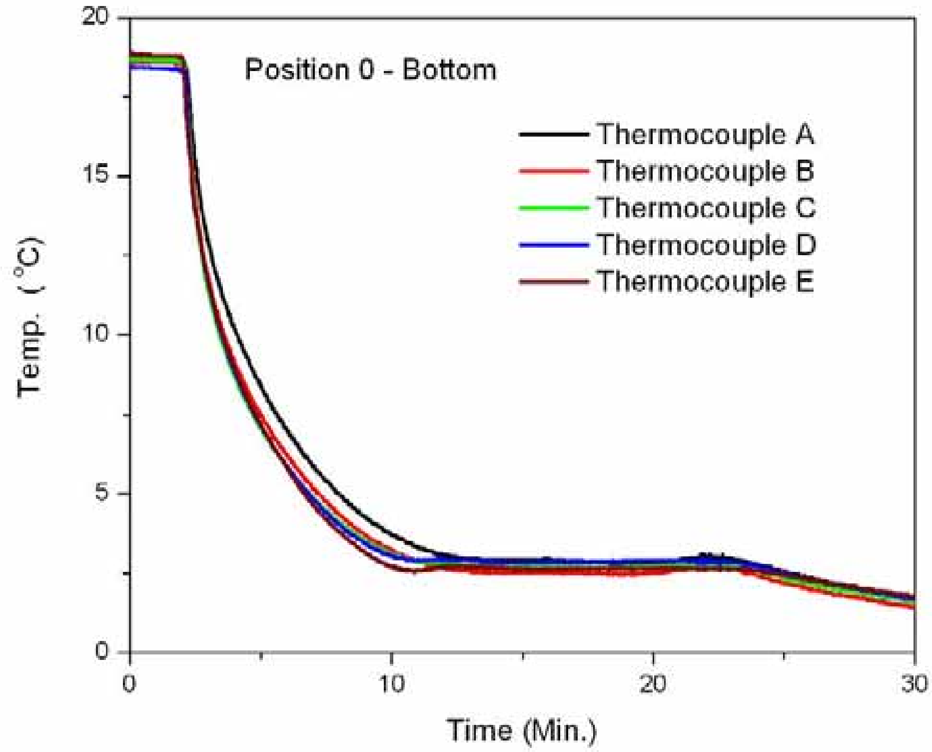

FIG. 8. Temperature versus time when the thermocouples were at Position 0.

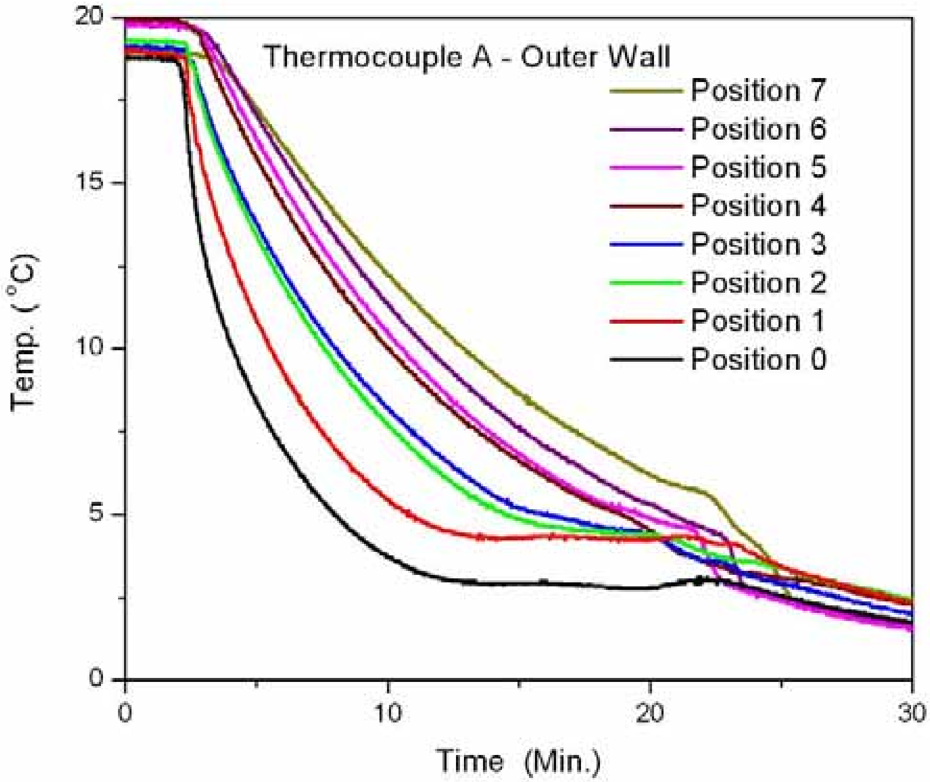

FIG. 9. Temperature versus time for thermocouple A as it is moved up the container of water. Again each position represents an individual run meaning that data was collected at Position 0, the water was allowed to warm, then the thermocouples were moved to Position 1 and the data was collected again as the water was cooled.

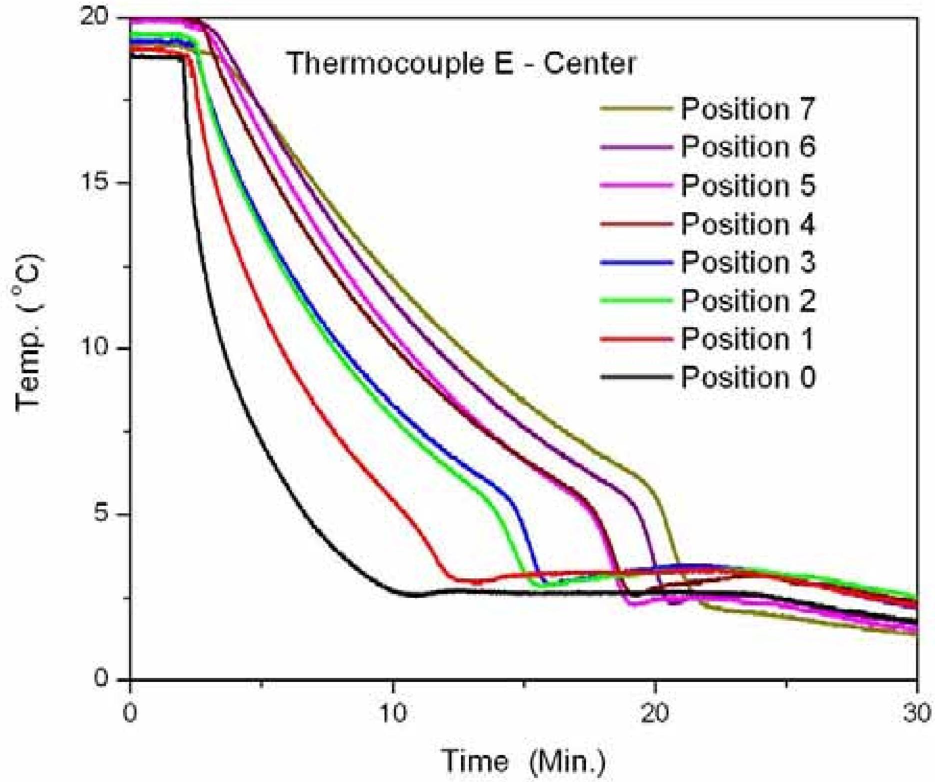

FIG. 10. Temperature versus time for thermocouple E as it was moved up the container of water.

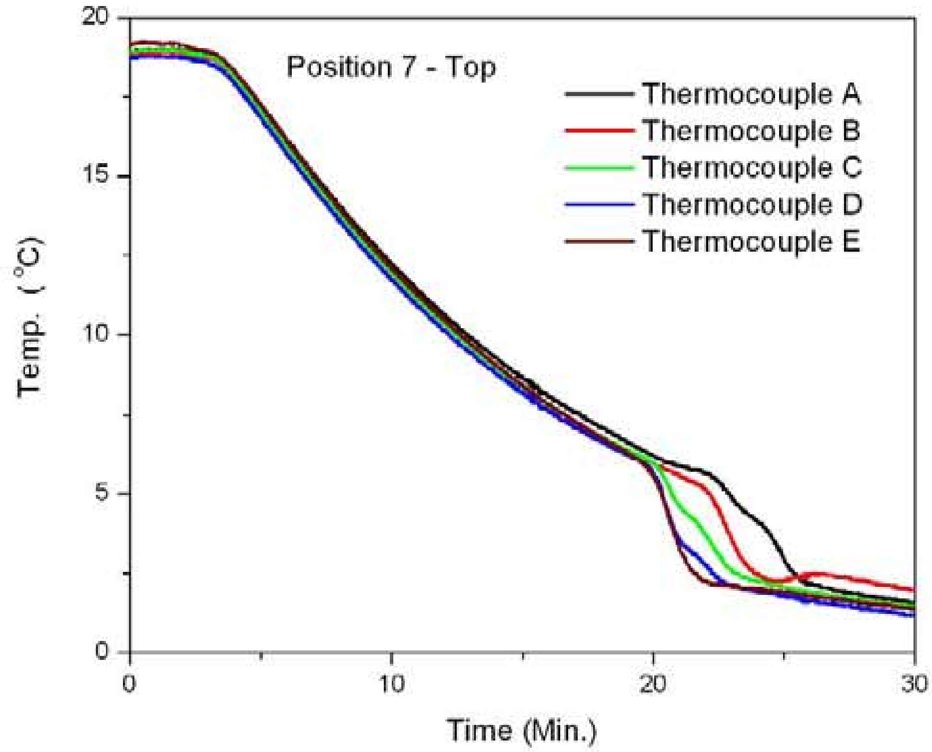

FIG. 11. Temperature versus time when the thermocouples were at Position 7.

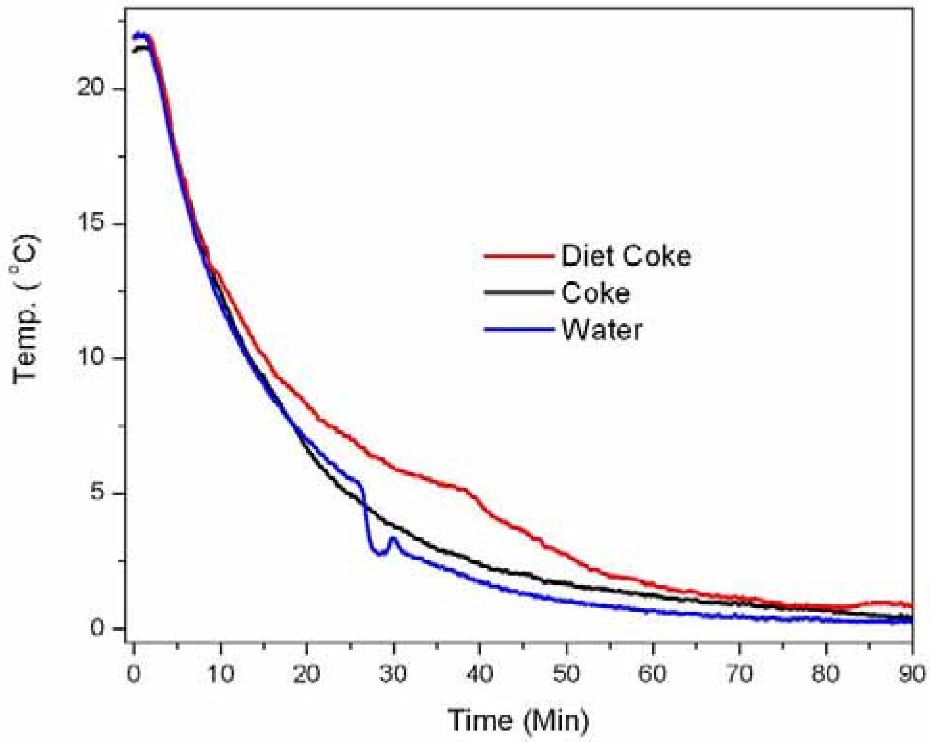

Fig. 12. Temperature versus time for the cooling curve with one thermocouple placed in freshly opened 20 oz containers of Coke, Diet Coke, and Tap Water. The containers were placed in an ice bath to cool. (Coke: 65 grams Sugar, 75 mg Na; Diet Coke: 0 grams Sugar, 75 mg Na)

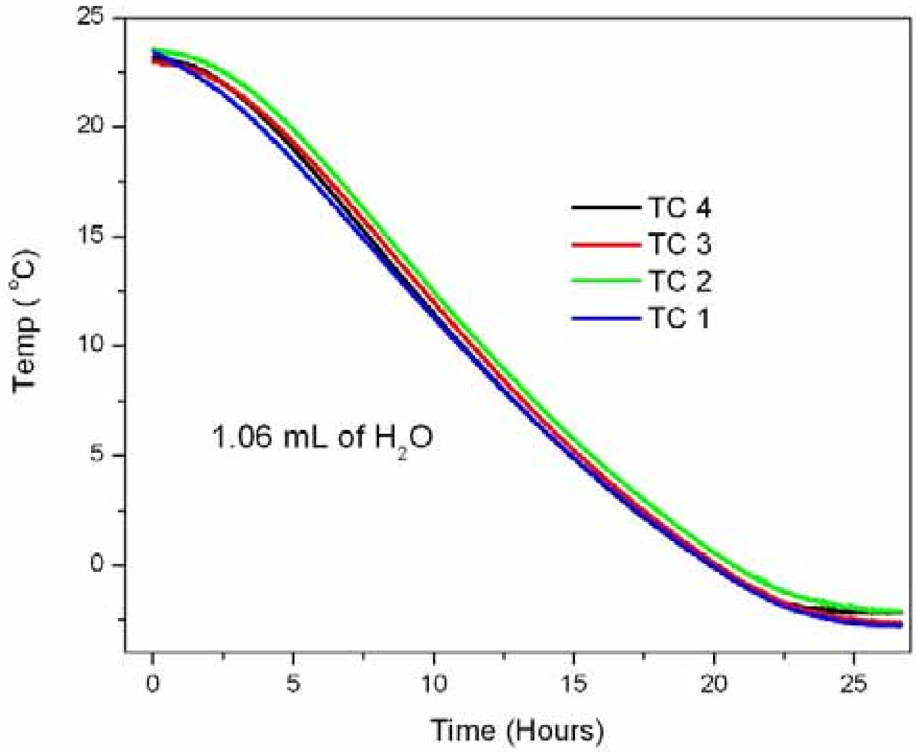

FIG. 13. A small drinking straw was used to demonstrate that if the volume of water is small enough, specifically its diameter, then the cold front effect will not be seen. Thermocouples 1-4 were evenly spaced up the side of the straw with TC 1 starting at the bottom.