Chapter 2

THE ANOMALOUS BEHAVIOUR OF WATER: A SIMPLE EXPERIMENT

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Abstract: A perception exists among students, and many instructors, that highly quantitative physics experiments can only be done in supervised physics laboratories and using specialized and costly equipment. This restrictive view poses an obstacle for the development of correspondence/online courses. With good imagination and adequate research, high quality physics experiments can be designed and performed safely and independently by the students at home using common materials and low-cost devices.

With this in mind, a simple procedure is proposed at the introductory physics level that allows students to observe and perform a quantitative study of the anomalous expansion of water. The procedure involves monitoring the volume of water below and above the anomalous temperature including some interesting observations such as the super-cooled state of water. The temperature at which water reaches its maximum density is estimated in the experiment. For the setup, students use commercially available equipment and common household items, and perform quantitative measurements that are comparable to traditional physics labs.

Key words: Physics, Home-lab, Experiments, Anomalous temperature

1. INTRODUCTION

The temperature of a gas or a liquid, based on the kinetic theory, is a measure of the average translational kinetic energy of the molecules. Therefore, raising the temperature of a liquid (for example) should increase the average separation between the molecules, leading to lower the density. The same principle applies to water, however, with a very interesting exception observed at low temperatures near the freezing point. At about 4°C water reaches its maximum density. Beyond this temperature water will always expand, whether it is being warmed up or cooled down.

This anomalous behaviour is an important characteristic of water, which played a significant role in sustaining marine life. Because of this unusual property, freezing of a body of water, due to changes in weather, begins at the surface. Since ice is also less dense than water, it floats forming an insulating layer that considerably slows thermal conduction from the warmer water below to the colder air above. As a result, life in relatively large fresh water lakes (for example) is protected from the harsh winter weather above and continues in liveable water temperature near 4°C (Soletta & Branca, 2005).

The observation and measurement of this anomalous behaviour near the freezing point is a very interesting and informative experiment in physics (and chemistry). However, incorporating a suitable experiment in an introductory lab course has some procedural and technical challenges. This is simply because the coefficient of volume expansion of water at low temperatures is very small. The water volume only changes by 0.013% in the temperature range 0°C – 4°C (De Paz, Pilo, & Puppo, 1984).

In our case, we had extra technical and financial restrictions, concerning the setup, caused by our intent to include these experiments in the home-lab components of distance education physics courses at Athabasca University (Al-Shamali & Connors, 2010). Therefore, the setup had to be inexpensive, transportable and doable. Also, it was important to ensure that the student can conduct the experiment at home independently and safely without compromising lab quality and acceptable learning outcomes. With these requirements in mind, we designed the experimental procedure discussed in this article.

2. DENSITY AND TEMPERATURE

Since its appearance in the 1960's, the lava lamp became a familiar fixture and a popular house decoration item (Leif, 2008). A close observation of this device provides a clear demonstration of the relationship between density and temperature of a liquid. The lamp contains two insoluble liquids with slightly different densities. Buoyant forces act to achieve a stable layering with the denser liquid at the bottom. This stability is disturbed by turning on a lamp that heats the liquid at the bottom, which interns expand, until its density becomes less than that of the liquid above and starts to rise. The temperature of the rising liquid, however, decreases as it moves away from the heat source and, eventually, becomes the denser liquid again and starts descending.

Considering a column of a single liquid, the temperature (and therefore the density) is not expected to be uniform throughout the liquid. However, buoyancy always acts to rearrange density distribution in a vertical continuum (or gradient) starting with the smallest density at the top to the largest density at the bottom of the column. Since density usually decreases with increasing temperature, the stable state also means a continuous temperature gradient from the warmest liquid at the top to the coldest liquid at the bottom.

Water, in particular, has the same general behaviour for the majority of the possible temperature range down to 4°C. At this temperature, however, water reaches its maximum density and expands as it gets colder. Therefore, away from this temperature, a water column should remain statically stable (no convection) during a gradual decrease (or increase) of its overall temperature. However, when the temperature inside the column starts to cross the 4°C mark, the stable density distribution is disturbed generating convection currents. Even though, the change in water density in the temperature range (4°C – 0°C) is relatively very small, it causes a dramatic reversal of the whole temperature gradient in the water column in order to revert to the stable density distribution. As a result, the upper and lower ends of the water column undergo significant temperature changes while this reordering of colder and warmer layers of water takes place.

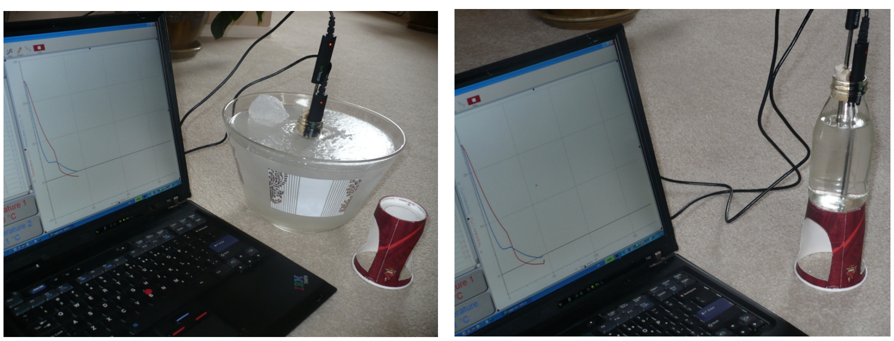
At this point, it should be emphasized that the main idea behind the experiment presented in this article is not new. Actually, relevant literature goes back as far as 1805 when Thomas Hope published a set of experiments to observe and study this interesting behaviour of water (Greenslade, 1985). In his experiments, Hope did not attempt to measure the water volume as a function of temperature. He, however, employed an indirect (but elegant) method that monitors the redistribution of the temperature gradient in a water column as a result of density changes around 4°C. Here, we present a modern and more practical experiment suitable not only for traditional undergraduate laboratories, but also for home-labs in distance education courses.ext section of your chapter begins here.

3. EXPERIMENT AND OBSERVATION

The main aspect of this experiment is the simplicity of its setup and procedure compared to the significant educational value and learning outcomes expected. Other than the commercially available Vernier temperature probe (Go!Temp), the experiment was conducted using common household items, including a personal computer, a small size glass juice bottle, a deep kitchen bowl and some table salt.

The water column was formed by filling the empty juice bottle with tap water, avoiding the narrow section of the bottle neck. The cold reservoir was created by filling the kitchen bowl with salt-water solution and then cooling it down in a home freezer for few hours or overnight. Note that, depending on the freezer's temperature and salt concentration, the solution will become slushy or covered with a soft crust of ice. In this case it should be easy to make a hole in the crust that fits the bottle.

For temperature measurements, we used two probes that were inserted in the bottle at different heights (see Fig 1). The first probe, with its tip about 1 cm below the water surface, was sensitive to the temperature in the upper layer of the water column. The second probe, on the other hand, was pushed all the way down the water column such that its tip was just above (but not touching) the bottom of the bottle. The two probes were connected through USB ports to a personal computer. The "Logger Lite" data-collection software, installed on the computer, displayed the temperatures measured by the probes and allowed the simultaneous recording of the temperatures at both ends of the vertical water column. The software was set to auto-record the temperatures every 2 seconds.



(a) (b)

Figure 1: (a) Water bottle cooling down in a cold salt-water solution reservoir (b) The water bottle warming up by the surrounding air at room temperature.

Figure 2 displays two graphs corresponding to the temperatures measured (in one of the trials) by the two probes as a function of time. In this trial of the experiment, the auto data collection started with the initial water temperature inside the bottle at about 16°C. Note that the temperature at the bottom of the water column was initially less than that at the top. After few minutes, the bottle was inserted in the cold reservoir, with temperature near –10°C. As a result, the water temperature inside the bottle started to drop very quickly, as shown in the graph. It is interesting to note that while the top layer of the water column remained warmer than the bottom layer, the temperature near the bottom cooled at a faster rate.

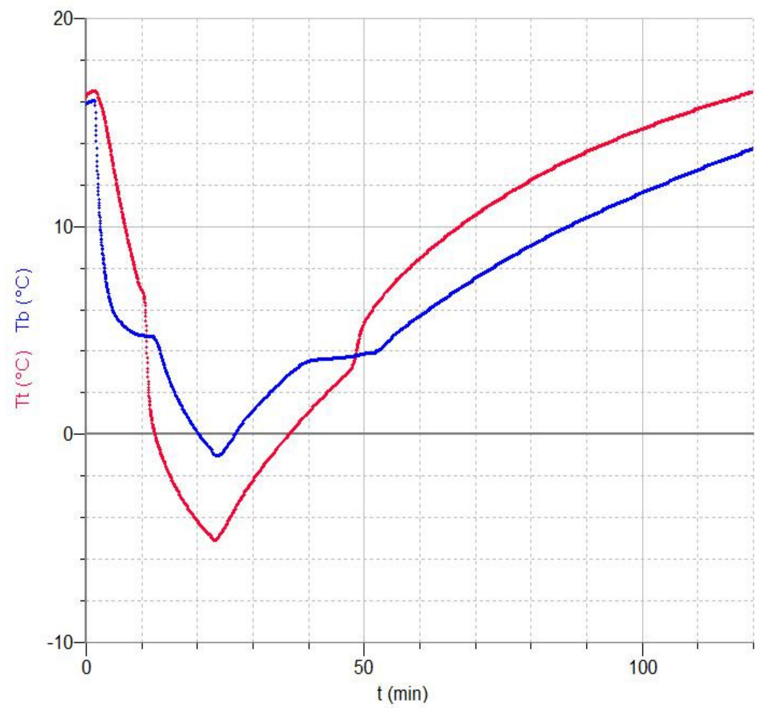


Figure 2: Temperatures of the top (red) and bottom (blue) layers of the water column inside the bottle.

When the temperature of the bottom layer reached about 6°C the cooling slowed down dramatically and nearly reached a plateau at about 4.5°C. This trend continued for more that 5 minutes before the temperature curve almost suddenly resumed cooling down. The temperature of the upper layer, however, dropped to about 7°C when it started to cool down much faster to a temperature of about 1°C. It is clear from the graphs that by this time the water near the top of the water column was colder than the water near the bottom, thus indicating a reversal in the temperature gradient of the water column. After that, the cooling continued (at a more normal rate) to subzero temperatures without freezing.

While the water column was in the super-cooled state, the bottle was carefully removed from the cold reservoir, dried out with a towel and allowed to warm up slowly by the surrounding air at room temperature. To minimize heat transfer irregularities, the bottle was placed on an inverted paper cup that had its bottom removed (see Fig 1b) thus allowing more uniform air-to-glass heat conduction from all sides of the bottle. As seen in the graph, the water temperature started to increase, but at a slower rate than the cooling process. This is expected due to the differences in thermal conductivities between water and air in the two reservoirs.

In the warming process, the overall temperature trend (in Fig 2) was almost the opposite of what was observed during the cooling process. At about 4°C the warming rate of the bottom layer in the water column had a sharp decrease in the warming rate during which the temperature remained almost constant for about 13 minutes. The colder upper layer, on the other hand, continued to warm up at a normal rate until about 3.5°C. After that, the temperature increased more sharply to about 5°C and then resumed increasing at a more normal rate. At this time, it was obvious that the initial temperature gradient was restored with the warmer water near the top and the colder water at the bottom of the water column.

4. SUPER-COOLING

As mentioned in the introduction, the main objective of this experiment was to demonstrate the anomalous behaviour of water at low temperatures (above 0°C). However, it was also very interesting to note that the experiment provided an opportunity to demonstrate the phenomenon of super-cooling in which water cools down to sub-zero temperatures without freezing. Using clean drinkable water and avoiding shaking the bottle, we easily reached (see Fig 2) a temperature of –5°C inside the bottle. However, it should be noted that if the super-cooled state is not stable and if the bottle is given a good shake, instant freezing occurs and the temperature inside jumps to 0°C.

This phenomenon was also an opportunity to check the temperature probe's calibration and measurement uncertainty. Figure 3 shows the result of a test in which the two probes were inserted together inside the bottle such that their sensitive tips are at the same height in the water column. Ideally in this situation, the two probes should display the same temperatures. However the discrepancy in the measurement is within the probe's uncertainty (± 0.5°C) reported by the manufacturer. Of particular interest here is the sudden rise in the graphs, which coincides with the instant freezing of the super-cooled water in the bottle. The temperature, as measured by each probe, deviates from the expected zero value only by the equipment uncertainty.

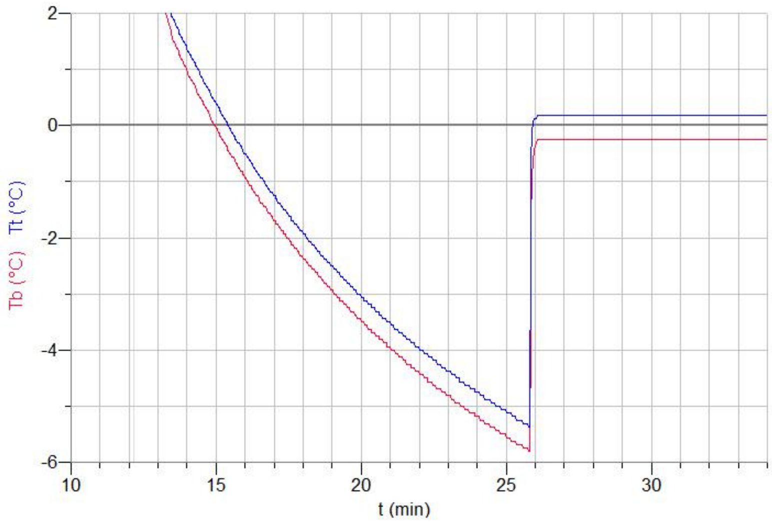


Figure 3: Cooling of the top (red) and bottom (blue) layers of the water column to the super-cooled state followed by instant freezing.

5. ANOMALOUS BEHAVIOUR

When the water column (or bottle) was placed in the cold reservoir, the temperature throughout the column started to drop very quickly, as seen in Fig 2. This is mainly due to thermal conduction, through the glass walls, from the warmer water inside the bottle to the colder water in the reservoir, according to the Second Law of Thermodynamics. From the temperature graphs, however, we notice that the bottom layer cooled faster than the upper layer in the water column. This can be explained by the argument that the relatively colder (and therefore denser) water formed just inside the bottle side walls convected down to the bottom and pushed the warmer water through the central column towards the upper layer. Therefore, while thermal conduction worked to reduce the overall temperature inside the bottle, convection currents accelerated the cooling process at the bottom of the column and slowed it down at the top. With this, we obviously disagree with the argument presented in (Gianino, 2007) to explain a similar observation referred to as the isothermal phase.

As the temperature of the bottom layer approached the anomalous temperature, the convection process mentioned above started to slow down, thus gradually reducing the cooling rate of the bottom layer. When the water near the bottom reached its maximum density the downward convection process at the side walls appears to have stopped and reversed direction. This means that the relatively cold water near the side walls started to convect upward towards the top layer pushing the relatively warmer water down through the center of the water column. This was reflected in the graph by the sudden cooling of the upper layer while the temperature of the bottom layer remained almost unchanged for a few minutes. Actually, in one of the trials (see Fig 4) the temperature of the bottom layer experienced an increase during this transient period. When the rearrangement of the temperature gradient was completed (colder at the top and warmer at the bottom) the cooling process resumed at a more normal rate. It is interesting to note that the cooling (and also the warming) rate of the water column was not affected by crossing the zero temperature line.

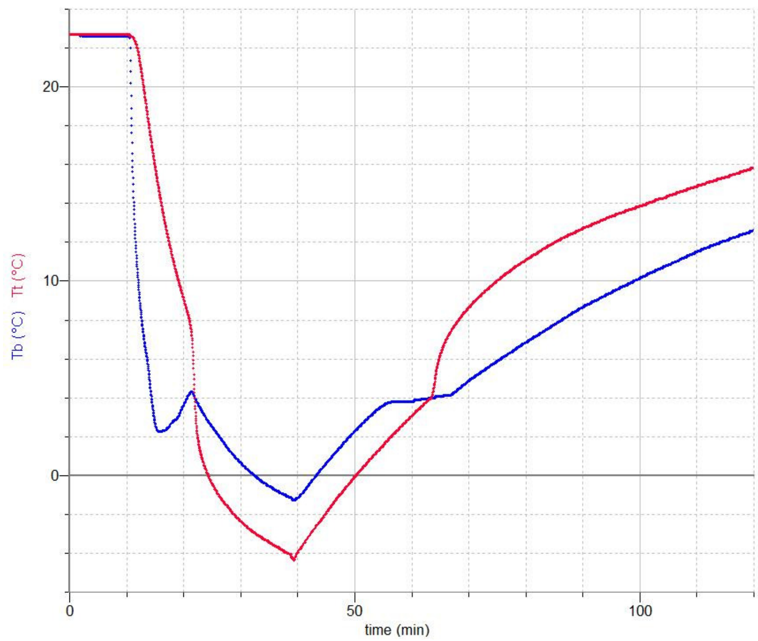


Figure 4: One of the trials of the experiment showing a transitory warming up of the bottom layer near the anomalous temperature during the cooling process of the water column.

When the water column was removed from the cold reservoir and started warming up by the surrounding air at room temperature, the opposite trend in temperature changes was observed. From Fig 2, we see that the temperatures at both ends of the water column initially increased at nearly similar rates. However, when the temperature of the bottom layer approached the anomalous temperature (of 4°C) the warming rate of this layer slowed down very quickly. This was obvious from the corresponding temperature curve which almost reached a plateau that continued for about 13 minutes during which the temperature increased by only a fraction of a degree. This was a sign that the bottom layer reached maximum density, at this anomalous temperature, and only water at this temperature sank down and remained at the bottom.

The upper layer, on the other hand, continued to warm up at the same rate until it approached the anomalous temperature (see Fig 2). The warming rate, after that, quickly increased crossing the temperature curve of the bottom layer. Apparently, this was triggered by the sinking of the heavy upper layer down the centre of the water column combined with the rise of the relatively less dense warm water near the side walls. When the rearrangement of the density gradient was completed, the water column continued warming up at a normal rate.

From the graphs in Fig 2, we clearly see that the accelerated change in the upper layer's temperature was centered about the 4°C mark. Also, the stabilization of the temperature in the bottom layer is also very close to this temperature within the instrument's precision and accuracy (±0.5°C). To show that such behaviour is a special characteristic of water, a similar procedure can be applied using other liquids (Branca & Soletta, 2005).

6. CONCLUSION

The anomalous behaviour of water near 4°C is a very interesting characteristic of this vital and abundant liquid on our planet. Therefore setting up a lab experiment that clearly demonstrates this behaviour and allows for a quantitative measurement of the anomalous temperature is of great educational value. In this article we presented a simple experimental procedure to achieve this objective, which involve observing the reversal of the temperature gradient in a water column as the temperature changes beyond the anomalous temperature.

The experiment also demonstrated another interesting phenomenon which is the super cooling of water. This demonstration challenges the belief among many students that water must freeze at 0°C.

Finally, we should emphasize that quality physics experiments can be designed at low cost and can be performed safely and independently by the student either as a home lab experiment or as an assignment. We believe that using imagination and dedicated research a wide range of highly quantitative physics lab experiments can be designed that satisfy this purpose. This is especially important in Distance education institutions such as Athabasca University.

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