Cooling of Water in a Flask: Convection Currents in a Fluid with a Density Maximum

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The effect of density inversion on the convective flow of water in a spherical glass flask cooled with the help of an ice-water bath is shown. The experiment was carried out by temperature measurements (cooling curves) taken at three different heights along the vertical diameter of the flask. Flows inside the flask are visualized by seeding the water with blue ink.

Background

Pure water, when compared with other liquids, displays some unusual properties. Perhaps the most interesting of such properties is what is called the *density anomaly*: whereas a *normal* liquid contracts as temperature decreases, liquid water expands when its temperature drops below 4ºC. This implies that the density of liquid water reaches a maximum value at this temperature.[1] The density anomaly of cold water has a lot of influence in both flow and cooling rates before freezing and plays an important role both in nature and in engineering applications.

In 1805 Thomas Charles Hope[2] carried out a series of experiments to show that water has its maximum density at a temperature between 39ºF and 40ºF (in Hope's work temperatures are given in degrees Fahrenheit). In these experiments Hope created by different methods vertical temperature gradients in a cylindrical glass jar filled with water and measured the temperature of the water at the top and the bottom of the jar. In one of the experiments the jar was filled with water at room temperature and was immersed in a water bath kept near the freezing point. Hope measured the temperature variation with time at top and bottom, and observed that the temperature at the bottom fell rather quickly to ~40ºF and stayed there for a while before falling again. The temperature at the top initially decreased more slowly and was higher than at the bottom, but during the time when the bottom remained at 40ºF the top became colder than the bottom. Hope concluded that above ~40ºF the colder water was denser, but below ~40ºF the warmer water was denser. A revision of Hope's experiments including temperature-time graphs has been reported by Greenslade in this journal.[3] Branca and Soletta[4] reproduced another Hope experiment in which the jar was filled with water under 4ºC and slowly warmed to room temperature. In Branca and Soletta's work, top and bottom temperatures were recorded by using calculator-based laboratory technology, and temperature-time graphs for water were compared with those obtained for denatured alcohol and cooking oil.

Other simple experiments can be used to show the maximum density of water at 4ºC. For example, if an unstirred mixture of ice and water is placed in a beaker, the ice remains at the surface (because its density is lower than that of the water) and, after coming to equilibrium, the water near the ice is at 0ºC, while the denser water at the bottom is at 4ºC. This experiment is very useful in environmental science education to show the possibility of life in a frozen lake. Recently, Soletta and Branca[5] carried out a nice experiment in which they created conditions similar to those present in a lake when the external temperature falls below 0ºC. In the experiment, water in a jar is cooled by means of a cryogenic mixture externally attached about halfway up the jar. Cooling curves for the water are recorded by means of two temperature probes located in the lower and upper part of the jar. This allows a qualitative discussion about heat exchange associated with convective currents inside the water.

In the present paper we discuss an experiment similar to Hope's. Our experiment consists of cooling water inside a spherical glass flask by means of an external ice-water bath at 0ºC and focuses on showing how the convective flows of the water inside the flask change their sense of rotation due to the density inversion. To visualize the flow patterns, a few drops of blue ink were injected into the water and the process was recorded using a DVD camcorder.

Experiment

Figure 1 shows the experimental setup. A 100-cm^3 spherical flask was filled with motionless water at room temperature (~19ºC) and closed with a rubber stopper. Three K-type thermocouples (-270ºC to 370ºC with a 0.1-cm diameter stainless steel probe) pass through the center of the rubber stopper and were placed at different heights along the vertical diameter inside the flask. One was located 3 mm from the bottom, the second one was situated at the center, and the third one was located at 3 mm from the top. Each thermocouple was pre-calibrated by being submerged sequentially in an ice-water bath and in a vessel with boiling water. An ice-water bath was formed by mixing water and crushed ice in a 2-L glass vessel. The bath was stirred, using a magnetic stirrer, to maintain a uniform temperature of 0ºC. The flask was suddenly and totally immersed in the ice-water bath. A data logger/PC[6] system recorded the thermocouple temperatures in real time.

Results

Figure 2 shows the cooling curves taken by the thermocouples during the cooling process. The instantaneous slope of each curve provides the cooling rate at the point where the probe is located. The qualitative interpretation of these curves

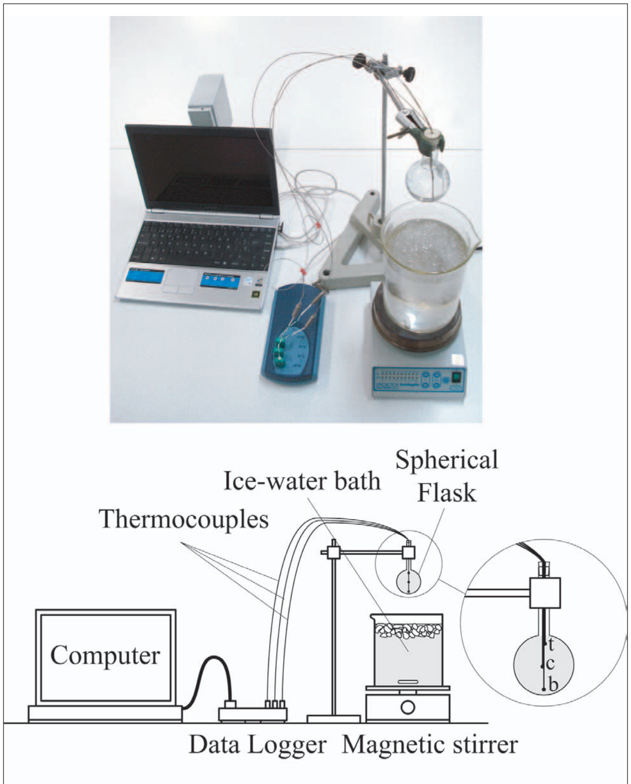

Fig. 1. Photo and scheme of the experimental setup used to analyze the effects of density inversion on the convective flow of water in a spherical glass flask cooled with an ice-water bath. The three type-K thermocouples are placed at different heights along the vertical diameter of the flask, bottom (Bot), middle (Mid) and top (Top). Their temperatures are recorded by means of a data logger connected to a PC.

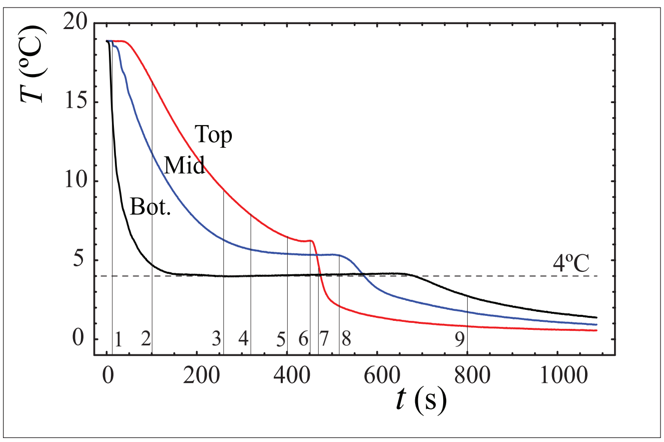

Fig. 2. Temperature versus time for the three thermocouples located at the bottom (black curve), middle (blue curve), and top (red curve) of the flask. Time is measured from the instant that the flask is immersed in the ice-water bath. The vertical lines marked from 1 to 9 correspond to the times of the frames shown in Fig. 3.

is the following: When the flask is immersed in the bath, the water temperature in a layer near the wall decreases quickly and hence the density in this layer increases. Therefore, the cooler water near the wall sinks following the direction of the wall toward the bottom and rises along a vertical central path. The bottom probe (T_{Bot}) is the first to detect the cooling process near time $t = 12$ s, followed by the middle probe (T_{Mid}) and, finally, the top probe (T_{Top}). The arrangement $T_{Bot} < T_{Mid} < T_{Top}$ continues while the temperatures of the three probes are greater than 4ºC. After this initial cooling stage, each cooling curve reaches a plateau where the temperature remains almost constant. The longest plateau occurs for the bottom probe at 4ºC beginning at time $t \sim 150$ s. Water at this temperature reaches its maximum density and tends to collect near the bottom of the flask. Next, the middle curve plateaus at $t \sim 350$ s and $T_{Mid} \sim 5$ºC. Finally the top curve plateaus briefly at $t \sim 430$ s and $T_{Top} \sim 6$ºC. Near $t = 450$ s, the temperature of the top probe begins to decrease quickly from 6ºC and its associated cooling curve intersects the other two. This suggests that cooler water coming from regions near the wall is arriving at the top of the flask. This cooler and denser water sinks along a vertical central path. This process causes the temperature at the center of the flask to begin dropping rapidly near 520 s. Finally, near $t = 630$ s, the temperatures of all three probes have dropped below 4ºC and approach 0ºC with $T_{Bot} > T_{Mid} > T_{Top}$. Therefore, between the initial and final cooling stages, a density inversion has occurred. That is, at the beginning of the experiment, the densest water at the bottom has the lowest temperature in the flask, and at the end of the experiment it has the highest temperature.

To visualize the convective flow patterns, a few drops of blue ink are injected into the bottom of the flask with the help of a Pasteur pipette. The cooling process is recorded with a DVD camcorder. Some frames captured from the camcorder recording are shown in Fig. 3. These frames correspond to the times marked in Fig. 2. Frame 1 (12 s after the immersion of the flask) shows a column of ink rising through the center of the flask. The interpretation of this effect is the following. When the flask is immersed in the bath, the spherical layer of water near the wall undergoes a rapid decrease in temperature and increase in density. Therefore, the cooler water near the wall tends to sink downward along the wall, collecting at the bottom of the flask. Water from the bottom is then displaced upward along a vertical central. Frame 2 (100 s) occurs during the initial cooling phase, in which $T_{Bot} < T_{Mid} < T_{Top}$. It shows a complete convective cell circulating downward along the walls and back upward through the center of the flask, shown schematically in Fig. 4(a). Frame 3 (260 s) shows the initial convective cell occupying a smaller volume of water in the upper section of the flask as more of the 4ºC water settles near the bottom. In addition, a second convective cell emerges near the bottom of the flask. This lower cell, generated by density inversion, circulates in a direction opposite that of the upper cell. This is because water that is cooled below 4ºC near the bottom sidewall moves upward slightly along the wall, return-

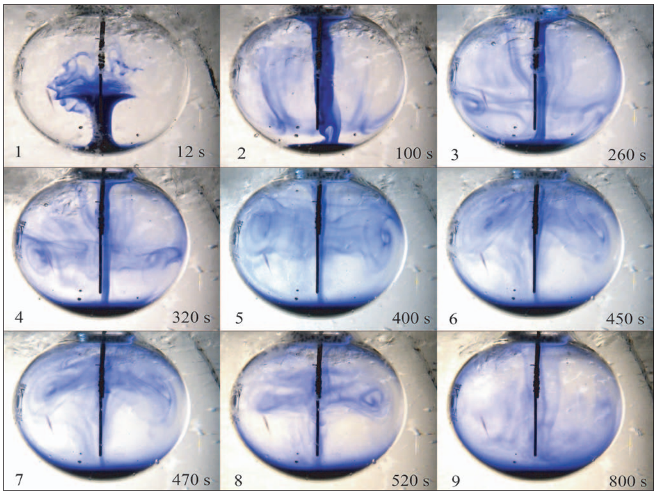

Fig. 3. DVD frames of water flow patterns inside the flask during the cooling process. The frame numbers correspond to the vertical lines marked from 1 to 9 in Fig. 2. Time is measured from the instant that the flask is immersed in the ice-water bath.

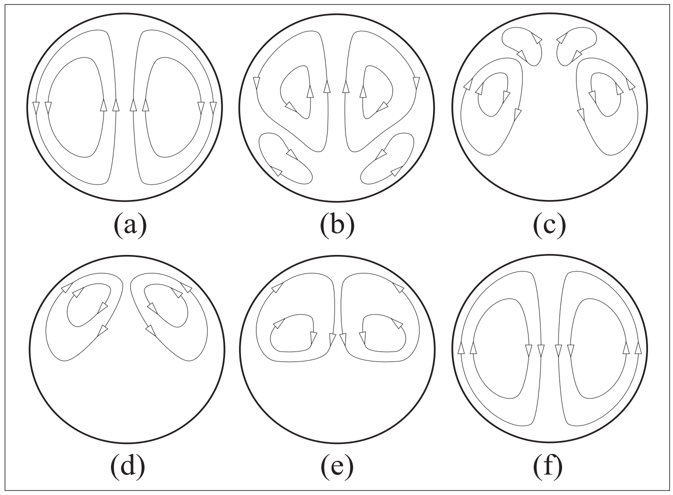

Fig. 4. Schematic diagrams of streamline patterns inside the flask. (a) All of the water is involved in only one convective cell sinking from the wall and rising by the center (this scheme corresponds to Frame 2 of Fig. 3). (b) A second convective cell generated by density inversion emerges from the bottom sidewall (Frame 3). (c) The upper convective cell decreases while the lower convective cell grows (Frame 5). (d) The upper convective cell has already vanished (Frame 6). (e) The convective cell is growing downwards along the vertical diameter (Frame 8). (f) All of the water participates in only one convective cell, but the circulation direction has changed with respect to that of the initial cell (Frame 9).

ing downward by the center of the flask. This effect is shown schematically in Fig. 4(b). Frame 4 (320 s) and frame 5 (400 s), both during the initial cooling phase, show that there is a progressive decrease in the volume of water involved in the upper convective cell and a corresponding increase in the counter-circulating volume of water involved in the lower convective cell (Fig. 4c). In frame 6 (450 s), the lower convective cell has nearly reached the top probe and it seems that the upper convective cell has already vanished [Fig. 4(d)]. This is just before T_{Top} begins to drop sharply and cooler water is expected to sink downward from the top of the flask. Frame 7 (470 s) shows that the convective cell starts to grow downwards along the vertical diameter. Frame 8 (520 s) shows that the convective cell has already reached the central probe that also begins to decrease its temperature [Fig. 4(e)]. Frame 9 (800 s) shows that the convective cell spans the total volume of the flask so that water rises near the wall and sinks along a vertical central path, as shown schematically in Fig. 4(f). At this point, the convective cell inside the flask shows a complete reversal of direction with respect to the initial cell, due to the density inversion.

Conclusion

This paper described a simple experiment to study the flow patterns in the presence of temperature gradients in a fluid with a density maximum. Water in a flask (100 cm^3 in volume) was cooled with the help of an ice-water bath. The effect of density inversion was observed in both the cooling curves and in the circulation reversal of the convective flow. The total time for the experiment was about 25 minutes. However, this time can be reduced (to about 15 minutes) by using a smaller flask (~ 50 cm^3 in volume). Then, the experiment can be suitable for a classroom demonstration. In this case, both the cooling curves and the flows inside the flask can be projected onto a screen in real time, helping with the discussion of the experiment.

Acknowledgments

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References

1. M. De Paz, M. Pilo, and G. Puppo, "Dynamic method to measure the density of water in the vicinity of its maximum," *Am. J. Phys.* **52**, 168–171 (Feb. 1984).
2. T. C. Hope, "Experiments and observations upon the contraction of water by heat at low temperatures," *Trans. Roy. Soc. Edinburgh* **5**, 379 (1805).
3. T. Greenslade Jr., "The maximum density of water," *Phys. Teach.* **23**, 474-477 (Nov. 1985).
4. M. Branca and I. Soletta, "Thermal expansion: Using calculator-based laboratory technology to observe the anomalous behavior of water," *J. Chem. Educ.* **82**, 613 (April 2005).
5. I. Soletta and M. Branca, "The frozen lake: A physical model using calculator-based laboratory technology," *Phys. Teach.* **43**, 214-217 (April 2005).
6. We have used the TC-08 temperature logger produced by Pico Technology Ltd.