Practical Applications of Freezing by Boiling Process

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Introduction to Freezing by Boiling

"Freezing by boiling" refers to the bizarre process by which a liquid in a vacuum will boil until it freezes. A liquid in a vacuum will boil as molecules can easily escape the liquid with less air pressure keeping them in the liquid. Thus, when a vacuum pump is attached to a chamber in which there is a liquid, it lowers the pressure of the chamber until it reaches the pressure at which the liquid will boil given the temperature at which it started. In stovetop boiling, the temperature of water is increased until water molecules have enough kinetic energy to escape under normal atmospheric pressure (1 atm). This, on the other hand, lowers the pressure to meet the temperature at which the liquid is found.

As the liquid boils (seen to right), molecules remaining in the liquid state give energy to those that escape. Clearly, molecules existing in the gaseous state have more kinetic energy than those unable to overcome intermolecular weak forces. As only minor amounts of heat would enter the system from the surroundings, molecules in the gas state must have gotten their extra energy from those that remained as a liquid. Thus, as the boiling process proceeds, the liquid is constantly losing heat. Continuing to run a vacuum pump stops pressure of gaseous molecules from building up, allowing the boiling process to continue. The process, however, does slow as the temperature of the liquid drops (less energy available to donate to boiling molecules).

Eventually, the temperature of the liquid drops enough that it freezes. Freezing is the point at which molecules do not have enough energy to move around freely and become locked into position due to intermolecular weak forces. Thus, freezing temperature is independent of pressure. Freezing is aided by small stones placed in the liquid that disrupt the symmetry of the molecules. As some molecules freeze, others continue to boil, giving off energy until all remaining molecules are frozen. Thus, the substance actually exists at all three states for a period of time. Thus, it is due to the cooling process of boiling under little or no pressure that a liquid freezes.

Method for Preliminary Observations:

A beaker with a measured volume of water is placed in a chamber connected to a vacuum pump. In order to measure the volume of water, water is poured from a graduated cylinder with 100 mL of water, with the difference of final volume from 100 mL being the amount poured. A few small stones (made of elements insoluble in water) are placed in the water to disrupt its symmetry and allow it to boil and then freeze more readily. The vacuum pump is turned on, and the time for the water to begin boiling and the time for the water to begin freezing are taken. Finally, the volume of water remaining after freezing is taken by melting the ice and pouring back into a graduated cylinder.

This process is repeated for different volumes of water in different sized beakers (different radii) to investigate how boiling rate (as seen through the time necessary for the water to freeze) is affected by surface area and water depth.

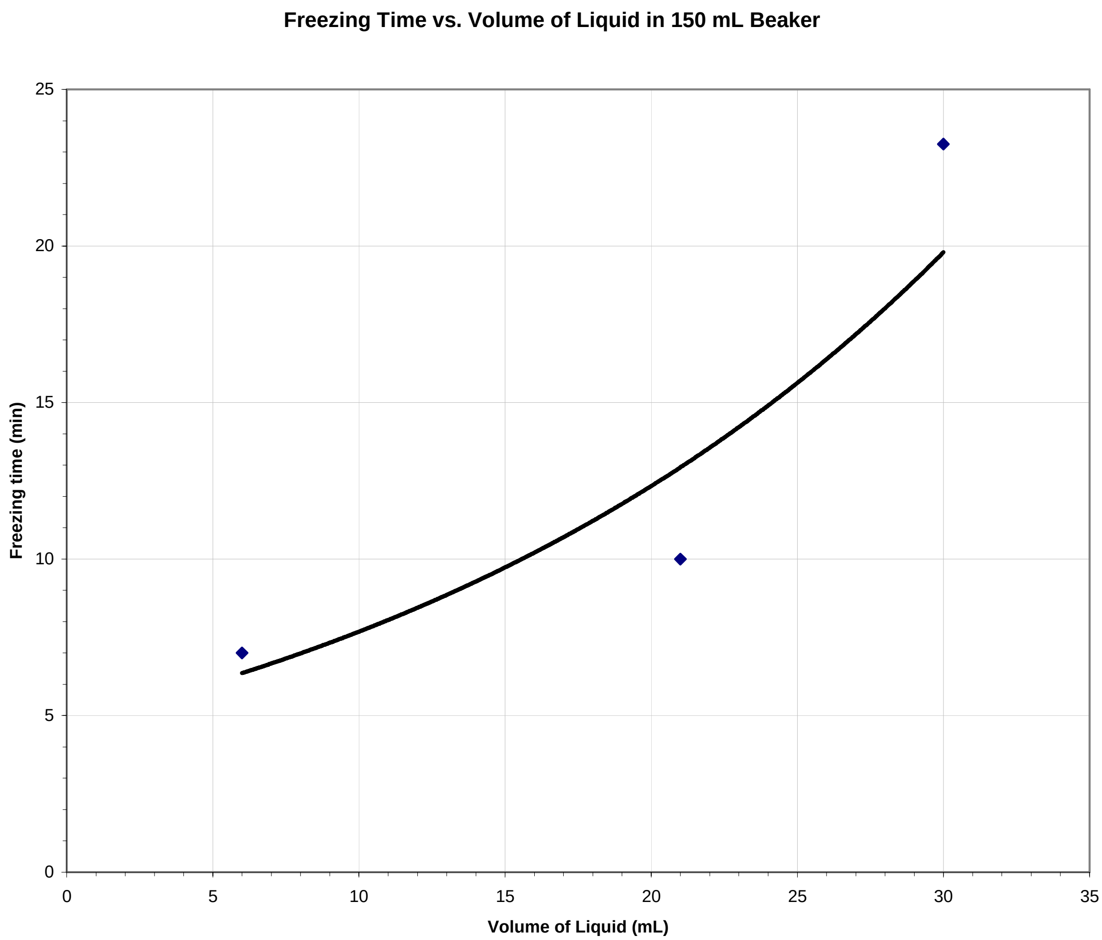
Data and Results:

Varying Depth in Different Beakers

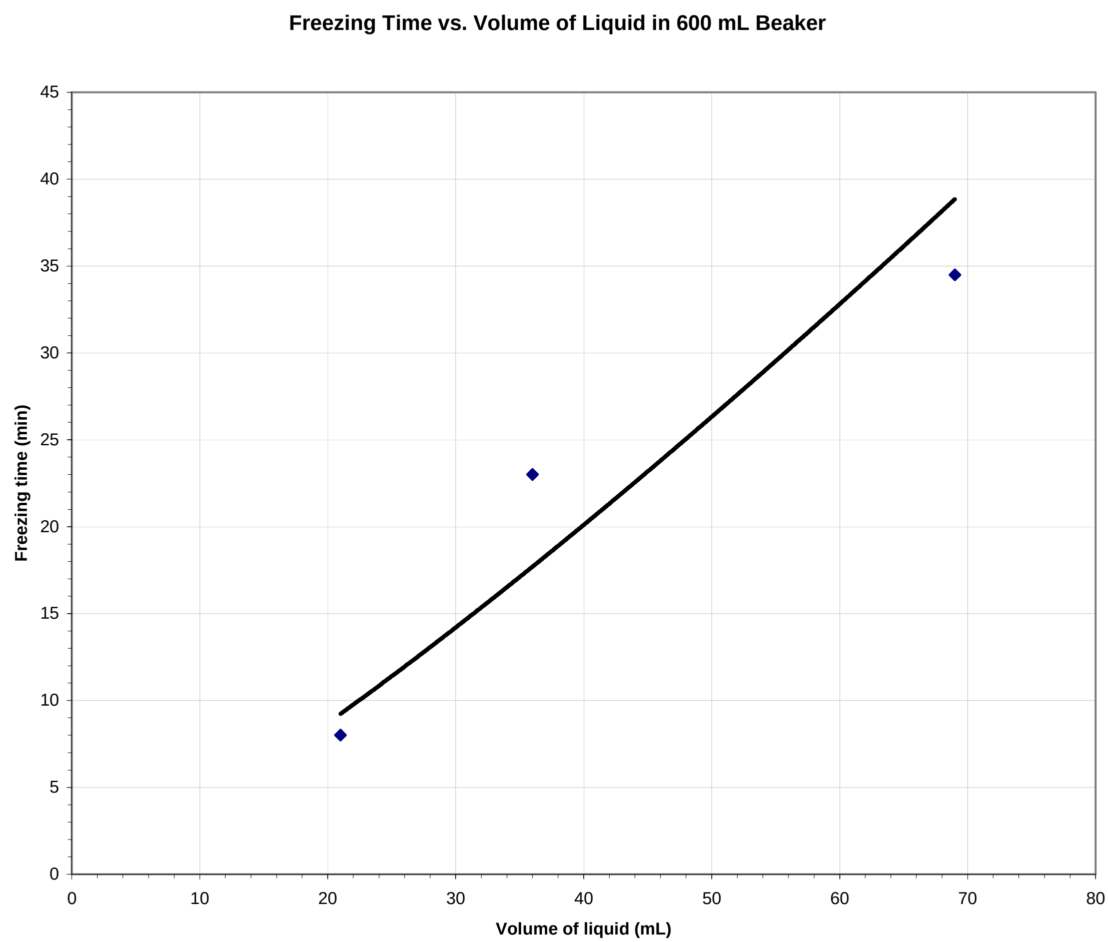
Size of cylinder (mL)	Volume of water (mL)	Depth of water (cm)	Time to boil (sec)	Time to freeze (min:sec)	Remaining water volume (mL)
50	11	1	45	17:30	9
50	5	0.5	50	15:00	4
50	19	1.5	45	Stop at 36:00, no freeze	15
150	21	1	45	10:00	18
150	6	0.5	50	7:00	4
150	30	1.5	45	23:15	25
600	21	0.5	45	8:00	19
600	36	1	45	23:00	33
600	69	1.5	50	34:30	61

Firstly, boiling time is independent of volume of liquid or container dimensions. This is because the liquid—regardless of volume—will boil once the pressure has reached sufficiently low to allow water molecules to escape easily at their given temperature. Thus, assuming the vacuum pump operates at the same strength and the liquid begins at the same temperature, the liquid will always boil after the same amount of time.

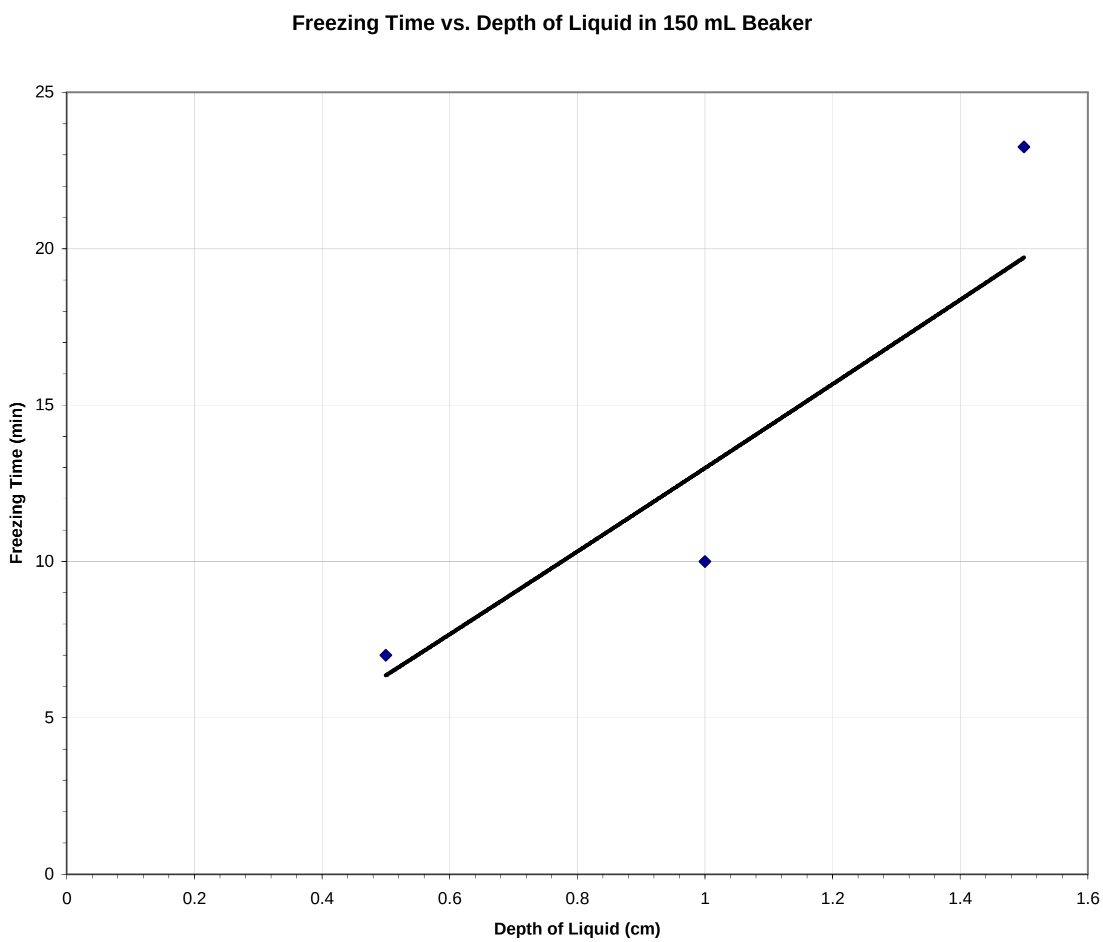
Clearly, the time it takes the liquid to freeze is dependent on the volume of the liquid, as seen in the following graphs:



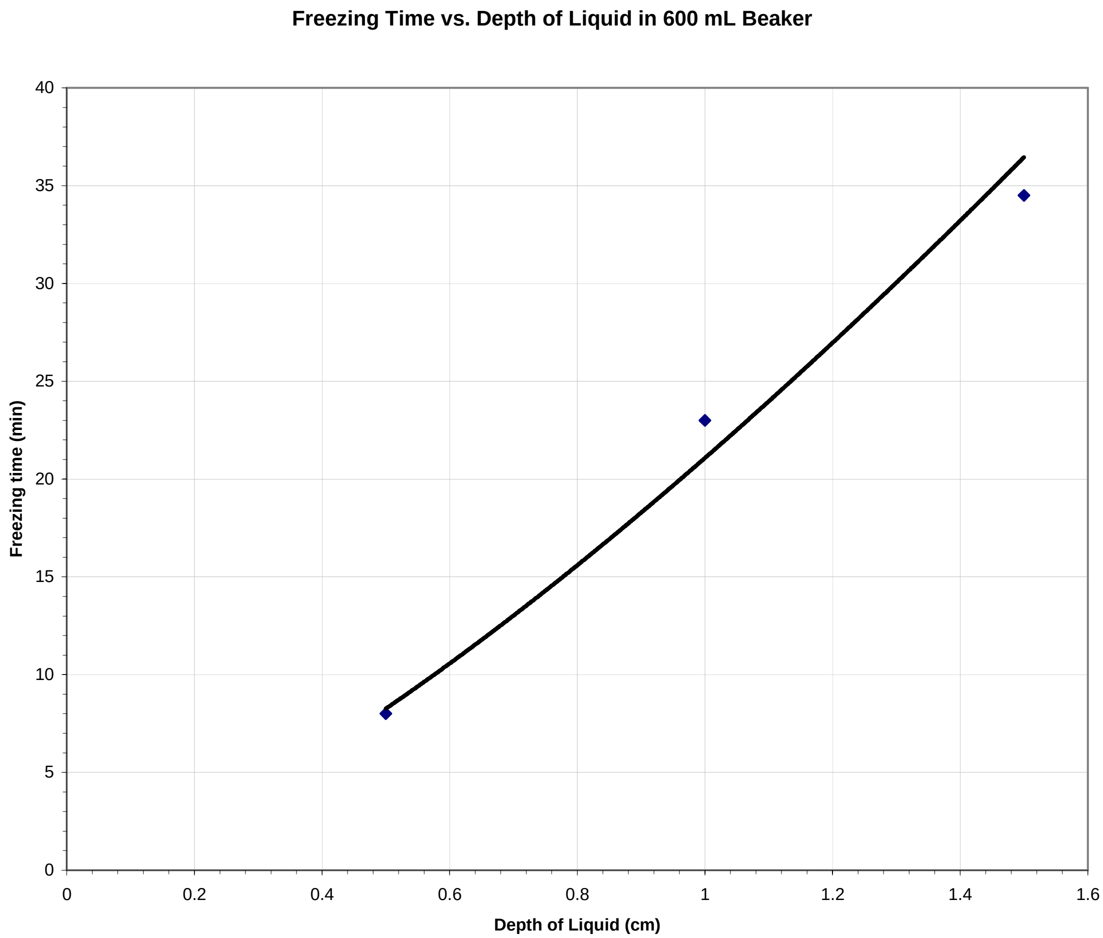
Freezing Time vs. Volume of Liquid in 150 mL Beaker
Freezing time (min)
25
20
15
10
5
0
0
5
10
15
20
25
30
35
Volume of Liquid (mL)



The more liquid there is, the more molecules there are that must give up heat in order to freeze. Thus, freezing time increases as volume does. Volume can be assumed to be equal to the product of the surface area of the liquid and the height of the liquid. Two trends are seen, the first being that the greater the surface area, the less time it takes to freeze (e.g.. 10 min for 21 mL in 150 mL beaker vs. 8 min for 21 mL in wider 600 mL beaker). The greater the surface area exposed, the more space exists across through which molecules can escape, and thus the faster a liquid will boil. Next, within the same beaker (same surface area), the deeper the water (greater volume), the longer it takes to freeze, as seen below.



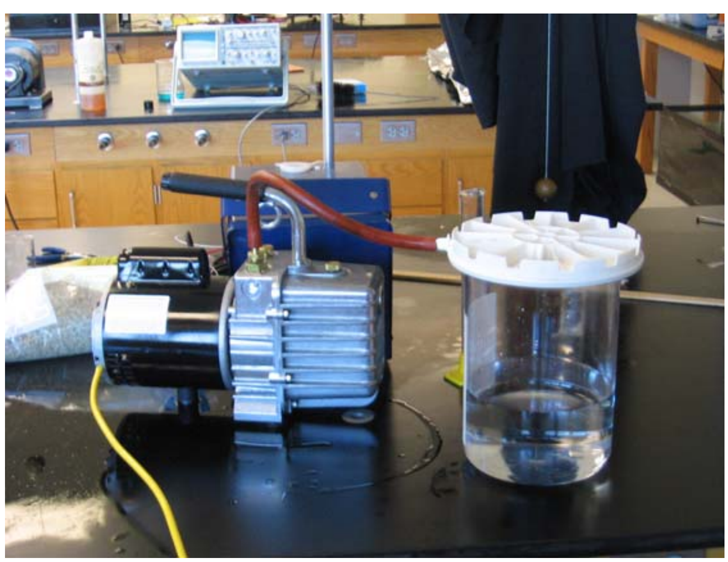
Freezing Time vs. Depth of Liquid in 150 mL Beaker
Freezing Time (min)
25
20
15
10
5
0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
Depth of Liquid (cm)



Thus, a liquid will boil fastest with a large surface area and small volume. The greater the surface area: volume ratio (inversely proportional to liquid depth), the faster it will boil. Thus, the shallower the liquid, the faster it boils.

Practical Applications

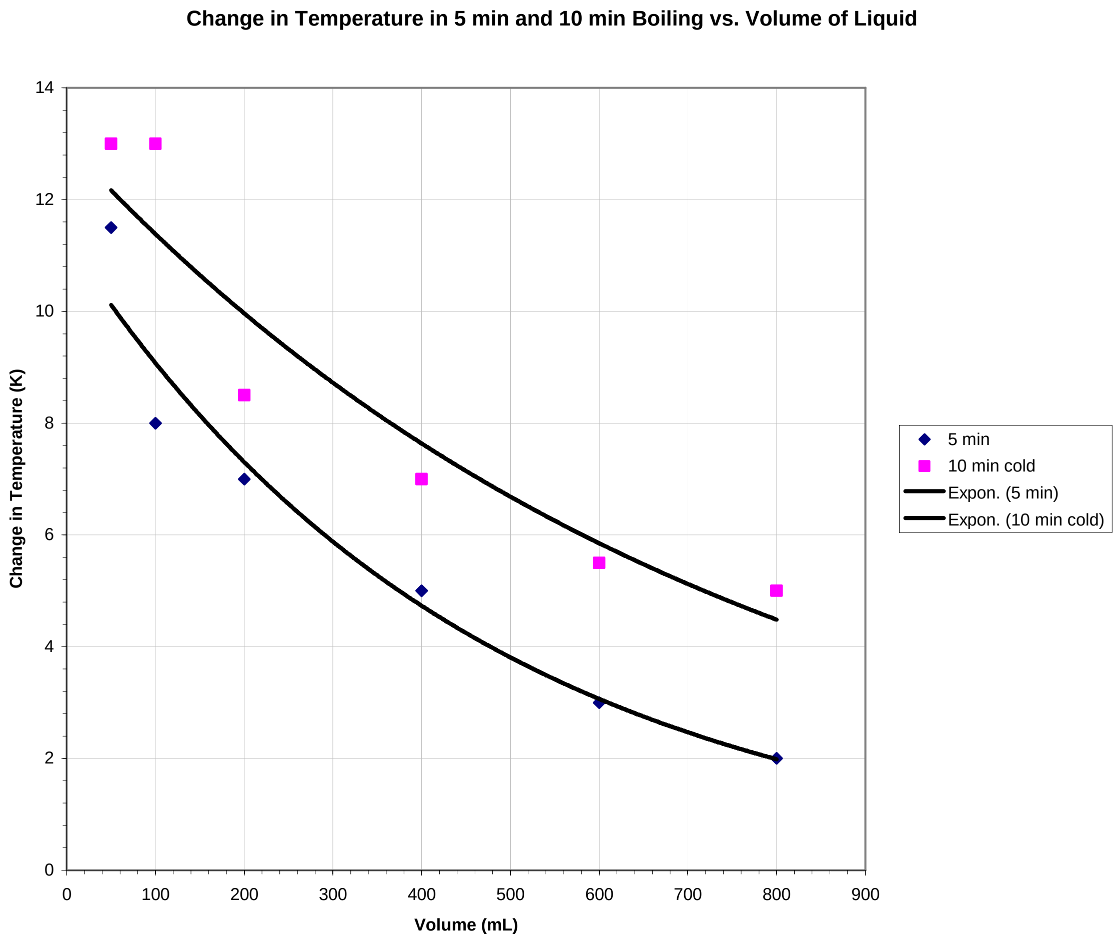
The process of freezing by boiling can be used to cool liquids by boiling off small amounts of the liquid. Water can be poured into a container that is made to be able to safely be evacuated. This container should have a wide base, and enough volume should be left empty such that the pressure will significantly decrease when air us pumped out. At right is a possible set up. Once the liquid has cooled a desired amount, the pump can be turned off and a valve into the



chamber closed such that air does not reenter the chamber. The difference in pressure between inside and out will force the cover to stay in place, sealing the chamber. The lack of air coming in will stop air convection from bringing heat to the water. Designs insulating the liquid from the outermost wall of the chamber will minimize heat conduction and radiation that would warm the liquid. In this way, the process can be used to cool liquids, as an alternative to adding ice that will dilute any liquid other than water. The chamber can then be detached from the vacuum pump and become a portable cooler.

The speed with which different volumes of water lose heat under these conditions was tracked by measuring the change in temperature of liquids starting at approximately the same temperature then boiled for a set amount of time. The data follow:

Initial temperature of water (Degrees Celsius)	Final temperature of water (Degrees Celsius)	Volume of water (mL)	Time when recorded final temperature (min:sec)
19	11	200	1:00
19	13.5	200	3:00
19.5	17	400	3:00
20	13	200	5:00
20	15	400	5:00
20	17	600	5:00
20	18	800	5:00
20	12	100	5:00
20	8.5	50	5:00
19.5	11	200	10:00
19	12	400	10:00
20	14.5	600	10:00
20	15	800	10:00
20	7	100	10:00
19	6	50	10:00

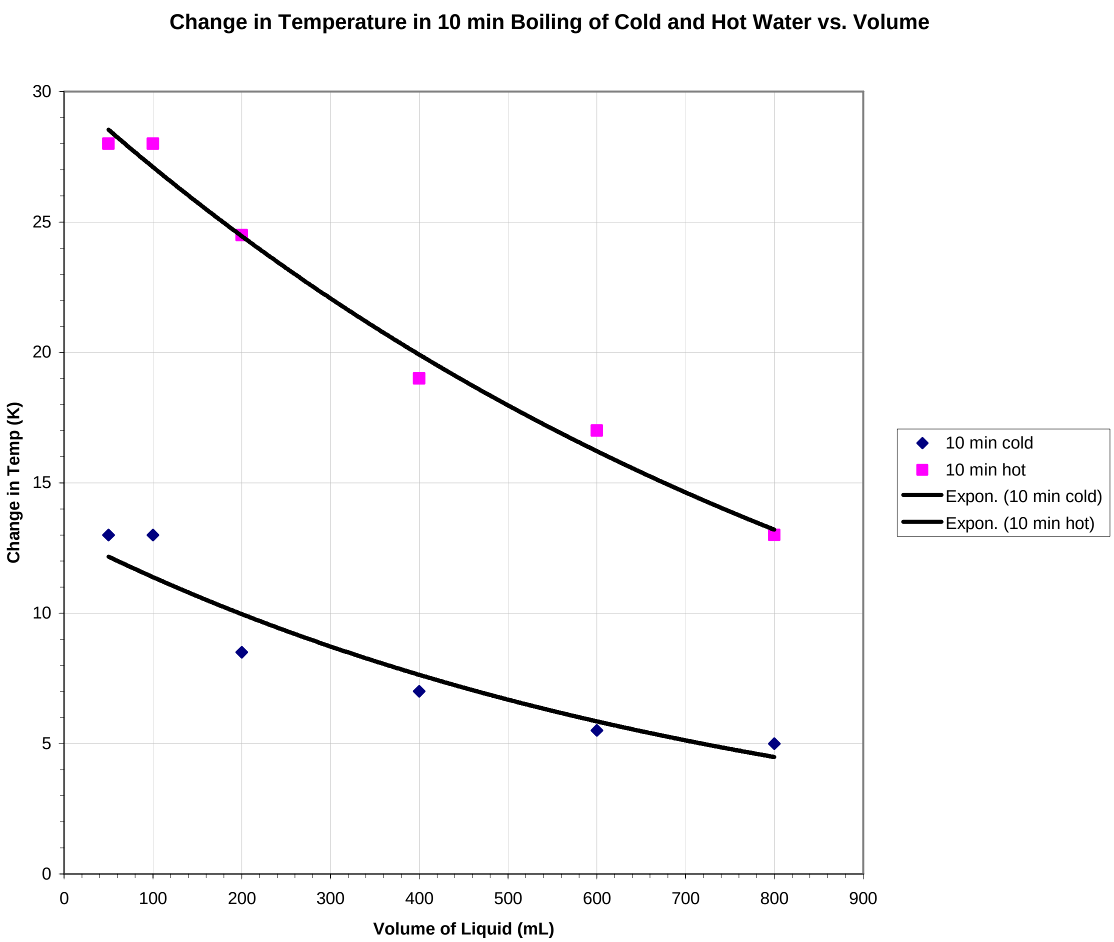


Clearly, the greater the volume, the less rapidly the temperature of the liquid drops. Given many more molecules, the average energy loss per molecule would be less with a fixed amount of energy given off to boiling molecules. Secondly, as the boiling process slows, so too does the drop in temperature (compare 10 min to 5 min). Nevertheless, small volumes of water starting at a relatively cool temperature to begin with experienced dramatic drops in temperature to become very cold water, suggesting that this device might be useful to quickly cool liquids.

Next, the process was repeated for liquid starting at a high temperature. The data follow:

Initial temperature of water (Degrees Celsius)	Final temperature of water (Degrees Celsius)	Volume of water (mL)	Time when recorded final temperature (min:sec)
39	14.5	200	10:00
38	19	400	10:00
40	23	600	10:00
39	26	800	10:00

39	11	100	10:00
39	11	50	10:00



The temperature drops significantly more rapidly when the liquid begins at a hot temperature. Newtonian thermodynamics tells us that the greater the difference in temperature, the faster heat exchange will occur. In this case, with much more energy available to the molecules than if they were colder, many more molecules are able to boil, taking energy from the liquid molecules. This device works to bring a liquid starting either hot or cold down to a cool temperature very rapidly. It could serve practically as the cooling equivalent to a microwave.