TFYA21 Assignment 4: The Mpemba effect

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1 Introduction

In this home assignment I'll investigate the Mpemba effect. The Mpemba effect is a process in which hot water can freeze faster than cold water. Four experiments will be conducted to try and verify this effect. Each experiment will test a different liquid or volume. The four liquid bodies to be tested are the following:

- 1l Battery Water
- 1dl Battery Water
- 2dl Schweppes Lemon
- 1dl Flux mouthwash

A discussion about the effect and the observed results will follow.

2 Equipment and method

The following equipment was used:

- Freezer
- 2dl Flux mouthwash
- 4dl of Schweppes Lemon
- 2.2l of battery water
- 2 glass containers
- 2 thermometers
- A saucepan
- Vodka

The experiments were conducted by me alone on these dates:

- Experiment 1, 1l Battery water: 7/3-2019 17:06 - 8/3-2019 03:36
- Experiment 2, 2dl Schweppes Lemon: 9/3-2019 17:13 - 22:28
- Experiment 3, 1dl Battery water: 10/3-2019 15:17 - 19:42
- Experiment 4, 1dl Flux mouthwash: 11/3-2019 14:55 - 19:30

The method used was similar for all experiments and it followed these steps

1. The liquid was placed in the freezer to cool it down to some wanted temperature.
2. The saucepan and glass containers were washed carefully and disinfected with Vodka.
3. Half of the liquid was heated to a certain temperature in the disinfected saucepan.
4. The hot and the cold liquids were poured into their respective glass container.
5. A thermometer(marked for hot or cold) was put into each container.
6. The containers were placed in the freezer and the digital thermometers were taped to a cabinet above the freezer.
7. The temperature of the two samples was noted every five minutes.

The methods differed a bit.
All of the experiments started at different temperatures. Later it will also be discussed that the settings on my freezer played a large part in how the results turned out. Also container size and thermometer placement was changed. Small drinking glasses were used for experiments 2,3 and 4 while two 1l boxes were used for experiment 1. This table summarizes how the experiments differed from each other.

Experiment	Initial temperature	Thermometer placement	Freezer settings
1	$T_H = 35.1°C$, $T_C = 8.5°C$	Did not think of	Regular(-18°C)
2	$T_H = 40.1°C$, $T_C = 7.1°C$	Did not think of	Regular(-18°C)
3	$T_H = 63.4°C$, $T_C = 3.3°C$	Taped in middle of glass	"Power Freeze"(-24°C)
4	$T_H = 65.4°C$, $T_C = 19.7°C$	Taped in middle of glass	"Power Freeze"(-24°C)

3 Result

Figure 1, 2, 3 and 4 below shows the results for experiment 1, 2, 3, 4 respectively. In the experiment with 1l of Battery water you can clearly tell that the Mpemba-effect was observed. In the case of the Schweppes it is not as clear from the graph but by opening the freezer after 100 minutes I could verify that the hot sample had frozen while the cold had not. In both of these experiments the hot sample shows a strange behaviour after freezing. The graphs get a saw-like shape.

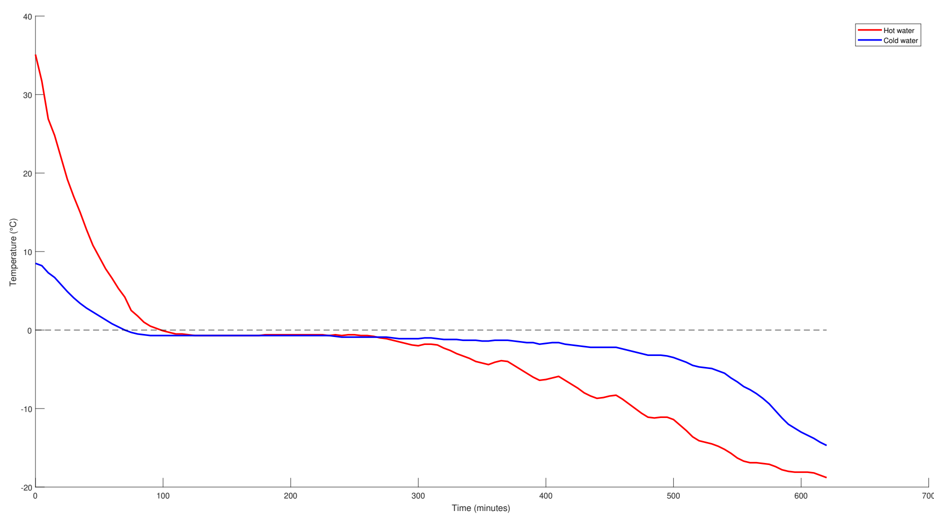

Figure 1: The temperature change of the 1l water samples

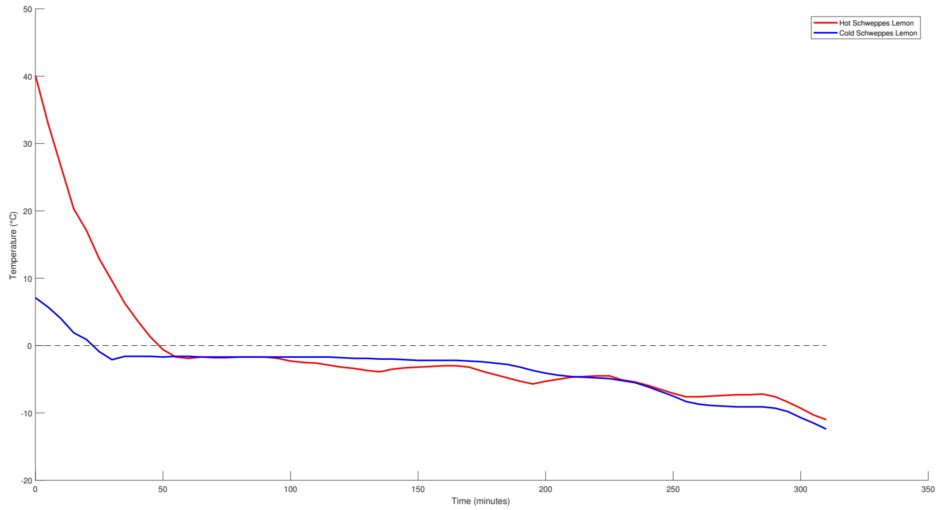

Figure 2: The temperature change of the 2dl Schweppes samples

In experiment 3 the Mpemba-effect is once again observed but the time gap between the hot and cold samples' freezing times is not as large as in experiment 1. After freezing the cold sample decrease its temperature much more rapidly than the hot one.

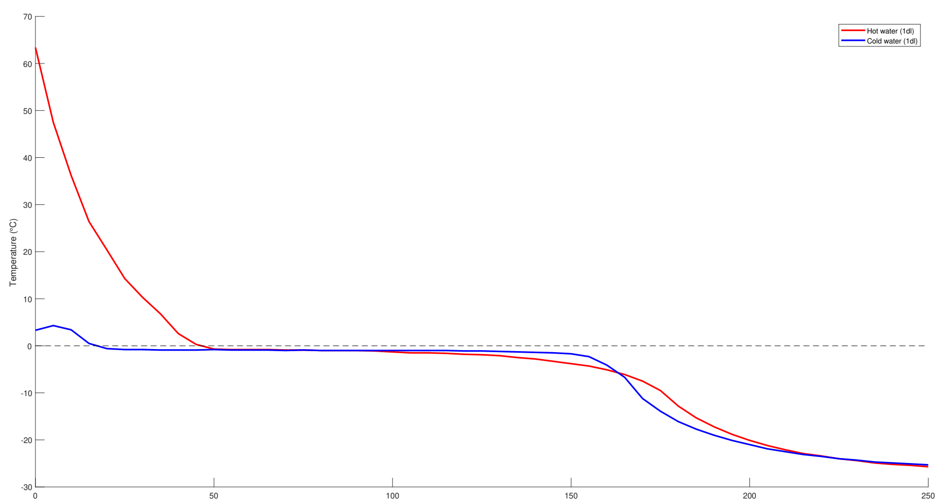

Figure 3: The result of the 1dl battery water experiment

In experiment 4 the Mpemba-effect was not observed! There was also a small undercooling of 1°C.

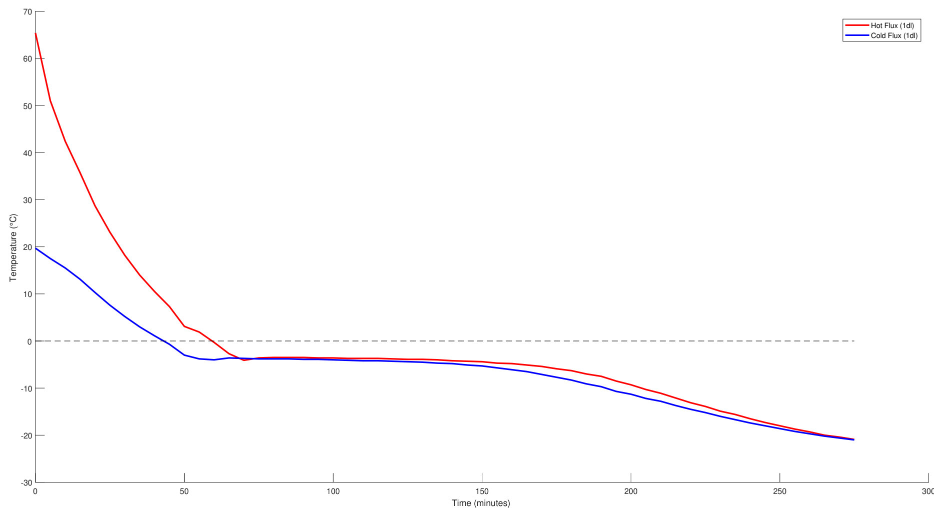

Figure 4: The result of the 1dl Flux experiment

After freezing, the Schweppes samples in experiment 2 differed a lot in volume.

Figure 5: The Schweppes samples after freezing

All of the data points can be found in the appendix.

4 Discussion

4.1 Battery water

The result very clearly supports the Mpemba-effect. The warm sample freezes before the cold sample in both experiment 1 and 3. But what causes this effect?

Evaporation of the hot water resulting in less water mass to freeze is one explanation. After melting my samples in experiment 1 I noticed that the container of cold water actually contained 100 ml more than the hot water container. This is quite substantial and is probably a result of not only evaporation, but also spilling and measurement errors. This difference in volume surely plays a large part in the freezing time difference. Though my intuition tells me that it is not responsible for the whole result, could one extra deciliter really make the freezing time almost three hours longer? I don't think so. In experiment 3 i couldn't tell any difference in volume after melting.

Some suggest that the hotter container would melt through a layer of insulating frost bringing it in contact with an even colder surface in the freezer. That sounds like a reasonable explanation to me but, my freezer did not have any frost in it so I doubt that would be the reason for the observed result.

I didn't observe any undercooling in any of the experiments with battery water. This was a shame since i did all in my power to have as clean water samples with as few nucleation sites as possible.

If the Mpemba effect is real it would imply that the water had some sort of memory of it's previous states. A mind-boggling thought. This "memory" must then somehow be stored either in the water or in it's surroundings, the container in this case. If you compare this phenomenon to that of shape-memory alloys it might not be so strange. Just like they can "remember" what shape they want to have in different temperatures, the hot water might remember that it used to be cold before heating and wants to freeze really bad. A bit far-fetched maybe.

A common feature in experiments 1 and 3 is that the hot sample, although freezing faster, is cooling down slower after freezing than the cold water. It is as though the cold sample is more careful to freeze in the "correct way" so that decreasing temperature further afterwards is easy. It could perhaps be so that the hot sample is experiencing somewhat of a fast cooling since the temperature difference is large. This fast cooling will give the constituents of the solution less time to diffuse into their optimal places. Perhaps the hot and cold samples have different crystalline structures after freezing. And if so the hot sample's ice would have worse heat transfer characteristics than the cold sample's ice making it slower to reach equilibrium with the freezer.

If you look at the part of the curves after the warm water has frozen completely in experiment 1 a sort of "saw" pattern appears in the temperature decrease. I found this peculiar. Either it has something to do with the properties of water or I found some hidden mechanism in my freezer. Perhaps it is the result of someone opening the freezer, but I don't think so. Also the saw teeth are about one hour long each. So I believe it is most likely some cooling mechanism in the freezer. For experiment 3 and 4 I changed the settings on my freezer to "Super Freeze" and it seems like it was indeed the freezers cooling mechanism that was haunting me. In figure 3 you can see that the result in experiment 3 is smooth.

4.2 Schweppes Lemon

It was nice to see that the Mpemba-effect could be observed for this liquid as well, I was not certain that it would. Schweppes lemon consists of many ingredients. It consists of mostly water and lemon juice with the rest being sugar, CO_2 and chemicals. To know what effect each of the ingredients have is hard but the main difference from water I would say is that it is carbonated.

In figure 3 you can see that the two samples have a different shape after freezing. The cold sample has popped out of its container. I believe this is caused by CO_2 bubbles trapped within the ice, making it's volume larger. The hot sample probably lost some CO_2 during heating. Not all of it though since I had a taste of the hot sample and could verify that it was still fizzy. Of course this difference in CO_2-concentration could have affected the result. Just by looking at the macroscopic structure I feel like the cold sample should freeze slower since it is more porous from the CO_2. This in turn should slow down heat exchange within the sample. So even though the graph shows Mpemba-behaviour, in this case it could probably be explained by other factors.

If it wasn't for the strange behaviour in my freezer I believe the plot in figure 2 could've turned out really nice. Maybe in this case the thermometer placement could be the answer to why the hot sample react stronger to the freezer than the cold one. In these smaller containers, if the thermometer was placed closer to the edge of the ice it will probably react stronger to the freezer's cooling mechanism. After looking I could verify that the thermometer in the cold sample was placed good in the middle while the thermometer in the hot sample was indeed a bit closer to the surface.

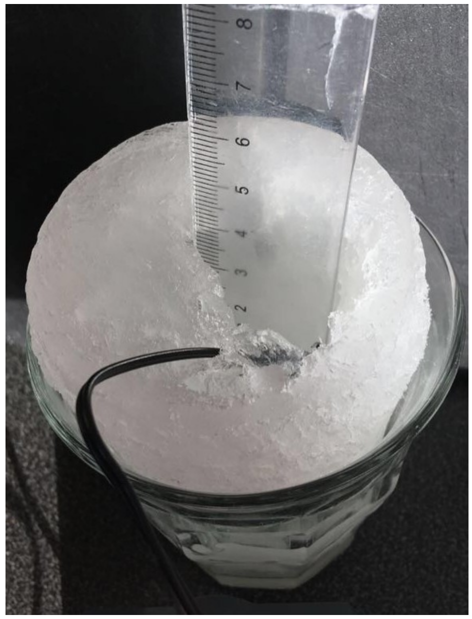

Figure 6: A large cavity in the cold Schweppes probably caused by entrapped CO_2

4.3 Flux

This experiment was the only out of the four where the Mpemba-effect could not be observed. I thought this was very peculiar. What makes Flux special in this context is it's high content of fluoride and alcohol. However Flux's main ingredient is still water so i thought that it would behave the same way as the other samples.

I have two guesses why the Mpemba-effect was not observed in this experiment. It could be that the contents of Flux react in a special way or perhaps it could be the starting temperatures of this experiment. Experiment 4 was the only experiment which had a cold sample with a starting temperature that was not really cold, $T_C = 19.7°C$. Why that would matter I can't say.

Figure 7: Solid Flux, very nice looking

If i had more time i would have tested a liquid that was not water based. That could have been interesting.

5 Appendix

The MATLAB code i used for the figures. All the measurements can be found in it.

```
clc
clear
ThotWater = [35.1,31.7,26.9,24.8,22.0,19.2,17.0,15.0,12.8,10.8,9.3,7.8,...
    6.6,5.3,4.2,2.5,1.8,1.0,0.5,0.2,-0.1,-0.3,-0.5,-0.5,-0.6,-0.7,-0.7,...
    -0.7,-0.7,-0.7,-0.7,-0.7,-0.7,-0.7,-0.7,-0.7,-0.6,-0.6,-0.6,-0.6,...
    -0.6,-0.6,-0.6,-0.6,-0.6,-0.6,-0.7,-0.6,-0.7,-0.6,-0.6,-0.7,-0.7,...
    -0.8,-1.0,-1.1,-1.3,-1.5,-1.7,-1.9,-2.0,-1.8,-1.8,-1.9,-2.3,-2.6,...
    -3.0,-3.3,-3.6,-4.0,-4.2,-4.4,-4.1,-3.9,-4.0,-4.5,-5.0,-5.5,-6.0,...
    -6.4,-6.3,-6.1,-5.9,-6.4,-6.9,-7.4,-8.0,-8.4,-8.7,-8.6,-8.4,-8.3,...
    -8.8,-9.4,-10.0,-10.6,-11.1,-11.2,-11.1,-11.1,-11.4,-12.1,-12.8,...
    -13.6,-14.1,-14.3,-14.5,-14.8,-15.2,-15.7,-16.3,-16.7,-16.9,-16.9,...
    -17.0,-17.1,-17.4,-17.8,-18.0,-18.1,-18.1,-18.1,-18.2,-18.5,-18.8];

TcoldWater = [8.5,8.2,7.3,6.7,5.8,4.9,4.1,3.4,2.8,2.3,1.8,1.3,0.8,0.4,...
    0.0,-0.3,-0.5,-0.6,-0.7,-0.7,-0.7,-0.7,-0.7,-0.7,-0.7,-0.7,-0.7,...
    -0.7,-0.7,-0.7,-0.7,-0.7,-0.7,-0.7,-0.7,-0.7,-0.7,-0.7,-0.7,-0.7,...
    -0.7,-0.7,-0.7,-0.7,-0.7,-0.7,-0.7,-0.8,-0.9,-0.9,-0.9,-0.9,-0.9,...
    -0.9,-0.9,-0.9,-1.0,-1.1,-1.1,-1.1,-1.1,-1.0,-1.0,-1.1,-1.2,-1.2,...
    -1.2,-1.3,-1.3,-1.3,-1.4,-1.4,-1.3,-1.3,-1.3,-1.4,-1.5,-1.6,-1.6,...
    -1.8,-1.7,-1.6,-1.6,-1.8,-1.9,-2.0,-2.1,-2.2,-2.2,-2.2,-2.2,-2.2,...
    -2.4,-2.6,-2.8,-3.0,-3.2,-3.2,-3.2,-3.3,-3.5,-3.8,-4.1,-4.5,-4.7,...
    -4.8,-4.9,-5.2,-5.5,-6.1,-6.6,-7.2,-7.6,-8.1,-8.7,-9.4,-10.3,...
    -11.2,-12.0,-12.5,-13.0,-13.4,-13.8,-14.3,-14.7];

tWater = (0:5:5*(length(ThotWater)-1));

ThotLemon = [40.1,32.9,26.6,20.3,17.1,12.9,9.6,6.3,3.7,1.3,-0.6,-1.7,...
    -1.9,-1.7,-1.8,-1.8,-1.7,-1.7,-1.7,-1.9,-2.3,-2.5,-2.6,-2.9,-3.2,...
    -3.4,-3.7,-3.9,-3.5,-3.3,-3.2,-3.1,-3.0,-3.0,-3.2,-3.8,-4.3,-4.8,...
    -5.3,-5.7,-5.3,-5.0,-4.7,-4.6,-4.5,-4.5,-5.1,-5.4,-5.9,-6.5,-7.1,...
    -7.6,-7.6,-7.5,-7.4,-7.3,-7.3,-7.2,-7.6,-8.4,-9.3,-10.3,-11.0];

TcoldLemon =[7.1,5.7,4.0,1.9,0.9,-0.9,-2.1,-1.6,-1.6,-1.6,-1.7,-1.6,...
    -1.6,-1.7,-1.7,-1.7,-1.7,-1.7,-1.7,-1.7,-1.7,-1.7,-1.7,-1.7,-1.8,...
    -1.9,-1.9,-2.0,-2.0,-2.1,-2.2,-2.2,-2.2,-2.2,-2.3,-2.4,-2.6,-2.8,...
    -3.2,-3.7,-4.1,-4.4,-4.6,-4.7,-4.8,-4.9,-5.2,-5.5,-6.1,-6.8,-7.5,...
    -8.3,-8.7,-8.9,-9.0,-9.1,-9.1,-9.1,-9.3,-9.8,-10.7,-11.5,-12.4];

tLemon = (0:5:5*(length(ThotLemon)-1));

ThotWater1dl = [63.4,47.5,36.2,26.4,20.4,14.3,10.3,6.8,2.6,0.3,-0.7,...
    -0.8,-0.8,-0.8,-0.9,-0.9,-1.0,-1.0,-1.0,-1.1,-1.3,-1.5,-1.5,-1.6,...
    -1.8,-1.9,-2.1,-2.5,-2.8,-3.3,-3.8,-4.3,-5.1,-6.1,-7.5,-9.5, -12.8,...
    -15.3,-17.2,-18.8,-20.1,-21.2,-22.1,-22.9,-23.4,-24.0,-24.4,-24.9,...
    -25.2,-25.4,-25.7];

TcoldWater1dl = [3.3,4.3,3.4,0.5,-0.6,-0.8,-0.8,-0.9,-0.9,-0.9,-0.8,...
    -0.9,-0.9,-0.9,-1.0,-0.9,-1.0,-1.0,-1.0,-1.0,-1.0,-1.0,-1.0,-1.0,...
    -1.1,-1.1,-1.2,-1.3,-1.4,-1.5,-1.7,-2.3,-4.1,-6.7,-11.2,-13.9,-16.1,...
    -17.7,-19.0,-20.1,-21.0,-21.9,-22.5,-23.1,-23.5,-24.0,-24.3,-24.7,...
    -24.9,-25.1,-25.3];
```

```
tWater1dl = (0:5:5*(length(ThotWater1dl)-1));

ThotFlux =[65.4,51.0,42.4,35.7,28.7,23.1,18.2,14.0,10.5,7.3,3.1,1.9,...
    -0.3,-2.7,-4.1,-3.6,-3.5,-3.5,-3.5,-3.6,-3.6,-3.7,-3.7,-3.7,-3.8,...
    -3.9,-3.9,-4.0,-4.2,-4.3,-4.4,-4.7,-4.8,-5.1,-5.4,-5.9,-6.3,-7.0,...
    -7.5,-8.5,-9.3,-10.3,-11.1,-12.1,-13.1,-13.9,-14.9,-15.6,-16.5,...
    -17.3,-18.0,-18.7,-19.3,-20.0,-20.4,-20.9];

TcoldFlux =[19.7,17.5,15.5,13.1,10.3,7.6,5.2,3.0,1.1,-0.7,-3.0,-3.8,...
    -4.0,-3.6,-3.7,-3.8,-3.8,-3.8,-3.9,-3.9,-4.0,-4.1,-4.2,-4.2,-4.3,...
    -4.4,-4.5,-4.7,-4.8,-5.1,-5.3,-5.7,-6.1,-6.5,-7.1,-7.7,-8.3,-9.1,...
    -9.7,-10.7,-11.3,-12.2,-12.8,-13.7,-14.5,-15.2,-16.0,-16.7,-17.4,...
    -18.0,-18.6,-19.2,-19.7,-20.2,-20.6,-21.0];

tFlux = (0:5:5*(length(ThotFlux)-1));

figure(1)
hold on
plot(tWater,ThotWater,'r','LineWidth',2)
plot(tWater,TcoldWater,'b','LineWidth',2)
plot(tWater,zeros(size(tWater)),'k--')
legend('Hot water (1l)','Cold water (1l)')
ylabel('Temperature ( C )')
xlabel('Time (minutes)')
hold off
figure(2)
hold on
plot(tLemon,ThotLemon,'r','LineWidth',2)
plot(tLemon,TcoldLemon,'b','LineWidth',2)
plot(tLemon,zeros(size(tLemon)),'k--')
legend('Hot Schweppes Lemon','Cold Schweppes Lemon')
ylabel('Temperature ( C )')
xlabel('Time (minutes)')
hold off
figure(3)
hold on
plot(tWater1dl,ThotWater1dl,'r','LineWidth',2)
plot(tWater1dl,TcoldWater1dl,'b','LineWidth',2)
plot(tWater1dl,zeros(size(tWater1dl)),'k--')
legend('Hot water (1dl)','Cold water (1dl)')
ylabel('Temperature ( C )')
xlabel('Time (minutes)')
hold off
figure(4)
hold on
plot(tFlux,ThotFlux,'r','LineWidth',2)
plot(tFlux,TcoldFlux,'b','LineWidth',2)
plot(tFlux,zeros(size(tFlux)),'k--')
legend('Hot Flux (1dl)','Cold Flux (1dl)')
ylabel('Temperature ( C )')
xlabel('Time (minutes)')
hold off
```