Science Fair 2006

How temperature affects capillary action

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What my experiment is about

My experiment is about how the temperature of water in a jar will affect how high the water will rise in a paper towel due to the phenomenon known as capillary action.

Theory

For my experiment's theory, I used Washburn's equation [1], which I got from Wikipedia. Washburn's equation is

$$\mathbf{L^2 = (y\ D\ t) \div (4\ n)}$$

in which L is length in meters, y is surface tension of the liquid in N m-1, D is average pore diameter of the material in meters, t is time in seconds, and n is viscosity of the liquid in N s m-2. The variables that change with temperature are y and n [2,3], but we can look them up on the web. We choose the value of t, and we measure the value of L. Using these allows us to compute the value of D.

Using the length from one of my preliminary experiments (5.5 cm at 20°C), I estimated D to be 0.0000014 m using

$$\mathbf{D = (4\ n\ L^2) \div (y\ t)\ .}$$

variable	value
t	120 s
y	0.0728 N m^{-1}
n	0.001002 N s m^{-2}
L	0.055 m
D	0.0000014 m

At 20°C, I measured L to be 0.055 m. But what would L be at different temperatures? I used Washburn's equation:

$$L = \sqrt{((y\ D\ t) \div (4\ n))}$$

to find out:

temperature in °C	y in N m^{-1}	n in N s m^{-2}	L in m
0	0.076	0.001792	0.042
40	0.069	0.000653	0.066
60	0.065	0.000467	0.076

Hypothesis

My hypothesis is that the hotter the water is, the higher it will rise on the paper towel.

Materials

For this experiment I used

- a jar half-filled with water
- strips of paper towel (1.5 cm by 28.5 cm) with a line marked on them in pen 5 cm from one end
- a ruler
- a thermometer and clip for holding it onto the jar
- a microwave oven (for heating water)
- a stopwatch
- a paperclip or other weight
- ice cubes.

Procedure for data collection

1. Prepare the strip by
   a) drawing a line 5 cm from the end and
   b) putting a weight on that end of the strip.

2. Prepare the water by
    a) putting it in a microwave oven or
    b) putting it in the refrigerator.
3. Measure and record water temperature.
4. Dip strip into water to line mentioned in 1.a) for 2 minutes, then remove.
5. Measure and record
    a) water distance above the line and
    b) water temperature
6. Repeat as many times as necessary.

Results

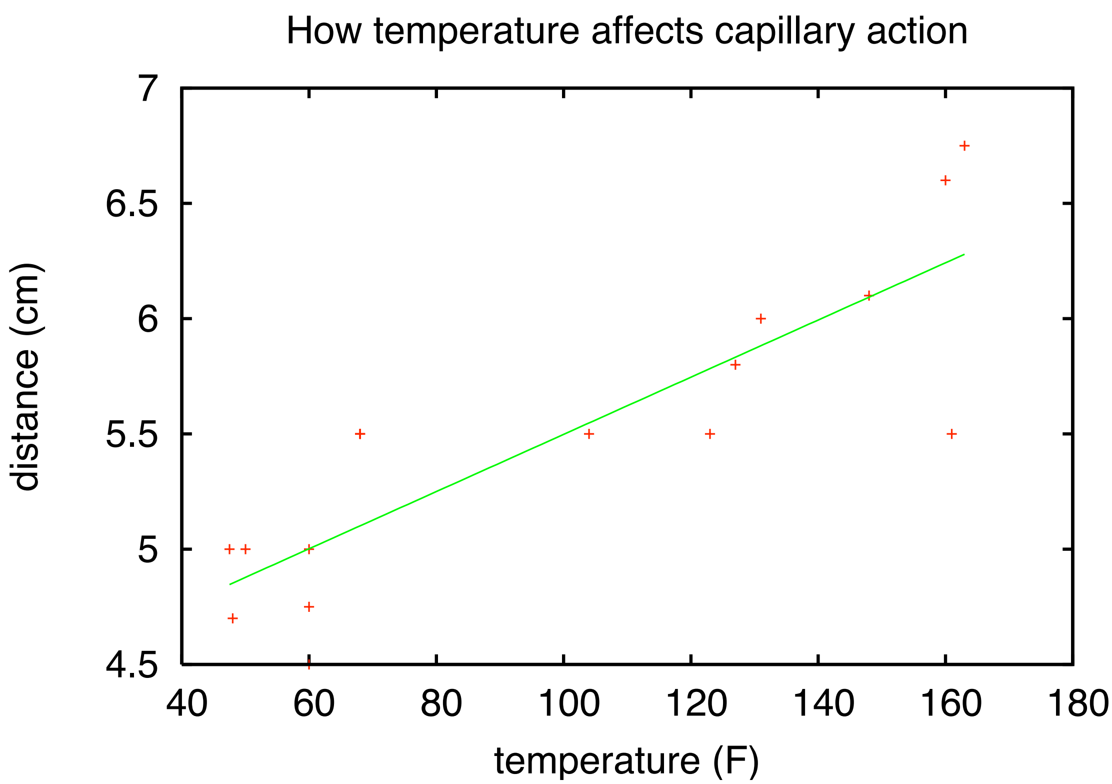
temp °F	L (cm)
47.5	5
48	4.7
50	5
60	5.0
60	4.75
60	4.5
68	5.5
68	5.5
104	5.5
123	5.5
127	5.8
131	6.0
148	6.1
160	6.6
161	5.5
163	6.75

Procedure for data analysis

1. Make a table (not plot) of length and temperature, using the average of the before and after temperatures.

2. Use the plotting program gnuplot to make a plot of length vs. temperature.

3. Also using gnuplot, fit a straight line to the dots. Fitting a straight line means putting in a straight line where there is the shortest difference in length (y) between the line and the points.



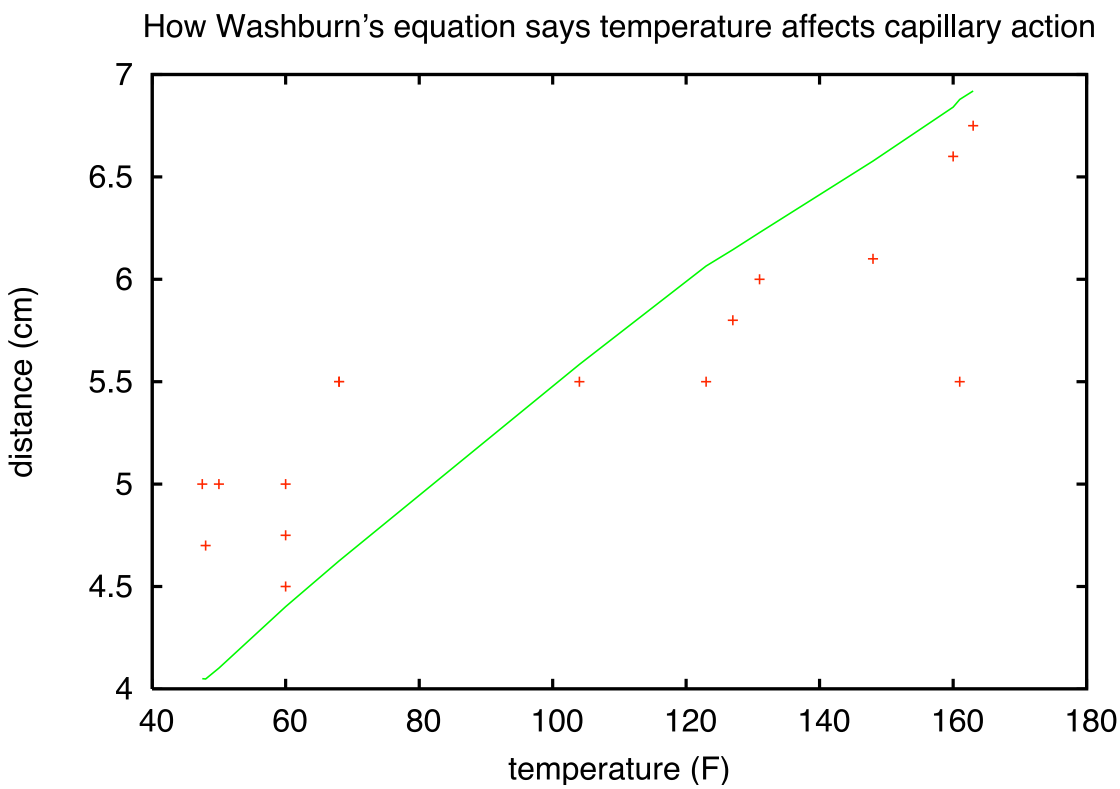
The plot showed me that my hypothesis was correct—on average the greater the temperature gets, the greater the length gets. But is the theory correct?

4. Add two new columns to the table in 1: temperature in °C and viscosity [3].

5. Use gnuplot to find the value of D that makes Washburn's equation fit the data best. Using my data, the best fit for D is $9.8 * 10^{-7}$ m, or nearly one micron.

6. Using this value of D, plot a graph for what Washburn's equation says should happen (using gnuplot).

This plot's line is slightly steeper than the previous one's. This means that as temperature increases the height of the water should increase more rapidly than it does. However, seeing as Washburn's equation does not take gravity into account, it is not as accurate as a formula that would. Also, since a taller column of water weighs more than a shorter column of water, the effect of gravity is greater the taller the column, making the effect of temperature smaller.



Conclusion

My hypothesis was correct—on average the hotter the water gets, the higher it rises on the paper towel. However, the effect is not as big as Washburn's equation says it should be.

Future work

If I ever repeat this experiment, a few things I might change are

* Measure how long it takes for water to rise a fixed distance at different temperatures. Thus the effect of gravity will be equal for all of these and thus cancel out.
* Design a Lego machine to automate the measuring of how long the water takes to go a certain distance.
* Do the experiment again with different materials to determine their average pore diameter (D).
* Experiment with different liquids instead of water. This would make the theory harder, since a web site is less likely to have surface tension and viscosity tables for, say, milk instead of water.

Acknowledgments

My dad, Kevin Karplus, gave me a few suggestions on how to do my experiment, helped me find stuff on the web, explained Washburn's equation and how to use gnuplot, and typed up my report and poster (taking dictation).

References

1. Wikipedia Washburn's equation http://en.wikipedia.org/wiki/Washburn%27s_equation

2. Surface Tension http://hyperphysics.phy-astr.gsu.edu/Hbase/surten.html

3. Physical characteristics of water (at the atmospheric pressure) http://www.thermexcel.com/english/tables/eau_atm.htm

Parental Comments

This project was an ambitious one for a 4th grader, so some parental help was needed, though perhaps not as much as a casual observer might assume. The initial idea of looking at capillary action and how temperature affects it was all his—we were worried that the effect might be too small to be measured with the crude equipment we had.

The experiment design was mostly his. I suggested some of the preliminary experiments that were used to decide what absorbent material to use (muslin, coffee filter, paper towel). I also suggested that he vary only the water temperature, as the temperature of the material would be too hard to measure. I also suggested the use of a clamp when he complained about his arm getting tired, and drilled holes in a clothespin so that it could be attached to Lego Technic pieces. He built a clamp using the clothespin, but ended up finding it too hard to use (friction between the paper and the pin was too high), so he went back to holding the strips by hand.

I helped him find material on the web about capillary action and the effects of temperature on viscosity and surface tension of water, as much of the material was written for physicists or chemical engineers.

He did the preliminary theoretical calculations on his pocket calculator, and I did the same set of calculations on my calculator. We found one discrepancy in the computations, but the error was in my data entry, not in his computations.

He needed three hands for his experiment, so I (or his classmate) started the stopwatch for him, and sometimes counted down the last few seconds of the 2-minute period. I also took photos of him for the poster.

I wrote the gnuplot scripts to do the plotting and the data fitting, but explained them carefully to him. I believe that he could now do the linear fitting, but not the more complicated fitting of Washburn's equation.

I typed the report and poster, taking dictation—the words are all Abe's. The layout of the poster is Abe's, though he did ask for suggestions on where to put the photos.

—Kevin Karplus