TPT: MS 550221 (Rev. 1) NIST: G2017-0658

Science at Home: Measuring a Thermophysical Property of Water with a Microwave Oven

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(Dated: January 17, 2018)

Abstract

A measurement of a thermophysical property of water is made using items found in the author's home. Specifically, the ratio of the energy required to heat water from the melting point to boiling to the energy required to completely boil away the water is found to be 5.7. This may be compared to the standard value of 5.5. The close agreement is not representative of the actual uncertainties in this simple experiment.

Heating water in a microwave oven can let a student apply the techniques of quantitative science based on questions generated by his or her scientific curiosity.

I. INTRODUCTION

I confess. I wanted to do something else. I wanted to know whether my conventional oven was calibrated properly. We'd just endured a week of slow-cooking chicken and very chewy cookies and we thought maybe there was something wrong with the oven. We still had the booklet and it turns out there's a secret setting to change the calibration.

In the real world, we adjusted the calibration by +35 °F (+19 °C) and the next batch of cookies came out right. A normal person would be happy at this point, but for someone working in a metrology institute ... are we really going to rely on cookie dough? (There is an ASTM International standard for testing ovens but who knows if it can be done in the home and it's $51.00 to find out.[1])

It seemed like there should be a way to set it to the right answer. Elementary, I said to myself. I'll just set it to 212 °F (100 °C) and see if some water in a glass baking pan boils. It didn't boil, but the pan acquired a shallow but visible wave extending across the whole pan, along with bubbles on the bottom of the pan which survived the trip back to room temperature. Maybe the point is that it's not 212 °F throughout the oven, so I tried 250 °F (121 °C). Again, no boiling. I was starting to think that the rule "A watched pot never boils" could be generalized to pans. So I tried 350 °F (177 °C), and it started to leave salt rings behind exposing its glass surface so I took it out before the pan broke. Curiously, even at 350 °F the water in the pan didn't boil in any obvious way — not with the familiar rolling boil of a pan on a stovetop.

I next turned to the web to see if there was a way to calibrate the oven with water. I didn't find anything, but I came on a neat video about cleaning your microwave oven by boiling water and coating the inside with hot water which you then wipe off.[2] So how long do you boil it for? One thing led to another, and I realized it was possible to measure a thermophysical property of matter in the home, namely the ratio of the energy required to raise water from 0 °C to 100 °C to the energy required to completely boil away the water. These are related to the heat capacity of the water and the heat of vaporization. It didn't quite seem possible to provide absolute numbers for either because of an unknown efficiency factor. But in the ratio, the efficiency cancels. So an experiment which could be done at home was born. A more sophisticated version of this experiment, oriented to laboratory equipment, has been presented earlier.[3] In addition, the enthalpy of vaporization of methanol, ethanol, acetone, and isopropanol was determined with a research-grade microwave oven.[4]

II. THE EXPERIMENT

The microwave oven is a Samsung SMH18165 rated at 1.7 kW.[5] Water was taken from the tap. About 4 L of a mixture of ice and water was left in a refrigerator at 2 °C (36 °F) overnight. This is presumed to make ice water at 0 °C which was used to start the experiment. There was a considerable amount of both ice and water on the day of the experiment. No adjustment was made for salt content or barometric pressure as these were estimated to be less than 1 °C and not visible with my equipment. The water was placed into nominal 5 oz. (140 mL) Styrofoam (polystyrene) cups. Each cup had a 6 mm layer of corrugated cardboard taped to the bottom to reduce the thermal contact. I used a Pelouze Model K5 postal scale for weighing the water. That proved more accurate than using the graduations on the available measuring Pyrex measuring cups which might have a substantial heat capacity. Temperature was measured with a Cen-Tech Infrared (IR) Thermometer Model 09a. These are all consumer items, none of which were acquired specifically for this experiment.

A. Safety

There are some hazards in this experiment. One is that it is possible to create superheated water in a microwave oven which appears quiescent but then goes into a rapid boil when you touch it.[6] This happened to me once years ago and it was pretty shocking. Fortunately, I didn't get hurt, but not everyone is so lucky. The way to ensure safety is to tap on the cup water with a stick before moving it. I used a wooden spoon for this.

A second hazard is that you can spill boiling water on yourself. Just be careful, make sure there aren't young children, pets, or cooks around, and wear closed-toe shoes with socks, long pants, and a long-sleeve shirt.

A third hazard is that vapor coming off the water can burn your palm. You won't necessarily notice this after one cup. The solution is to put on a light glove and handle the cup by the side to avoid exposing your palm to the rising steam.

Additionally, do not put plastic or glass in the microwave unless it is rated for that use. Never put metal in the microwave and keep boiling water away from ordinary glass. Do not

FIG. 1. The equipment used in this experiment is shown in the microwave oven with the glass plate visible. From left to right, the objects shown are the scale, the wooden spoon, the quarters, the IR thermometer, and a styrofoam cup.

let all the water boil away.

There is an eye hazard as well: the IR thermometer comes with a Class IIIa laser, a red beam for alignment. Reflections of the laser off of water can be dangerous. Simply leave the laser off.

B. Calibration

The first thing a metrologist does is to calibrate the instruments. If I wanted to calibrate a scale at work, I would hunt down a set of calibrated weights. But I'm at home. As luck would have it, I had two rolls of 40 quarters each. The U. S. Mint says that a quarter has a weight of 5.670 g (0.2000 oz.).[7] I'm guessing the 0.2000 oz. came first, but its just as well: the postal scale is marked in ounces too. One roll of quarters comes in at 7.9 oz. and the second brings it up to 16.0 oz. Eighty-seven quarters is 17.3 oz. So we're off by at most 0.1 oz. which is 3 g and there's no obvious bias. In this paper, I report the postal scale readings converted to grams.

TABLE I. Calibration points for thermometer. The IR thermometer was pointed at four systems for which the temperature was known to some extent. Fahrenheit values are given where the data was acquired on that scale. The boiling point of water is given to within 1 °C, even including a correction for barometric pressure 101 kPa (29.8 inHg) on the day of the experiment.[8, 9] The water was boiled in the microwave oven.

	Measurement	Expectation	Other measurement
Ice water	1.2 °C to 2.4 °C	0°C	
House thermostat	22.4 °C		20.6 °C (69 °F)
Mouth	34.5 °C		36.0 °C (96.9 °F)
Boiling water	89 °C to 91 °C	100 °C	

I also want to calibrate my thermometer. By the traditional definition, the melt water should be at 0 °C and the boiling water at 100 °C. I also pointed the IR thermometer at the house thermostat as well as into my mouth whose temperature I could measure with a fever thermometer. The results, shown in Table I were satisfactory except for the temperature of boiling water. I'm not sure why the latter was so far off, but perhaps water is somewhat transparent in the infrared and the cooler bottom of the cup is being read. Perhaps it has something to do with the emissivity of the water, or a partial reflection of the infrared in the room. Perhaps food coloring would improve the situation. Exploring this would be a research topic in itself, so I simply accept that that the temperature scale is off by a couple of degrees Celsius except at the top of the scale where it's off by 10 °C. In this paper, I report uncorrected readings from the thermometer.

C. Experiment and Raw Data

The experiment was performed as follows: a pitcher of ice water was taken out of the refrigerator and 156 g (5.5 oz.) of water (without ice) was poured into a nominal 5 oz. Styrofoam cup. (Incidentally, a U. S. fluid ounce of water weighs one ounce.) The temperature was taken and the water was placed into the microwave oven at full power for 30 s, 60 s, 90 s, or 120 s. Care was taken to place the cup of water over a glass bead visible on the bottom of the rotating glass plate. After the time, the temperature of the water was taken with the IR thermometer, it was placed on the scale, the temperature was logged (giving the scale a moment to stabilize), then the scale was read and the water was placed back in the oven. The oven was started after 45 s. It took anywhere from just over 30 s to a harrowing 43 s to make and record the measurements and get the cup back into position. The door of the microwave oven was left open during the measurements both to let the oven dry out and to make it easier to put the cup back in.

The temperature data are shown in Fig. 2. There is a relatively rapid rise in temperature followed by a plateau. Of course, it takes longer to get to the boiling with more frequent measurements. In many cases, at the onset of boiling, there was the classic vigorous disturbance of the surface, but this did not persist for more than a portion of one heating time.

In order to determine the time to boil more precisely, the data from 30 s, 60 s, 90 s, and 120 s of heating were augmented by heating fresh cups of melt water for 100 s and 110 s. Given that visible boiling was only observed at 120 s, and that the temperature is still rising below 120 s, 120 s is taken to be the time to boil the water.

The mass is shown in Fig. 4. A run was halted when the mass of water in the cup was measured to be less than 48 g (1.7 oz.). After the heating to boiling is complete, the mass of the water remaining in the cup is seen to decrease linearly in time. In Fig. 5, the data are replotted as a function of the time in the oven. All points more or less fall on the same line. This was a surprise, as I expected that more frequent cooling would result in some energy going to reheating the water to boiling. Based on the data I am forced to neglect any such effect.

D. Comparison to Known Values

The heat capacity of water is 4.184 J/(g °C).[10] Since we raise the temperature by 100 °C of 156 g of water, that's 65.3 kJ. That can be compared to the rated power of the microwave oven, 1.7 kW, times the time to boil, 120 s, or 204 kJ. That represents an overall heat transfer efficiency of 32%.

For the second part of the experiment, shown in Fig. 5, the combined data shows a mass loss of 110 g in 480 s. (The final zero in 110 is not a significant figure.) This figure may be extrapolated to a loss of 156 g in 680 s. The ratio of the time-to-evaporate to the time-to-boil is therefore 680 s/120 s = 5.7.

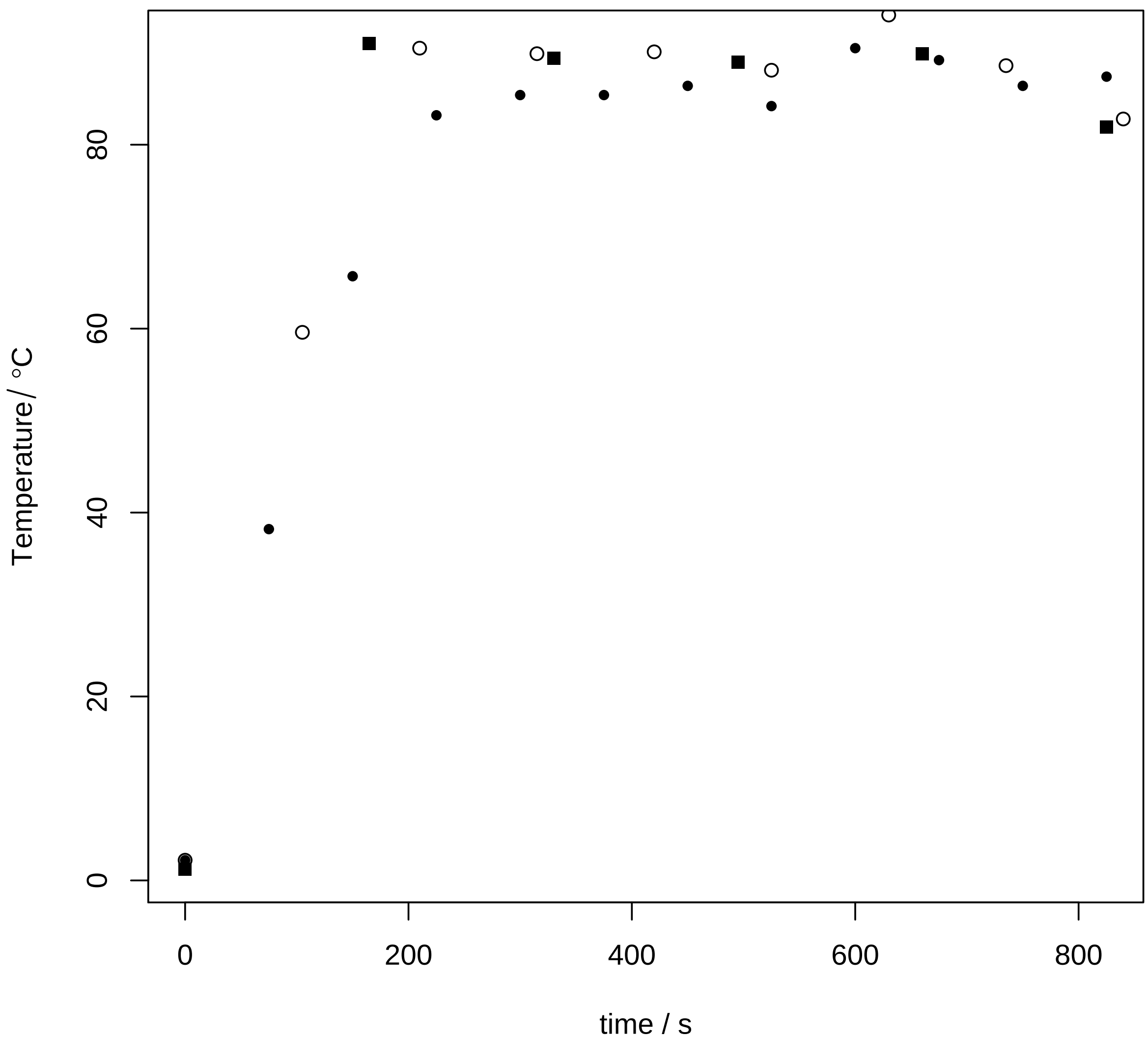

FIG. 2. Temperature readings after a given time in the microwave oven with 45 s measurement breaks. The times were 30 s (filled circles) 60 s (open circles) and 120 s (filled squares). Measurements were also taken at 90 s, but are not shown for clarity.

The expected energy required to vaporize 156 g of water is given by the latent heat of water, 2.23 kJ/g,[11] times the mass, or 348 kJ. In 680 s, 1160 kJ are generated by the microwave so the efficiency of heat transfer is 30% in this portion of the experiment.

The ratio of the energy-to-evaporate to the energy-to-boil is 348 kJ / 65.3 kJ = 5.5. So the measurement is off by 4% from the standard value. This agreement is much better than

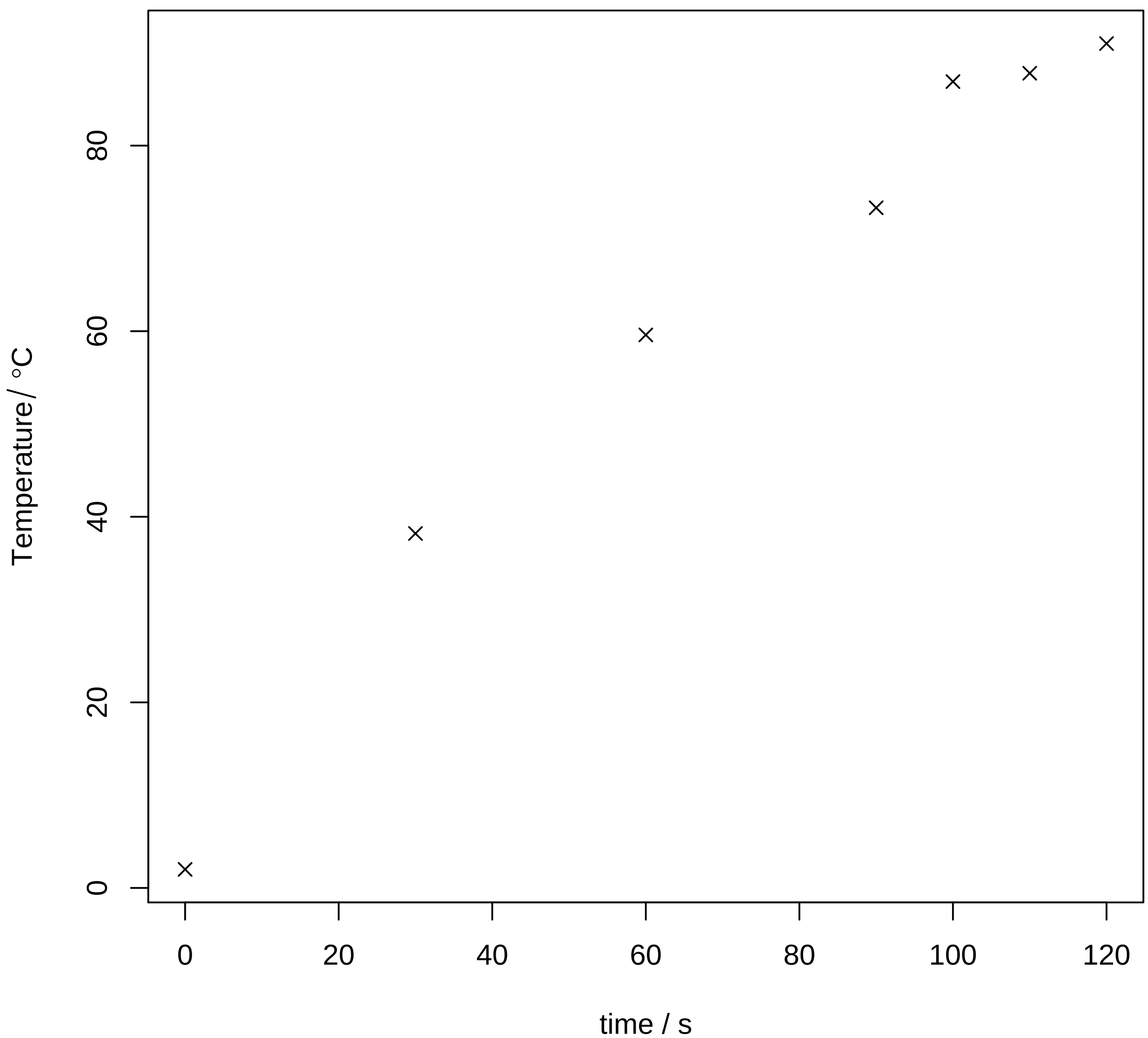

FIG. 3. Temperature of initial 156 g (5.5 oz.) of ice water after a given time in the microwave oven. Each data point represents a different cup of water.

a careful estimate of the uncertainties would suggest. For example, I didn't account for heat loss due to sources other than evaporation, water condensed onto the walls of the microwave and reheated, the 6 g mass loss before boiling, and the variation in mass loss between the four data sets.

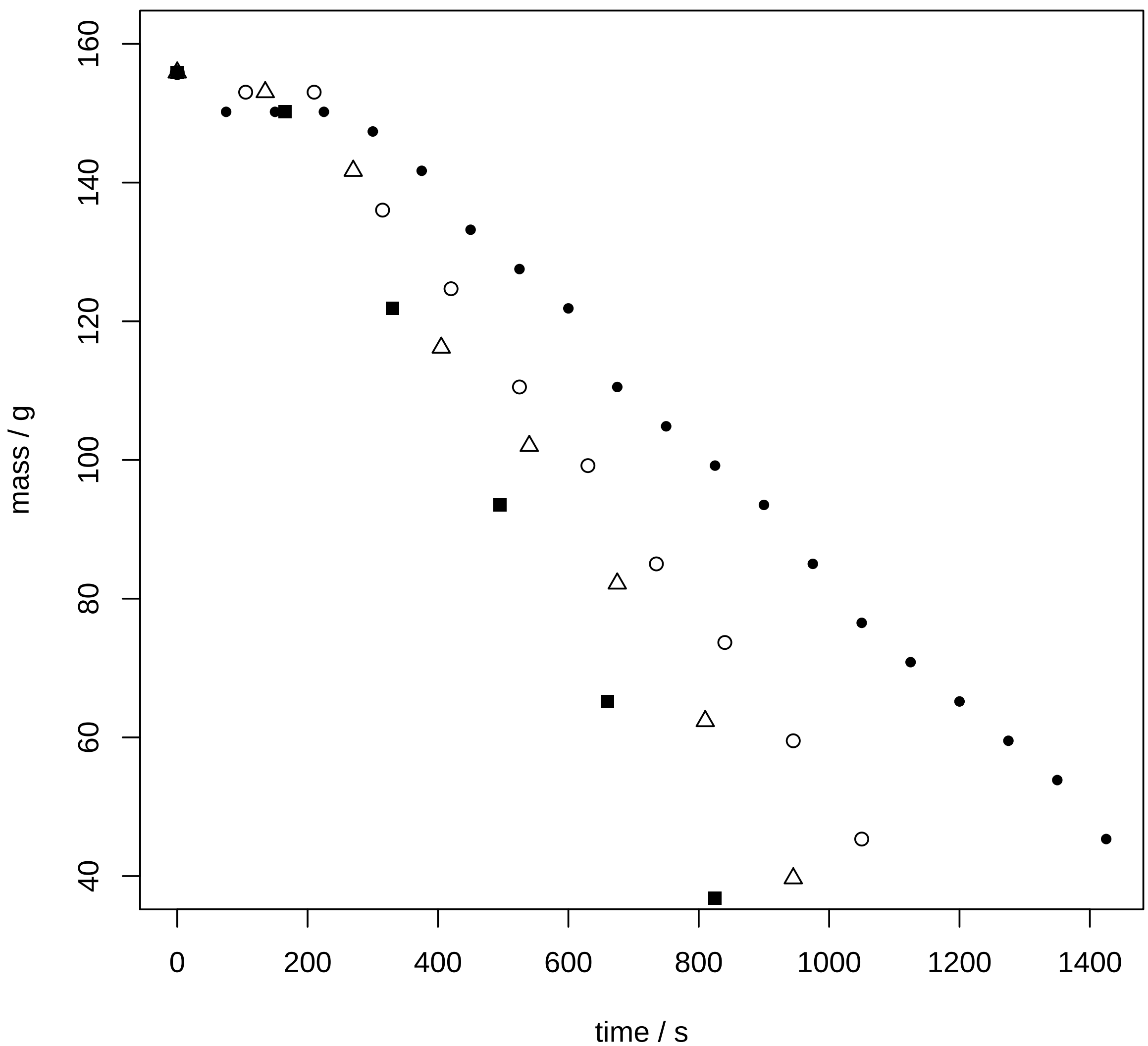

FIG. 4. Mass of water retained (from the initial 156 g) after a given total amount of time. Measurements taken with 90 s of heating (open triangles), with other symbols as in Fig. 2. The time plotted includes the measurement time (with power off).

III. CONCLUSIONS

Using only items found in my home, I was able to study heating and boiling water. The data show that before boiling, the temperature of the water rises but its mass remains nearly constant. After boiling, its temperature becomes constant, but the mass decreases. This

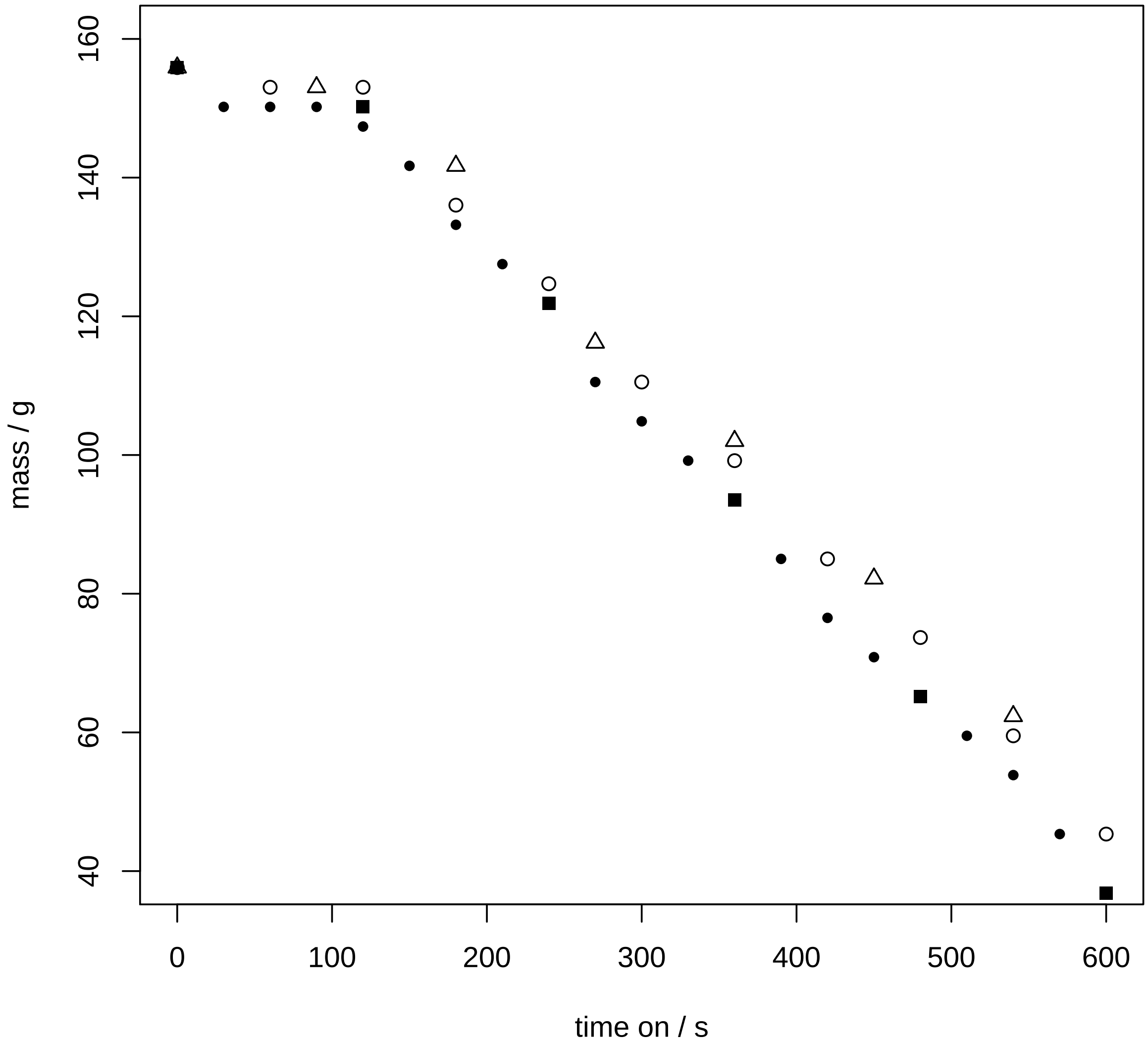

FIG. 5. Data of Fig. 4 replotted with the time including only the time with the power on. The measurement time is excluded.

is the basic picture of boiling. Moreover, the experiment made a plausible estimate of a thermophysical property of water, namely the ratio of the energy required to bring water to a boil compared to the energy required to vaporize the water completely.

Many variants of the experiment can be envisioned. For example, does the 50% power setting really deliver 50% power? This could be examined by heating 2 Styrofoam cups of water at full power and 1 cup at half power. Would putting one Styrofoam cup inside another improve the thermal insulation? Should the microwave oven be wiped to prevent reheating of water which condensed on its walls?

Ice could be studied as well. For example, if you put a cup of water and a cup of ice into the microwave, does the ice melt? What if the ice and the water are in the same cup? Does it matter if it is ice from the freezer or ice from melt water?

A microwave oven can be used to allow a student's scientific curiosity to be backed by quantitative science in the home.

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[1] ASTM F2093-11, "Standard Test Method for Performance of Rack Ovens" https://www.astm.org/Standards/F2093.htm, retrieved 15 February 2017.

[2] "How to Clean a Microwave Oven," https://www.youtube.com/watch?v=vl2Dw-eMhD4, retrieved 15 February 2017.

[3] J. Güémez and C. Fiolhais and M. Fiolhais, "Revisiting Black's experiments on the latent heats of water," *Phys. Teach.* **40,** 26–31 (2002).

[4] A. P. Kennedy, Sr., "Determination of enthalpy of vaporization using a microwave oven," *J. Chem. Ed.* **74,** 1231–1232 (1997).

[5] Mention of commercial products does not imply endorsement by the author's institution.

[6] wikiHow, "How to Boil Water in the Microwave" http://www.wikihow.com/Boil-Water-in-the-Microwave, retrieved 13 May 2017.

[7] US Mint, "Coin Specifications," https://www.usmint.gov/about_the_mint/index583f.html?-action=coin_specifications, retrieved 15 February 2017.

[8] "Rockville, Maryland Past Weather" http://www.localconditions.com/weather-rockville-maryland/20847/past.php, for 12 February 2017; retrieved 20 February 2017.

[9] "Water Altitude Boiling Point Calculator" http://www.csgnetwork.com/h2oboilcalc.html, retrieved 20 February 2017.

[10] US Geological Survey, "Specific Heat Capacity of Water," https://water.usgs.gov/edu/heat-capacity.html, retrieved 15 February 2017.

[11] Wolfram Alpha, http://www.wolframalpha.com/input/?i=latent+heat+of+vaporization+of+water, retrieved 15 February 2017.