Curriculum Units by Fellows of the Yale-New Haven Teachers Institute
2020 Volume II: Chemistry of Food and Cooking

The Physics of Cooking: How Energy Conservation and Thermodynamics Can Improve the Lives of Millions

Curriculum Unit 20.02.02
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Introduction and Rationale

Introduction

Food is near and dear to every one of us. We rely on it for sustenance and health, yet the understanding of food, the energy contained within it, and how it compares to our energy requirements, is likely limited. The number of Americans cooking at home increased from 2003 to 2016, especially among men[1] , with roughly two-thirds of all calories being store-bought and consumed at home depending on income[2,3] . Reported home cooking occurs at higher rates among those of low income[1,3] . Despite this the U.S. Bureau of Labor Statistics reported in 2015 that the average household spends $3,008 per year on eating out[4] . With a U.S. adult obesity rate of 42.4% in 2017-2018[5] , whether families are eating at home or eating out, it appears that there is a lack of understanding of, or appreciation for the science of foods.

Additionally, with about 48 million cases of food poisoning each year in the United States, leading to approximately 3,000 deaths, food safety remains a concern[6] . Many of these cases result from undercooked meat, particularly chicken. On the other end, overcooking or irresponsible cooking behavior led to 48% of home fires and 21% of home fire deaths from 2012 to 2016[7] . Physics is incredible in its ability to transform the way students look upon the world. Applying a little bit of physics can help us to better understand not only energy balance in our bodies, but also heat transfer in cooking. A few simple equations and experiments can help us to think more rationally and quantitatively about food and cooking. This unit aims to help students learn about the physics of food and cooking and apply the knowledge to act more responsibly and prevent some of the cases of obesity and food poisoning.

With the newly adopted Next Generation Science Standards (NGSS) in Connecticut and the focus on real-world connections and 21st century skills, the theme of cooking can be a great way to make physics engaging for students. Studying the physics concepts of energy conservation and thermodynamics can help make a seemingly abstract and quantitative subject more relatable and accessible for students. This unit has originally been designed for 11th and 12th graders in New Haven, Connecticut. Coming from a low-income community, many of the students will have an even greater reason to engage with these topics. According to

Census.gov, 25.9% of New Haven residents live in poverty[8] . Moreover, the 2018 median household income in New Haven is approximately 65% of the national median and only 54% of the state's median[8] . With higher rates of home cooking[1,3] and of childhood obesity[9] in low-income households, these topics are expected to be especially relevant and important for many of my students.

Unit Description

This curriculum unit, exploring the energy in food and the thermodynamics of cooking, will include 5 days of 80-minute lessons in which the students will pick a particular food to study. The food will either need to be purchased or produced, and will need to be a food that begins as batter or liquid and solidifies during cooking. For those students who, for any reason, cannot bring in the food, they will be provided a brownie, cupcake, or other common food item. The project will contain two main components or parts. First, the energy stored within the food will be analyzed by applying mathematics. This will require conversion between a common physics unit of kilojoules (kJ) and a common household unit of kilocalories (kcal, CAL or Calories). Students will then need to apply their knowledge of work and energy conservation to provide an example of physical exercise that would be required for them to expend an equal amount of energy that is contained in their food. If a student is uncomfortable sharing their own mass, they may use the common example of a 70-kg person. The second part of their project will involve them using experimental data to determine the heat diffusion constant for their particular food by using a method similar to that described by Rowat *et al*. published in 2014, "The kitchen as a physics classroom[10] ." This can be done by placing several thermocouples in their food sample (or probing with toothpicks as will be described later) while heating until the center of the food gets to a desired temperature. Once the diffusion constant is determined, it can then be used to derive an equation that will allow the students to determine the required cooking time based on the size of the food sample. Although larger meals may be interesting samples for the experiment, the food samples must remain reasonably small so that the experiment can be completed within a single class period and can be cooked using toaster ovens or small classroom heaters. Students, in groups of 2-3, will be required to share their data with the class so that the results can be discussed. Students will be graded on their mathematical analysis and an accurate derivation of an equation to predict cooking time based on their measured diffusion constant. Teacher checks will be structured strategically throughout the process to ensure student projects meet the requirements and that student groups remain on pace. By relating energy in food to exercises with equal outputs, and by generating equations to ensure foods will be cooked properly, students not only learn physics in an engaging way but also learn how physics can be used to tackle real-world problems.

Background

Energy Balance

For their projects, students will choose a type of food that begins as batter and needs to be baked, such as a brownie or cupcake. In the first part of their projects, students will explore how much physical activity they would need to complete in order to expend the same amount of energy as is contained within the food. This will give students a greater appreciation for how food can contribute to weight gain and obesity. Students will calculate the number of kilocalories contained within their food and then choose a specific type of exercise in which the amount of work or energy expended can be easily calculated. We will use climbing stairs as an example later. Finally, students will calculate how much of their exercise needs to be completed (how many stairs need to be climbed, for example) to “burn” or expend the energy contained within their single brownie or cupcake.

In order to understand energy balance in the context of food and calories, students must first understand the law of conservation of energy in physics and the first law of thermodynamics. Students will need to know the definitions of work, kinetic energy, potential energy (especially gravitational potential energy), and heat loss (in the form of friction), and the equations for calculating them. In addition to these concepts in physics, students may need to convert the unit of weight of carbohydrates, proteins, and fats from pounds or ounces to grams if they are using a homemade recipe and also the energy stored from kilocalories to kilojoules.

Figure 1: Nutrition label for a brownie product

Nutrition Facts

Serving Size 1/4 cup mix (33g)
Servings Per Container about 16

Amount Per Serving	Mix	As Prepared*
Calories	140	180
Calories from Fat	30	70
	% Daily Value***	
Total Fat 3.5g**	**5**%	**12**%
Saturated Fat 1.5g	**8**%	**10**%
Trans Fat 0g		
Cholesterol 0mg	**0**%	**3**%
Sodium 110mg	**5**%	**5**%
Total Carbohydrate 27g	**9**%	**9**%
Dietary Fiber 1g	**4**%	**4**%
Sugars 18g		
Protein 1g		
Vitamin A	0%	0%
Vitamin C	0%	0%
Calcium	0%	0%
Iron	6%	6%

*Prepared as directed with water, vegetable oil and egg.
**Amount in mix.
***Percent Daily Values are based on a 2,000 calorie diet. Your daily values may be higher or lower depending on your calorie needs:

	Calories:	2,000	2,500
Total Fat	Less than	65g	80g
Sat Fat	Less than	20g	25g
Cholesterol	Less than	300mg	300mg
Sodium	Less than	2,400mg	2,400mg
Total Carbohydrate		300g	375g
Dietary Fiber		25g	30g

To begin, students will need to calculate the amount of energy in their food of choice. The knowledge they need will depend on whether they buy a mix or bring a homemade recipe. In the case that a boxed recipe is used they will need to use a nutrition label like the one shown above to determine the number of kilocalories in their single brownie, for example. As shown in Figure 1 above, brownie mixes will almost always show you two Calorie values, one for the dry mix, and one "As Prepared" after adding some wet ingredients such as milk, eggs, and oil. This can make our calculation tricky unless we know exactly one sixteenth of the batter was used for our sample. A solution would be to measure the mass of any added wet ingredients when making the batter, add that to the total mass of the dry mix, and then use the mass of the individual sample relative to the total mass of the recipe to find the Calories in the individual sample. For instance, if 45 grams of water, 109 grams of oil, and 100 grams of eggs were added to the dry mix, then our total mass of the batter would be 782 grams. If the batter of our individual brownie sample has a mass of 50 grams then that would represent about 6.4% of the total batter and thus 6.4% of the total 2,880 Calories, assuming the ingredients are distributed evenly. This would mean we have roughly 184 Calories in our individual sample. Since the energy exerted from exercise will be calculated in Joules, the students need to convert this amount of energy in Calories to Joules. One kilocalorie is equal to about 4,184 Joules or 4.184 kilojoules so this means our individual sample contains about 770,000 Joules of energy. A summary of the calculation is shown below.

Mass of water: 45 g
Mass of oil: 109 g
Mass of 2 eggs: 100 g
Mass of dry mix: 33 g/serving * 16 servings = 528 g

Total mass of batter: 45 g + 109 g + 100 g + 528 g = 782 g

Mass of individual sample: 50 g
Percent mass of total: 50 g / 782 g * 100% = 6.4% of total mass
Percent Calories of total: 6.4% of total Calories

Total Calories in prepared mix: 16 servings * 180 kcal/serving = 2,880 kcal
Calories in sample: 2,880 kcal * 6.4% / 100% ≈ 184 kcal
1 kcal ≈ 4,184 Joules
Joules in sample: 184 kcal * 4,184 Joules/kcal = 769,856 Joules

Alternatively, students may have prepared their sample from scratch using a homemade recipe. If this is the case, additional information will likely be needed. To illustrate how to calculate Calories using a homemade recipe, we will use a simple brownie recipe from Allrecipes.com[11] . First, it may be useful for students to know how many Calories are contained within one gram of each type of macronutrient. Carbohydrates and proteins both contain about 4 kcal per gram, fats contain about 9 kcal per gram and alcohol contains about 7 kcal per gram[12] . This can give students better sense for the energy contained within specific ingredients. However, more information is needed since many ingredients like flour or eggs, for instance, contain more than one macronutrient. Therefore, additional resources are needed. The U.S. Department of Agriculture’s (USDA) FoodData Central is a great tool to get a reliable approximation of Calories contained within specific ingredients[13] . Using this tool, we can generate the following table based on the Allrecipes.com recipe mentioned above.

Table 1: Allrecipes Brownie Recipe Data Collected with USDA FoodData Central

Ingredient	**Amount**	**Amount in grams**	**Calories**	**Energy in Joules**
Butter	1/2 cup	113.5	815	3,409,960
White Sugar	1/2 cup	188	724	3,029,216
Eggs	2 large	100.6	148.8	622,579

Vanilla Extract	1 tsp	4.2	12.1	50,626
Cocoa Powder (Unsweetened)	1/3 cup	28.7	65.3	273,215
All-purpose flour	1/2 cup	62.5	227.5	951,860
Salt	1/4 tsp	1.5	0	0
Baking Soda	1/4 tsp	1.15	0	0
TOTAL MASS		**500.15**		
TOTAL KCAL			**1992.7**	
TOTAL JOULES				**8,337,457**

Next, students will need to understand the physics behind physical exercise. Most students will likely be familiar with the idea that energy cannot be created nor destroyed, only transformed or transferred. In physics, we call this the law of energy conservation or the first law of thermodynamics, which states that the total energy within an isolated system will remain constant. If we consider the example of climbing stairs, we can say that the initial energy (E_i) plus any external work (W_{ext}) put into the system will equal the final energy (E_f). This can be represented by the equation below.

$E_i + W_{ext} = E_f$

This simple equation can be expanded to show the specific components contributing to energy totals on both sides of the equation. To do this we can say that the initial potential energy at the bottom of the stairs (PE_i), plus the initial kinetic energy (KE_i), plus any external work put into the system will equal the final potential energy at the top of the stairs (PE_f), plus the final kinetic energy (KE_f), plus any heat loss due to friction (ΔE_T for change in thermal energy). This can be summed up with the following equation.

$PE_i + KE_i + W_{EXT} = PE_f + KE_f + \Delta E_T$

Before students can fully apply such an equation to a physical activity like climbing stairs, they need to understand how each of these components is defined and calculated. First, potential energy can be broadly defined as stored energy resulting from the position of some parts of a system relative to other parts. In this case, however, we only care about gravitational potential energy or the energy the person has due to their height after climbing the stairs. The formula for this type of potential energy is $PE = mgh$, where m is mass, g is the acceleration due to gravity, and h is height. Both m and g should remain constant in the case of a person climbing a set of stairs. The variable that will change from one side of the equation to the other is the height. To make our equation simpler we can set our initial or starting height to 0 meters, cancelling out the entire "*mgh*" term on the left side of the equation. Kinetic energy (*KE*) can be simply defined as the energy something has due to its motion and can be calculated with the equation $KE = ½mv^2$, where v is the object's velocity. Kinetic energy is not very relevant in this case since we can say the person is not moving before climbing the stairs and that they have stopped moving after reaching the top of the stairs. Therefore, v in each "$½mv^2$" term will equal zero, cancelling them out on both sides. Work in physics is defined as the product of the force applied to an object and a parallel displacement, and is measured in Joules (J). For example, the work done by a rightward force of 10 Newtons (N) that displaces an object 5 meters (m) would be 50 Joules (J). The equation for work is therefore $W = F*d$, where d is displacement and F is the force exerted parallel to the displacement. If the force is not already parallel to the displacement then the equation can be modified to $W = F\cos\Theta * d$, where theta (Θ) is the angle between the force and the displacement of the object. In this case of climbing stairs, we will assume that the force exerted by the person in moving horizontally on the staircase will be small compared to the force of climbing vertically. Thus, we will neglect all horizontal force and only use the force exerted to move one's body in the upward/vertical direction. The equation for force is mass multiplied by acceleration, or $F = ma$. In this case of climbing stairs we will assume that the person is moving vertically upward at a constant velocity, therefore the acceleration or "*a*" used to find the force exerted will be equal to the positive value of acceleration due to gravity g, or 9.8 m/s^2 (making the net acceleration zero, hence a constant velocity). This, of course, would require students to reveal their mass, which may be a little too personal for some students. Because of this, it is suggested that 70 kg be mentioned as an alternative to using your own mass since this is a common mass of a human being often used in calculations. The heat loss component of this equation refers to the energy lost due to heat because of friction (usually between the object and the ground). Here we will assume the person is climbing the stairs in a very efficient manner and that energy lost due to friction is negligible. Thus, we can set this term to zero and we can begin to calculate.

With students now familiar with each of the components of the energy conservation equation, we can then use the amount of energy in the unit of Joules contained in the chosen food to calculate the height gain needed when climbing stairs to offset or "burn" an equal amount of energy. Looking at our law of conservation equation and assuming that the starting height is zero, we can cross out the terms PE_i, KE_i, KE_f, and ΔE_T as shown below.

$PE_i + KE_i + W_{EXT} = PE_f + KE_f + \Delta E_T$

$W_{EXT} = PE_f$

We then find that the work put in by the person climbing the stairs will equal the gravitational potential energy gained due to the height change. This is the amount of energy exerted by the person's exercise of climbing the stairs. If we want to calculate the height gain required to "burn" the energy contained in our individual brownie sample, we can simply set the brownie's energy in Joules equal to the final potential energy. If we then consider that the American architects typically use a height for each stair step of about 0.19 meters (or about 7.5 inches), we can then calculate the required number of stairs climbed to expend the energy contained in the brownie. Assuming, there are typically 12 steps in a flight of stairs, we can also calculate the number of flights required. An example of the calculation is shown below using a person with a mass of 70 kg.

Brownie Energy in Joules = PE_f
769,856 J = PE_f
769,856 J = mgh_f
769,856 J = (70 kg)(9.8 m/s^2)(h)
769,856 = 686h
$h \approx$ 1,122 m

Average stair step ≈ 0.19 m tall
1,122 m / 0.19 m per stair ≈ 5,905 stairs
5,905 stairs / 12 stairs per flight ≈ 492 flights of stairs

For a 70-kg person to burn off the 769,856 J (or 184 kcal) contained in our one brownie, he or she needs to climb about 5,905 stairs or 492 flights of stairs. It is important to note that this is an approximation with an assumption that a constant force is applied and neglects horizontal displacement. Because our movement is not 100% efficient it is likely to require significantly fewer stairs to expend 184 kcals. For example, according to Acefitness.org's "Physical Activity Calorie Counter" it would take only about 20 minutes of climbing stairs for a 70-kg person to burn 184 kcals[14] . At a rate of 90 stairs per minute, a medium pace for climbing stairs, it would only require 1,800 stairs to burn 184 kcals. Still, this lesson activity can be a good way for students to gain appreciation for the amount of energy contained in the food we eat.

Thermodynamics

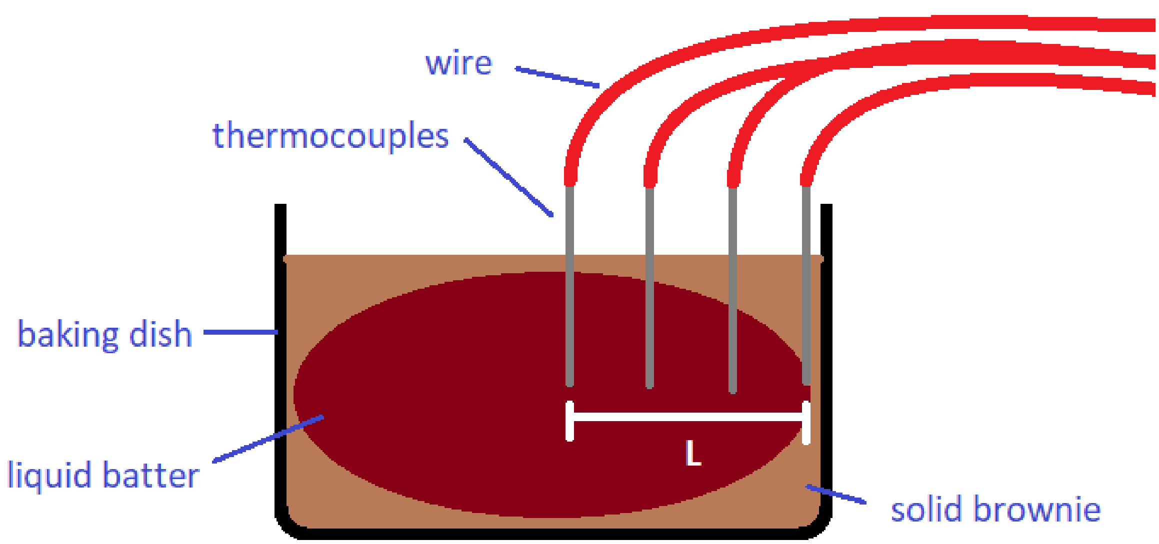
The second part of the project involves cooking the batter of the students' food and experimentally determining the thermal diffusion constant of the batter. This part is inspired by Rowat's 2014 paper, "The Kitchen as a Physics Classroom" published in *Physics Education*. This paper contains many great ideas for hands-on physics labs relating to food[10] . Here, the experiments are modified to be more suitable for a high school physics classroom. Rowat *et al.* describe thermal energy transfer within food with the equation below where $T(t)$ is the temperature of a food after a certain amount of time, T_{in} is the initial temperature of the food, T_{out} is the external temperature or temperature of the oven cooking the food, t is time, τ_0 is the time constant, L is the distance travelled by the thermal energy, and D is the thermal diffusion constant.

$$T(t) = (T_{in} - T_{out})e^{-t/\tau 0} + T_{out};\ \tau_0 = L^2/4D$$

We can use this equation to help determine the proper cooking time for a food sample given its size if we know the thermal energy diffusion constant. Although we may have some potential uses for this equation, we can focus primarily on a simpler equation $L = \sqrt{(4Dt)}$, which shows that the distance traveled by the thermal energy is proportional to the square root of time. By making a few assumptions, we can use this equation along with a relatively simple experiment to roughly determine the diffusion constant (D) for our batter. With a food, such as a brownie or a cupcake, which starts as batter and solidifies, the batter will have a certain temperature at which it solidifies. If we wait until the outer layer solidifies, the solid layer should progress at a rate that is proportional to the square root of time, thus the equation $L = \sqrt{(4Dt)}$, where "L" is the distance progressed by the solid layer. Once the outer layer of the brownie solidifies, we can time how long it takes for the solid layer to reach the center, and then use this time to calculate the thermal diffusion constant for our sample batter. We can do this by rearranging our $L = \sqrt{(4Dt)}$ equation to solve for the thermal diffusion constant to get $D = L^2/4t$. We can calculate this thermal diffusion constant where our initial batter temperature is approximately 21°C (room temperature) and our external or oven temperature is 175°C. We can then use the calculated diffusion constant to estimate the cooking time needed for a batch of brownies of a different size (L or length from outer edge to center, radius in the case of a circular cooking dish) if we use the same or similar temperatures. It is worth noting that this equation would ideally be applied to foods with more of a spherical shape, like a Thanksgiving turkey for instance, where "L" is roughly constant from any outer surface of the food. In the case of brownies, for example, if a large baking sheet is used (increasing the length and width) but the height of the brownies remain only one or two inches then the center may solidify from the top and bottom before the heat actually diffuses through batter from the sides. Such considerations offer incredible opportunities to question students about the limitations of our equations.

There are several methods we can use to time the progression of the solid layer of the brownie towards the center. Both are similar in concept, but one is higher tech and will likely yield a more accurate thermal diffusion constant. Unfortunately, this higher tech option is likely to be more expensive and/or more difficult to implement in the high school physics classroom. This higher tech option involves using thermocouples to read temperature inside the brownie as it is cooking. If we know the temperature at which the batter solidifies, we will know the approximate moment the center of the brownie solidifies based on the temperature reading. Thermocouples are electrical components that generate a voltage when exposed to a temperature gradient. To most effectively read data from thermocouples and have it automatically converted to temperature we would need a data acquisition switch unit, such as the Keysight 34970A/34972A Data Acquisition/Switch Unit. This unit is expensive, however, which makes this method less than ideal for a high school classroom, especially one with a limited budget. Theoretically, it should be possible to measure the voltage generated by the thermocouples with a simple multimeter and then manually convert to a temperature using a thermocouple temperature voltage table. This would likely prove very difficult to do in an efficient fashion while cooking the sample within a toaster oven, for example. For these reasons, a much simpler, although less accurate, method will be discussed. If the more advanced thermocouple option is chosen, however, a possible setup is shown below in Figure 2. This figure is likely to bring clarity to the setup for both methods.

Figure 2: Possible Setup of Brownie Sample with Thermocouples



A significantly simpler method can give us a very rough estimate of the diffusion constant. This can be done by frequently probing the brownie with toothpicks in locations similar to those of the thermocouples in Figure 2. It is suggested this experiment is repeated at least 3 to 4 times so as to more accurately pinpoint the time at which various distances from the edge of the brownie are solidifying. By repeating the experiment several times and fine-tuning the time it takes for the solid layer of the brownie to reach the center, the oven can be opened fewer times, which is an obvious concern since we will not want to continue disturbing the temperature of the oven, T_{out}. While this experiment has its obvious limitations, if care is taken it can give us a rough estimate of the diffusion constant and will help students gain a better understanding of thermodynamics. Interestingly, Rowat mentions that one of her students was so confident in their experimentally determined equations that they used it to “estimate the cooking time of her family’s Thanksgiving turkey.”[10]

It is important to note that whatever recipe or mix is chosen it should be of a consistent nature so that thermal diffusion constant can be expected to remain constant throughout the batter. Therefore, using brownies with chocolate chips or M&Ms, for instance, is not advised. Also, it is important to preheat the oven and try to open the oven door as few times as possible in order to keep the oven temperature (T_{out}) as stable as possible. Other notable limitations of this experiment include energy loss due to water evaporation from the surface of the batter, changes to the heat diffusion constant after solidification of the batter, minor amounts of convection while the batter is still fluid, and other factors. That said, probing students about these limitations and the accuracy of their estimates is likely to provide important training in science and engineering.

Lastly, as an example, we can cook a circular brownie with a diameter of 5 centimeters (cm) where it is 2.5 cm from any point along the outer edge to the center of the brownie (2.5 cm is our L). If we experimentally determine, using either previously mentioned method, that it takes 10 minutes, or 600 seconds, for the brownie's solid layer to reach the center, what is the estimated diffusion constant? This problem can be solved by the calculation shown below.

$D = L^2 / 4t$
$D = ?$
$L = 2.5$ cm
$t = 600$ s

$D = (2.5)^2 / (4*600)$
$D = 6.25 / 2{,}400$
$D = 0.0026\ \text{cm}^2/\text{s}$

The thermal diffusion constant of the brownie batter is 0.0026 cm^2/s.

Lesson Plans

Overview

This unit is designed to be implemented during the fourth marking period as a culmination of thermodynamics. It is to last for two weeks, equal to five 80-minute class periods. Using food as a method of studying thermodynamics and energy conservation will engage students and provide real-life applications for the material. Obesity and food poisoning remain prominent issues in the United States and students will work to investigate the physics behind these problems. Upon choosing a food sample to study, students will determine the energy contained within it in terms of kilocalories. They will then calculate the amount of exercise needed to expend the same amount of energy. Next, in groups of 2-3, students will cook their food samples to determine the thermal diffusion constant of their food. Finally, students will individually write a 1-page discussion about what they learned, the importance of these topics, and the limitations of their work. Significant portions of their grade will be determined by their ability to make accurate calculations and to demonstrate understanding in their discussion paper. Related NGSS standards, learning objectives, a timeline, required materials, a more detailed description of the thermal diffusion constant lab, and a suggested grading rubric for the unit are outlined below.

Timeline

Teacher checks will be required at least once per class period to ensure students remain on pace. Each day is designed for one 80 minute class period.

Day 1: Introduction to the unit, first law of thermodynamics, the physics of exercise and thermal diffusion. Students will begin brainstorming their plans for a food sample and chosen exercise.

Day 2: Calculation of energy contained in the food sample and amount of chosen exercise to burn said energy.

Day 3: First day of thermal diffusion lab. Students will cook at least two batches of their food sample.

Day 4: Second day of thermal diffusion lab. Students will cook at least another two batches of their food sample.

Day 5: Data analysis and class discussion on the assumptions made throughout the unit and limitations of the thermal diffusion lab.

Materials

For each group of students you will need:

- Batter for 3-4 cupcakes or brownies (3-4 trials recommended)
- Individual baking dishes
- A toaster oven (this can potentially be shared amongst several groups)
- Toothpicks
- Hot hand protector
- Balance
- Ruler
- 4 thermocouples (optional, advanced)
- Multi-meter (optional, advanced)
- Jumper wire (optional, advanced)
- Data acquisition switch unit (optional, advanced)

Description of Thermal Diffusion Lab

As mentioned previously, in order to determine the thermal diffusion constant using the simple method outline below, students will need to choose a food sample that solidifies while cooking. Brownies or cupcakes are recommended and brownies were used in the example below. The food samples will need to be cooked in small individual containers and will need to be cooked in the classroom so toaster ovens are recommended for this purpose. The objective of the lab is to determine the time it takes for the center of the food (brownie in this case) to solidify with the clock starting only once the outer edge of the brownie has solidified. This is done using the equation, $D = L^2 /4t$, as described in more detail above. This equation requires we also know the L, which would be the distance from the outer edge to the center of the brownie, or the radius in the case of our cylindrical brownie shown below in Figure 3. To determine when the brownie solidified toothpicks were used. Some clues as to when this happens can be supplied visually but ultimately the brownies needed to be cooked several times to really narrow in on the exact time the outer edge and the center of the brownie solidified. The data shared below was generated from separate trials or batches of six individual brownies. With time and supplies limited in the classroom it is unlikely students will be able to conduct this many trials, however, at least three or four trials are recommended per group in order to get more reliable data. Data can even be pooled between the entire class (if the same method is used) to determine a class average for the thermal diffusion constant. Since only two time points are needed (the point when the outer edge solidifies and the point when the center solidifies) the toothpicks were only used to probe in two locations (the outer edge and the center) as shown in Figures 3 and 4. This differs from the four locations probed using thermocouples shown in Figure 2. Figure 5 is provided to show an example of a partially cooked brownie to demonstrate how the solid layer progresses over time, along with some other materials used in the experiment. The procedure, data, and images provided below offer a more detailed example of how to conduct the experiment.

A toaster oven was preheated to 350°F before an individual brownie was placed inside. The brownies were cooked in individual aluminum cupcake trays with a cylindrical shape giving the brownies an approximate diameter of 6.35 cm. This means the *L* value, or length from the outer edge to the center, was 3.175 cm. Care was taken to open to the toaster oven as few times as possible to probe the brownies and to keep the door open and the brownies outside the oven for as little time as possible. The experiment was conducted six times, with six individual brownies, to narrow in on a precise time the brownie's outer edge solidified and a time the brownie's center solidified. Solidification was defined as the toothpick having no liquid batter on it after having taken it out (a small amount of solid material on the toothpick is inevitable). An example of what a post-probe toothpick looks like when the brownie's outer edge had solidified is shown in Figure 3. Figure 4, on the other hand, shows a toothpick that probed the same brownie at the same, 20-minute mark, time point but in the center of the brownie and represents an example of what a toothpick may look like when the brownie has not solidified. Additionally, a food thermometer was used to measure the temperature the brownie batter was solidifying. The batter appeared to be solidifying at roughly 138°F. This measurement was not necessary to calculate the thermal diffusion constant; it was only measured out of curiosity. After six trials, it was determined that brownie's outer edges solidified at approximately the 20-minute mark and the centers solidified at approximately the 34-minute mark. This made the *Dt* equal to 840 seconds (14 minutes). Thus, the thermal diffusion constant *D* was calculated to equal 0.00300 cm^2 /s as shown below.

$D = L2 / 4t$
$D = (3.175)2 / (4)(840s)$
$D = 10.08cm2 / 3{,}360s$
$D = 0.00300\ cm2/s$

Figure 3: Brownie after 20 minutes of cooking (left), toothpick with solid brownie residue (right). This toothpick was placed in the brownie's outer edge.

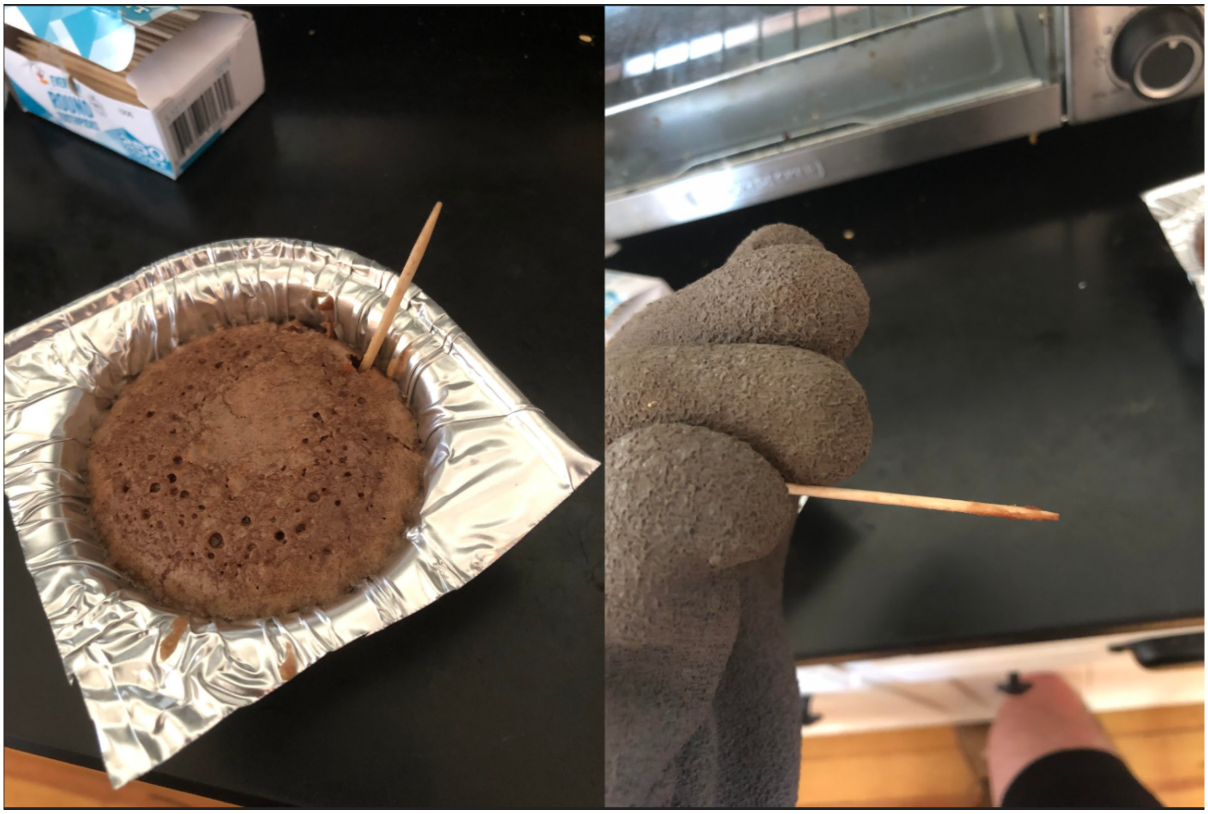


Figure 4: Brownie after 20 minutes of cooking (left), toothpick with liquid brownie residue (right). This toothpick was placed in the brownie’s center.

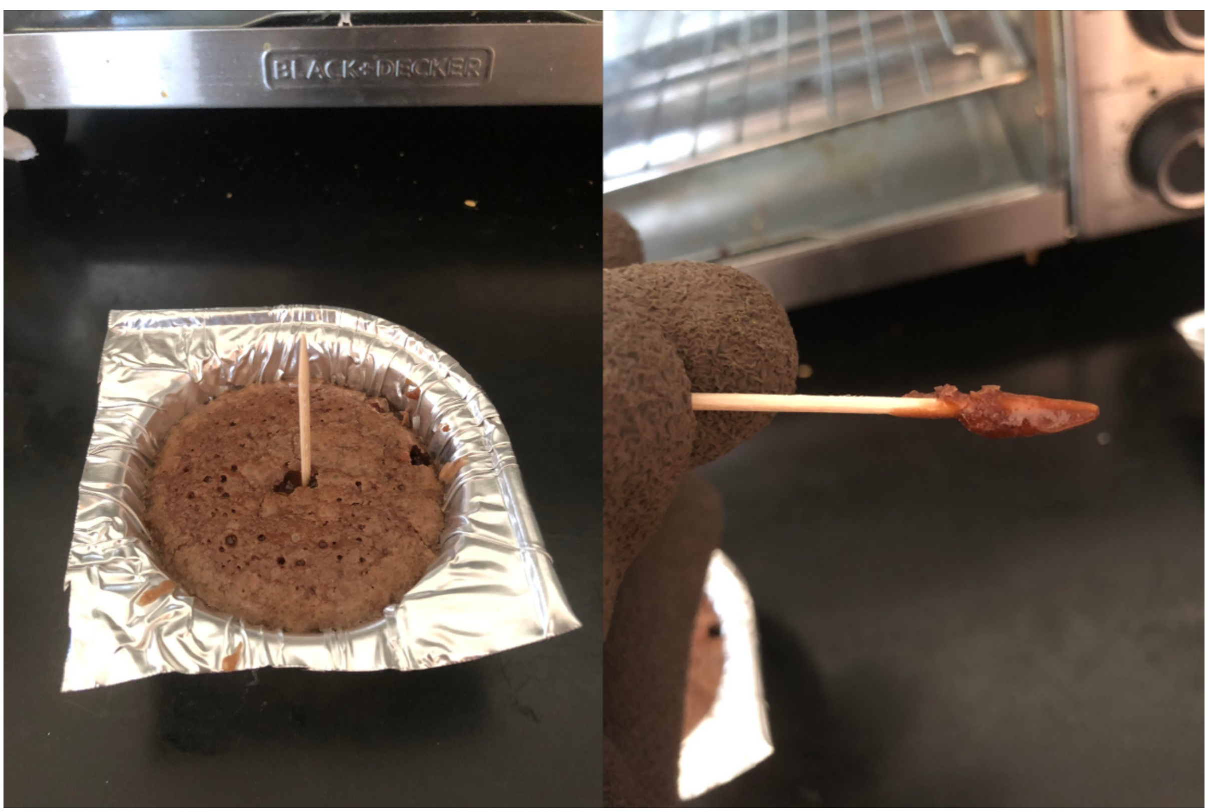


Figure 5: Partially cooked brownie after 28 minutes of cooking with gooey center (left), materials used (right).

Grading Rubric

Component	Percentage
Accurate calculation of CAL in food sample	10
Description of Exercise	10
Calculation to determine amount of exercise required to burn kilocalories in food sample	20
Participation/collaboration with classmates	10
Data sheet from thermal diffusion lab	10
Calculation of thermal diffusion constant	10
1-page written discussion on the importance and limitations of the what was learned	30

Appendix on Implementing District Standards

Related NGSS Standards

HS-PE-PS3-4: Plan and conduct an investigation to provide evidence that the transfer of thermal energy when two components of different temperature are combined within a closed system results in a more uniform energy distribution among the components in the system (second law of thermodynamics).

HS-PE-ETS1-2: Design a solution to a complex real-world problem by breaking it down into smaller, more manageable problems that can be solved through engineering.

Learning Objectives

Students will be able to (SWBAT) understand and discuss the first law of thermodynamics

SWBAT read nutrition labels and accurately calculate the amount of kilocalories in a food sample

SWBAT apply conservation of energy equations to calculate the amount of exercise required to burn a specific amount of kilocalories

SWBAT work collaboratively with classmates to generate and collect data

SWBAT calculate the thermal diffusion constant of food sample given collected data

SWBAT think critically to identify limitations of an experiment or activity

Resources / Reading List

https://www.sciencedirect.com/topics/food-science/thermal-property-of-food

https://flavourjournal.biomedcentral.com/articles/10.1186/2044-7248-2-5

https://campas.me.ucsb.edu/sites/campas.me.ucsb.edu/files/publications/physics_education_2014_rowat.pdf

https://www.khanacademy.org/science/physics/thermodynamics/specific-heat-and-heat-transfer/a/what-is-thermal-conductivity

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