Eggstraordinary Eggsperiments
An Activity to Teach Heat Transfer Concepts to K-12 Students

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Abstract

There has been a decline in number of students enrolling in engineering over the last two decade and the USA is projected to face a shortage of engineers. A simple and relatively cheap heat transfer demonstration to engage high school students and to increase their interest in STEM careers is presented. We demonstrate how experimental, mathematical, and computational methods can be used to predict and model the process of cooking an egg, with the ultimate purpose of demonstrating various aspects of STEM careers. For educators, ***http://www-personal.umich.edu/~ajyshih/egg/Eggsperiment/Home.html*** *contains resources beyond those reported in this paper.*

Keywords: Elementary/Middle School Science, High School/Introductory Chemistry, Laboratory Instruction, Hands-On Learning/Manipulatives, Catalysis, Kinetics, Reactions

1. Introduction

An experiment and simulation suitable for a K-12 teacher to demonstrate heat transfer principles to his/her class is presented. The ultimate goal is to motivate and expose K-12 school students toward pursuing engineering and the sciences as a career path. (Eniola-Adefeso 2010, Eniola-Adefeso 2012)

2. Background

There are three types of heat transfer: conduction, convection, and radiation. Conduction involves the transfer of heat through a solid. Convection involves the energy exchange between a surface and a fluid. There are two different types of convection: natural and forced. Natural convection is caused by a difference in fluid density due to temperature (e.g. warm air rises as cool air falls). Forced convection is caused by an external force on the fluid over the surface. Radiation is heat transfer between two objects that are not in contact. (Welty et al. 2001)

Heat flux equations for the three heat transfer types:

Conduction: $q/A=-k\nabla T$
Convection: $q/A=h\Delta T$
Radiation: $q/A=\sigma T^4$

where,
q = heat transfer rate
A = area
T = temperture
k = conductive heat transfer coefficient
h = convective heat transfer coefficient
σ = Stefan-Boltzmann constant, $5.676*10^{-8}$ W/(m^2K^4)

The three main components of an egg include the egg shell, egg white, and the yolk. Conduction can be modelled through these three layers. The egg shell, a very thin layer in comparison to the other two layers, makes up only 10% of the egg composition. Therefore, the conduction of heat through the shell may be neglected.

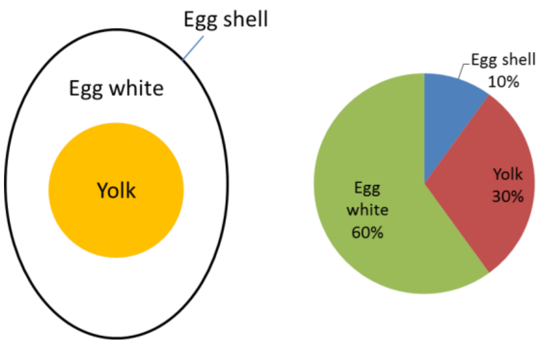


Figure 1: Three main components of an egg.

3. Experimental Materials and Methods

The materials used are listed below:

- 12 eggs
- Water
- Ice
- Electric kettle
- Steamer
- Oven
- Bowl
- Pot
- Baking pan
- Oven mitt

- Timer
- 3 thermometers

Determine which cooking method is to be studied

- If boiling – Fill electric kettle with enough water and bring to boil.
- If steaming – Fill steamer with water and start steaming.
- If baking – Preheat oven to 350˚F

Carefully place 3 eggs into the cooking compartment and start the timer. After 5 minutes take out the 1st egg and cool it in cold water for 2 minutes. After 10 minutes take out the 2nd egg and cool it in cold water for 2 minutes. After 15 minutes take out the 3rd egg and cool it in cold water for 2 minutes. For each set of eggs observe how much of the egg was cooked and its ease to peel.

4. Computational Method

COMSOL Multiphysics 3.4 (COMSOL AB, Stockholm, Sweden) was used to model heat transfer through an egg. The following assumptions were made in the set-up of this simulation:

- 2-D heat transfer
- Egg has a ellipsoid shape
- Conduction through shell is negligible
- $T_{envirionment}$= 100°C (boiling water)
- Coagulation of egg yolk occurs in the range 65° to 70°C, but physical properties remain constant
- Fresh egg whites coagulate in the range 62° to 65°C, but physical properties remain constant

5. Experimental Results and Discussion

Boiling

After 5 minutes, the outer edge of the white near the shell is solid, but the inside of the white is not cooked well. After 10 minutes, the egg is semi-done. While the center of the yolk is still dark orange, it is not runny. After 15 minutes, the egg is completely cooked. The yolk is a golden yellow solid, and the white has solidified as well.

Steaming

After 5 minutes, neither the yolk nor the white are cooked. In ten minutes, the white is solid, but the yolk is still dark orange. Within 15 minutes, the egg is done cooking and looks perfect besides the cracked shell.

Baking

In 5 minutes, the egg is still completely raw. After ten minutes, white specks are scattered within the mostly clear egg white. The yolk is still liquid. After 15 minutes, the white is mostly done cooking, while the yolk still needs to cook longer since it is runny.

Tabulated and pictorial results are in Tables 1 and 2 in addition to Figure 2.

Table 1: Time required to cook yolk and egg using boiling, steaming, and baking.

Boiling Time (minutes)	Yolk Cooked	White Cooked
5		
10		✓
15	✓	✓
Steaming Time (minutes)	**Yolk Cooked**	**White Cooked**
5		
10		✓
15	✓	✓
Baking Time (minutes)	**Yolk Cooked**	**White Cooked**
5		
10		
15		✓

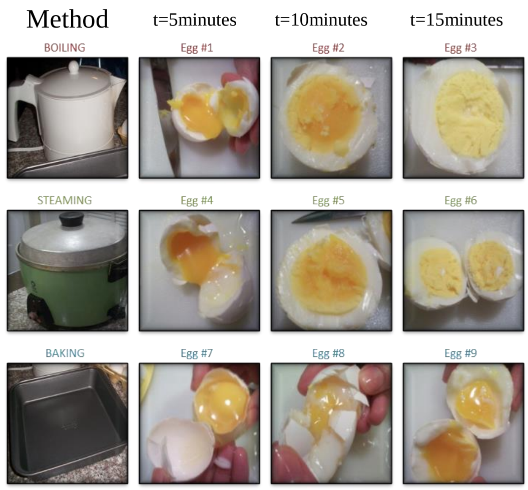


Figure 2: Photos of egg after 5, 10, and 15 minutes while boiling, steaming, and baking.

Table 2: Ease of peel after boiling an egg for 15 minutes then cooling using three different methods.

Method of cooling	Initial temperature	Cooled temperature (after 5 minutes)	How does it peel?
Ice water	190°F	150°F	Well
Running water	190°F	100°F	Well
Sitting on counter	190°F	160°F	Easiest (cracked shell)

Based on our experimental results, it takes between 10-15 minutes to fully hard-boil an egg by means of boiling and steaming. Baking requires more than 15 minutes for both the yolk and egg white to cook. This further illustrates that fluid properties and convection play a significant role in heat transfer. Boiling and steaming both exhibit similar rates of heat transfer whereas baking exhibits a slower rate.

Our results showed that forced convection is more effective in cooling the egg. Running water was able to cool the center of the egg faster than ice water and ambient air. Ice water was able to cool the egg down faster than ambient air, but only by a difference of 10 °F.

6. Computational Results

The egg properties used in COMSOL are presented in Table 3. (Coimbra et al. 2006) Figure 3 shows the time-resolved transfer of heat into the egg when submerged in a 100°C environment. A large egg, as defined by the United States Department of Agriculture, is one whose mass ranges from 23 to 26 ounces. The time required to heat a large egg the point where the temperature is 65°C or higher at any point in the egg (i.e. soft boil), varies from 5 to 6 minutes (depending on the egg mass) from COMSOL simulations, consistent with experimental observations.

Component	Cp (J/g-K)	k (W/m-K)	ρ (g/cm^3)	R (mm)
Yolk	2.7	0.34	1.032	14
White	3.7	0.54	1.038	22 to 29.35
Shell		225		

Table 3: Physical properties of egg yolk, white, and shell used in COMSOL simulation

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p \mathbf{u}_{\text{trans}} \cdot \nabla T = \nabla \cdot (k \nabla T) + Q$$

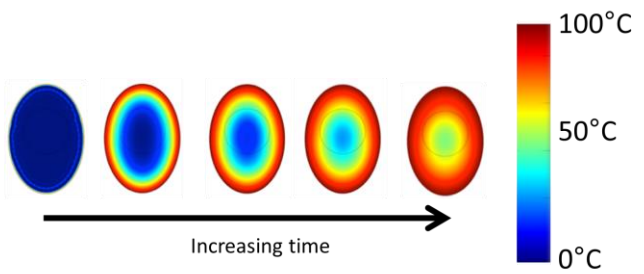
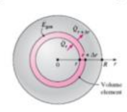


Figure 3: Time-resolved transfer of heat into egg.

7. Mathematical Results

C.D.H. Williams derived and reported a heat transfer equation from heat transfer through a spherical egg in 2000, presented in Figure 4. Using the equation, the physical properties in Table 3, and assuming that the heat capacity of the spherical egg is uniformly 3.7 J/g-K, we predict from the mathematical model that it will take 5 minutes to soft-boil a large egg.



$$\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 \frac{\partial T}{\partial r}\right) + \frac{\dot{e}_{gen}}{k} = \frac{1}{\alpha}\frac{\partial T}{\partial t}$$

• • •

$$t_{\text{cooked}} = \frac{M^{2/3} c \rho^{1/3}}{K \pi^2 (4\pi/3)^{2/3}} \log_e \left[0.76 \times \frac{(T_{\text{egg}} - T_{\text{water}})}{(T_{\text{yolk}} - T_{\text{water}})} \right]$$

Figure 4: Differential equation for heat transfer through a sphere and final form after applying boundary conditions relevant to hard-boiling an egg.

8. Conclusions

We report a simple and relatively cheap heat transfer demonstration designed to increase high school student's interest in STEM careers. We demonstrate how experimental, mathematical, and computational methods can be used to predict and model the process of cooking an egg, with the ultimate purpose of demonstrating various aspects of STEM careers. http://www-personal.umich.edu/~ajyshih/egg/Eggsperiment/Home.html contains resources that outline experimental, mathematical, and computational methods in addition to safety considerations and worksheets.

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