Determining the degree to which a hen's egg is cooked by boiling

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Abstract. Eggs are very good sources of low-cost and high quality protein. They are delicious and can be eaten well cooked, medium-cooked or raw. The objectives of this study were to define and determine the degree to which a hen's egg is cooked by boiling without breaking its shell. Assuming that an egg has a radial symmetry and a constant density, the moment of inertia is proportional to its mass and square of its radius. As the eggs are heated, the protein inside them turns harder. That affects the apparent moment of inertia of an egg. The torsion pendulum was used to measure rotational motion of an egg. Two springs were attached to the side of the egg holder to create restoring torque, hence oscillation. A photo gate together with a 10-slot disc was used to detect the rotational motion of the egg. The period of the oscillation was recorded. The results show that the moment of inertia of raw eggs and hard boiled eggs are different and both are proportional to MR^2(mass and radius square) of the eggs. The ratio of of liquid core (uncooked part) to the whole egg has a linear relationship to the $(T^2 - T_0^2)/MR^2$ and this value can be used to determine the degree to which an egg is cooked.

1.Introduction

Eggs are very good sources of low-cost and high quality protein. The whites are rich sources of selenium, vitamin D, B6, B12 and minerals such as zinc, iron and copper. The huge number of eggs are consumed in the world annually. The main safety concern of eating eggs is risk of salmonella food poisoning which can be prevented by cooking eggs at a high enough temperature for a long enough period of time, meaning the hard boiled eggs carry a much lower salmonella risk. However, half boiled eggs are also delicious. Thus, the objectives of this study were to define and determine the degree to which a hen's egg is cooked by boiling without breaking its shell.

2.Material and method

2.1. Moment of inertia of an egg

Assume that an egg has a radial symmetry, and a constant density [1,2]. Thus the moment of inertia is proportional to the mass and square of its radius. As the eggs are heated, the protein inside them turns harder. This changes the viscosity of the eggs[3], which in turn affects the apparent moment of inertia of an egg. Normally, the moment of inertia is a function of mass and dimensions of the object. For the egg it can also be the function of degree which an egg is cooked because as the egg is oscillating, the liquid part inside the egg tends to slip with respect to the shell. So, the moment of inertia of an uncooked egg is less than hard-boiled egg of the same mass and dimensions. Moment of inertia of the system plus that of the egg about the egg's symmetry axis can be written as

$$I_{measured} = I_{solidshell} + I_{liquidcore} + I_0 \,. \tag{1}$$

$$I_{measured} = \alpha MR^2 - \alpha m r^2 + \beta(m r^2) + I_0 \,, \tag{2}$$

where M is the total mass of the egg, R is the outer radius, m is mass of the liquid part, r is the inner radius of liquid part, α and β are radius of gyration of the hard-boiled egg and soft-boiled egg, and I_0 is the moment of inertia of the instrument. When the system is oscillating, the period squared is proportional to the moment of inertia. Rearrange equation (2) and using the egg's equation of motion, the period of oscillation of an egg can be written as

$$\frac{T^2 - T_0^2}{MR^2} = \alpha - (\alpha - \beta)\frac{m r^2}{MR^2} \,. \tag{3}$$

Note that all other constants are absorbed into α and β.

2.2. Defining degree to which eggs are cooked

From equation (3) the ratio of the moment of inertia of the liquid part and that of the whole egg can refer to the degree of which the eggs are cooked and can be determined by the experiment. For the well-cooked egg the ratio become zero, and it is close to one for the raw egg.

2.3. Measuring the degree to which the eggs are cooked by torsion pendulum

The torsion pendulum experimental setup is shown in figure 1. Two springs were attached to the side of the egg holder to create restoring torque, hence oscillation. A photo gate together with a 10-slot disc were used to detect the rotational motion of the egg. The photo gate works by detecting an infrared radiation emitted from the infrared LED located at the opposite side of the 10-slot disc. The 10-slot disc either allows infrared beam to pass or to be blocked. When the infrared signal passes through the slot, sensor will send unblocked signal to analyzer. Using the blocking and unblocking times, the analyzer can determine angular velocity of the oscillation.

The moment of inertia of the device was calculated from the period of oscillation of the system without an egg. The device has moment of inertia of 0.0556 g cm^2. Moment of inertia of eggs with different degree of cookedness was found by measuring the period of oscillation of the system with an egg placed on the holder. The eggs were cooked in boiled water ranging from 5 to 15 minutes. To measure m and r, the eggs were cracked into two halves. The liquid part of the eggs was removed, and the remaining mass and the inner radius of solid part were used to find m and r.

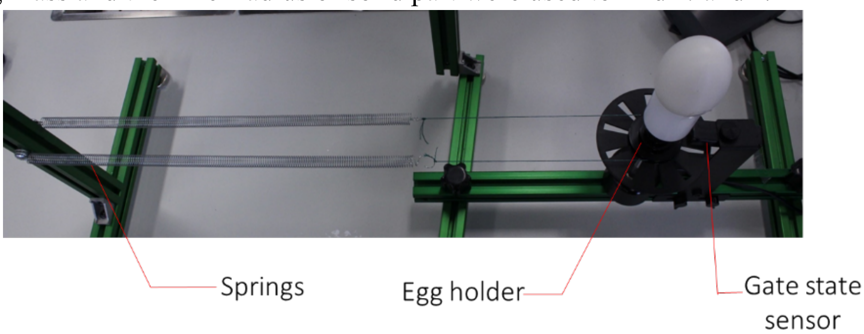


Figure 1. Experimental setup

3.Results and discussion

3.1. The rotational motion of an egg

The graph in figure 2 below shows the typical oscillation of the system with an egg attached to the apparatus. The period of oscillation was found by fitting the graph with the function

$$y = Ae^{-bt}\sqrt{\sin^2(Ct + D)}. \quad (4)$$

The signal from photogate cannot be negative value, therefore this graph shows the absolute value of the angular velocity of the egg. The absolute function of sin wave is difficult to write down as an equation so the fitting equation $y = Ae^{-bt}\sqrt{\sin^2(Ct + D)}$ were used to determine the period of oscillation instead. The period of oscillation is obtained from ω (C in equation 4). The damping coefficient b indicates that the system has friction.

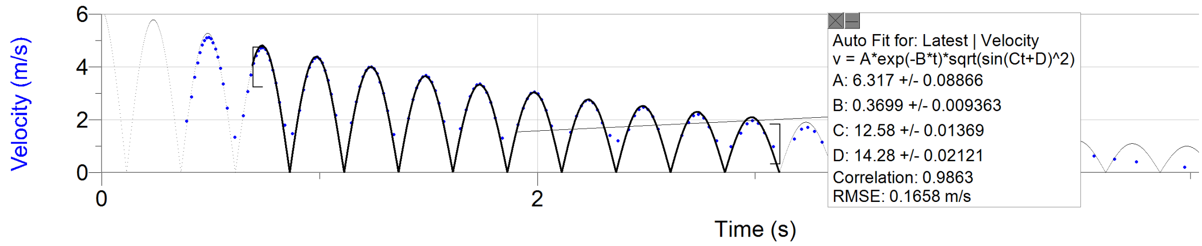
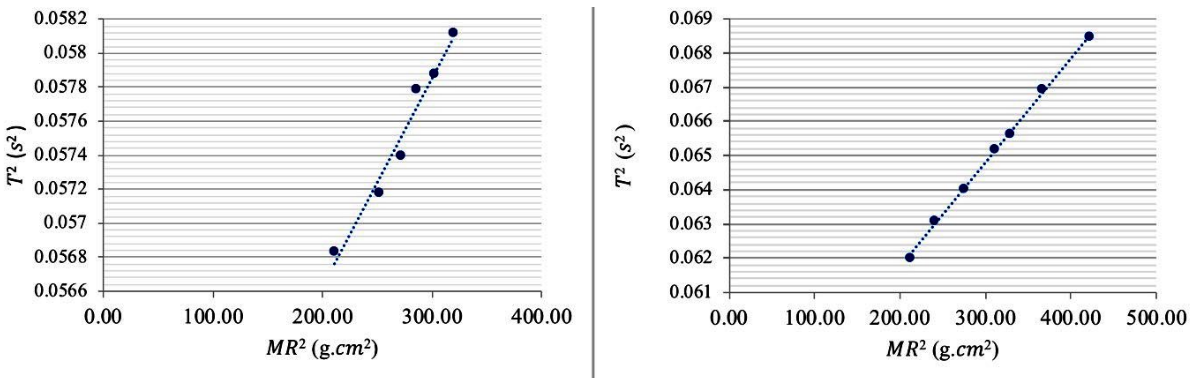


Figure 2. Typical velocity-time graph obtained from photo gate.

3.2. The relationship between $T^2(s^2)$ and $MR^2(g\,.\,cm^2)$ of raw egg and hard-boiled egg.

To confirm that MR^2 is directly proportional to moment of inertia of the egg, different sizes and masses of egg were used. Each of the eggs was attached to the egg holder, the egg was then set to oscillate and the period of each egg was measured. The period squared was plotted with MR^2. The relationship between T^2 and MR^2 for raw eggs is shown in figure 3(a), and that for hard-boiled eggs is shown in figure 3(b).



(a) **(b)**

Figure 3. The relationship between $T^2(s^2)$ and $MR^2(g\,.\,cm^2)$ of (a) raw egg and (b) hard-boiled egg. Note that error bars are too small to be seen.

The results confirm that moment of inertia of hard-boiled and raw eggs are different. To investigate different degree to which an egg is cooked, the eggs were put in the boiled water for different amount of time. Then they were put, one at a time, in the apparatus and the period was measured. The relationship between $\dfrac{T^2 - T_0^2}{MR^2}$ and $\dfrac{mr^2}{MR^2}$ was plotted and is shown in figure 4.

3.3. The relationship between $\dfrac{T^2 - T_0^2}{MR^2}$ and $\dfrac{mr^2}{MR^2}$

In figure 4, $\frac{T^2 - T_0^2}{MR^2}$ and $\frac{mr^2}{MR^2}$ have linear relationship and the value of $\frac{mr^2}{MR^2}$ is in the range of 0 (hard-boiled egg) to 1.0 (raw egg). For the hard-boiled egg, there is no liquid part and all parts of the egg move together. For the raw egg, the viscous liquid part acts as a damper and the motion of the shell and the liquid part are not uniform. This results in lower effective moment of inertia and hence, period of the motion. However, for the value of $\frac{mr^2}{MR^2}$ between 0 and 0.2 $\frac{T^2 - T_0^2}{MR^2}$ is constant. This is because the yolk, even if it is still liquid, become more viscous and can follow the motion of the whole egg. Regardless to their mass and size, the eggs with the same mr^2 ratio of liquid core to the whole egg have the same value of $\frac{T^2 - T_0^2}{MR^2}$, which can be measured without cracking the egg shell. Therefore, degree to which an egg is cooked can be derived from measuring period of oscillation and compare with the reference graph in figure 4 from this experiment. There are, however, possible parameters that might affect the results, for example, the thickness of the egg shell, the size of the egg yolk, the variation of the egg shape and liquid viscosity inside the egg. Further study on these parameters is suggested.

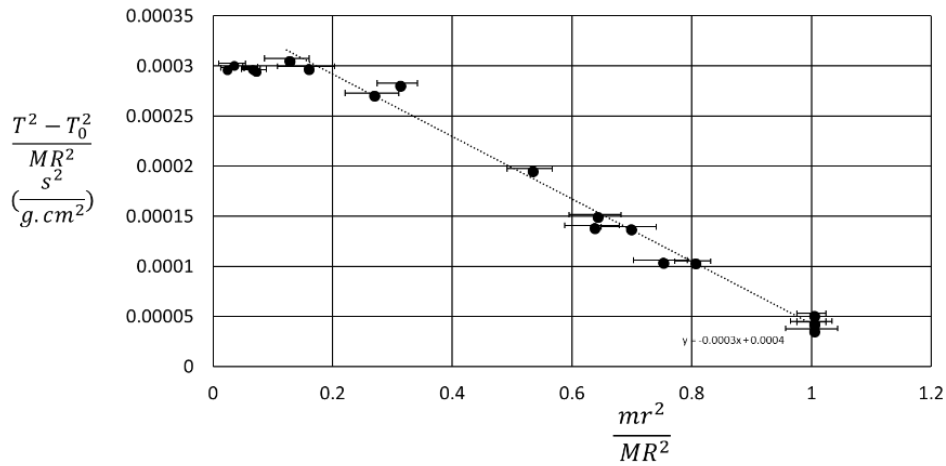


Figure 4. The relationship between $\frac{T^2 - T_0^2}{MR^2}$ and $\frac{mr^2}{MR^2}$

4.Conclusion

The torsion pendulum was used to measure moment of inertia of eggs with different degree of which they are cooked. The results show that the moment of inertia of raw eggs and hard boiled eggs are different and both are proportional to MR^2. Based on the assumption that the density of an egg is uniform, the degree to which a hen's egg is cooked is defined as the ratio of MR^2 of liquid core to the whole egg. It was found that $\frac{mr^2}{MR^2}$ has a linear relationship to the $\frac{T^2 - T_0^2}{MR^2}$. The period of oscillation can be used to determine the degree to which an egg is cooked.

Reference

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