Final report for physics project

SUBJECT:
Low-cost TPA machine for evaluating the tenderness parameters of boiled chicken breast and validating the heat diffusion equation.

Written by
Student:
Chieh-Ann Liao

Supervisor:
Pi-Hui Tuan

Department of Physics, National Chung Cheng University, Chiayi, Taiwan

Contents

- Abstract -

The project experiment aims to explore the tenderness differences of chicken breasts under two common cooking methods: boiling and poaching. Based on thermodynamics, the significantly different thermal diffusion processes for the boiled and poached chicken will lead to distinct thermal gradients and result in different moisture loss rates from the chicken samples to the surrounding water. To further study the effects of moisture loss on the tenderness of chicken breast, we construct a device to perform the texture profile analysis (TPA). The TPA results show that with a more drastic moisture loss rate, the boiled chicken is tougher compared to the poached chicken with a slower and steadier moisture loss.

Keywords: Texture Profile Analysis (TPA), Heat diffusion, boiled chicken tenderness.

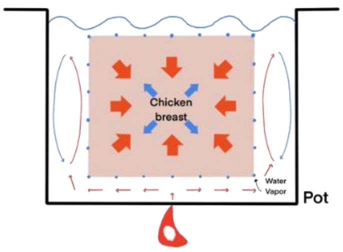
I. Introduction

1.1 Motivation

Sous vide chicken is a common method for treating chicken meat. However, different heating condition often leads to differences in the physical properties of the meat, such as tenderness and chewiness. We are curious about this and believe it would be interesting to explain it using the physics we have learned.

1.2 Basic principle

The principles of the entire process involve two parts: the heat diffusion model and TPA methods. Firstly, when the chicken is being heated, the water molecules collide with the meat's surface. These collisions transfer momentum into heat, resulting in macroscopic heat transfer. This heat transfer causes a nonuniform temperature distribution inside the chicken breast, creating a gradient field inside the chicken breasts. This gradient pushes the water content from the inside of the chicken to the outside due to the denaturation of muscle proteins (Fig1). These processes follow the diffusion model shown below (Eq.1), and the mass transfer equation coupled with the heat transfer equation (Eq.2).



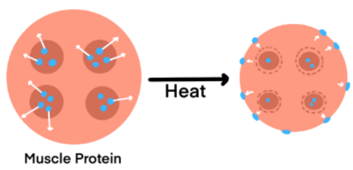


Fig. 1 Muscle protein shrinkage

Fig. 2 Diffusion Sectional diagram

$$\begin{cases} \rho_{mm} c_{p,mm} \dfrac{\partial T}{\partial t} = k_{mm} \left(\dfrac{\partial^2 T}{\partial y^2} + \dfrac{\partial^2 T}{\partial z^2} \right) & Eq(1) \\ \rho_{mm} c_{p,mm} \dfrac{\partial C}{\partial t} = k_{mm} \left(\dfrac{\partial^2 C}{\partial y^2} + \dfrac{\partial^2 C}{\partial z^2} \right) & Eq(2) \end{cases}$$

Secondly, TPA methods are a common technique for determining the physical properties of food products, such as hardness, tenderness, chewiness, and gumminess.

The TPA procedure involves compressing a sample twice under the same conditions, including compression period and compression speed. By performing this compression procedure, we can plot a force-time graph, which will show two peaks (Fig.3). By analyzing this plot, we can compute the physical properties of the meat mentioned above, formula and coupled parameter shown below (Fig.4).

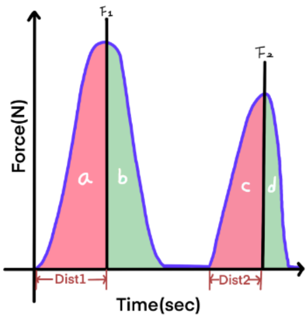


Fig. 3 Typical TPA plot

$$\begin{cases} Hardness = F_1 \\ Springness = (dist2)/(dist1) * 100 \\ Cohesiveness = (d+e)/(a+b) \\ Chewiness = Hardness * Cohesiveness * Springness \end{cases}$$

Fig. 4 TPA properties formula

II. Project Outline

2.1 Paper review & Expected outcome

Our literature review focuses on “the transport phenomena of a chicken breast during roasting in a convective oven”. The paper discusses how heat flux affects the texture of the meat and sets experiments to reason this. We aim to learn their setup & analysis methods, but we will use boiling & poaching as our heating method. Based on the literature review, we learned that the rate of moisture loss in chicken breasts significantly affects tenderness. Therefore, by setting two different heating methods (result different rate of moisture loss) we expect to obtain two comparable outcomes and calculate their tenderness parameters. Finally, we will use MATLAB to simulate a two-dimensional heat diffusion model to visualize the heating process.

2.2 Project schedule

We will spend about three months exploring this topic, roughly dividing it into four phases:

literature review and setup modeling

↓

standardizing the experiment

↓

conducting qualitative analysis

↓

plot the data to discuss the result

and our work period:

Work	March	April	May	Spent day
Literature review				3/4 ~ 5/13 70 days
Set up experiment				3/10 ~ 4/21 42 days
Confirming SOP				3/18 ~ 5/13 56 days
Data analysis Simulation				4/7 ~ 5/20 42 days
Result organization				5/14 ~ 5/24 10 days

2.3 Bills of material (BOM)

Heating set	TPA Machine
Induction cooker	Stepper motor
Thermal sensor	Ballscrew
Fresh chicken breast	Acrylic
Plastic bag	Arduino UNO
Electronic Scale (resolution : 0.01g)	Power Supply (9V)

Our TPA machine may cost 1740 NTD to build brand new, which is relatively low-cost compared to a professional TPA machine that costs 199,000 NTD.

III. Setup Implementation

3.1 Sample preparation

The experimental samples we use are fresh chicken breasts purchased from the supermarket on the day of the experiment. We will cut them into rectangular shapes of approximately 3x3x1 cm^3. Next, we will place them in plastic bags and label them. (Fig. 5)

Fig. 5 Prepared Sample

3.2 Experiment setup

Our experimental setup is separated into two parts: the heating set and the TPA machine. First, to heat these samples we use an induction cooker and a pot, set up with supports on both sides of the pot. Our samples will be suspended in the middle, immersed entirely in water, as shown in the diagram (Fig. 6) below:

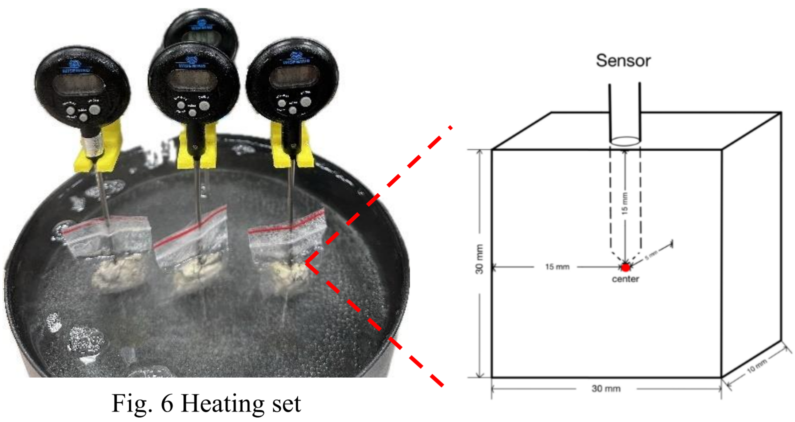


Fig. 6 Heating set

Next, we will place the cooked samples on the TPA machine (Fig. 7), and we turn on the power supply then stepper motor start to rotate. The stepper motor drives the ball-screw, causing the acrylic plate to move downward. (note: we set the compression speed at 1mm/s) Then sample start being compressed. A complete TPA measurement is when the sample compressed twice.

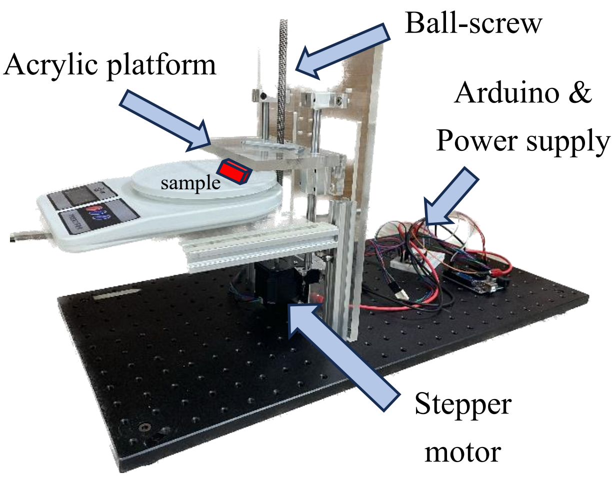
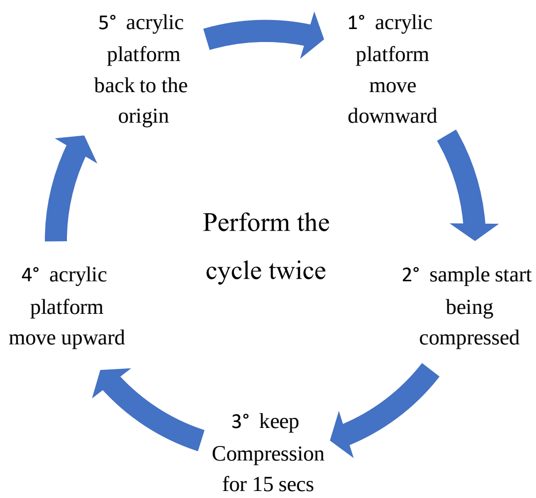


Fig. 7 TPA machine



3.3 Experiment design & Measurement

We set two different heating condition: Boiling and Poaching set. The boiling method refers to heating the water to approximately 100°C and then placing the sample into the pot to start the experiment; Poaching method refers to placing the sample into water at room temperature (30°C), then heating it to start the experiment.

Experiment design				
Heating Method	Boiling		Poaching	
Initial Condition	Sample 30°C	Reservoir 100°C	Sample 30°C	Reservoir 30°C
Heating duration	15 mins		15 mins	

(note: if poaching’s reservoir reach 74°C, hold on it until the experiment ended)

And we conducted three types of measurements: temperature, weight, and tenderness parameters.

3.3.1 Temperature measurements

We measured both the reservoir temperature and the core temperature of the samples (core position shown in Fig. 6) and recorded these temperatures every 3 minutes.

To ensure the temperatures were usable, we also calibrated the thermometers. (For thermometers, we use WISEWIND pen-shaped digital thermometers, temperature range: -10°C to +200°C, resolution: 0.1°C, sampling every second) We used four thermometers, and they may have a maximum measurement difference of 0.5°C. (accepted error)

We also measured the reservoir and found that the entire heating environment is almost uniform. Therefore, we assume that the heating conditions for each surface of the samples are nearly consistent for further simulation and discussion.

3.3.2 Weight measurements

Weight measurement focuses on the sample. As explained in section 1.2, the heating process causes water content from the chicken breast to be lost outward. Therefore, we first measure the initial weight of sample and then record the weight of lost moisture due to heating every three minutes. The method involves removing the sample, leaving behind any moisture and the plastic bag (Fig. 8), ensuring the outer surface of the plastic bag is dry. After sealing the plastic bag, we place it on an electronic scale to record the weight of moisture loss.

Fig. 8 Lost moisture sealed in plastic bag

3.3.3 Tenderness measurements (TPA)

Tenderness measurement was briefly mentioned in section 1.2. Compressing the samples, we can obtain force-time plot. We ensure compression conditions as consistent as we can for each sample.

In addition, we chose samples with relatively smooth surfaces for tenderness measurements because we believe that angular surfaces could lead to uneven force distribution during compression, resulting in experimental errors. (Fig. 9)

As for the electronic scale, although we did not calibrate it with a level, we checked that it was nearly parallel to the tabletop and the acrylic plate. Since we are measuring relative values rather than absolute values, this setup adequate for our purposes.

Fig. 9(a)　smooth , ideal sample

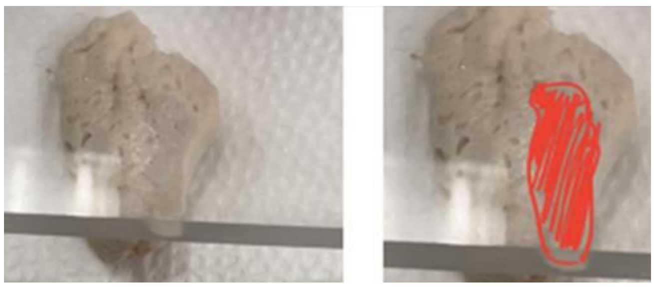
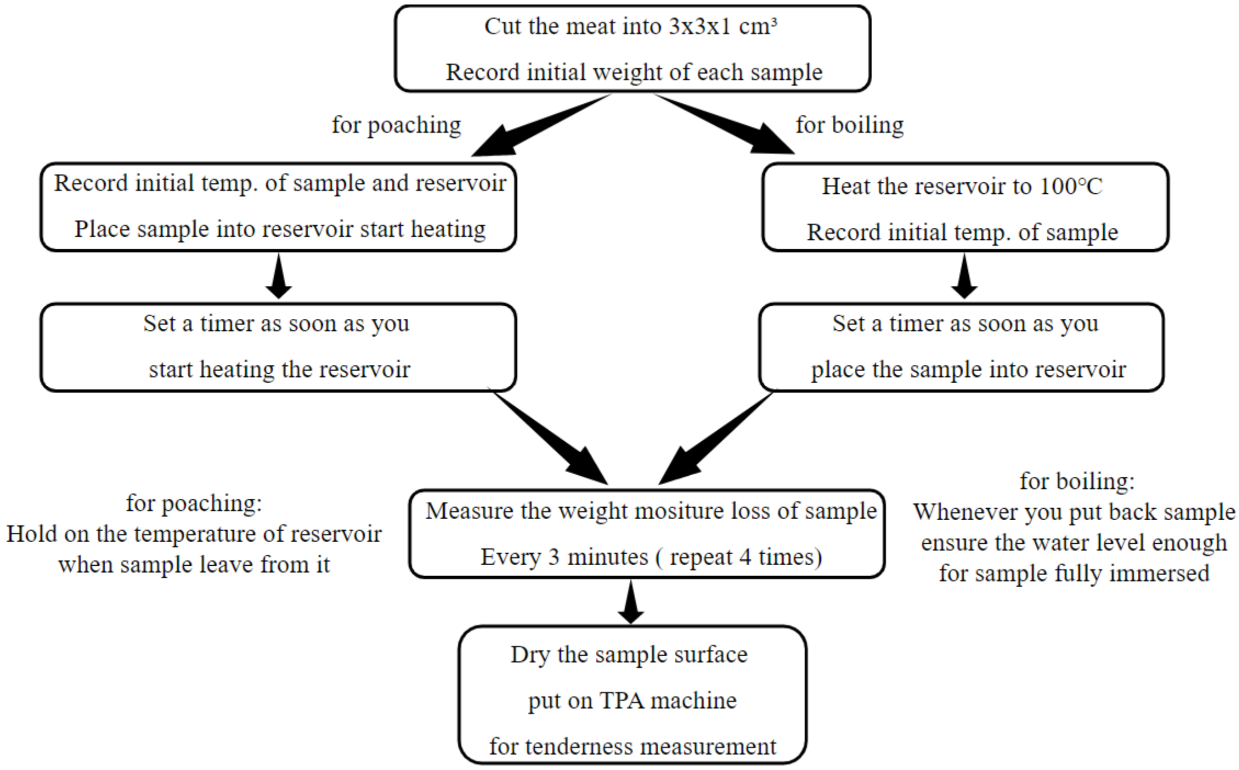


Fig. 9(b)　angular , unusable sample

3.4 Summary and Workflow

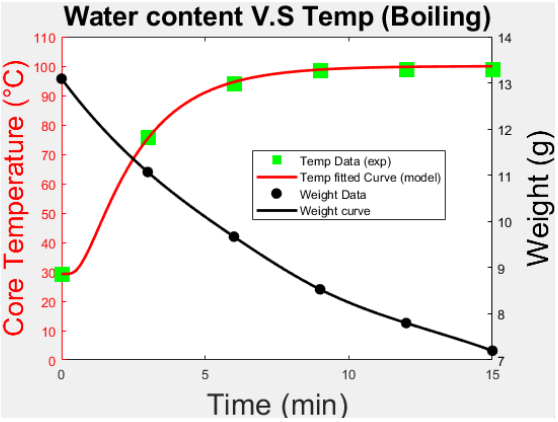
To summarize this section, we can create a workflow.



IV. Results & Discussion

4.1 Moisture loss vs. Temperature plot

We plot the weight and temperature curves on the same figure. The weight decline curve represents moisture loss, which is meaningful as we understand that moisture loss is related to temperature. Results are shown below (Fig. 11), with 11(a) for Boiling and 11(b) for Poaching. From the Boiling method plot, we can see that the moisture loss curve drops drastically, while the core temperature of the sample rises in an exponential saturation way. (note: the red curve fitted by using the two-dimensional heat diffusion model) In the Poaching method plot, we find that the rate of moisture loss gradually increases, while the core temperature of the sample rises in a nearly linear manner. (note: the blue line represents the temperature rise curve of the reservoir).



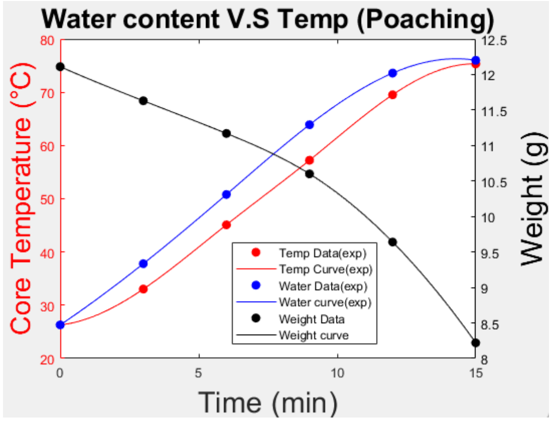


Fig. 11 Water content vs. Temperature plot

(a) Boiling method (b) Poaching method

comparison	Boiling method	Poaching method
Moisure loss curve	Drops drastically	Drops gradually increase in speed
Core temperature curve	Rises in an exponential saturation manner	Rises in a nearly linear manner

4.2 TPA measurement plot

The TPA results shown in the figure below (Fig. 12). Where 12(a) is the Boiling method, and 12(b) is the Poaching method. Here, we can have some interpretation of these two figures.

First, we can see that the orange line corresponds to the value of force for the first peak represents the hardness of the sample. Under the same compression parameters we set for the TPA machine, the force value for Boiling is higher than that for Poaching. This means that samples using the boiling method are firmer and have a tighter arrangement of muscle fibers compared to those using the poaching method.

Next, the red line highlights the raising time to first peak. It shows that boiling method sample reaches the peak earlier than that of poaching. This implies that the samples using the poaching method have a looser arrangement of muscle fibers, with some spaces between the fibers. This delays the overall compression time to the peak. Additionally, it can be further found that during the second compression of the samples, the sample of poaching method are compressed later. Therefore, it is likely that during the first compression, the spaces between the muscle fibers in the poaching method samples were compressed, reducing the sample height and delaying the start-timing of the second compression.

Lastly, we can also compare the height difference between the two peaks. In the boiling method, the two peaks are almost the same height (as indicated by the nearly horizontal green line). However, for the poaching method, we can see that there is a difference between the two peaks — the second peak is lower than the first. This may imply that the muscle fibers of the poaching method samples start to break down during the second compression, such as fracturing or fragmenting.

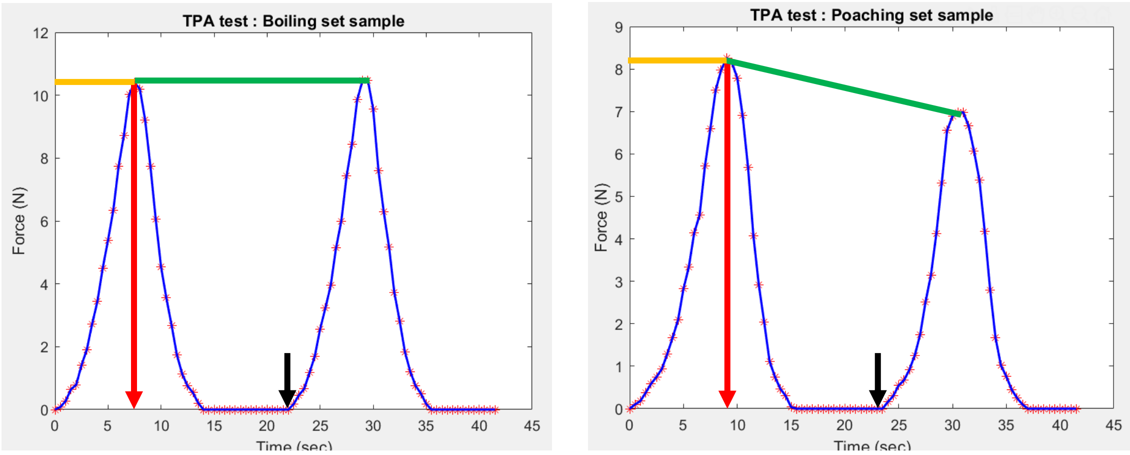
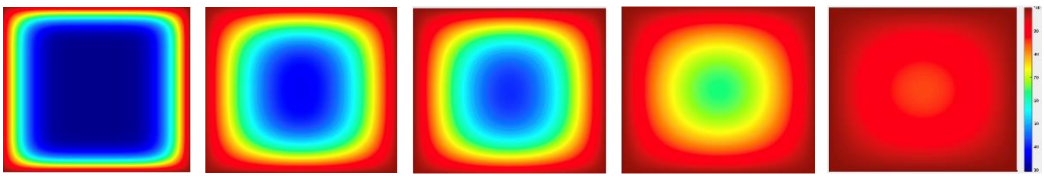


Fig. 12 TPA Result

(a)Boiling method (b)Poaching method

4.3 Simulation

Our simulation utilizes MATLAB's PDE Toolbox, employing the finite difference method to compute the temperature distribution of the samples. Fig. 13 below shows the heating profile of the sample using the boiling method. The comparable thing in this section is the thermal diffusivity coefficient. Compared to what we found in the literature, the coefficient we fitted are larger than those described in the paper, approximately 1.5 times larger than what was reported in the literature. The paper reports a thermal diffusivity coefficient of 1.43 mm^2/s, while ours measures 2.14 mm^2/s.



4.4 Overall summarization & conclusion

In our project, we successfully utilized the heat diffusion equation to interpret the process and set up a low-cost TPA machine to evaluate the tenderness properties of chicken breast. We applied two common cooking methods with different heating conditions, which may lead to different tenderness properties. The methods are boiling and poaching. These two methods were chosen because of their significant difference in heat flux, with boiling having a much higher heat flux than poaching.

Combining the results, we can confirm that the faster the moisture loss curve drops, the firmer the tenderness of the chicken; the more tightly arranged the muscle fibers. Additionally, we found that our thermal diffusivity coefficient is 1.5 times larger than the coefficient we found in the literature review. We attribute this difference to the contrasting density of the samples, which may further provoke discussion about differences in the breeding environment of the chickens.

V. Potential improvements

5.1 Professors' advice

When the professors commented our results, there were many discussions. Here are the suggestions and feedback they provided:

- when measuring weight, we should not conduct repeated trials on the same piece of sample. This does not align with the way of presenting the data continuously, as the process of stopping and reheating the sample leads to errors.
- when measuring tenderness, the force application area depends on the sample itself, making the results less objective and consistent.
- we could consider plotting force vs. displacement and differentiating the curve to interpret what happens to the sample during compression.
- when analyzing the moisture-temperature curves, we can interpret the curves from a biological perspective. For example, understanding how the behavior of muscle proteins affects the concave of the weight loss curve.

5.2 Future work

To enhance the overall completeness and accuracy of our work, we have outlined several tasks to be completed during the summer vocation, as follows:

- Modify the method for weight measurement so that each sample is heated only once, avoiding repeated heating.
- Set up the Arduino HX711 module to improve the efficiency and accuracy of TPA measurements.
- Modify the compression method; specifically, we will use a cylindrical object to compress the samples and ensure that each sample is compressed over the same area.
- Attempt to analyze the elastic coefficient of the samples by plotting force versus displacement to understand the problem.

References

[1] F. Rabeler, A.H. Feyissa, "Modelling the transport phenomena and texture changes of chicken breast meat during the roasting in a convective oven," J. Food Eng. 237, 60-68 (2018)

[2] K. Siripon, A. Tansakul, G.S. Mittal, "Heat transfer modeling of chicken cooking in hot water," Food Research International 40, 923-930 (2007)