

A Novel, Simple, Accurate Method For Experimental Determination of Thermal Diffusivity: Measure 9 Types of Foods

Lisa Rousha Wang

The Pennington School, 112 W Delaware Ave, Pennington, NJ 08534

Abstract

We present a simple, low-cost, and straightforward method to measure the thermal diffusivity of various foods. 9 different types of foods are studied and their thermal diffusivities are experimentally determined. The foods which are studied include potato, sweet potato, pumpkin, taro, radish, eggplant, lemon, tomato, and onion. We pre-cut the foods into a spherical shape and then insert a small and thin thermo-couple sensor to the center of the spherically-shaped food, and immerse the food samples in the boiling water. The center temperature is recorded throughout the heating process. We then compare the heating curve as the function of time with the simulation results, where the thermal diffusivity is used as the fitting parameter. This method allows us to intentionally vary the diameter of the spheres, i.e., adding a controlled parameter in order to validate the results. We are able to determine all the thermal diffusivity data with good consistency between the measurement data and the simulation results. This method can be generalized to determine thermal diffusivity for other types of materials.

Keywords

Heat transfer, Fourier's Law, Heat transfer equation, Thermal diffusivity, Thermal conductivity, Specific heat.

1. Introduction

Thermal diffusivity is an important material property. [1-3] It can be expressed as $\alpha = k/\rho c$, where α is the thermal diffusivity in m^2/s , ρ is the density (kg/m^3) and c is the specific heat ($J/(kg \cdot K)$). [4-10]

Thermal diffusivity is the core parameter which plays a key role in the heat transfer process, which is described by the heat transfer equation: $\nabla \cdot \nabla T = \frac{1}{\alpha} \frac{\partial T}{\partial t}$. The equation describes one of the most important physical phenomena governing the world – heat transfer and exchange. [1-10]

Being able to accurately measure the thermal diffusivity of a material is important since the thermal diffusivity is an important material parameter which is essential to understand materials' thermal properties and further in materials' various applications. Thus, a consistent, simple, and low-cost measurement method is thus highly desirable. [4-10]

Thermal diffusivity is often measured with the flash method, [4-8] which is a method for the determination of the thermal diffusivity of different materials. It involves heating a strip or cylindrical sample with a short energy, such as, laser, pulse at one end and analyzing the temperature change, i.e., reduction in amplitude and phase shift of the pulse, a short distance away. [4-8] For instance, the sample is subjected to a high intensity short duration radiant energy pulse. The power source can be a laser or a flash lamp. The energy will then be absorbed by the specimen and emitted again on the top of the sample. This radiation results in a temperature rise on the surface of the sample. This temperature rise is recorded from an infrared (IR) detector. The detector signal shows the duration of the measurement and the normalized temperature rise on the surface of the sample, where the light pulse occurs. For the calculation of the thermal diffusivity, it is necessary to determine the baseline and the maximum temperature rise. This is done by a suited fitting model. Additionally, the model determines the time at which half of the maximum temperature raise was reached. Such a method requires expensive instruments and more complex process. Other alternative methods [12-24] also involve expensive and complex equipment and process.

2. Our method in experimental measurement and theoretical simulation

Our research presents a consistent, simple, low-cost, fast, and accurate method to measure the thermal diffusivity of various foods. The samples used in our method are very easy to prepare. Different food samples are carefully cut into nearly perfect spheres with different diameters. The diameter of the food was measured by a caliper.

For the temperature measurement, we need to measure temperature at a special location, i.e., the center of the sample. Thus, the temperature sensor head needs to be small as we need to track the temperature as a function of time. A special thermo-couple device is used. The thermo-couple has a small size with a diameter around 1 mm and the thickness of the plastic cloth is also about 1 mm in diameter. The thermo-couple is inserted into the center of the spherical shaped food sample to measure the temperature rising as the function of time during the heating process.

Thermal couples with small diameters are used to measure the center temperature of the samples. The samples are immersed in boiling water (100 °C). We track the center temperature rise as the function of time.

In term of the cost, the total cost for the materials, tools, and instruments used in this research is less than \$200. Thermal couple and electronics we used cost \$60, the caliper costs \$20, all the

food materials cost \$50, and other containers, cooking wares, and suppliers cost \$50. Furthermore, it takes less than 30 minutes to measure each sample, and the measured results are consistent and accurate.

Why do we want to use a sphere shape? Spherical symmetry makes the distance from the center only “parameter”. Theoretically, it is easy to simulate. Experimentally, it is easy to measure. The comparison between the theoretical calculation and the experimental measurement become possible and straightforward.

For the theoretical simulation, the following theoretical model is considered. We adopt a spherical approximation with heating coming uniformly from all directions. This was achieved by using a water bath which heats water uniformly and achieves temperature uniformity. The sample has an initial uniform temperature. The sample is a uniform material with known thermal and physical parameters (i.e., diameter). The temperature at the center of the sphere is calculated (and measured) as the function of time. The diameter of the sample is a controlled variable. Various samples are compared.

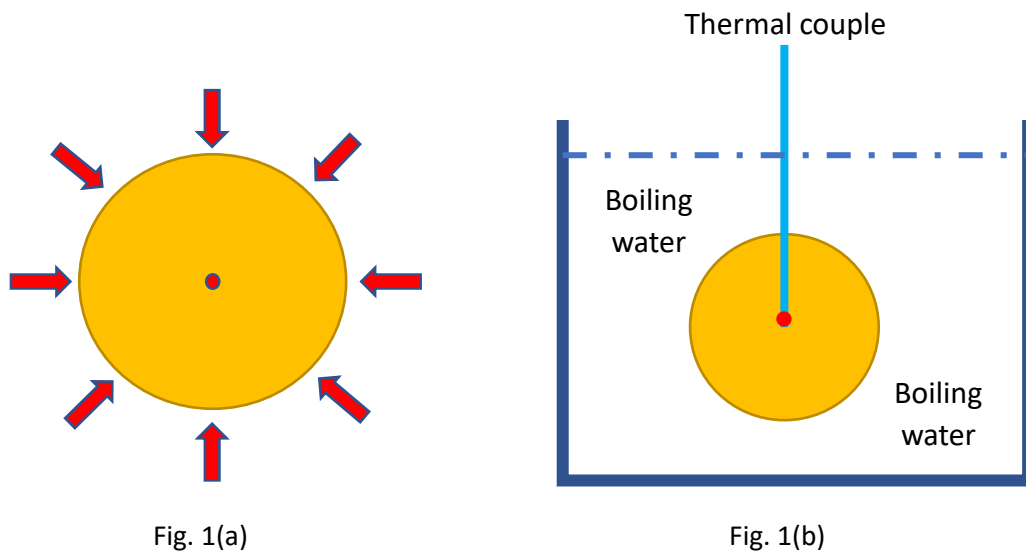


Fig. 1 (a) shows schematically an ideal sphere with azimuthal symmetry in the thermal transfer process. Fig. 1 (b) shows schematically the experimental realization of the azimuthal symmetrical configuration. The sphere-shaped food sample is immersed into boiling water with a thin thermal couple probe tightly inserted into the center of the sample. The thermal couple measures continuously the temperature at the center location of the food sample.

Fig. 2 shows the thermal couple (right) and the control electronics (left) used in this research. A Proster digital thermocouple temperature thermometer with two K-type thermocouple probes and a backlight LCD. It has dual channel to measure two temperatures simultaneously. The K-type thermocouple measuring range is from -50°C to 300°C with an accuracy $\pm 1.5\%$ and a resolution 0.1°C .

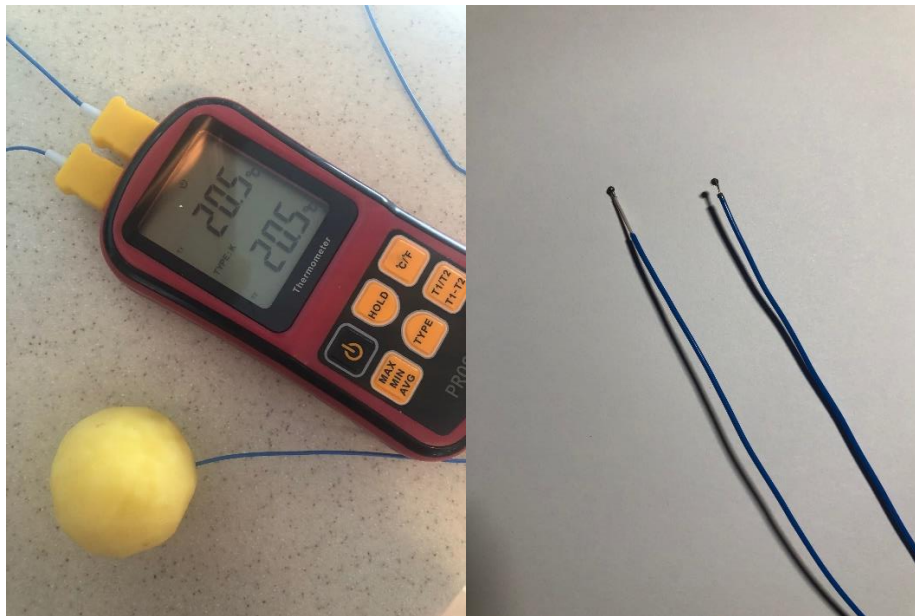


Fig.2 The thermo-couple and temperature measurement device. The thermo-couple has a small size with a diameter around 1 mm and the thickness of the plastic cloth is also about 1 mm in diameter. The thermo-couple is inserted into the center of the spherical shaped food to measure the temperature rising as the function of time during the heating process.



Fig. 3 The three different foods are cut into nearly perfect spheres with different diameters (left: sweet potato, center: potato, right: taro).

Fig. 3 shows representatively three different food samples which were cut into spherical shape with various diameters. The food samples used in this study include 9 different types of food, i.e., potato, sweet potato, pumpkin, taro, radish, eggplant, lemon, tomato, and onion. All the food samples were pre-cut and shaped into a sphere shape with pre-determined radii, ranging from 15 mm to 31 mm.

The sample cutting and preparation process is straightforward. The cutting process is done manually with a regular kitchen used vegetable “Y” peeler such as a Westmark Gallant Vegetable "Y" Peeler or any similar type. For each sample, the sample preparation process takes about 5 minutes. For potato, sweet potato, pumpkin, taro, radish, and eggplant, a similar peeling process is used to prepare rounded-shaped samples. For samples such as onion, lemon, and tomato, we started with an onion or lemon or tomato with a shape and dimension (i.e., diameter) very close to what we want for the final samples, thus, we only need to remove the skin and do not need to deal with cutting, which is difficult due to the nature of those types.

During the sample cutting and peeling process, a caliper is used to measure and monitor the shape and diameter of the sample. There is no need to make a perfectly shaped sphere since the analysis indicates that the impact from a deviation from the perfect spherical shape can be neglect on the final diffusivity result. [18, 25] A more detailed analysis can be found in the results and discussions section of this paper.

3. Experimental results

Fig. 4 shows the measured temperature as the function of time for 5 potato samples with various radii from 15.75 mm to 29.75 mm. The center temperature of the food sample, measured by the thermal couple, shows that as the radius of the sample increases, the rising of the temperature at the center of the sample slows down.

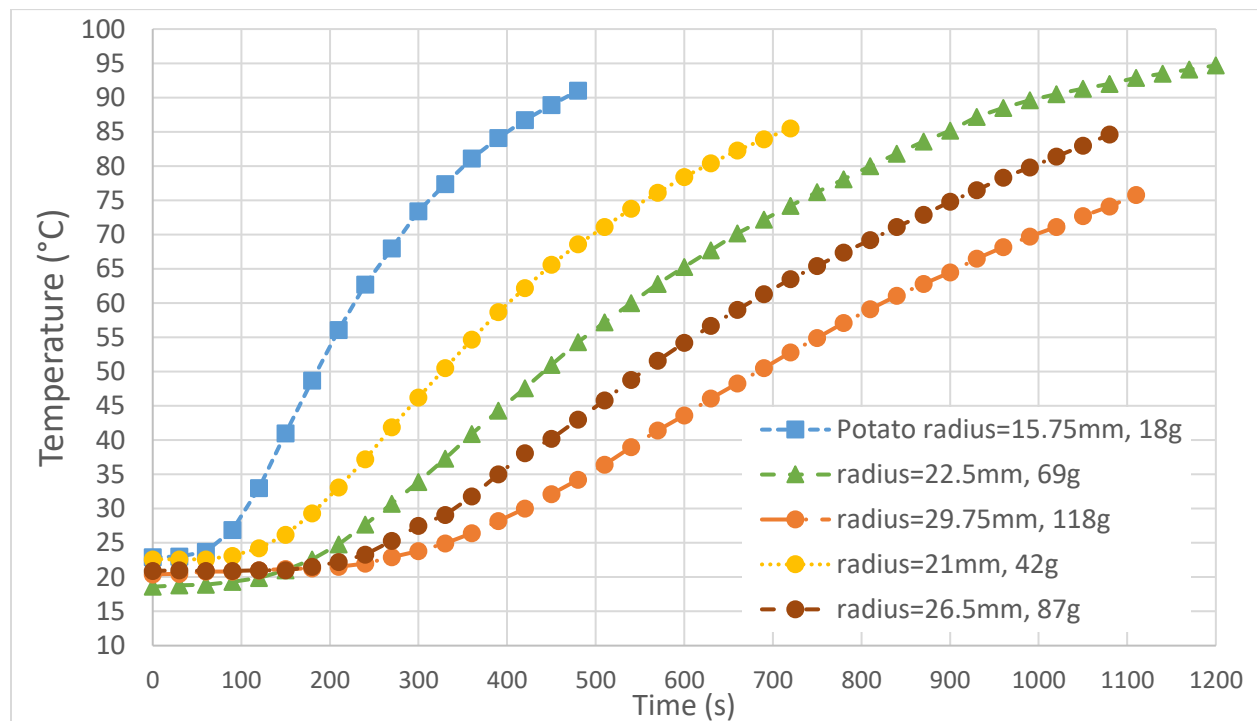


Fig. 4 Potato samples with 5 different diameters (15.75mm, 21mm, 22.5mm, 26.5mm, and 29.75mm) were measured. The temperature of the center of the sphere sample is recorded as the function of time as shown in dots.

Fig.5 shows the measurement result (dots) for a potato sample with a radius of 22.7 mm. The two solid curves, one in gray and one in red, are theoretical calculation curves, with the thermal diffusivity as the variable parameter. Please refer to the next section below for the theoretical modeling and calculation. For the gray curve, the thermal diffusivity used is $1.326 \times 10^{-7} \text{ m}^2/\text{s}$. For the red curve, the thermal diffusivity used is $1.414 \times 10^{-7} \text{ m}^2/\text{s}$. It shows that the value of $1.326 \times 10^{-7} \text{ m}^2/\text{s}$ fits the curve almost perfectly, while the value of $1.414 \times 10^{-7} \text{ m}^2/\text{s}$ seems a bit higher. However, the value of $1.414 \times 10^{-7} \text{ m}^2/\text{s}$ fits the experimental curve better during the initial phase (0 to 250 seconds).

Fig.6 shows the measurement result (dots) for another potato sample with a radius of 22.5 mm. The two solid curves, one in gray and one in red, are theoretical calculation curves, with the thermal diffusivity as the variable parameter. For the gray curve, the thermal diffusivity used is $1.326 \times 10^{-7} \text{ m}^2/\text{s}$. For the red curve, the thermal diffusivity used is $1.414 \times 10^{-7} \text{ m}^2/\text{s}$. It shows that the value of $1.326 \times 10^{-7} \text{ m}^2/\text{s}$ fits the curve well for the center part of the time duration, however, the value of $1.414 \times 10^{-7} \text{ m}^2/\text{s}$ fits the experimental curve better during the initial phase and the ending phase.

Both Fig.7 and Fig. 8 show the measurement result (squares) for another two potato samples with a radius of 20.0 mm and 25.0 mm, respectively. The solid curve is theoretical calculation curves, with the thermal diffusivity as the variable parameter. For the solid curve, the thermal diffusivity used is $1.326 \times 10^{-7} \text{ m}^2/\text{s}$.

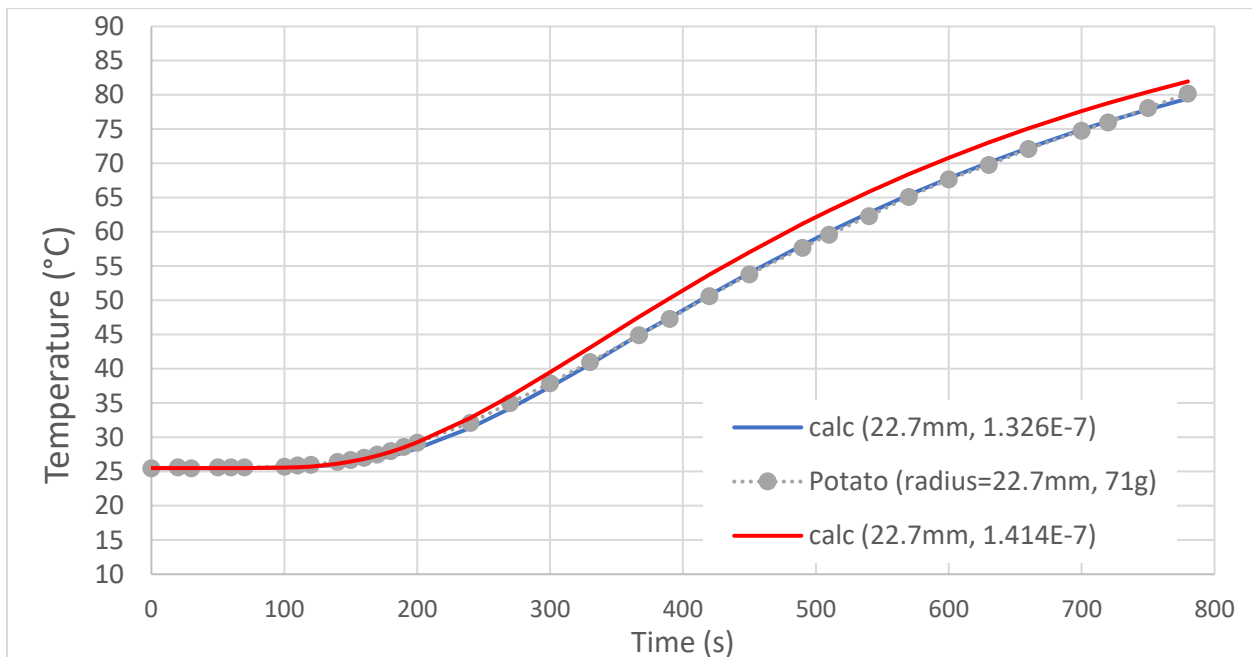


Fig. 5 A potato sample with a diameter of 22.7mm was measured. The temperature of the center of the sphere sample is recorded as the function of time as shown in dots. The solid curves are calculated results based on the thermal diffusivity data as indicated in the figure.

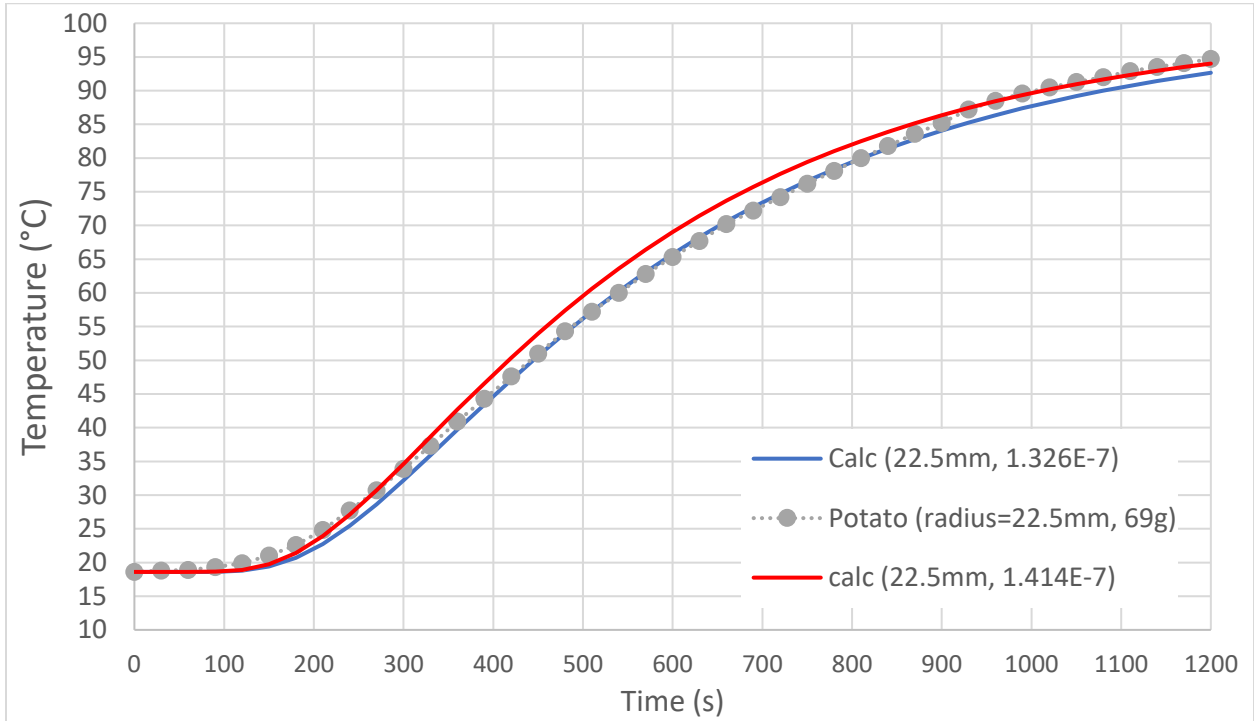


Fig. 6 A potato sample with a diameter of 22.5mm was measured. The temperature of the center of the sphere sample is recorded as the function of time as shown in dots. The solid curves are calculated results based on the thermal diffusivity data as indicated in the figure.

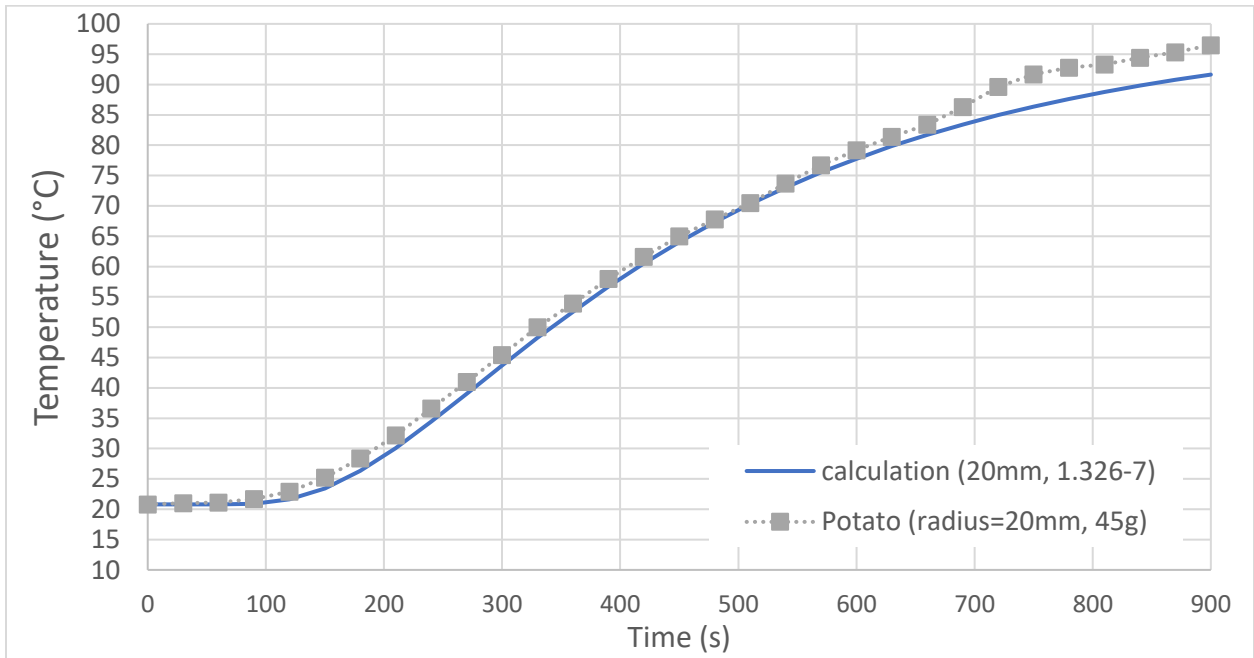


Fig. 7 A potato sample with a diameter of 20mm was measured. The temperature of the center of the sphere sample is recorded as the function of time as shown in squares. The solid curve is calculated results based on the thermal diffusivity data as indicated in the figure.

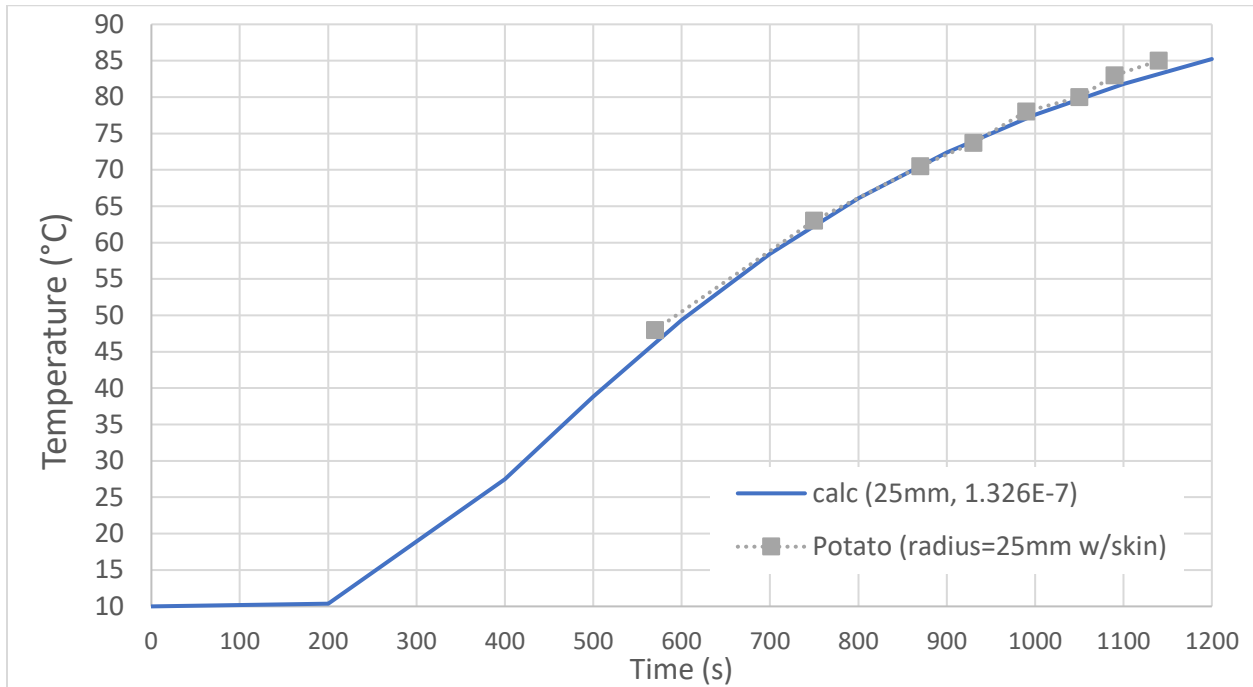


Fig. 8 A potato sample with a diameter of 25mm was measured. The temperature of the center of the sphere sample is recorded as the function of time as shown in squares. The solid curve is calculated results based on the thermal diffusivity data as indicated in the figure.

Fig.9 shows the measurement result (dots and triangles) for two sweet potato samples with a radius of 23.0 mm and 25.3 mm, respectively. The solid curves are theoretical calculation curves, with the thermal diffusivity as the variable parameter. For both the green and the gray solid curves, the thermal diffusivity used is $1.665 \times 10^{-7} \text{ m}^2/\text{s}$. Thus, the same value of the thermal diffusivity fits both samples of different radii well.

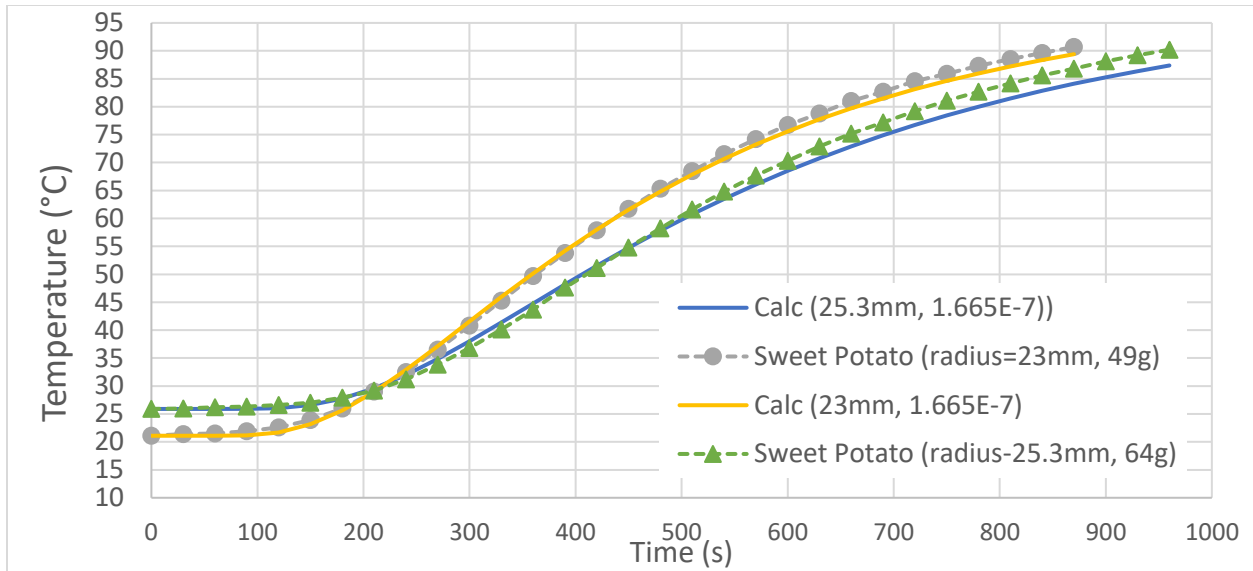


Fig. 9 Sweet potato samples with two different diameters (23mm and 25.3mm) were measured. The temperature of the center of the sphere sample is recorded as the function of time as shown in dots (23mm sample) and in triangles (25.3mm sample). The solid curves are calculated results based on the thermal diffusivity data as indicated in the figure.

Fig.10 shows the measurement result (dots and triangles) for two taro samples with a radius of 25.75 mm and 26.5 mm, respectively. The solid curves are theoretical calculation curves, with the thermal diffusivity as the variable parameter. For both the green and the gray solid curves, the thermal diffusivity used is $1.4986 \times 10^{-7} \text{ m}^2/\text{s}$. Thus, the same value of the thermal diffusivity fits both samples of different radii well.

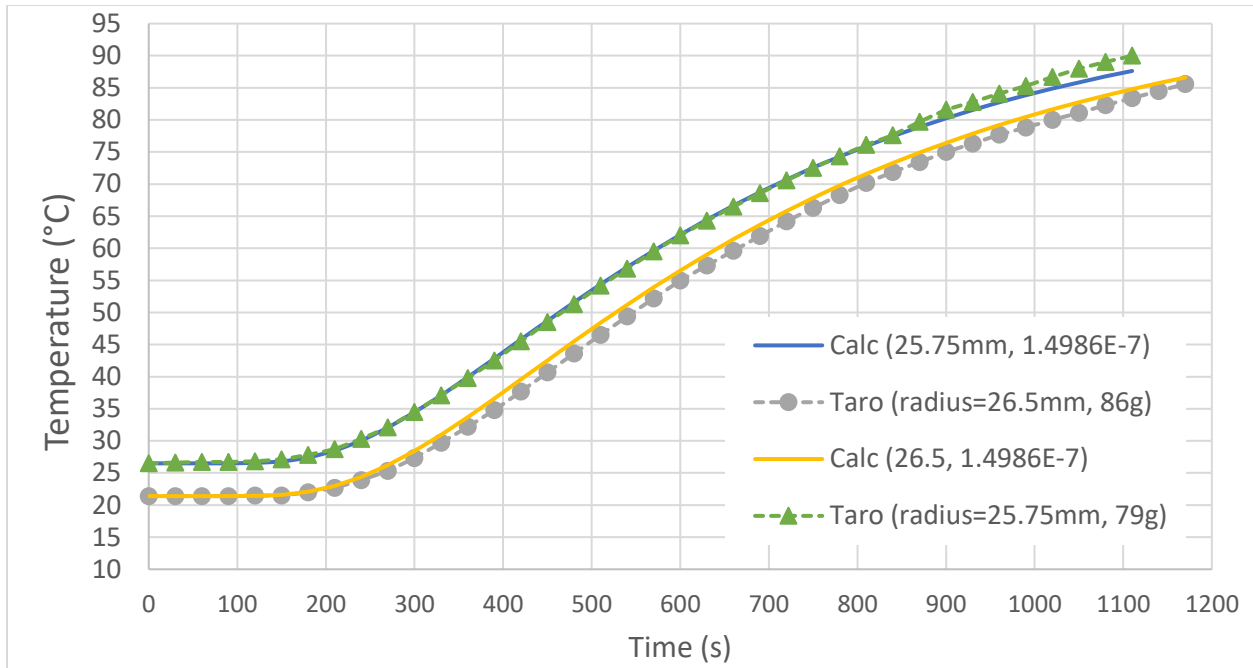


Fig. 10 Taro samples with two different diameters (25.75mm and 26.5mm) were measured. The temperature of the center of the sphere sample is recorded as the function of time as shown in dots (26.5mm sample) and in triangles (25.75mm sample). The solid curves are calculated results based on the thermal diffusivity data as indicated in the figure.

Fig.11 shows the measurement result (dots and triangles) for two pumpkin samples with a radius of 17.5 mm and 25.0 mm, respectively. The solid curves are theoretical calculation curves, with the thermal diffusivity as the variable parameter. For all the four calculation curves, the thermal diffusivity used is between $1.4986 \times 10^{-7} \text{ m}^2/\text{s}$ and $1.72 \times 10^{-7} \text{ m}^2/\text{s}$. A value of the thermal diffusivity in this range fits both samples well.

Fig.12 shows the measurement result (square) for an onion sample with a radius of 31.5 mm. The solid curve is theoretical calculation curve, with the thermal diffusivity as the variable parameter. For the calculation, the thermal diffusivity used is $1.6 \times 10^{-7} \text{ m}^2/\text{s}$.

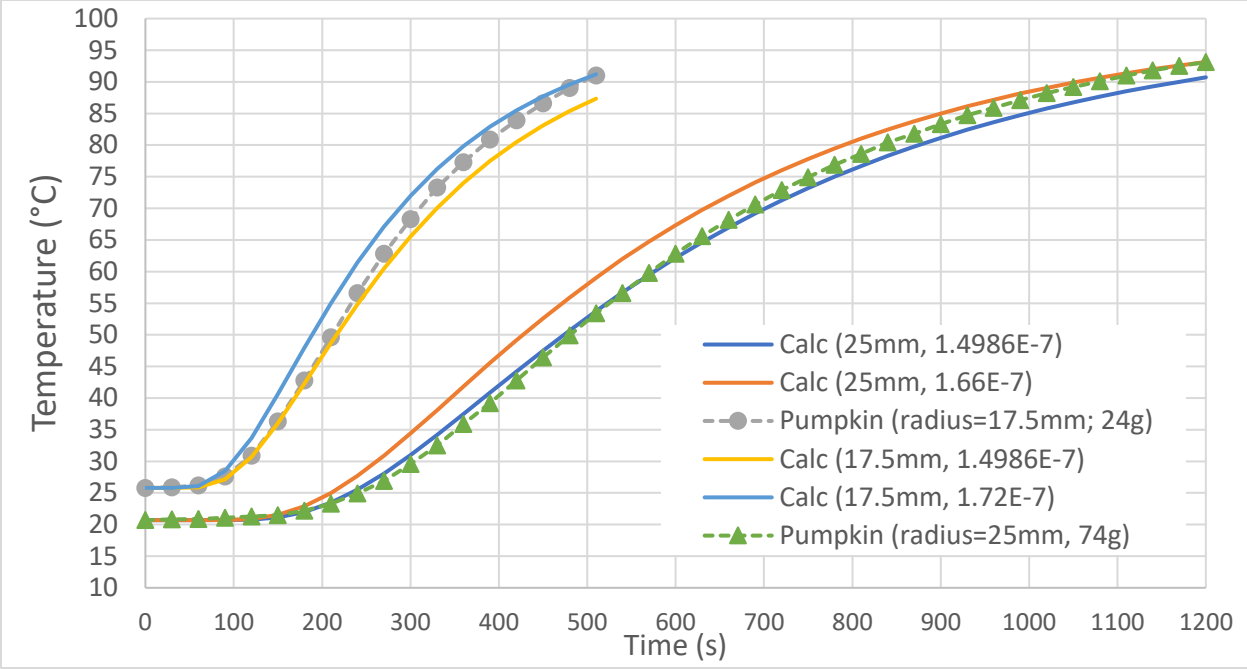


Fig. 11 Pumpkin samples with two different diameters (17.5mm and 25mm) were measured. The temperature of the center of the sphere sample is recorded as the function of time as shown in dots (17.5mm sample) and in triangles (25mm sample). The solid curves are calculated results based on the thermal diffusivity data as indicated in the figure.

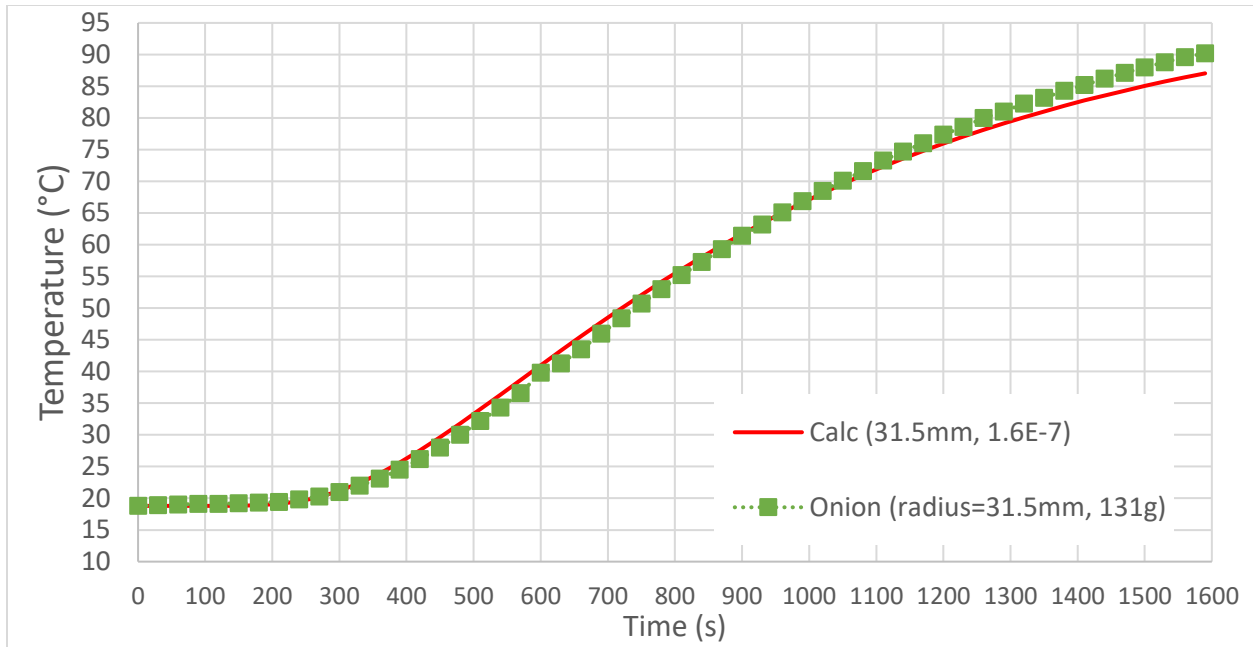


Fig. 12 An onion sample with a diameter of 31.5mm was measured. The temperature of the center of the sphere sample is recorded as the function of time as shown in squares. The solid curve is calculated results based on the thermal diffusivity data as indicated in the figure.

Fig.13 shows the measurement result (square) for a tomato sample with a radius of 25 mm. The two solid curves are theoretical calculation curves, with the thermal diffusivity as the variable parameter. For the calculation, the thermal diffusivity used are $1.4 \times 10^{-7} \text{ m}^2/\text{s}$ for blue and $1.6 \times 10^{-7} \text{ m}^2/\text{s}$ for red.

Fig.14 shows the measurement result (square) for a lemon sample with a radius of 26 mm. The solid curve is theoretical calculation curve, with the thermal diffusivity as the variable parameter. For the calculation, the thermal diffusivity used is $1.6 \times 10^{-7} \text{ m}^2/\text{s}$.

Fig.15 shows the measurement result (square) for an eggplant sample with a radius of 23.5 mm. The two solid curves are theoretical calculation curves, with the thermal diffusivity as the variable parameter. For the calculation, the thermal diffusivity used are $2.2 \times 10^{-7} \text{ m}^2/\text{s}$ for blue and $5.0 \times 10^{-7} \text{ m}^2/\text{s}$ for red.

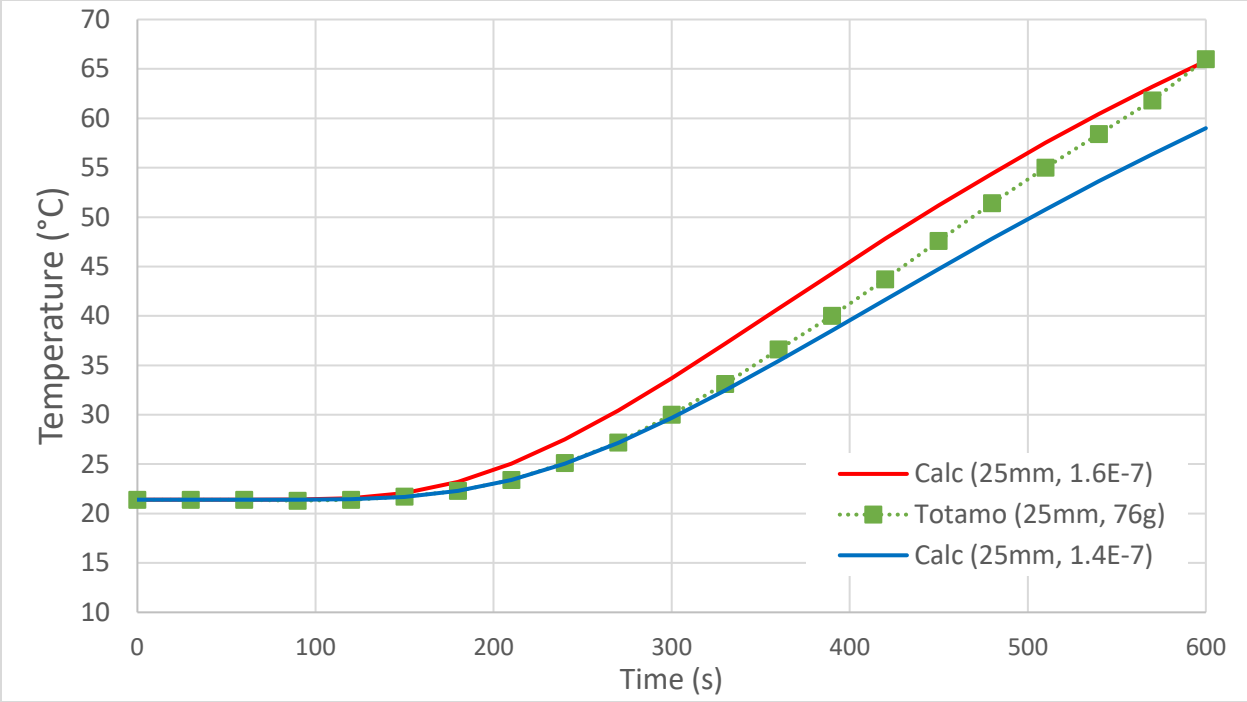


Fig. 13 A tomato sample with a diameter of 25mm was measured. The temperature of the center of the sphere sample is recorded as the function of time as shown in squares. The solid curves are calculated results based on the thermal diffusivity data as indicated in the figure.

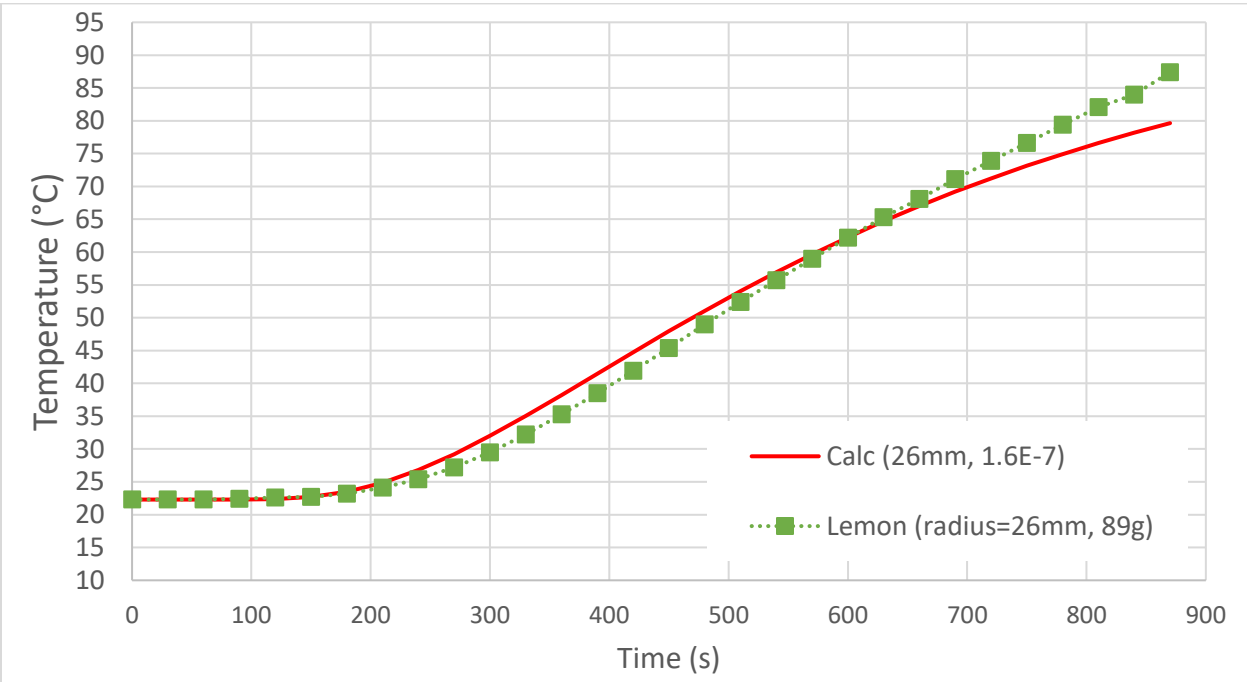


Fig. 14 A lemon sample with a diameter of 26mm was measured. The temperature of the center of the sphere sample is recorded as the function of time as shown in squares. The solid curve is calculated results based on the thermal diffusivity data as indicated in the figure.

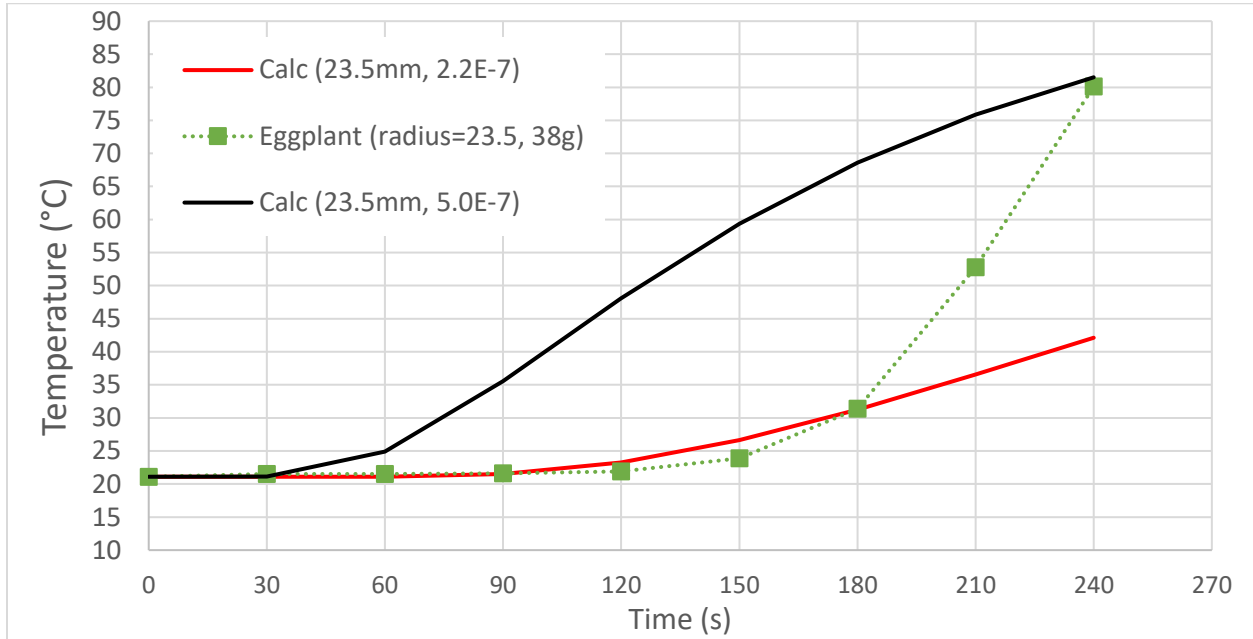


Fig. 15 An eggplant sample with a diameter of 23.5mm was measured. The temperature of the center of the sphere sample is recorded as the function of time as shown in squares. The solid curves are calculated results based on the thermal diffusivity data as indicated in the figure.

4. The theoretical model and simulation

In this section, we present a detailed physics model [25] for the calculation of the thermal transfer process which is corresponding to our experiments discussed above.

4.1. General discussion

Fourier's Law states [9-15] that the heat flux q (in W/m^2) is proportional to the temperature gradient, i.e., $q = -k \cdot \frac{dT}{dx}$ for one-dimensional system. For 3-dimensional system, $\vec{q} = -k \cdot \nabla T$ where \vec{q} is a vector and ∇ is the gradient. k is thermal conductivity in $W/(cm \cdot K)$.

This leads to the one-dimensional heat diffusion equation:

$$\frac{\partial^2 T}{\partial x^2} = \frac{\rho c}{k} \frac{\partial T}{\partial t} = \frac{1}{\alpha} \frac{\partial T}{\partial t}$$

Where $T = T(x, t)$ and $\alpha = k/\rho c$ is the thermal diffusivity in m^2/s , where ρ is the density (kg/m^3) and c is the specific heat ($J/(kg \cdot K)$).

In three-dimension, the heat transfer equation becomes:

$$\nabla \cdot \nabla T = \frac{1}{\alpha} \frac{\partial T}{\partial t}$$

Where,

$$\begin{aligned} \nabla \cdot \nabla T &= \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \quad (\text{for Cartesian coordinates}) \\ &= \frac{1}{r^2 \sin \theta} \left[\sin \theta \frac{\partial}{\partial r} \left(r^2 \frac{\partial T}{\partial r} \right) + \frac{\partial}{\partial \theta} \left(\sin \theta \frac{\partial T}{\partial \theta} \right) + \frac{1}{\sin \theta} \frac{\partial^2 T}{\partial \varphi^2} \right] \quad (\text{for spherical coordinates}) \\ &= \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial T}{\partial r} \right) + \frac{1}{r^2} \left(\frac{\partial^2 T}{\partial \theta^2} \right) + \frac{\partial^2 T}{\partial z^2} \quad (\text{for cylindrical coordinates}) \end{aligned}$$

For a sphere with azimuthal symmetry, during the heat transfer [18, 2-25], we have $\frac{\partial T}{\partial \theta} = 0$ and $\frac{\partial^2 T}{\partial \varphi^2} = 0$, the heat transfer equation becomes

$$\frac{1}{r^2} \left[\frac{\partial}{\partial r} \left(r^2 \frac{\partial T}{\partial r} \right) \right] = \frac{1}{\alpha} \frac{\partial T}{\partial t}$$

Solving this differential equation leads to the following solution with the detailed derivation described in ref. [25]

$$T(r, t) = \sum_{\lambda} \left[(A \cos \sqrt{\lambda} \cdot r + B \sin \sqrt{\lambda} \cdot r) \cdot \frac{e^{-\lambda \alpha t}}{r} \right]$$

For cooking (heating) food with food starting with low temperature T_0 and surrounded at high temperature (bath temperature) T_h , we have the following boundary conditions:

$$T(r, 0) = T_0 \quad (0 \leq r \leq R), \text{ where } R \text{ is the radius of the sphere.}$$

$$T(\geq R, t) = T_h$$

We have:

$$A = 0, \text{ and } \lambda = \left(\frac{n\pi}{R} \right)^2 \text{ where } n = 1, 2, 3, \dots$$

We then have:

$$T(r, t) = T_h - \frac{2R(T_h - T_0)}{\pi \cdot r} \sum_{n=1}^{\infty} \left[\frac{(-1)^{n+1}}{n} \sin \frac{n\pi r}{R} \cdot e^{-\alpha n^2 \pi^2 t / R^2} \right]$$

for $(0 \leq r \leq R)$

We define

$$\tau = \frac{R^2}{\pi^2 \cdot \alpha} \text{ as the time constant.}$$

Thus, we have:

$$T(r, t) = T_h - \frac{2R(T_h - T_0)}{\pi \cdot r} \sum_{n=1}^{\infty} \left[\frac{(-1)^{n+1}}{n} \sin \frac{n\pi r}{R} \cdot e^{-t/\tau} \right]$$

The temperature at the center of the sphere is ($r = 0$):

$$T_c = T_h - 2(T_h - T_0) \sum_{n=1}^{\infty} [(-1)^{n+1} \cdot e^{-t/\tau}]$$

We can spell out the equation with some of the initial (and deciding) terms:

$$T_c = T_h - 2(T_h - T_0) \{ e^{-t/\tau} - e^{-4t/\tau} + e^{-9t/\tau} - e^{-16t/\tau} + e^{-25t/\tau} - e^{-36t/\tau} + e^{-49t/\tau} - \dots \} \quad (1)$$

$$\text{Where: } \tau = \frac{R^2}{\pi^2 \cdot \alpha} \text{ and } \alpha = \frac{k}{\rho c}$$

Equation (1) is used in all the center temperature versus time calculations, where T_h is set at 100°C, and R is the radius of the food sample per measurement used with a caliper, and α , the thermal diffusivity, is used as a fitting parameter in all the simulation fittings in the above section.

5. Results and discussions

Table 1 summarizes all the results of the measured thermal diffusivities for the 9 different types of food. To compare our measurement data with the pre-existing values for various food types, we have done extensively literature researches.

T.R.A. Magee et. al. [26] measured the thermal diffusivity of potato using a thermal diffusivity tube under transient heat transfer conditions by two different methods, the log method and the slope method, both based on the solutions of the Fourier equation. Both methods gave similar results for potato, $1.30 \times 10^{-7} \text{ m}^2/\text{s}$ and $1.44 \times 10^{-7} \text{ m}^2/\text{s}$. M. A. Rao et. al. [27] reported the average thermal diffusivity value for potato as $1.70 \times 10^{-7} \text{ m}^2/\text{s}$. According to the Engineering ToolBox, [28] the thermal diffusivity for potato is $1.23 \times 10^{-7} \text{ m}^2/\text{s}$ for cooked and mashed potato and $1.70 \times 10^{-7} \text{ m}^2/\text{s}$ for flesh potato. For tomato pulp, the thermal diffusivity is $1.48 \times 10^{-7} \text{ m}^2/\text{s}$. A. Farinu et. al. [29] determined the thermal diffusivity for sweet potato to be $1.2 \times 10^{-7} \text{ m}^2/\text{s}$. Obot et. al. [30] measured the thermal diffusivity for white radish to be

$1.869 \times 10^{-7} \text{ m}^2/\text{s}$. In Encyclopedia of Food Sciences and Nutrition [1-3], potato has a reported thermal diffusivity of $1.3 \times 10^{-7} \text{ m}^2/\text{s}$. H. Kocabiyik et. al. [31] measured the thermal diffusivity of pumpkin seeds to be $1.289 \times 10^{-7} \text{ m}^2/\text{s}$. A.E. Drusas et. al. [32] measured tomato paste, the thermal diffusivity of tomato pastes was estimated as $1.42 \times 10^{-7} \text{ m}^2/\text{s}$. Abhayawick et. al. [33] measured onion for a value between $1.1 \times 10^{-7} \text{ m}^2/\text{s}$ and $1.5 \times 10^{-7} \text{ m}^2/\text{s}$ depending on the moisture's content. Luis A. Minim et. al. [34] measured lemon Juice and had a result between 1.160×10^{-7} and $1.785 \times 10^{-7} \text{ m}^2/\text{s}$.

We have repeated the measurements for potato with multiple samples. The results we obtained are very consistent, which indicates the consistency of this measurement method. The obtained result for potato is between $1.32 \times 10^{-7} \text{ m}^2/\text{s}$ and $1.50 \times 10^{-7} \text{ m}^2/\text{s}$ with a tight range, and the result is in excellent agreement with some of the reported values, [26] and in good agreement with all the other reported values. [1-3, 27, 28]

Compared with all those available data we can find in the published literature, [1-3, 16, 26-34] the thermal diffusivity data we got are either in good agreement or have a tighter value range.

Compared to all the published thermal diffusivity data we can find, our work produces very consistent and reliable data, and some of the data, such as thermal diffusivity for eggplant, pumpkin (not pumpkin seed), lemon (not lemon juice), and tomato (not tomato pulp or paste) are reported for the first time to our knowledge. Furthermore, the method presented in this work offers some great advantages, such as, simplicity, affordability, low-cost, fast speed, and reliability. Any potential measurement errors could come from the following factors.

- (1) The thermo couple temperature measurement error mainly comes from the position accuracy. We need to measure the center temperature of the spherical sample. However, this error is believed to be small based on the excellent repeatability and agreement between samples of the same type and samples with different radii.
- (2) The thermo couple sensor tip might move during the heating process. Such problem might cause some temperature data irregularity for a later part of the heating curve, as indicated in Fig. 7 (after 700 seconds in time).
- (3) The error of the measurement of the sample's diameter (radius). This error could be reduced with the help of the accurate mass measurement.
- (4) The error of the shape deviation from the perfect sphere. To analyze the impact of the shape deviation, we define a shape factor S . [18, 25] Since the transferred heat is proportional to the surface area and the received energy per volume is inversely proportional to the total volume, thus the inverse of the baking time (or heating time) is proportional to the surface area and inversely proportional to the volume of the piece. Our analysis indicates that small shape deviation leads to very small impact to the accuracy of the final data, as indicated by the good agreement between different samples with random deviation of the shape.

Food	Diameter (mm)	Thermal diffusivity ($10^{-7} \text{ m}^2/\text{s}$)	
		Low end value	High end value
Potato	45.4	1.32	1.42
Potato	45	1.32	1.42
Potato	50	1.32	1.42
Potato	40	1.32	1.42
Potato	31.5	1.32	1.48
Potato	59.5	1.32	1.50
Potato	42	1.32	1.48
Potato	46	1.32	1.50
Potato	53	1.32	1.50
Potato (reheated)	51	1.52	1.60
Pumpkin	50	1.50	1.66
Pumpkin	35	1.50	1.72
Sweet potato	50.6	1.66	1.84
Sweet potato	46	1.66	1.75
Taro	51.5	1.50	1.60
Taro	53	1.40	1.50
Radish	40	1.30	1.40
Radish	41	1.55	1.65
Onion	63	1.60	1.78
Eggplant	47	2.20	5.00
Lemon	52	1.50	1.70
Tomato	50	1.40	1.60

Table 1. 9 different types of foods along with their determined thermal diffusivities. The data were determined based on fitting the measured temperature curve with the theoretical model with the thermal diffusivity as the fitting parameter.

6. Summary

We present a simple, low-cost, and straightforward method to measure the thermal diffusivity of food. 9 different types of foods were studied and their thermal diffusivities are experimentally determined. The foods which are studied include potato, sweet potato, pumpkin, taro, radish, eggplant, lemon, tomato, and onion. We pre-cut the foods into a spherical shape and then insert a small and thin thermo-couple sensor to the center of the ball-shaped food, and cook the ball-shaped food in the boiling water. The center temperature is recorded through the heating process, and then we compare the heating curve as the function of time with the simulation results, where the thermal diffusivity is used as the fitting parameter. This method also allows us to intentionally vary the diameter of the spheres, i.e.,

adding another variable in order to valid the results. We are able to determine all the thermal diffusivity data with good matching between the measurement data and the simulation results.

7. Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

8. Author Declarations

Conflict of interest

The authors have no conflicts to disclose.

9. References:

1. B.R. Becker, B.A. Fricke, Thermal Properties of Foods, in Encyclopedia of Food Sciences and Nutrition (Second Edition), 2003.
2. N. N. Mohsenin, Thermal properties of Foods and Agricultural Materials. Gordon and Breach Science Publishers, New York, (1980).
3. V. E. Sweat, Thermal Properties of Foods. In: Engineering Properties of Foods, Ed.: M. A. Rao, S. S. H. Rizvi, M. Dekker, NY-Basel, pp. 99-138, (1995).
4. W.J. Parker; R.J. Jenkins; C.P. Butler; G.L. Abbott (1961). "Method of Determining Thermal Diffusivity, Heat Capacity and Thermal Conductivity". Journal of Applied Physics 32, 1679 (1961); <https://doi.org/10.1063/1.1728417>
5. Dickerson, R.W. 1965. An Apparatus for the Measurement of the Thermal Diffusivity of Foods. Food Technol., 19: 198–204.
6. K.Porsdal Poulsen, Thermal diffusivity of foods measured by simple equipment, Journal of Food Engineering, Volume 1, Issue 2, 1982, Pages 115-122
7. J. Blumm; J. Opfermann (2002). "Improvement of the mathematical modeling of flash measurements". High Temperatures – High Pressures. 34 (5): 515. doi:10.1068/htjr061
8. Thermitus, M.-A. (October 2010). "New Beam Size Correction for Thermal Diffusivity Measurement with the Flash Method". In Gaal, Daniela S.; Gaal, Peter S. (eds.). Thermal Conductivity 30/Thermal Expansion 18. 30th International Thermal Conductivity Conference/18th International Thermal Expansion Symposium. Lancaster, PA: DEStech Publications. p. 217. ISBN 978-1-60595-015-0. Retrieved 1 December 2011.
9. Edward A. Olszewskia, From baking a cake to solving the diffusion equation, American Journal of Physics 74, 502 (2006); <https://doi.org/10.1119/1.2186330>.
10. H. Nelson, S. Deyo, S. Granzier-Nakajima, P. Puente, K. Tully, J. Webb, A mathematical model for meat cooking, Eur. Phys. J. Plus (2020) 135:322, <https://doi.org/10.1140/epjp/s13360-020-00311-0>.

11. H. C. Chang, J. A. Carpenter, R. T. Toledo, Modeling heat transfer during oven roasting of unstuffed turkeys, *Journal of Food Science*, Vol. 63, Issue 2, June 2008.
<https://doi.org/10.1111/j.1365-2621.1998.tb15721.x>
12. Jan Taler, Paweł Ocioń, Transient Heat Conduction in Sphere, January 2014, DOI: 10.1007/978-94-007-2739-7_400, In book: *Encyclopedia of Thermal Stresses* (pp.6186-6198).
13. M.E. Shmalko, R. O. Morawicki, and L. A. Ramallo, Simultaneous determination of specific heat and thermal conductivity using the finite-difference method, *Journal of Food Eng.* 31, 531-540, (1996).
14. Srivastava A.K, Shukla S.K, Singh U.K, “Modeling and Evaluation of Thermal Diffusivity and Activation Energy of Potato slices in Forced Convection Multi Tray Solar Dryer”, *American Journal of Food Science and Technology*, 2015, Vol. 3, No. 2, 27-32, Available online at <http://pubs.sciepub.com/ajfst/3/2/1>
15. T.R.A.Magee and T.Bransburg, “Measurement of thermal diffusivity of potato, malt bread and wheat flour”, *Journal of Food Engineering*, Volume 25, Issue 2, 1995, Pages 223-232.
16. CHAPTER 9, THERMAL PROPERTIES OF FOODS, 2006 ASHRAE Handbook—Refrigeration (SI)
17. Mathews, F.W., Jr. and C.W. Hall. 1968. Method of finite differences used to relate changes in thermal and physical properties of potatoes. *ASAE Transactions* 11(4):558.
18. Minh, T.V., J.S. Perry, and A.H. Bennett. 1969. Forced-air precooling of white potatoes in bulk. *ASHRAE Transactions* 75(2):148-150.
19. Riedel, L. 1969. Measurements of thermal diffusivity on foodstuffs rich in water. *Kaltetechnik* 21(11):315-316.
20. Sweat, V.E. 1985. Thermal properties of low- and intermediate-moisture food. *ASHRAE Transactions* 91(2):369-389.
21. Adefemi Farinu & Oon-Doo Baik (2007) Thermal Properties of Sweet Potato with its Moisture Content and Temperature, *International Journal of Food Properties*, 10:4, 703-719, DOI: 10.1080/10942910601137482
22. Kotecha, P.M.; Kadam, S.S. Sweet potato. In *Handbook of Vegetable Science and Technology: Production, Composition, Storage and Processing*; D.K. Salunkhe; S. S. Kadam.; Eds. Marcel Dekker; New York, 1998, 71–98.
23. Choi, Y.; Okos, M.R. Effects of Temperature and Composition on the Thermal Properties of Foods. In *Food Engineering and Process Applications*, Vol. 1; Lemaguer, M.; Jelen, P.; Eds.; Elsevier, London, 1985; 93.
24. Krishna Kumar, P., Bhunia, K., Tang, J., Rasco, B. A., Takhar, P. S., & Sablani, S. S. (2018). Thermal transition and thermo-physical properties of potato (*Solanum tuberosum* L.) var. Russet brown. *Journal of Food Measurement and Characterization*, 12(3), 1572-1580.
<https://doi.org/10.1007/s11694-018-9772-x>
25. Yifei “Jenny” Jin, Lisa R. Wang, and Jian Jim Wang, Physics in turkey cooking: Revisit the Panofsky formula, *AIP Advances* 11, 115316 (2021); <https://doi.org/10.1063/5.0067811>
26. T.R.A. Magee and T. Bransburg, “Measurement of thermal diffusivity of potato, malt bread and wheat flour”, *Journal of Food Engineering*, Volume 25, Issue 2, 1995, Pages 223-232.
[https://doi.org/10.1016/0260-8774\(94\)00025-5](https://doi.org/10.1016/0260-8774(94)00025-5).
27. M. A. Rao, J. Barnard, J. F. Kenny, “Thermal Conductivity and Thermal Diffusivity of Process Variety Squash and White Potatoes,” *Transactions of the ASAE*. 18 (6): 1188-1192. (doi: 10.13031/2013.36767)

28. Engineering ToolBox, (2020). Foodstuff - Thermal Diffusivity.
https://www.engineeringtoolbox.com/foodstuff-thermal-diffusivity-d_2176.html.
29. A. Farinu and O. Baik, "Thermal Properties of Sweet Potato with its Moisture Content and Temperature," *International Journal of Food Properties*, 10:4, 703-719, (2007) DOI: 10.1080/10942910601137482.
30. M.S. Obot, C. Li, T. Fang, J. Chen, "Measurement of thermal properties of white radish using easily constructed probes," *PLoS ONE* 12(3): e0171016. (2017)
doi:10.1371/journal.pone.0171016.
31. H. Kocabiyik, B. Kayisoglu and D. Tezer, "Effect of Moisture Content on Thermal Properties of Pumpkin Seed," *International Journal of Food Properties*, 12:2, 277-285, (2009) DOI: 10.1080/10942910701673519.
32. A.E. Drusas and G.D. Saravacos, "Thermal conductivity of tomato paste," *Journal of Food Engineering*, Volume 4, Issue 3, 1985, Pages 157-168.
33. L. Abhayawick, J. Laguerre, V. Tauzin, A. Duquenoy, "Physical properties of three onion varieties as affected by the moisture content," *Journal of Food Engineering*. 55. 253-262. (2002)
10.1016/S0260-8774(02)00099-7.
34. L. A. Minim, V. R. N. Telis, V. P. R. Minim, L. A. P. Alcantara, and J. Telis-Romero, "Thermophysical Properties of Lemon Juice as Affected by Temperature and Water Content," *J. Chem. Eng. Data* 2009, 54, 8, 2269–2272, 2009. <https://doi.org/10.1021/je900155c>