The Physics Behind Cooking Intelligence

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Abstract

Cooking reflects human's highest intelligence from both scientific and artistic perspectives. This work investigates the essential physics behind intelligence in cooking. The physics behind cooking time and preparation method is carefully studied and quantitatively presented, which reveals the most interesting science behind various recipes, tricks, and mysteries to achieve optimal temperature and flavor in cooking and culinary arts. Firstly, the cooking time's square power relation with the food's physical dimension explains the most delicate thoughts behind fast cooking and why Chinese and Indian foods prefer shredding the food into tiny pieces before cooking. Secondly, the orders of difference in magnitude between thermal and mass diffusivity coefficients explain many food preparation methods used widely throughout centuries of human history in both Eastern and Western culinary cultures.

Introduction

"My definition of Man is, a "Cooking Animal." The beasts have memory, judgment, and all faculties and passions of our mind, in a certain degree; but no beast is a cook…" --- James Boswell.

We, as a human species, have been cooking since we were called intelligent animals or even before that. As Richard Wrangham states in his famous book "Catching Fire – how cooking made us human," cooking, which provided our ancestors with cooked foods, particularly meat, could even have defined or shaped our evolution process. [1]

In 1998, cooking historian Michael Symons concluded, "cooking is the missing link… defining the human essence… I pin our humanity on cooks." In a 2001 book on the history of food, historian Felipe Fernandez-Armesto declared cooking "an index of the humanity of humankind."

Through millions of years of our development in cooking, tons of intelligence have been invented, developed, improved, and then instilled back into the cooking process's refinery from its masters.

In the past few decades, cooking science has become one of the heavily studied science subjects. Researchers have been looked into cooking process from all perspectives, chemistry, biology, physics, engineering, nutrition, physiology, microbiology, biochemistry, etc. As of today, we continue to learn new knowledge from cooking, and to reflect on the wisdom of the cooking process which has been developed over thousands of years. Meanwhile, the new scientific understanding which we realize from studying cooking also further helps us on better understand and improve the cooking process.

As cooking enthusiasts, we have been cooking and studying cooking and we constantly were amazed by the new understanding and new questions generated in this journey.

Why can't we cook the duck eggs while getting them salted to the way we like within the same process and duration? Cooking the eggs only takes about 5 to 10 mins, however, the salting process to make the famous salted duck eggs requires 10 to 30 days. The similar question exists for salted pork, salted fish, salted duck, salted vegetables, and many more salted foods.

For the popular French Fries, in a cooking oil bath with a temperature around 150-160 ℃, with a dimension of typical 5x5 mm in cross section, it only takes 30 seconds to get them cooked, i.e., to reach over 100 ℃ across the whole fries. Why do we need to have a double frying process in the standard McDonald's recipe, with the first frying for 5 mins at 163 ℃? That alone is ten times the duration required to heat the fries from the heating perspective, and the second frying for 2-3 mins at an even higher temperature like 180 ℃. The intervals between the two fryings can be days or even months?

Why different types of noodles or spaghettis with similar cross-section dimensions (diameters) would need a cooking time, while being soaked in boiling water, ranging from 1-3 mins to 12-14 mins, an order of magnitude in difference?

While Chinese stir-frying dishes only take about 3 mins to cook, is it because of the need of heating process alone? If we look at the hot-pot, the similar-sized food only takes about 20 seconds to dip in the 100 ℃ pot to be ready to eat (but with a dipping source to gain flavor). What prevents us from further shrinking down the cooking time in the stir-frying cooking?

Questions like the above can go on and on…

During cooking, the temperature profile, i.e., how long, how fast, how high the heating process goes, is the key to lead to successful dishes. However, the flavor and texture, which is governed by the distributions of salt, sugar, spice, oil, moisture, and many other parameters, is also crucial to achieve the best taste and overall result. Both heating and flavoring process are governed by essentially the similar transfer equation although the key diffusion coefficient is different in these two processes. The physical equations describing those processes are described in the supplementary material.

Three Important Aspects in Cooking

In the following, we discuss the three most important aspects of physics in cooking.

(1) Diffusion coefficients: thermal vs. mass diffusion coefficient

The heating process is governed by the thermal transfer process, which is described by the heat transfer equation: $\boldsymbol{\nabla} \cdot \boldsymbol{\nabla}\mathrm{T} = \frac{1}{D_T}\frac{\partial T}{\partial t}$, where T = T (x, t) and D_T = k/ρc is the thermal diffusivity in m^2/s, where ρ is the density (kg/m^3) and c is the specific heat (J/(kg · K)).

The distribution of salt, sugar, water, oil, and other molecules and ions, is governed by the mass transfer process, which is described by a similar equation (so-called Fick's 2nd Law): $\boldsymbol{\nabla} \cdot \boldsymbol{\nabla}\mathrm{c} = \frac{1}{D_M}\frac{\partial c}{\partial t}$, where c = c (x, t) is the density and D_M is the diffusion coefficient in m^2/s.

Besides the so-called initial and boundary conditions, the key difference between those two types of processes is their diffusion coefficients, D_T and D_M.

For typical foods we deal with in our life, their D_T is in the range around 1.5x10^{-7} m^2/s. The table 1 lists out the thermal diffusivity for some of our daily food materials such as pork, chicken, beef, lamb, fish, bread, turkey, potato, and water. The reason that all those foods have similar thermal diffusion coefficient is because, all the foods are made of mostly water. Thus, their thermal diffusion coefficient should be similar to the value of water, which is 1.38x10^{-7} m^2/s. For examples, table 2 lists out the water content range for some selected foods. For the foods we are interested in, the water content ranges from 50% to over 80%.

Material properties	**Unit**	**Pork**	**Chicken**	**Beef**	**Lamb**	**Fish**	**Bread**	**Egg**	**Turkey**	**Potato**	**Water**
density	Kg/m3	1100	1150	1150	1150	1150	800	1038	1050	1100	1000
specific heat	J/(Kg K)	3130	3500	3230	2800	3620	2720	3000	3530	3670	4200
thermal conductivity	W/(m K)	0.45	0.45	0.48	0.5	0.54	0.5	0.58	0.5	0.55	0.58
thermal diffusivity	m2/s	1.31E-07	1.12E-07	1.29E-07	1.55E-07	1.30E-07	2.30E-07	1.86E-07	1.35E-07	1.36E-07	1.38E-07

Table 1. Physical parameters, including the thermal diffusivity (thermal diffusion coefficient), for some of our daily food materials.

Percentage	Food Item
100%	Water
90–99%	Fat-free milk, cantaloupe, strawberries, watermelon, lettuce, cabbage, celery, spinach, pickles, squash (cooked)
80–89%	Fruit juice, yogurt, apples, grapes, oranges, carrots, broccoli (cooked), pears, pineapple
70–79%	Bananas, avocados, cottage cheese, ricotta cheese, potato (baked), corn (cooked), shrimp
60–69%	Pasta, legumes, salmon, ice cream, chicken breast
50–59%	Ground beef, hot dogs, feta cheese, tenderloin steak (cooked)
40–49%	Pizza
30–39%	Cheddar cheese, bagels, bread
20–29%	Pepperoni sausage, cake, biscuits
10–19%	Butter, margarine, raisins
1–9%	Walnuts, peanuts (dry roasted), chocolate chip cookies, crackers, cereals, pretzels, taco shells, peanut butter
0%	Oils, sugars

Table 2. The water content range for some selected foods. Source: The USDA National Nutrient Database for Standard Reference, Release 21 provided in Altman. (Altman P. Blood and Other Body Fluids. Washington DC: Federation of American Societies for Experimental Biology; 1961.)

However, the reported mass diffusion coefficients, D_M, is in the range from 1.0x10^{-12} m^2/s to 1.0x10^{-8} m^2/s, with the most credible reported values around 2-5x10^{-10} m^2/s, for diffusion of salt, sugar, water, etc. in the body of the typical foods.

For examples, NaCl diffusion in cheese has D_M at 1 to 5.5 X10^{-10} m2/s at 10-15 ℃. NaCl diffusion in pure water at 12.5℃ is 1.16x10^{-9} m^2/s. Lactose (sugar) diffusion in cheese is at 3-4x10^{-10} m2/s. The diffusivities of sodium chloride in chicken breast were in the range of 8.99 · 10^{-10} m^2/s –9.55 · 10^{-10} m^2/s. Moisture diffusivity in different types of fishes: 0.1 – 3.5 x 10^{-10} m^2/s. Mostly, 1-3.5 x 10^{-10} m^2/s. Moisture

diffusivity in cereal: 10^{-11} m^2/s. Moisture in fruits: 10^{-10} m^2/s. Salt in beef: 5-39 x10^{-10} m^2/s (30-85°C). Salt in Frankfurter ham: Na: 14-22x10^{-10} m^2/s; Cl: 19-86x10^{-10} m^2/s (58-81°C). Moisture in pork sausage: 4.7-5.7x10^{-11} m^2/s (20°C). Moisture in vegetables: 2-40x10^{-10} m^2/s (5-120°C). Salt and sugar in vegetables: 2-30 x 10^{-10} m^2/s. (5 – 120°C). Citric Acid in potato: 4x10^{-10} m^2/s. (25°C). The D_M values in rainbow trout fillets decreased with increasing salting time and ranged from 6.64 × 10^{-10} m^2/s to 16.45 × 10^{-10} m^2/s. NaCl diffusion in Chinese cabbages is 1.7-11.6x10^{-11} m^2/s. Effective diffusion coefficient of NaCl (Dm) in pork tissue: 0.6 – 5 x 10^{-10} m^2/s dependent on the brine NaCl concentration. Diffusion coefficient of salt in potato tissue was measured to be (3.45-4.39) x 10^{-9} m^2/s. Diffusion of chloride, nitrite, and nitrate in beef and pork is in the range of 1-5x 10^{-10} m^2/s. Salt diffusion in beef, salmon, and cheese is 1-7 x 10^{-10} m^2/s. Salt and acetic acid into herring is 1-6 x 10^{-10} m^2/s. Salt diffusion in salted duck eggs: 2x10^{-10} m^2/s to 2x10^{-11} m^2/s. Apparent diffusion coefficients of water in noodles during boiling were 4 to 7 × 10^{-10} m^2/s.

Furthermore, the dependency of the diffusion coefficient D_M on temperature is well characterized by the so-called Arrhenius Equation: $D_M = D_0\, exp\left(-\frac{E_a}{RT}\right)$, where D_0 is a pre-exponential factor (m^2/s). E_a is the activation energy (J/mol). R is the gas constant (8.31441 J/(mol K)), and T is the absolute temperature.

Based on the activation energy from the literature, the effective diffusion coefficient $D_M$increases roughly by a factor of 10 when temperature increases from 20 °C to 100 °C, by a factor of 25 when temperature increases from 20 °C to 150 °C, and by a factor of 60 when temperature increases from 20 °C to 200 °C. (We assume the E_a, the activation energy, with a value of 26 J/mol.)

(2) The square power relation

Depending on the initial and boundary conditions and the geometry shape of the food, the solutions of the thermal or mass transfer equations can be solved precisely (see the supplementary materials). Under reasonable approximations, with all other conditions and parameters being the same, the time to reach the same endpoint is inversely proportional to the diffusion coefficient but quadratically proportional to the dimension, i.e., radius or thickness. The food with a critical dimension doubled would result in 4 times the heating time or mass transfer time. The square power relationship between the heating time and the critical dimension of the food piece becomes the dominant factor in cooking.

(3) The difference in the order of magnitude between thermal and mass diffusion coefficients

On average, the difference of orders of 2 to 3 in the two diffusion coefficients would lead to 100 to 1,000 times difference in the time duration. Such difference between thermal diffusion and mass diffusion is what makes the cooking process so delicate and complicated but interesting.

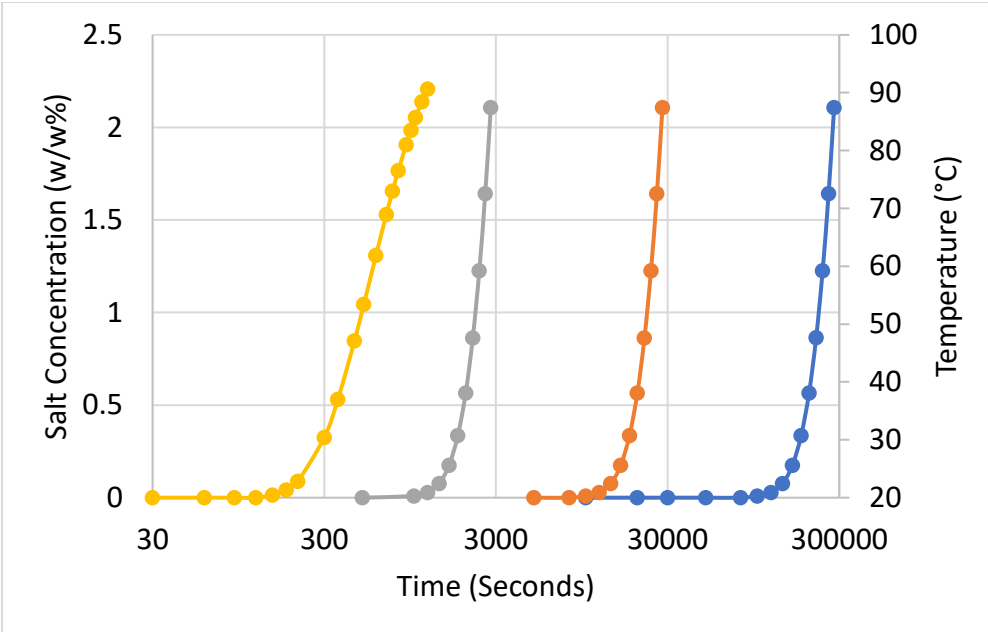

Fig. 1 shows the calculated temperature and salt diffusion as a function of time for a spherical food piece with a diameter of 50 mm (for instance, a meatball). The yellow curve shows the center temperature rise with time during cooking with the thermal diffusivity of $1.5\text{x}10^{-7}$ m^2/s. The gray, orange, and blue curves are the calculated center salt concentration with time, with the salt diffusion coefficient of $1.5\text{x}10^{-10}$ m^2/s (blue), $1.5\text{x}10^{-9}$ m^2/s (orange), and $1.5\text{x}10^{-8}$ m^2/s (gray).

As shown in Fig. 1, the required heating time for the center of the food ball with a diameter of 50 mm to reach 85 °C is about 1000 seconds (about 17 mins). However, the time required for the center of the food ball to reach w/w1% salt concentration can be as long as 7 hours to 70 hours. The large difference between these two durations mean that the food can be quickly cooked but without flavor since it takes much longer for the flavor to diffuse in.

We will quantitatively examine those important aspects with some examples next.

Some Examples

In the following, we look into a few cooking examples in details.

Cooking of meatballs, meat slices, vegetable pieces, etc.

In our discussion below, we adopt a bath temperature of around 100℃, and the meats have an initial temperature of around 10 ℃. We throw the meat into the hot environment and wait for enough cooking time before the food is ready. [16]

For pork, beef, chicken, lamb, fish, and shrimp, their thermal properties are very similar within a tight range. [9, 26-32] For density, it is around 1100 to 1150 kg/m^3, the specific heat c ranges from 2800 (lamb), 3100 (pork), 3230 (beef), 3500 (poultry) to about 3650 (fish and shrimp) $J/(kg \cdot K)$, and the thermal conductivity K ranges from 0.45 (all meats) 0.54 (fish) $W/(m \cdot K)$. [26, 27]

Regarding the minimum (interior) cooking temperature, it is about 72 to 75 ℃ for all the meats (pork, ham, poultry, beef, lamb, veal, seafood). [26, 27] For steak, in particular, the interior temperature for

“rare” steak is 54 ℃, for “medium rare” is 63 ℃, for “medium well” is 71 ℃, and for “well” is 75 ℃. [9, 13, 16, 26-32] Adhering to the pork cooking temperature guidelines issued by U.S. Department of Agriculture (USDA) [26, 27] will result in an optimum eating experience of enhanced flavor and safety. For pork, the interior temperature for “medium rare” is 63 to 65 ℃, for “medium well” is 65 to 71 ℃, and for “well” is 75 ℃. [9, 13, 16]

We first use the equation (see the supplementary material) to calculate meatballs (in perfect spherical shapes). The meatballs have a radius of R. Figure 2 shows the calculated cooking times versus the square of radius R, i.e., R^2, for various radius of pork meatballs. The two different colored dots refer to different center temperature, the blue is for center temperature of 75 ℃ and the orange is for center temperature of 85 ℃, which means well cooked. The straight lines are fitting lines.

It is clear that the cooking time to reach the same center temperature has a perfect (with the fitting $R^2 = 1.00$) square relationship with the radius of the meatballs. For a meatball with a radius of about 1 to 2 mm, it only takes about few seconds (1.57 to 8 second) to reach the required temperatures. For a meatball of 12.5 mm in radius (i.e., about 1 inch in diameter), it takes 245 second to reach 75 ℃ at the center of the piece, and takes 308 second to reach 85 ℃ at the center of the piece. For a meatball of 25 mm in radius (i.e., about 2 inch in diameter), it will take 980 second to reach 75 ℃ at the center of the piece, and takes 1230 second to reach 85 ℃ at the center of the piece.

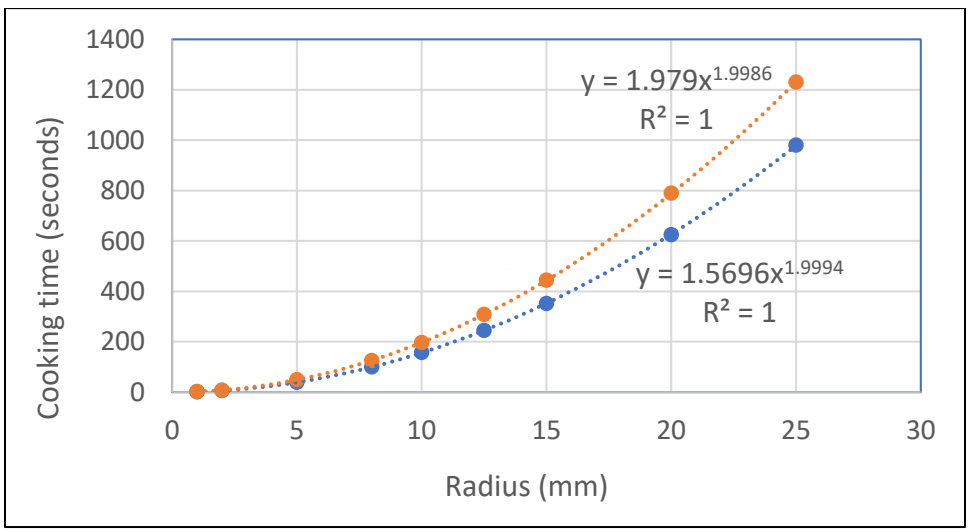

Fig. 2 Cooking time of meatballs, in seconds, as a function of the radius of the meatballs, in millimeters. The blue dots are the ones with the temperature at the center of the meatball reaching 75℃, and the orange dots are the ones with the center temperature reaching 85℃. The dotted curves are the fitting curves with the fitting parameters listed in the figure.

The meat slices have a thickness of L. Figure 3 shows the calculated cooking times versus the square of thickness L, i.e. L^2, for various thicknesses of pork or beef slices. The two different colored dots refer to different center temperature, the blue is for center temperature of 75 ℃ and the orange is for center temperature of 85 ℃, which means well cooked. The straight lines are fitting lines.

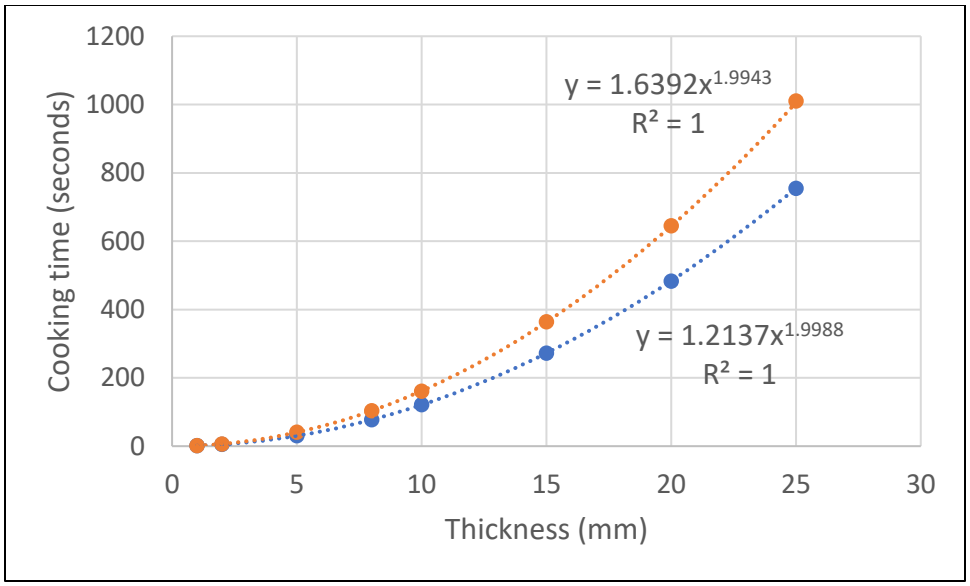

Fig. 3 Cooking time of thin meat slices, in seconds, as a function of the thickness of the meat slices, in millimeters. The blue dots are the ones with the temperature at the center of the meat slice reaching 75℃, and the orange dots are the ones with the center temperature reaching 85℃. The dotted curves are the fitting curves with the fitting parameters listed in the figure.

It is clear that the cooking time to reach the same center temperature also has a perfect (with the fitting $R^2 = 1.00$) square relationship with the thickness of the meat slices. For a meat slice with a thickness of about 1 to 2 mm, it only takes about a few seconds (1.21 to 6.5 seconds) to reach the required temperatures. For a meat slice of 25 mm in thickness (i.e., about 1 inch), it will take 755 seconds to reach 75 ℃ at the center of the slice and takes 1010 seconds to reach 85 ℃ at the center of the slice.

We see that with a similar critical dimension, it takes much longer for a slice to reach the same center temperature as what a ball does. A slice with a thickness of 25 mm requires a cooking time that is equivalent to a ball with a radius of about 23 mm or a diameter of about 46 mm, which is 2 times the thickness of the slice. For the slice, the heat goes in from one direction, which is perpendicular to the slice surface. In comparison, for the ball, the heat goes in from all directions.

In the discussion above, a cube with a side length of a is equivalent to a sphere with a diameter of 0.8a. That is, for a meatball with 25 mm (1 inch) in diameter, it takes the same time to reach the same center temperature as a meat cube with a side length of 20 mm. It is about the same if this applies to a short cylinder shape.

Our calculated cooking times for hot-potting, boiling, stewing meats in the shape of balls, cubes, short cylinders, and thin slices match very well with the corresponding times from our real-time experiences.

For instance, in the Chinese hot-pot case, [4, 16] we typically only dip the meat (lamb, beef, fish) slices (with thickness from 0.5 to 2 mm) for only a few seconds. Our calculations call for 1.5 seconds for 1 mm thick meat slice and about 5-7 seconds for 2 mm thick meat slices. For fish or beef balls, the typical diameters are around 20 mm, and the dipping/cooking time is typically a couple of minutes to a few minutes. Our calculation gives around 3 mins for 20-mm diameter meatballs. For large meatballs (Lion

Balls) or cubes (Pork Cube), they have diameters of around 50 mm (2-inch), and the typical cooking time in boiled soup is around 20 mins. Our calculation gives 16-20 mins.

Chinese stir-frying:

Stir-frying (Chinese: 炒; pinyin: chǎo) is a Chinese cooking technique in which ingredients are fried in a small amount of very hot oil while being stirred in a wok. The technique originated in China 2000 years ago and in recent centuries has spread into other parts of Asia and the West.

The stir-frying cooking technique is one of the major cooking methods in Chinese or Asian (Indian) cuisine. Stir-frying originated during the Han Dynasty (206BC – 220AD). [33, 34] Archeologists found pieces of evidence of woks and thinly sliced food in ancient civilization sites. Stir-frying became the dominant and primary Chinese cooking method during Ming Dynasty (1368 – 1644).

The ancient nomadic lifestyle in China required the people then to be able to cook fast, clean easily, carry effortlessly, use minimal cooking oil, and consume minimal precious fuel, which means the cooking method had to be the most energy-efficient. The wok with a close to parabola shape can be heated up fast with least energy and concentrate the heat to the food at the bottom of the wok from the perspectives of conduction, convection, and radiation. The high heat nature and less cooking oil required accidentally led to more healthy food. The method eventually spread quickly to Japan around 1868 to 1912 and then to North America and the rest of the world in the 20th century. The chronic shortage of fuel, i.e., wood, coal, and other fuel types, might be one of the major reasons behind stir-frying's popular acceptance in ancient and modern China and other parts of the world.

Chinese has been cooking typical and famous Chinese dishes like "Fish flavored shredded thread-pork," "Pepper shredded beef," "Kung Pao chicken," "Sichuan boiled fish," "Braised pork balls," "General Tso's chicken," "Chinese fried rice," "Sweet & sour pork," "Mapo tofu," "Chow Mein," "Shredded potato," or essentially similar dishes for hundreds if not thousands of years. [4, 16, 33, 34]

Another key leading to the feasibility of fast-speed cooking or shortest cooking time with stir-frying belongs actually to the main topic of this research. Before cooking, stir-frying requires the raw foods, no matter in what kind of original sizes and shapes and materials, to be shredded into small pieces in the shapes of thread/wire, sphere, thin slice, cube, etc.

According to the square-relation rule as indicated above (or refer to the supplementary materials for detailed mathematical analysis), a reduction in critical dimension by a factor of 10 will lead to a 100-time reduction in cooking time in order to reach the same temperature in the center of the pieces. As shown in both Fig. 2 and Fig. 3, with shapes of sphere and thin plate as representatives, the cooking time can be reduced in orders of magnitudes if the food is shredded into small dimensions. For instance, the cooking time would be only a few seconds to less than a couple of minutes, with the critical dimension less than about 5 to 10 mm. The food is stirred continuously during the cooking to make sure all the pieces get uniform heating as being cooked. In addition to the speed, the shredding process also makes the flavors (salt, spice, pepper, sweet, and other sources) easily go into the food, and along with the intensity of the heat, the stir-frying produces dishes that are noted for their color, texture, flavor, and nutrition.

Comparing Chinese wok restaurants with many western-styled restaurants, Chinese restaurants have a fast delivery speed after ordering. Sometimes, your dishes can be ready in just a few minutes after you order, thanks to the principles mentioned above.

The famous "Spyce Kitchen," [35, 36] the robotic restaurant founded by four MIT graduates and Michelle 4-Star cook, claimed fast on-site cooking delivery with a cooking time of fewer than 3 minutes, is based on stir-frying cooking method with shredded food pieces.

Even though Chinese stir-frying is famous for its speed and taste, if we compare the cooking time between stir-frying and hot-pot dipping for the similar dimensioned foods, we realize that hot-pot dipping can get some food ready within 10 seconds (7 ups and 8 downs), while stir-frying still needs 2 to 3 minutes. Again, when we consider the diffusion of water, salt, soy-sauce, spice, etc., we can understand why.

Eggs and salted "Duck" eggs:

For most people, we are very familiar with egg cooking since we cook and eat eggs on a daily basis. Not everyone knows salted eggs, especially salted duck eggs. As a delicacy, salted egg (or salted egg yolk) is nothing new. It's been a staple of Chinese cuisine for centuries. Nobody knows exactly how old the delicacy is, but it's estimated that the Chinese were eating it even when the Ming Dynasty began in the 1300s. There have always been three traditional ways to make a salted egg. You can brine the eggs in a salt solution, dry-brine them by encrusting them with a layer of coarse salt or coat them with a sort of muddy paste thing. Each way turns out pretty much the same result, a yolk that's a deep orange color has a grainy yet oozey texture and, of course, is satisfyingly salty.

Our real-life experiences (or recipes) tell us that it takes about 5-10 mins to cook an egg or a duck egg in a boiling water, while making salted eggs or duck eggs takes 20 to 30 days if not longer. Why are they so different?

When approximating an egg as a sphere with a typical diameter of 40 mm (equivalent to a size AA egg in the U.S.), our calculation shows that it takes about 370 seconds (6 mins) to reach a center temperature above 70 ℃, which is above the coagulation temperature. The egg is cooked in boiling water at 100 ℃. A thermal diffusivity coefficient of 1.86×10^{-7} m^2/s is used.

To simulate the salting process, the egg is immersed into saturated saltwater with a salt density of 25% w/w. The center of the egg needs to reach a salt concentration of 2% before the process is done. With a reported salt diffusion coefficient of 1.86×10^{-10} m^2/s, this process takes about 133,400 seconds, which is about 37 days.

In principle, we could potentially salt the eggs at a higher temperature which would increase the diffusion coefficient of salt into the egg. However, it also raises the risk of reducing the storage time of those eggs.

Salted meat:

People have been making and eating salted pork for centuries, if not longer. Many Chinese people love good salted pork or yān xián ròu (腌咸肉) when dining out. We love salted pork made using Sichuan peppercorns, which give off a wonderful aroma with none of the numbing effect when they are kept

whole in a salt curing application. The salted pork you can get at a store is usually cured with only salt, and most of the time, it's nauseatingly salty.

In America, along with hardtack, salt pork was a standard ration for many militaries and navies throughout the 17th, 18th, and 19th centuries, seeing usage in the American Civil War, War of 1812, and the Napoleonic Wars, among others. Salt pork now finds use in traditional American cuisine, particularly Boston baked beans, pork, and beans, and to add its flavor to vegetables cooked in water, as with greens in soul food. It is also central to the flavoring of clam chowder. It generally is cut and cooked (blanched or rendered) before use. Salt pork that contains a significant amount of meat, resembling standard side bacon, is known as "streak o' lean." It is traditionally popular in the Southeastern United States. As a stand-alone food product, it is typically boiled to remove much of the salt content and to partially cook the product, then fried until it starts to develop a crisp exterior. It may be eaten as one would eat bacon or used to season other dishes like traditional salt pork.

Traditionally, salted pork is made by rubbing enough dry salt with other spices around the pork and then keeping them in a dry and low-temperature environment for a duration from a few days to a couple of months.

Like salted eggs, the orders of difference in magnitude of the two diffusion coefficients, D_T and D_M, explain the big difference between the cooking time (which is typically 10 mins to 1 hour) and the salting process (many days to even months).

French fries:

The best French fries, like the ones we eat in McDonald's, go with two frying processes in a high-temperature oil bath. Each of the frying processes happened in a hot oil bath with a temperature around 170 ℃ to 190 ℃, takes a few minutes, with a total frying time of about 10 mins.

With a dimension of typical 5x5 mm in cross-section, it only takes 23 seconds to get them cooked (D_T = 1.28×10^{-7} m^2/s), i.e., to reach over 100 ℃ across the whole fries, why do we need to have a double frying process in the standard McDonald's recipe, with the first frying for 5 mins at 163 ℃, that alone is 10 times of the duration required to heat the fries from the heating perspective, and the second frying for 2-3 mins at an even higher temperature like 180 ℃. The intervals between the two fryings can be days or even months?

The answer lies again in a mass diffusion coefficient for the cooking oil and water, which is two orders of magnitude smaller than the heat diffusion coefficient. Our calculation, as shown in table 3, shows that it takes more than 15 mins for the oil molecules to diffuse into the center of the French fries (D_M = 1.28×10^{-9} m^2/s and center oil concentration reaching 10%), in comparison to only 23 seconds to reach a temperature of more than 100 ℃ in the center of the fries. Furthermore, to achieve a crispier eating taste, the moisture also needs to diffuse out of the fries in a good amount. The water diffusion process is also governed by a diffusion coefficient which is two orders of magnitude smaller than the heat diffusion coefficient. The reason to have the 2nd oil frying is mostly due to the fact that we want to give enough time for the water and oil to diffuse without burning off the fries at a high temperature for too long. The second frying helps to achieve the crispy in and out.

In comparison, for some French fries with much thicker dimensions, such as over 10 mm in width, even with a double-frying process, it is hard to achieve a good quality in the center of the thick fries because

even though it takes not too long to get them cooked, but the diffusion of both oil and water can never be done with enough time. It results in French fries with soft, moisture inner parts.

Noodles and spaghetti:

The origin of thin, string-like pieces of dough that are often dried and then cooked is hard to pinpoint. What is called noodles is sometimes only considered to be the modern East Asian variety and not the general type and correspondingly its origin is usually listed as Chinese, but when it includes pasta it becomes more controversial. The earliest written record of noodles in China is found in a book dated to the Eastern Han period (25–220 CE). It became a staple food for the people of the Han dynasty. Food historians generally estimate that pasta's origin is from among the Mediterranean countries: a homogenous mixture of flour and water called itrion as described by the 2nd-century Greek physician Galen, among 3rd to 5th centuries Palestinians itrium as described by the Jerusalem Talmud and itriyya (Arabic cognate of the Greek word), string-like shapes made of semolina and dried before cooking as defined by the 9th-century Aramean physician and lexicographer Isho bar Ali. In 2005 a team of Chinese archaeologists reported finding an earthenware bowl that contained remains of 4000-year-old noodles at the Lajia archaeological site. The findings were said to resemble Lamian, a type of Chinese noodle. Analyzing the husk phytoliths and starch grains present in the sediment associated with the noodles, they were identified as millet belonging to Panicum miliaceum and Setaria italica. The findings being noodles were disputed because millet, being gluten-free, isn't suitable for making noodles as we know them. Wheat wasn't widely cultivated until the Tang dynasty (618–907 CE).

Spaghetti is a long, thin, solid, cylindrical noodle pasta. It is a staple food of traditional Italian cuisine. Like other pasta, spaghetti is made of milled wheat and water and sometimes enriched with vitamins and minerals. Italian spaghetti is typically made from durum wheat semolina. The first written record of pasta comes from the Talmud in the 5th century AD and refers to dried pasta that could be cooked through boiling, which was conveniently portable. Some historians think that Berbers introduced pasta to Europe during conquest of Sicily. In the West, it may have first been worked into long, thin forms in Sicily around the 12th century, as the Tabula Rogeriana of Muhammad al-Idrisi attested, reporting some traditions about the Sicilian kingdom. The popularity of spaghetti spread throughout Italy after the establishment of spaghetti factories in the 19th century, enabling the mass production of spaghetti for the Italian market.

With both noodles and some spaghettis with similar diameter or size of the cross-section, we found that it only takes 2 minutes to cook ready for some noodles (D_M = 1.28x10^{-9} m^2/s, diameter 1.5 mm, center water concentration 30%), but it may take more than 20 minutes to get some spaghettis cooked ready for eat (D_M = 1.28x10^{-10} m^2/s, diameter 1.5 mm, center water concentration 30%).

For the noodles and spaghettis with a similar diameter of 1 to 2 mm, the heating process only takes less than 5 to 10 seconds (D_T = 1.28x10^{-7} m^2/s, diameter 1.5 mm). Again, the huge difference in cooking times is caused by the low and varied mass (mainly water) diffusion coefficient.

Our research shows that the water diffusion coefficient in some noodles can be one order of magnitude larger than the one in some spaghettis. It can well explain the order of magnitude difference in the cooking times, between 1-2 mins and 10-20 mins.

Sous Vide:

Where every discussion about Sous Vide focuses on its precise and uniform temperature control and profile across the whole food (particularly meat) piece, we like to point out one important advantage and aspect of Sous Vide – the shrinkage of the gaps between the heating process and mass transfer (salt, taste, water, flavor, etc.) process.

A typical Sous Vide process, as the food is kept within a vacuumed plastic bag, takes half a day (12 hours) to 3 days (72 hours) to "cook," allowing the temperature reaching, precisely, consistently, uniformly, slowly, across everywhere inside the food piece, to a temperature mostly around 52-60 ℃. However, if you look carefully into the heating process, it doesn't need so long to raise the whole piece's temperature from, for instance, 5 ℃ to 55 ℃.

The reason that Sous Vide needs a typical duration of 12-72 hours is not because of the heating process requirement, rather it is really due to the mass diffusion process. It is the mass diffusion process that leads to a more uniform texture, color, and flavor profile within the whole food piece.

Our calculation shows that, with a bath temperature at 55 ℃, it takes less than 1 hour (43 mins in exact) for the center of the food of size 50 mm in diameter to reach within 0.5 ℃ of the bath temperature (D_T = 1.3×10^{-7} m^2/s, diameter 50 mm, center temperature concentration 54.5 ℃).

However, for the salt, oil, water, or other molecules to diffuse enough into the center, it would take 50-100 hours ($70\ hours\ if\ D_M$ = 1.3×10^{-10} m^2/s, diameter 50 mm, center salt concentration 1%).

The mathematical model is discussed in detail in the supplementary materials or in our previous publications [ref. 16].

Why are the two diffusion coefficients so different? Fundamentally, the thermal diffusion process doesn't require the physical transportation of atoms, molecules, or ions over an inter-molecule distance. The heat or temperature is basically the vibration of the molecules. Like sound travels at 310 m/s in air, such vibration could propagate at a much higher speed across the food media network. However, air molecules themselves can never travel so fast physically from one place to another (as a result of collisions between the molecules along the way and other reasons.) This is why the mass diffusion coefficient is orders of magnitude smaller than the thermal diffusion coefficient.

Based on a well understanding of the physics of cooking, how can we make an ideal dish then? Ideal dishes are the ones with the optimal heating (temperature) profile along with optimal taste, flavor, and texture profile. Could we achieve all of these in one cooking process?

Knowing all of the above physics in cooking, we may think that an ideal cooking process is how to close up the gaps between the thermal diffusion and the mass diffusion processes. Ideally, we have to either find a way to increase the mass diffusion coefficient or slow down the thermal diffusion coefficient or alternatively, we have to find a process which can afford a long cooking process that gives the mass diffusion enough time while not running the risk of overcooking or burning the food from the thermal process.

Clearly, Sous Vide is a process that essentially achieves this. On the other hand, as the diffusion time has a square relationship with the physical dimension, in the cooking like Chinese stir-frying, cutting the food into smaller dimensions essentially helps to close up the two processes.

Conclusions

Cooking reflects human's highest intelligence from both scientific and artistic perspectives. This work investigates the essential physics behind intelligence in cooking. The physics behind cooking time and preparation method is carefully studied and quantitatively presented, which reveals the most interesting science behind various recipes, tricks, and mysteries to achieve optimal temperature and flavor in cooking and culinary arts. Firstly, the cooking time's square power relation with the food's physical dimension explains the finest thoughts behind fast cooking and why Chinese and Indian foods prefer shredding the food into tiny pieces prior to cooking. Secondly, the orders of difference in magnitude between thermal and mass diffusivity coefficients explain many food preparation methods used widely throughout centuries of human history in Eastern and Western culinary cultures.

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Supplementary Materials

Theoretical considerations

Thermal transfer

Fourier's Law states [21-25] that the heat flux q (in W/m^2) is proportional to the temperature gradient, i.e., $\vec{q}$ = - k· ∇T where $\vec{q}$ is a vector and ∇ is the gradient. k is thermal conductivity in W/(cm· K).

This leads to the heat transfer equation: $\nabla \cdot \nabla T = \frac{1}{\alpha}\frac{\partial T}{\partial t}$, where T = T (**r**, t) and α = k/ρc is the thermal diffusivity in m^2/s, where ρ is the density (kg/m^3) and c is the specific heat (J/(kg · K)).

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

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

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

We then have:

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

$$\text{for } (0 \leq r \leq R) \qquad (1)$$

We define

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

Thus, we have:

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

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

$$T_c = T_h - 2(T_h - T_0) \sum_{n=1}^{\infty} \left[(-1)^{n+1} \cdot e^{-n^2 t/\tau} \right] \quad (3)$$

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

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

Mass transfer

Fick's Law states [31, 32] that the mass transfer (i.e., diffusion) equation follows $\nabla \cdot \nabla C = \frac{1}{D}\frac{\partial C}{\partial t}$, where C = C (x, t) and D is the mass diffusion coefficient in m^2/s.

For a sphere with azimuthal symmetry, during the mass transfer, we have $\frac{\partial C}{\partial \theta} = 0$ and $\frac{\partial^2 C}{\partial \varphi^2} = 0$. For brining (soaking) food with food starting with low concentration C_0 and surrounded at high concentration (bath concentration) C_h, we have the following boundary conditions:

$C(r,o) = C_0$ $(0 \leq r \leq R)$, where R is the radius of the sphere.

$$C(\geq R, t) = C_h$$

We then have:

$$C(r,t) = C_h - \frac{2R(C_h - C_0)}{\pi \cdot r} \sum_{n=1}^{\infty} \left[\frac{(-1)^{n+1}}{n} \sin \frac{n\pi r}{R} \cdot e^{-Dn^2\pi^2 t/R^2} \right]$$

for $(0 \leq r \leq R)$ (5)

We define

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

Thus, we have:

$$C(r,t) = C_h - \frac{2R(C_h - C_0)}{\pi \cdot r} \sum_{n=1}^{\infty} \left[\frac{(-1)^{n+1}}{n} \sin \frac{n\pi r}{R} \cdot e^{-n^2 t/\tau} \right] \quad (6)$$

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

$$C_c = C_h - 2(C_h - C_0) \sum_{n=1}^{\infty} \left[(-1)^{n+1} \cdot e^{-n^2 t/\tau} \right] \quad (7)$$

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

$$C_c = C_h - 2(C_h - C_0)\{e^{-t/\tau} - e^{-4t/\tau} + e^{-9t/\tau} - e^{-16t/\tau} + e^{-25t/\tau} - e^{-36t/\tau} + e^{-49t/\tau} - \ldots\} \quad (8)$$

The square-relation rule

When we carefully look at the both equations of (4) and (8), the value of the second term and also all the later terms in the parentheses goes down very quickly compared to the first term, thus, it has a much smaller contribution to the whole sum. The other higher order terms have even smaller contributions which can be ignored without causing any meaningful error in the calculations. In all our numerical calculations discussed later, to build our confidence, we intentionally compared the calculation results with only the first term, first two terms, first three terms, first four terms, and first 16 terms.

Based on our numerical calculation, in the case that we are confident that the first term dominates the result, we can ignore all the higher order terms other than the first term in the parentheses, we get

$$T_c = T_h - 2(T_h - T_0)\{e^{-t/\tau}\}$$ from the equation (4), and

$$C_c = C_h - 2(C_h - C_0)\{e^{-t/\tau}\}$$ from the equation (8).

We can re-arrange the equations into:

$$t = \tau \cdot ln\left\{\frac{2(T_h - T_o)}{T_h - T_c}\right\} \text{ and } t = \tau \cdot ln\left\{\frac{2(C_h - C_o)}{(C_h - C_c)}\right\}$$

since $\tau = \frac{R^2}{\pi^2 \cdot \alpha}$ or $\tau = \frac{R^2}{\pi^2 \cdot D}$ and $\alpha = \frac{k}{\rho c}$, we have:

$$t = \frac{R^2}{\pi^2 \cdot \alpha} ln\left\{\frac{2(T_h - T_o)}{T_h - T_c}\right\} \quad (9)$$

and

$$t = \frac{R^2}{\pi^2 \cdot D} ln\left\{\frac{2(C_h - C_o)}{(C_h - C_c)}\right\} \quad (10)$$

Thus, both new approximated equations with only the first term considered give a square dependence to the critical dimension, i.e., the radius R for the sphere.

A Simple Approach to Determine Diffusion Coefficient of Salt in Various Food

Abstract

5 different types of foods were studies and their diffusion coefficient of salt are experimentally determined with a simple and low-cost method. The foods which are studied include potato, sweet potato, pumpkin, taro, and radish. We pre-cut the foods into a spherical shape with known diameters and then brine them into the pre-mixed salt solution. After a certain soaking time, the ball-shaped piece is taken out and cut out a small piece from its center. A compact salt meter (LAQUAtwin-salt-11) made by Horiba was used to determine the salt concentration. The salt concentration at the center of the piece was measured as the diameter or the soaking time is used as variables. We then fit the measured data with the simulation. We are able to determine the following diffusion coefficient data with good matching between the measurement data and the simulation results. Furthermore, the diffusion coefficient of salt in potato was also measured at 100℃. The activation energy is thus determined to be around 74meV or 7.13 kJ/mol.

Introduction

The diffusion coefficient is the core parameter which plays a key role in the mass transfer equation: $\boldsymbol{\nabla} \cdot \boldsymbol{\nabla}\mathrm{T} = \frac{1}{D}\frac{\partial T}{\partial t}$. The equation describes one of the most important physical phenomena governing the world – mass transfer and exchange. [1, 2]

It is an important material parameter which is essential to understand materials' properties and further in materials' various applications. Being able to accurately measure the diffusion coefficient of a material is important. Thus, a simple and low-cost measurement method is thus highly desirable. [3-8]

Salt, i.e., sodium chloride, plays an important role in food. It is essential to understand the salt diffusion process accurately in order to understand the food science and furthermore, it has significant implications for food processing and food storage. [9-17]

To measure the salt diffusion coefficient, an accurate measurement of the salt concentration and salt distribution is required. Previously, several experimental methods have been used. [4-7]

One of the methods require to use Nuclear Magnetic Resonance (NMR) Imaging. [4, 5] NMR Imaging has been used to measure the salt distribution and concentration, which has benefited the eld of chemistry and medicine in important ways, helping researchers and chemist to identify and measure certain elements found on the periodic table.

Another method relies on a conventional method called Titration, [3, 10] which has continuously been used to measure salt concentration. Titration can be performed manually or by using an automatic titrator. This popular titration method determines the chloride ion concentration. Silver nitrate is used as the indicator and is added until all of the chloride ions

are precipitated. So, this method also measures the amount of chloride (Cl) and uses the mass percent weights to determine sodium chloride (NaCl) and or sodium (Na). The titration method does require the use of a silver electrode/ph electrode (or combined silver electrode), silver nitrate, and someone who understands how to run the method (manual or via automatic titrator).

Besides Titration and NMR Imaging, Near Infrared, or NIR, spectroscopy was also used in previous work to determine salt concentration and distribution. [6, 7]

All of these methods either requires expensive instruments or complex processes. [3-7]

Furthermore, we have done a thorough review of previous work on measuring and estimating on the mass diffusion coefficients. [16-30] In the work by Floury et al., NaCl diffusion in cheese was studied and the diffusion coefficient was determined to be around 1-5.5X10^{-10} m^2/s at around 10-15℃ by the NMR method. The diffusivities of sodium chloride in chicken breast were measured to be in the range of $8.99 \cdot 10^{-10}$ m^2/s to $9.55 \cdot 10^{-10}$ m^2/s. [17] Salt in beef was 5-39 x10^{-10} m^2/s. [18] Salt and sugar in vegetables were determined to be 2-30 x 10^{-10} m^2/s. [30] NaCl diffusion in Chinese cabbages was 1.7-11.6x10^{-11} m^2/s. [20]

Effective diffusion coefficient of NaCl (Dm) in pork tissue was 0.6 – 5 x 10^{-10} m^2/s dependent on the brine NaCl concentration. [21, 28-29] Diffusion coefficient of salt in potato tissue was measured to be (3.45-4.39) x 10^{-9} m^2/s. [26] Diffusion of chloride, nitrite, and nitrate in beef and pork is in the range of 1-5x 10^{-10} m^2/s. Salt diffusion in beef, salmon, and cheese was 1-7 x 10^{-10} m^2/s. Salt and acetic acid into herring is 1-6 x 10^{-10} m^2/s. [22] Salt diffusion in salted duck eggs was 2x10^{-10} m^2/s to 2x10^{-11} m^2/s. For dehydrated slated meat, the salt diffusion coefficient for wet salting was 0.26 x 10^{-10} m^2/s at 20℃ and 0.25 x 10^{-10} m^2/s at 10℃ and for the dry salting the values were 19.37 x 10^{-10} m^2/s at 20℃ and 17.21 x 10^{-10} m^2/s at 10℃. [29]

It was found that, for most materials, the diffusion coefficients are in the range between 10^{-9} m^2/s to 10^{-11} m^2/s. Increase temperature from room temperature to 100℃ will increase the diffusion coefficient by roughly a factor of 10. [28, 30]

The temperature dependent of the diffusivity can be expressed as the Arrhenius type equation with the activation energy as the parameter to determine how temperature affects the diffusion coefficient. It was found that the activation energy was around 66kJ/mol for salt to diffuse in Chinese cabbages. [20]

Our method in experimental measurement and theoretical simulation

Our research presents a simple, low-cost, fast, and accurate method to measure the salt diffusion coefficient in 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 radii. The diameter of the food was measured by a caliper.

For the salt concentration measurement, we need to measure it at a special location, i.e., the center of the sample. We adopt a low-cost compact salt meter, LAQUAtwin-salt-11 made by Horiba, to measure the salt concentration at the center of the food sample. Although it is a destructive measurement, the measurement is simple, quick, low-cost, and straightforward. A small piece of about 1 mg weight is taken from the center of the sample, and then it is measured for salt concentration with the compact salt meter.

In term of the cost, the total cost for the materials, tools, and instruments used in this research is less than $800. The compact salt meter (LAQUAtwin-salt-11) made by Horiba costs $180, and the 200g x 0.1mg Digital Analytical Balance Lab Precision Scale from U.S. Solid costs $480. The caliper costs $20, all the food materials including salts cost $80, and other containers, cooking wares, and suppliers cost $100. 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 salt diffusing uniformly from all directions. This was achieved by using a water-based brine which contains salted solution with high uniformity. The sample has an initial close to zero salt concentration. The sample is a uniform material with known physical parameters (i.e., diameter). The salt concentration at the center of the sphere is calculated (and measured) as the function of time and radii. The radius of the sample is a controlled variable. Various samples are compared.

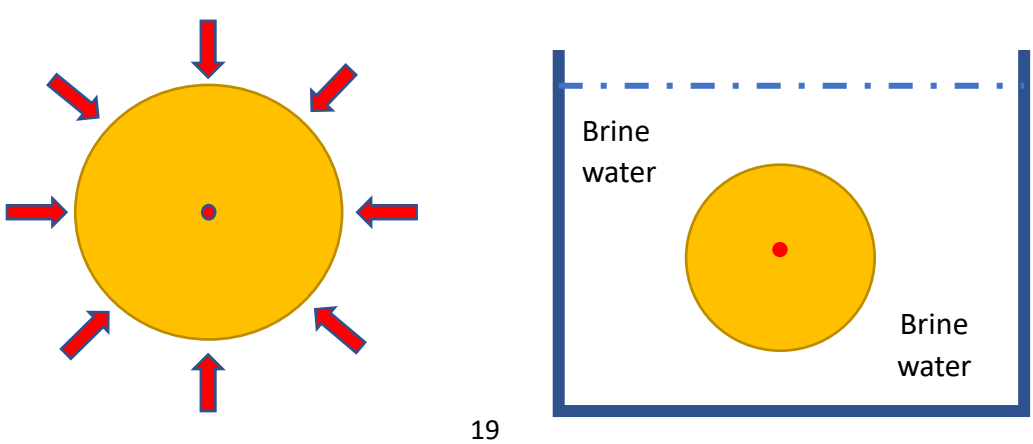


Fig. 1(a) Fig. 1(b)

Fig. 1 (a) shows schematically an ideal sphere with azimuthal symmetry in the salt diffusion process. Fig. 1 (b) shows schematically the experimental realization of the azimuthal symmetrical configuration. The sphere-shaped food sample is immersed into brine water for a period of time ranging from 1 hour to 24 hours.

Fig. 2 shows the compact salt meter, LAQUAtwin-salt-11 made by Horiba, used in this research. HORIBA's unique compact meter integrates the electrode, display and sample container to enable simple, effective on-site testing by direct measurement from a single drop. The LAQUAtwin-salt-11) can measure between 0% to 10% in absolute concentrations with a relative precision of +/-4%.

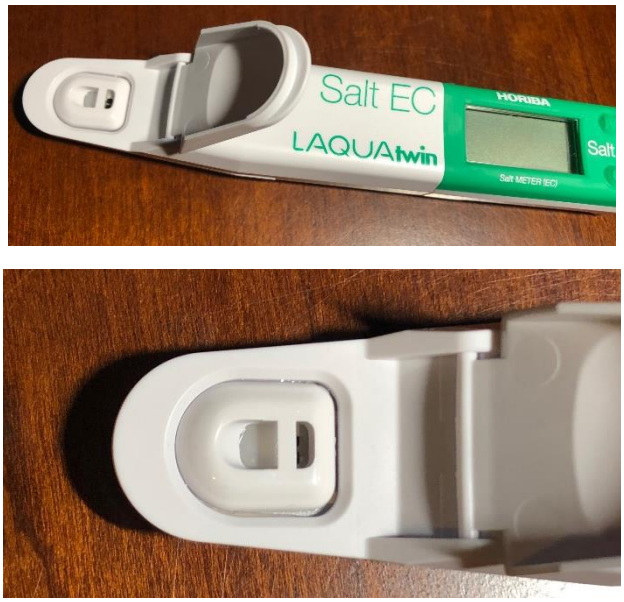


Fig. 2 A compact salt meter (LAQUAtwin-salt-11) made by Horiba was used to determine the salt concentration. HORIBA's unique compact meter integrates the electrode, display and sample container to enable simple, effective on-site testing by direct measurement from a single drop. The LAQUAtwin-salt-11) can measure between 0% to 10% in absolute concentrations with a relative precision of +/-4%.

Fig. 3 shows representatively different food samples which were cut into spherical shape with various diameters. The food samples used in this study include 5 different types of food, i.e., potato, sweet potato, taro, radish, and pumpkin. All the food samples were pre-cut and shaped into a sphere shape with pre-determined radii, ranging from 13 mm to 31 mm.

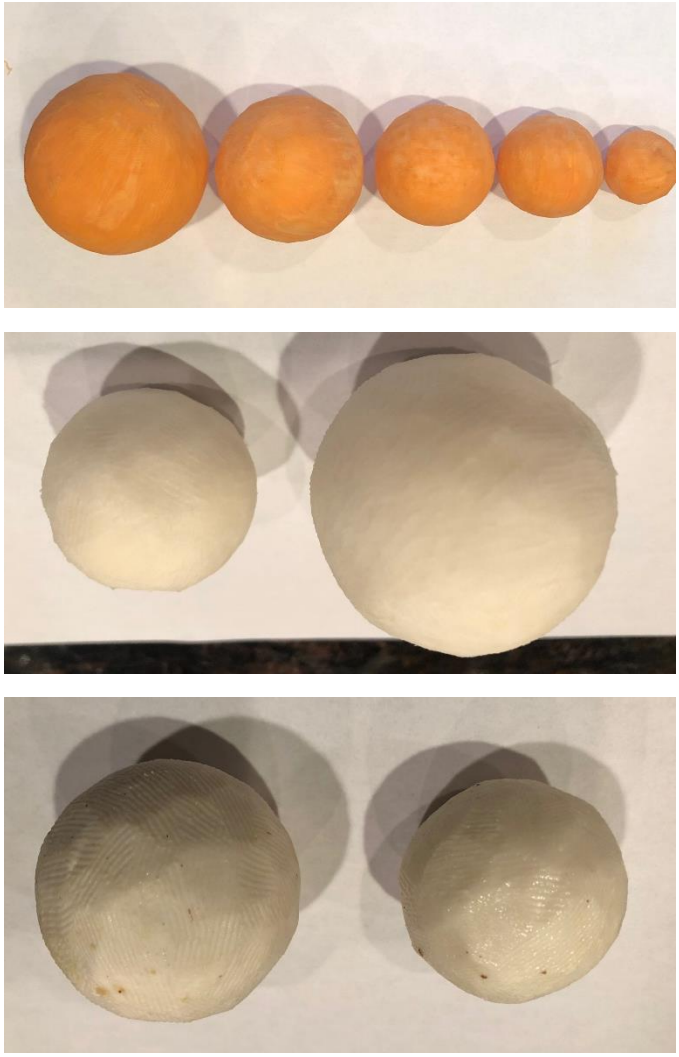


Fig. 3 Different foods are cut into nearly perfect spheres with different radii.

Experimental results

Fig. 4 shows the measured center salt concentration (dots) from three different potato samples which have the same radii, as the function of time. It shows that with a longer brine time, the center salt concentration increases with the brine time duration. The three solid curves are theoretical simulation results with different salt diffusion coefficient, $8x10^{-10}$ m^2/s, $1x10^{-9}$ m^2/s, and $1.2x10^{-9}$ m^2/s, respectively. The curve with $1x10^{-9}$ m^2/s for the salt diffusion coefficient fits the experimental data well.

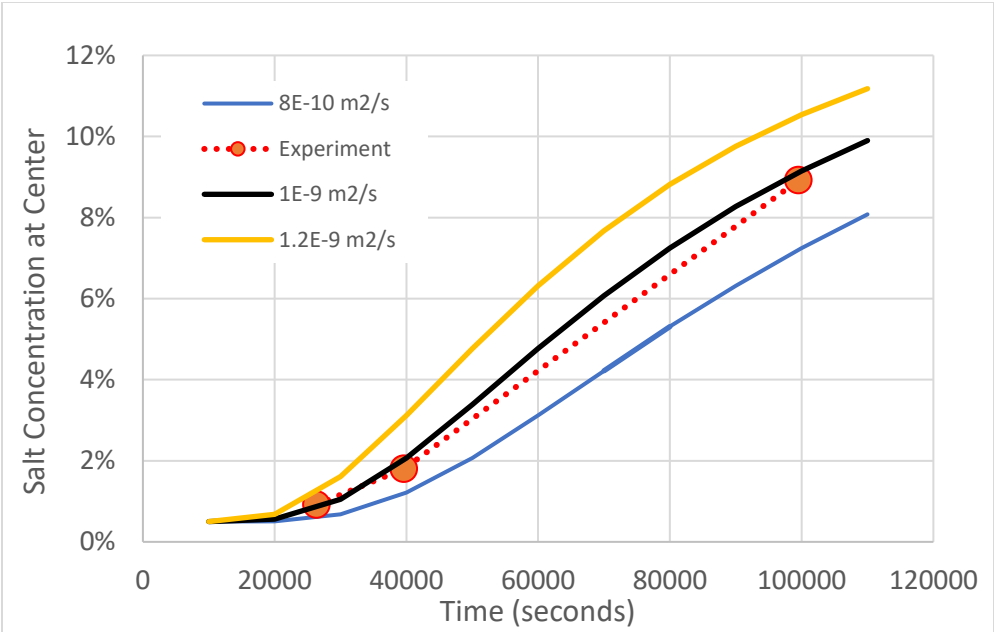


Fig. 4 Potato samples with same radius (24mm) were measured. The salt concentration at the center of the sphere sample is recorded as the function of brine time as shown in dots. The solid curves are the simulation with the diffusion coefficient as the only variable.

Fig.5 shows the center salt concentration measurement results (dots) for two potato sample with different radii of 24 mm and 28.5 mm, respectively. The brine time duration for the two samples is exactly same, 24 hours or 86400 seconds. The three solid curves are theoretical simulation results with different salt diffusion coefficient, $8x10^{-10}$ m^2/s, $1x10^{-9}$ m^2/s, and $1.2x10^{-9}$ m^2/s, respectively. The curve with $1x10^{-9}$ m^2/s for the salt diffusion coefficient fits the experimental data well.

Fig.6 shows the center salt concentration measurement results (dots) for five potato sample with different radii of 13mm, 18mm, 21.5mm, 27mm, and 31mm, respectively. The brine time duration for the two samples is exactly same, 24 hours or 86400 seconds. The three solid curves are theoretical simulation results with different salt diffusion coefficient, $6x10^{-10}$ m^2/s, $9x10^{-10}$ m^2/s, and $1x10^{-9}$ m^2/s, respectively.

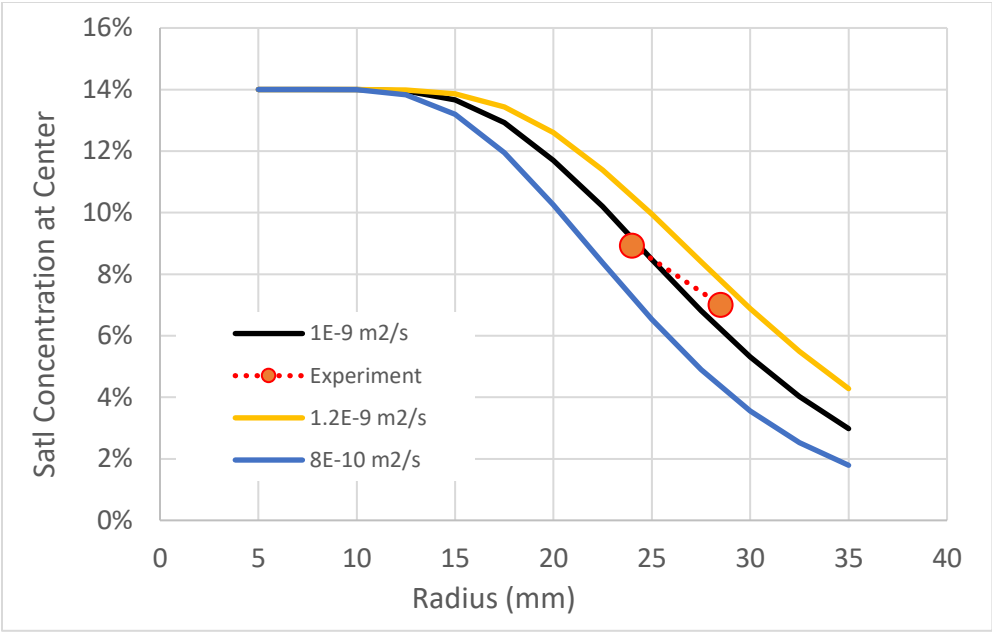


Fig. 5 Two potato samples with different radius (24mm and 28.5mm) were measured. The brine time duration is kept at 24 hours (86400 seconds). The salt concentration at the center of the sphere sample is recorded as the function of radius as shown in dots. The solid curves are the simulation with the diffusion coefficient as the only variable.

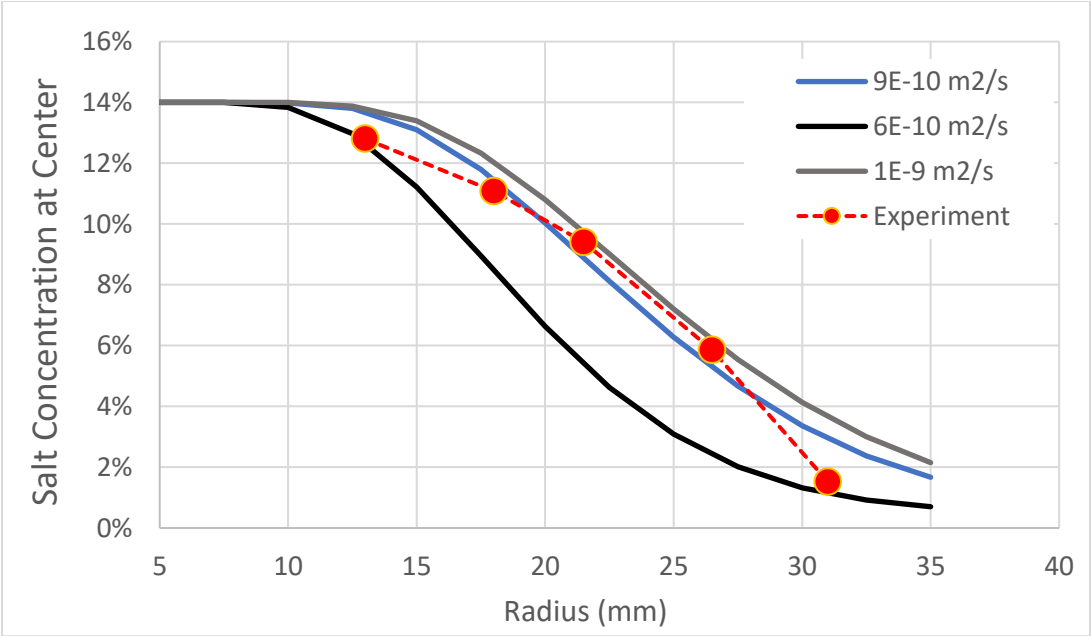


Fig. 6 5 sweet potato samples with different radius (13mm, 18mm, 21.5mm, 27mm, and 31mm) were measured. The brine time duration is kept at 24 hours (86400 seconds). The salt concentration at the center of the sphere sample is recorded as the function of radius as shown in dots. The solid curves are the simulation with the diffusion coefficient as the only variable.

Fig.7 shows the center salt concentration measurement results (dots) for two taro sample with different radii of 21 mm and 24.5 mm, respectively. The brine time duration for the two samples is exactly same, 24 hours or 86400 seconds. The three solid curves are theoretical simulation results with different salt diffusion coefficient, $6x10^{-10}$ m^2/s, $7.5x10^{-10}$ m^2/s, and $9x10^{-10}$ m^2/s, respectively. The curve with $7x10^{-10}$ m^2/s for the salt diffusion coefficient fits the experimental data well.

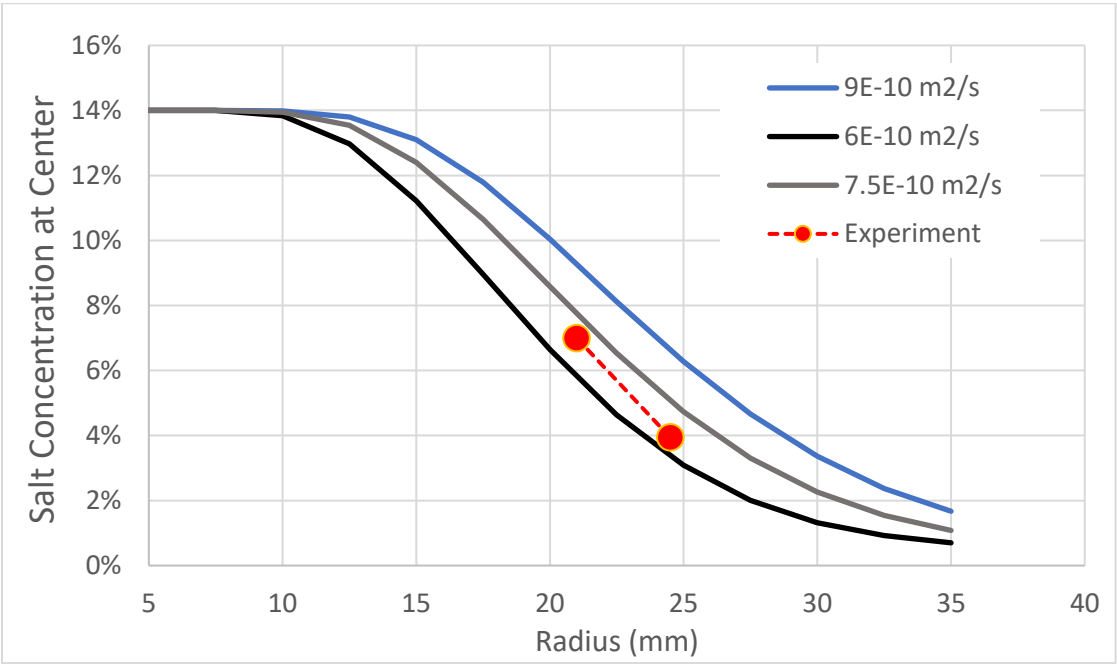


Fig. 7 Two taro samples with different radius (21mm and 24.5mm) were measured. The brine time duration is kept at 24 hours (86400 seconds). The salt concentration at the center of the sphere sample is recorded as the function of radius as shown in dots. The solid curves are the simulation with the diffusion coefficient as the only variable.

Fig.8 shows the center salt concentration measurement results (dots) for two radish samples with different radii of 19 mm and 25.5 mm, respectively. The brine time duration for the two samples is exactly same, 24 hours or 86400 seconds. The three solid curves are theoretical simulation results with different salt diffusion coefficient, $6x10^{-10}$ m^2/s, $7.5x10^{-10}$ m^2/s, and $9x10^{-10}$ m^2/s, respectively. The curve with $7.5x10^{-10}$ m^2/s for the salt diffusion coefficient fits the experimental data well.

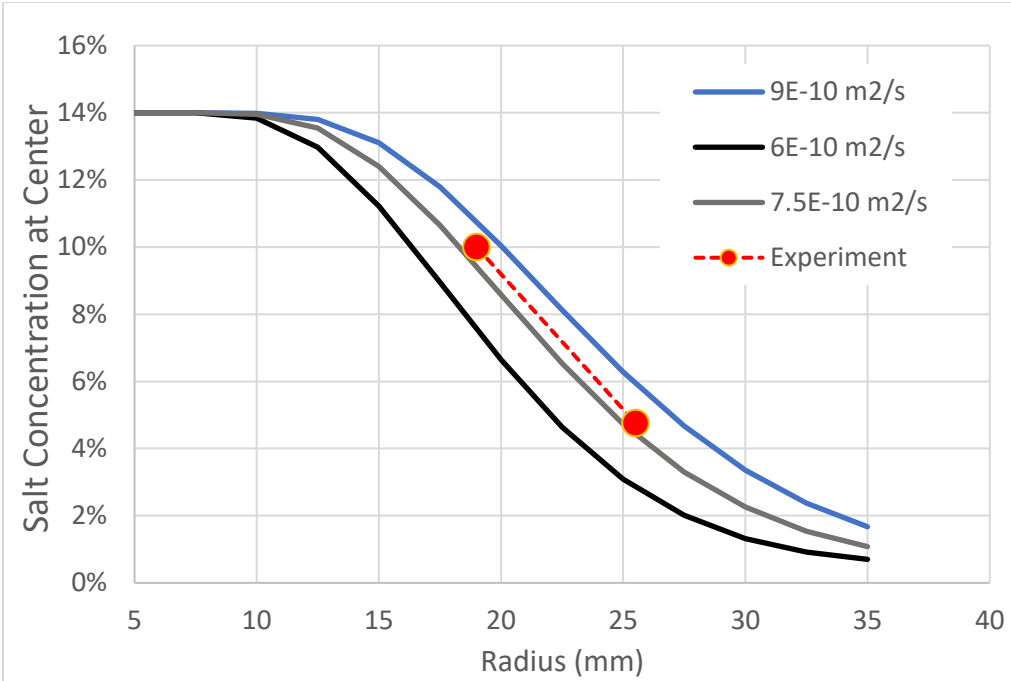


Fig. 8 Two radish samples with different radius (19mm and 25.5mm) were measured. The brine time duration is kept at 24 hours (86400 seconds). The salt concentration at the center of the sphere sample is recorded as the function of radius as shown in dots. The solid curves are the simulation with the diffusion coefficient as the only variable.

In this research, we also studied the dependency of the diffusion on temperature. The dependency of the diffusion on temperature is described by the Arrhenius equation as follow: [28, 30]

$$D_e = D_0 e^{-\frac{E_a}{RT}}$$

Where D_e is the effective diffusion coefficient in m^2/s. E_a is the activation energy in meV or J/mol. D_0 is the pre-exponential factor in m^2/s. R is the gas constant (8.314 J/mol K). T is the absolute temperature.

We need to measure the salt diffusion coefficients at two different temperatures. Our experimental setup and measurement method allows us to do this.

Fig.9 shows the center salt concentration measurement results (dots) for two potato samples with different radii of 24 mm and 26 mm, respectively. Unlike all the experiments discussed above which were done at room temperature, the brine for this case was done at 100 °C. The

brine time duration for the two samples is exactly same, 3 hours or 10800 seconds. The three solid curves are theoretical simulation results with different salt diffusion coefficient, $7x10^{-9}$ m^2/s, $8x10^{-9}$ m^2/s, and $1.1x10^{-8}$ m^2/s, respectively. The curve with $1x10^{-8}$ m^2/s for the salt diffusion coefficient fits the experimental data well.

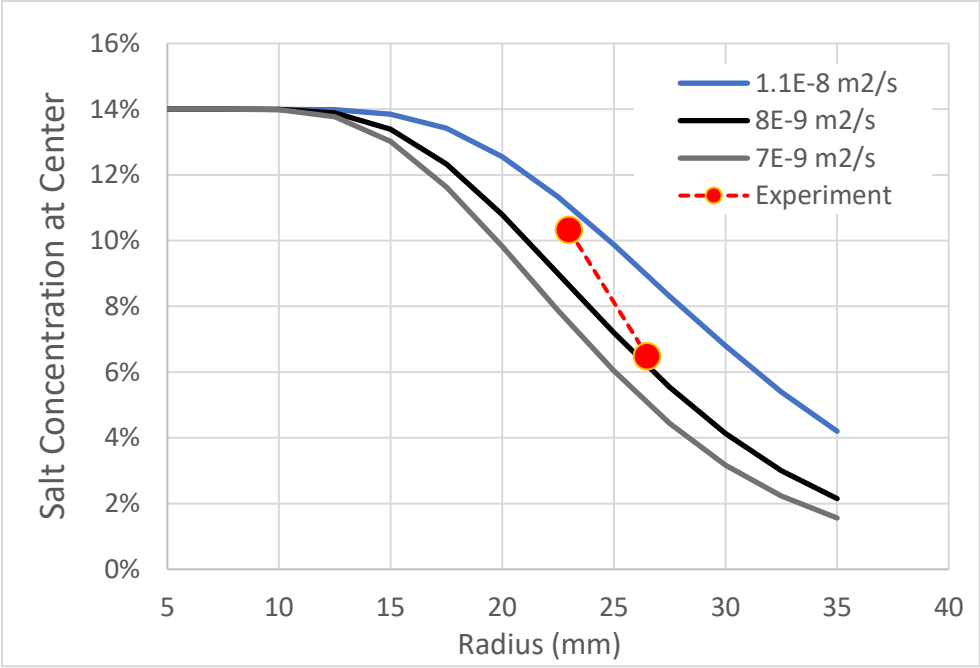


Fig. 9 Two potato samples with different radius (24mm and 26mm) were measured at 100℃. The brine time duration is kept at 3 hours (10800 seconds). The salt concentration at the center of the sphere sample is recorded as the function of radius as shown in dots. The solid curves are the simulation with the diffusion coefficient as the only variable.

For comparison, Fig. 10 shows the two sets of data with one is done at room temperature and the other is done at 100 °C.

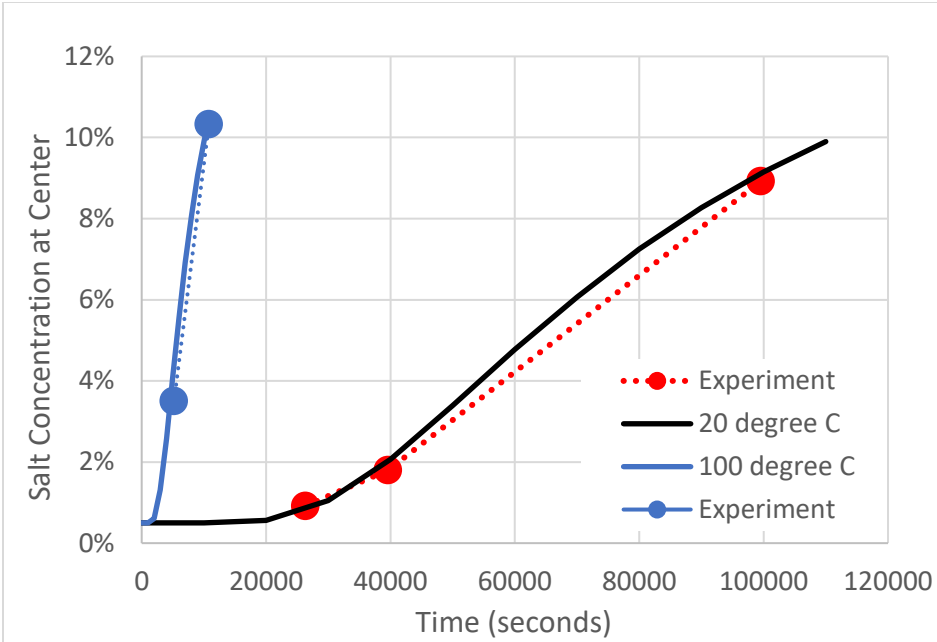


Fig. 10 Potato samples with same radius (24mm) were measured at two different temperatures (20℃ and 100℃). The salt concentration at the center of the sphere sample is recorded as the function of brine time as shown in dots. The solid curves are the simulation with the diffusion coefficient as the only variable.

With T = 373K for our case, and De is between 8×10^{-9} to 1.1×10^{-8} m2/s, and D_0 is between 8×10^{-10} to 1.2×10^{-9} m2/s, we derive the activation energy to be around 74meV or 7.13 kJ/mol based on the Arrhenius equation, $D_e = D_0 e^{-\frac{E_a}{RT}}$.

The theoretical model and simulation

The transportation of salt, sugar, water, oil, and other molecules and ions, is governed by the mass transfer process, which is described by an equation so-called Fick's 2nd Law similar to the heat transfer equation: [31, 32]

$$\nabla \cdot \nabla c = \frac{1}{D}\frac{\partial C}{\partial t}$$

Where C = C (x, t) is the concentration of the molecules or ions, which is the function of location and time. D is the diffusion coefficient of the molecules or ions in m^2/s.

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

2.1. General discussion

Fick's Law states [31, 32] that the mass transfer (i.e., diffusion) equation follows

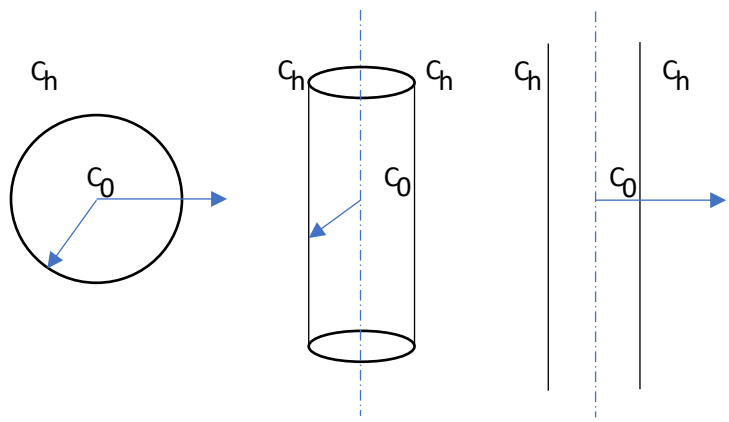
$$\frac{\partial^2 C}{\partial x^2} = \frac{1}{D}\frac{\partial C}{\partial t}$$

Where C = C (x, t) and D is the mass diffusion coefficient in m^2/s.

In three-dimension, the mass transfer equation becomes:

$$\boldsymbol{\nabla} \cdot \boldsymbol{\nabla} \mathrm{C} = \frac{1}{D}\frac{\partial C}{\partial t}$$

Where,



(a) Sphere (b) Cylinder (c) Plate

Fig. 2 shows schematically three different configurations: sphere (a), long cylinder (b), and parallel plate (c).

$$\boldsymbol{\nabla} \cdot \boldsymbol{\nabla} T = \frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial y^2} + \frac{\partial^2 C}{\partial z^2} \qquad (for\ Cartisian\ coordinates)$$

$$= \frac{1}{r^2 \sin\theta}\left[\sin\theta \frac{\partial}{\partial r}\left(r^2 \frac{\partial C}{\partial r}\right) + \frac{\partial}{\partial \theta}\left(\sin\theta \frac{\partial C}{\partial \theta}\right) + \frac{1}{\sin\theta}\frac{\partial^2 C}{\partial \varphi^2}\right] \qquad (for\ spherical\ coordinates)$$

$$= \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial C}{\partial r}\right) + \frac{1}{r^2}\left(\frac{\partial^2 C}{\partial \theta^2}\right) + \frac{\partial^2 C}{\partial z^2} \qquad (for\ cylinderical\ coordinates)$$

1.2. A sphere with azimuthal symmetry

For a sphere with azimuthal symmetry, during the mass transfer, we have $\frac{\partial C}{\partial \theta} = 0$ and $\frac{\partial^2 C}{\partial \varphi^2} = 0$, the mass transfer equation becomes

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

Applying $V = r \cdot T$ to the above equation, for $0 \leq r \leq R$ we get:

$$\frac{\partial^2 V}{\partial r^2} = \frac{1}{D}\frac{\partial V}{\partial t}$$

We can decouple V(r, t) into:

$$V(r,t) = R(r) \cdot T(t)$$

And we get:

$$\frac{\partial V}{\partial t} = R(r) \cdot \frac{\partial T}{\partial t} = R(r) \cdot T'(t)$$

And:

$$\frac{\partial^2 V}{\partial r^2} = T(t) \cdot R"(r)$$

Then we have:

$$T(t) \cdot R"(t) = \frac{1}{D} \cdot R(r) \cdot T'(t)$$

It can be rearranged into:

$$\frac{R"(r)}{R(r)} = \frac{1}{D} \cdot \frac{T'(t)}{T(t)}$$

Since the left side is only be r-dependent and the right side is only be t-dependent, and since they equal to each other, they must be neither r- or t- dependent. So, we have:

$$\frac{R"(r)}{R(r)} = \frac{1}{D} \cdot \frac{T'(t)}{T(t)} = -\lambda$$

Then we have:

$$R" + \lambda R = 0$$

And

$$T' + \lambda DT = 0$$

From the above equation, we have:

$$\frac{dT}{dt} = -\lambda DT$$

$$\frac{dT}{T} = -\lambda D \cdot dt$$

$$\int_0^t \frac{dT}{T} = -\lambda D \cdot \int_0^t dt$$

$$lnT(t) - lnT(0) = -\lambda Dt$$

$$T(t) = e^{-\lambda Dt} \cdot T(0)$$

For

$$R'' + \lambda R = 0$$

$$\frac{d^2R(r)}{dr^2} = -\lambda \cdot R(r)$$

$$R(r) = \mathrm{A}\cos\sqrt{\lambda}\cdot r + \mathrm{B}\sin\sqrt{\lambda}\cdot r$$

Now we have:

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

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

For brining (soaking) food with food starting with low concentration C_0 and surrounded at high concentration (bath concentration) C_h, we have the following boundary conditions:

$C(r,o) = C_0\ (0 \le r \le R)$, where R is the radius of the sphere.

$$C(\ge R,t) = C_h$$

We have:

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

We then have:

$$C(r,t) = C_h - \frac{2R(C_h - C_0)}{\pi\cdot r}\sum_{n=1}^{\infty}\left[\frac{(-1)^{n+1}}{n}\sin\frac{n\pi r}{R}\cdot e^{-Dn^2\pi^2 t/R^2}\right]$$

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

We define

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

Thus, we have:

$$C(r,t) = C_h - \frac{2R(C_h - C_0)}{\pi\cdot r}\sum_{n=1}^{\infty}\left[\frac{(-1)^{n+1}}{n}\sin\frac{n\pi r}{R}\cdot e^{-t/\tau}\right]$$

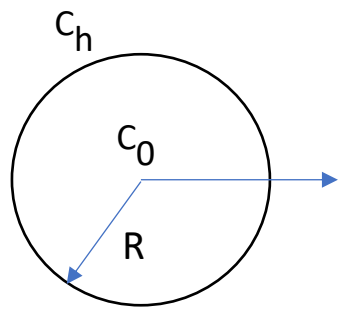


Fig. 3. The sphere configuration, with a radius of R, used in our calculation.

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

$$C_c = C_h - 2(C_h - C_0)\sum_{n=1}^{\infty}\left[(-1)^{n+1}\cdot e^{-t/\tau}\right]$$

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

$$C_c = C_h - 2(C_h - C_0)\left\{e^{-t/\tau} - e^{-4t/\tau} + e^{-9t/\tau} - e^{-16t/\tau} + e^{-25t/\tau} - e^{-36t/\tau} + e^{-49t/\tau} - \ldots\right\} \quad (1)$$

$$\text{Where: } \tau = \frac{R^2}{\pi^2 \cdot D}$$

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.

Results and discussions

Table 1 summarizes all the results of the measured salt diffusion coefficients for the 5 different types of food. Compared with the available data we can find in the published literature, [ ] the salt diffusion coefficient data we got are either in excellent agreement or have tighter uncertainty.

	Diffusion Coefficient (10^{-10} m^2/s) @ 20℃	
Food	**Low end value**	**High end value**
Potato	8.0	12.0
Pumpkin	11.0	13.0
Sweet potato	6.0	10.0
Taro	6.0	7.5
Radish	7.5	9.0

Table 1. 5 different types of foods along with their determined diffusion coefficient of salt. The data were determined based on fitting the measured salt concentration at the center of a spherical shaped food with the theoretical model with the diffusion coefficient as the fitting parameter.

Any potential measurement errors could come from the following factors.

(1) The salt concentration measurement error. Several factors may contribute to this error. One is the salt concentration measurement accuracy from the compact meter. The other comes from the sample preparation process since we had to cut off a small piece, about 1 mg of weight of the sample from the center of the spherical sample. The test result is actually an average of the sampled piece. The position accuracy could also introduce the error. However, the overall error is believed to be small based on the good repeatability and agreement between samples of the same type and samples with different radii.
(2) Any error comes from the brine process. In our simulation, we assume a uniformly environment which the sample sits in. The real situation may depend on the exact experimental condition and situation. However, we do not expect any error caused by this to be significant.
(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.

The error of the shape deviation from the perfect sphere. To analyze the impact of the shape deviation, we define a shape factor S. [32] Since the salt diffusion process is proportional to the surface area and the received salt per volume is inversely proportional to the total volume, thus the salt concentration in the center of the sample 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. We applied the following approximation and considerations for shapes which deviate from the ideal sphere.

Thus, our conclusion is that an approximate sphere with a small deviation from a perfect sphere only cause very minor impact to the final result.

Summary

5 different types of foods were studies and their diffusion coefficient of salt are experimentally determined with a simple and low-cost method. The foods which are studied include potato, sweet potato, pumpkin, taro, and radish. We pre-cut the foods into a spherical shape with known diameters and then brine them into the pre-mixed salt solution. After a certain soaking time, the ball-shaped piece is taken out and cut out a small piece from its center. A compact salt meter (LAQUAtwin-salt-11) made by Horiba was used to determine the salt concentration. The salt concentration at the center of the piece was measured as the diameter or the soaking time is used as variables. We then fit the measured data with the simulation. We are able to determine the following diffusion coefficient data with good matching between the measurement data and the simulation results. Furthermore, the diffusion coefficient of salt in potato was also measured at 100℃. The activation energy is thus determined to be around 74meV or 7.13 kJ/mol.

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