Osmosis in the Kitchen

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In culinary circles, the phenomenon of osmosis is sometimes given as an explanation for water transfers during culinary processes, but the mechanisms given are not always correct. As discussed here, cooking is not the sole field in which wrong descriptions of osmosis are given, so it is probably helpful to give some information on what osmosis really is and how it works. Here, we consider practical cases, and we conclude by discussing the possible mechanisms, as well as incorrect descriptions.

Osmosis and Semipermeable Membranes

In some textbooks, osmosis is explained using a U tube, with the two halves separated by a “semipermeable membrane”, i.e., a membrane that is said to be crossed by water but not by other molecules or ions, such as sodium or chloride ions (Figure 64.1). It is often said that “water moves from the compartment with solutes and water toward the other compartment” (Goubet, 2017) until an equilibrium is reached.

One early observer of osmosis in this kind of circumstances was the French clergyman and physicist Jean- Antoine Nollet (1700–1770): in 1748, using an animal bladder to separate chambers containing water and wine, he noted that the volume in the wine chamber increased and, if this chamber was closed, a pressure developed (Nollet, 1748).

However, the term “osmosis” was introduced only in 1826, under the two forms endosmosis and exosmosis, by the French physician and physiologist Henri Dutrochet (1776–1847): “Indeed, when the denser of the two fluids is in the cavity, water moves into it by the action that I called endosmosis; on the contrary, when the denser of the two fluids is outside the cavity, the less dense fluid inside is pushed outside by an opposite action that I shall call exosmosis” (Dutrochet, 1826). Dutrochet derived the term “osmosis” from the Greek ὀσµός, impulse.

Later, other scientists such as the British chemist Thomas Graham (1805–1869) and the German plant physiologist Wilhelm Pfeffer (1845–1920) created more resistant artificial membranes (Wisniak, 2013) with which they could study the phenomenon: Graham made them from rubber, and Pfeffer made them in the walls of an unglazed porcelain vessel by reacting copper salts with potassium ferrocyanide to form a copper ferrocyanide precipitate membrane on the surface of the vessel. Pfeffer used this membrane to separate a sucrose solution inside the vessel from water outside, and he found that water flowed from the water side to the sucrose side. He observed that the flow was proportional to the sucrose concentration; furthermore, a pressure applied inside the vessel produced a filtration flow proportional to the pressure. Pfeffer defined osmotic pressure as the hydrostatic pressure necessary to stop osmotic flow across a barrier (e.g., a membrane) that is impermeable to the solute.

In 1887, the Dutch chemist Jacobus Henricus van’t Hoff used the experimental results of Pfeffer and others to postulate that, for dilute solutions, the osmotic pressure $\Pi$ is related to the solute concentration, establishing the law:

$$\Pi = \Delta c RT$$

(64.1)

where $\Delta c$ is the solute imbalance between reservoirs, $c$ the molar concentration of the solute (mol.m$^{-3}$), $T$ the absolute temperature (K) and $R$ the constant of ideal gases (8.31 J.mol$^{-1}$.K$^{-1}$). For example, for seawater (3%, w/w, sodium chloride) at 25 °C, the osmotic pressure is about 25 bars.

In the 19th century, the American physical chemist Josiah Willard Gibbs (Gibbs, 1875) calculated the osmotic equilibrium
using the chemical potential that he had just introduced, the chemical potential of the solution being equal to the chemical potential of pure water plus the potential energy of the water raised by osmosis. It is noteworthy to add that this thermodynamic treatment avoided any consideration of mechanisms; in particular, it needed no assumption about the “diaphragm”, i.e., the semipermeable membrane.

Of course, the scientific study of osmosis did not stop with this result: Marbach and Bocquet (2019) discussed recent results, in particular using molecular dynamics, for various cases.

Where Are These Semipermeable Membranes?
When does osmosis take place in the kitchen? Not always where it is said to be! For example, it is often proposed that salt (more or less pure sodium chloride) would draw the juices from grilled meat by osmosis, but is it true? And more precisely, how much of the mass decrease of the muscular tissue is really due to osmosis?

Experiments to study this question (see the chapter in this volume on salt and grilled meat) showed that the quantitative contribution to osmosis is probably much less than the effect of the disorganization of the collagenic tissue through heating, triggering a contraction of meat fibres, and juices being excluded.

Osmosis is also sometimes discussed for meat stock preparation, and, even more precisely, it was used as an argument for the wrong theory of “cooking by expansion” in public French culinary education; in stocks, water would have flowed into the meat by osmosis, but weighing the meat (Figure 64.2) is enough to demonstrate that, on the contrary, meat shrinks during cooking, again because of collagenic denaturation (This, 2008).

On the other hand, osmosis can be readily observed with the product obtained after putting a chicken egg (with its shell) in vinegar. First, the shell dissolves (effervescence is observed, carbon dioxide being produced during the reaction of calcium carbonate with acetic acid), so that an egg inside a soft membrane is obtained (Figure 64.3).

With this system, it is easy to experiment with osmosis in the kitchen; adding salt to the vinegar makes the egg shrink, whereas putting the egg in pure water makes it expand (reversibly).

For these two experiments with meat or egg, the question was primarily one of education, but osmosis can also be used practically when making fruits in syrup (Figure 64.4). The issue for this preparation is the shrinkage of the fruits (e.g., cherries, mirabelles, plums, etc.) in concentrated (high sucrose concentration) syrups, and their swelling and degradation in light (low concentration) syrups. Indeed, here again, the skin of the fruits acts as a semipermeable membrane separating the syrup outside and the sweet inside. Of course, the solution is to store the fruits in a syrup for which the osmotic pressure is zero, but how to make it?

In 1997, I proposed that fruits float at the surface of concentrated syrups, whereas they sediment in light syrups, because of the respective densities of the outer and the inner solution. This leads

![FIGURE 64.2](image1.png)

**FIGURE 64.2** In some culinary textbooks, it is claimed that meat stock should be made by putting meat in cold water, “otherwise juices cannot escape from the meat”, and sometimes, it is also stated that osmosis would be responsible for the “expansion” of meat during the process. A simple experiment of measuring the mass of two pieces of beef meat (Bos taurus, semitendinosus) having the same initial mass refutes this incorrect theory: the piece of meat put in cold water (blue crosses) lost less mass than the piece in hot water (red crosses) until about 150 minutes, after which time the masses of the two pieces were equal. Also, the volume of the pieces of meat was measured, and the decrease corresponded to the mass lost. In particular, regarding the topic of this chapter, no osmosis could be active enough against the meat shrinkage due to the contraction of the collagenic tissue.

![FIGURE 64.3](image2.png)

**FIGURE 64.3** When an egg is dipped in vinegar, the shell dissolves, and the egg can be observed inside a semipermeable membrane (in particular, the yolk can be observed, floating in the egg white, which demonstrates that, inside the egg, the yolk is always in the upper place, whatever the orientation of the egg). When the shell-deprived egg is put in pure water, or on the contrary, in a concentrated brine, it will expand or contract by osmosis, respectively.

![FIGURE 64.4](image3.png)

**FIGURE 64.4** When fruits such as plums are in a “light syrup” (aqueous solution with a low concentration of sucrose), they sediment; in contrast, they float when the concentration of sucrose is greater than inside the fruits (the effect of the kernel is weak). Storing the fruits in a syrup of the same osmotic force as the fruits avoids both shrinkage and expansion of the fruits.
to an obvious proposal: put the fruits in a concentrated syrup and add water until the fruits gently begin to descend.

Other Culinary Processes with Osmosis

Osmosis occurs along with other phenomena in many culinary processes. For example, storing zucchinis in salt is sometimes advised, for various reasons, but mainly for avoiding bitterness: for 30 minutes according to Montagné (1996); 1 hour according to Verboom (1880) and Comolly (2003), the latter adding that one-third of the weight is lost; for more than 2 hours according to Raymond (1887); for 24 hours according to Bonnechère (1904). These differences in culinary precisions are important, but what are the results?

We tested this “culinary precision” before extending the experiment to other fruits and vegetables. First, assuming that the soaking would take place primarily by the cut surfaces of the plant tissue, slices of various thicknesses were prepared (this assumption was tested later), soaked and weighed regularly (Figure 64.5).

It can be observed that the mass decreases first rapidly, for about 75 minutes, before stabilization. If the goal is to soak as rapidly as possible, 1 hour and a quarter is a better choice than 1 hour.

Of course, one could ask whether the size of salt crystals is important, but experiments with 1-cm thick slices covered with either fine or coarse culinary salt did not show any difference after 50 minutes of soaking (mass measurements were performed every 5 minutes). However, the maximum loss was reached 10 minutes earlier for fine salt.

Now, because we wanted to know whether the stabilization at about 75 minutes was the limit, we studied this specifically by burying slices in salt for many days. At the same time, we dipped slices of the same fruit in sugar, in vinegar or in flour. It appeared that soaking is faster and more efficient with sugar (60% in one week) than with salt (37–43% depending on the thickness). With vinegar (8% acetic acid), the loss was slightly lower than with salt, and with flour, it was almost nil.

In some other culinary books, the reason for soaking zucchinis in salt is not bitterness but oil absorption during frying (Mordelet, 1994). Soaking, here, is advised to last for 1 hour, but this time was challenged again, the main result of these experiments showing that soaking for 2 hours produced over-salted slices.

Coming back to muscular tissues, which are also made of cells, what about the same experiment as for zucchinis? Here, one has to take into consideration the anisotropy of the tissue, and results also depend on the collagenic content. In Figure 64.6, we show an example of the results for the muscular tissue obliquus internus, for which the intact fibres were parallel to the surface of the piece.

Mechanisms

Osmosis is not fully understood, and the mechanisms are still being discussed, because various cases have to be considered. Of course, these mechanisms depend on the particular solutions (ionic or not) and membranes, as has been apparent since the beginning of the scientific studies of osmosis, but other conditions can also be considered, such as the application of electric fields, for example.

There are many misconceptions about the mechanisms of osmosis, as discussed by Kil (1982), Stein (1986), Borg (2003), Kramer and Myers (2013) and Marbach and Bocquet (2019). Some theories are incorrect because they have a teleological flavour, such as when it is said that the water molecules move “in order to” dissolve the more concentrated solution: water molecules have no intention or goal – they just move at random. For some other theories, the defects are more subtle.

For example, Van’t Hoff suggested a physical explanation (Van’t Hoff, 1887; Meyer, 1890) in analogy with the kinetic gas theory, i.e., the theory considering that gases are made of molecules that collide according to the laws of mechanics; the pressure exerted against the walls of the container equals the total momentum transferred by the molecules colliding per unit time. Van’t Hoff proposed that, in a solution, the water molecules would move through the membrane, whereas the solute molecules would transfer their momentum to the membrane; only the impermeable solute molecules would account for the osmotic pressure (“bombardment hypothesis”) (Kil, 1982). However, it appeared that this theory had shortcomings, as the osmotic flow between solutions of identical hydrostatic pressure does not deform a membrane, whereas a similar flow induced by a hydrostatic pressure drop across the membrane causes bulging. The osmotic flow is therefore generated by a flow of water through the membrane, and not by the impact of solute molecules.

Another incorrect theory is that the volume occupied by the solute, at the aperture of any pore of the membrane, displaces some water molecules and thereby decreases the number of water molecules per unit volume; as a result, fewer water molecules arrive per unit volume at the pore from the side with

![FIGURE 64.5](attachment:figure_64_5.png) The mass of slices of zucchinis dipped in salt. Here, slices of different thicknesses (i.e., masses) were studied. The size of the dots corresponds to the standard deviation for three slices of the same mass.
higher solute concentration, and this should result in a net flux of water through the pore from lower to higher solute concentration. However, this was refuted by Paganelli and Stein, 1957; Stein, 1986), who measured the diffusive entry of tritiated water into red blood cells.

Borg (2003) discussed other incorrect theories and concluded that any mechanical description of osmosis has to go back to the very concept of pressure and its explanation in terms of the virial theorem; the solute-retardation mechanism could be used when looking for a simple but true explanation of osmosis. Manach and Bocquet (2020) reviewed recent developments on osmotic theories, and it would be both useless and impossible to summarize everything here; it can merely be observed that molecular simulations today have now become an efficient tool to explore osmosis. Direct simulations can be performed using two explicit reservoirs with difference of solute concentration. For example, such implementation was used by Kalra et al. (2003) in the study of osmosis across carbon nanotubes. Also, osmosis has been rationalized in more simple terms by simplifying the explicit membrane description to reduce it to a confining potential acting on the solute only (Yoshida et al., 2017).

Applications

Osmosis is widely used for various applications, but one of the most important is seawater desalination. Here, the particular osmosis performed is “reverse osmosis”, which relies on the very simple principle of applying an external large hydrostatic pressure to counterbalance the osmotic pressure difference and induce a flow of water towards the low-concentration side; the pressures involved are typically in the range of 30–50 bars in order to exceed the osmotic pressure.

In a different approach, forward osmosis (combined with thermal methods) makes use of draw solutions to counterbalance the salinity-induced osmotic pressure. Generating a high osmotic pressure, typically above the 30 bars of pressure between seawater and fresh water, requires draw solutes that are highly soluble in water and also of a sufficiently small size (hence, low molecular weight) (Marbach and Bocquet, 2019).

More applications are discussed in the chapter dealing with membrane filtration, as the fractionation of plant tissues is a process that can become important for producing the raw ingredients for note by note cooking (see the chapter on this in this book).

Conclusion

In the kitchen, many incorrect ideas about osmosis are transmitted by textbooks, and, on the other hand, there are many circumstances in which a liquid has to be concentrated (fond, demi-glace, glacé or sauces), or diluted (syrups or brines), or modified (sauces), and the full potential of osmotic techniques is still in its infancy. There is no doubt that the advent of membrane processes can be an asset for the future of cooking techniques.

REFERENCES

Bonnechère C. 1904. La cuisine du siècle, Brochard, Paris.


