TECHNICAL NOTE

Transient heat transfer in a boiled potato: a study related to food process engineering

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This paper examines the transient heat transfer within a potato while it is being cooked in boiling water. For spherically shaped potatoes it has been shown that for most of the heating process the potato behaves as a homogeneous conducting material whose temperature rise is satisfactorily described by Fourier's equation for transient conduction. Microscopic examination of the potato structure shows how, when its temperature rises above about 65°, the gelatinization and swelling of the starch granules cause mechanical disintegration of the tuber tissue. This process corresponds to the potato beginning to change from raw to cooked, and it also leads to a deviation from the theory of the ideal solid. It has been shown, for the variety of potato used, that for the center to cook before the outside overcooks the potato should have a maximum diameter of 40 mm.

Keywords: heat transfer; conduction; cooking; vegetable matter

Introduction

The analysis of transient conduction in an engineering context is often limited to materials which retain their physical and chemical properties during the heat transfer process and the associated change in temperatures. The changes in the thermal properties are usually accommodated by taking the mean values between the maximum and minimum temperatures involved. This paper considers the transient heat transfer through a substance whose physical structure also undergoes a change as a result of temperature. The substance that has been used is a potato which, of course, becomes cooked as its temperature rises. It would be fatuous to claim that a potato is an engineering material, but it is a substance with which everyone is familiar, as is the process of boiling potatoes before we eat them. Furthermore, not only are we familiar with boiled potatoes, but we are also familiar with potatoes having hard uncooked centers or "falling" surfaces. What happens to a potato when it cooks? How does the heat penetrate the potato? And how big should a potato be for it to cook evenly throughout so that the center is cooked before the outside is overcooked? These questions are addressed and answered in this paper while at the same time a detailed study is made of the heat transfer mechanism involved.

The effect of temperature on potato tissue

To limit the experimental variables, the study was confined to one variety of potato. Although it is recognized that different varieties of potato behave differently on cooking, the results and observations made using the one variety will nevertheless be generally applicable.

It was necessary to establish what happens to a potato as it changes from a raw to a cooked state and to investigate the criteria which define when a potato is cooked and overcooked. The former was investigated by heating slices of potato, approximately 1 mm thick, in a pan of water from ambient up to 100°C, and removing a slice at each 5°C temperature rise. On reaching 100°C, heating was continued and thereafter slices were removed at time intervals of 1 min. Samples taken from the removed slices were microscopically examined and compared; changes were photographed with a Leitz Metalloplan large field microscope. It was found that at about 65°C the cellular structure of the potato changed visibly. Figure 1 shows the potato structure before this temperature. The photograph shows the potato cells containing granules of starch. Talburt and Smith[1] found that at temperatures above 50°C, water passes from the nonstarchy parts of the potato cell into the starch granules which, as a result, begin to swell. Beyond about 65°C the starch begins to gelatinize. The extent of the swelling of the starch granules renders visual differentiation between them and the cell walls difficult, giving the illusion in Figure 2 that the starch granules have disappeared. The swelling also causes rupture of the cell walls, allowing starch to escape from the cell. This phenomenon gives cooked potatoes their familiar waxy texture.

This change in structure, however, is not the only requirement which the potato has to satisfy before it is cooked. A second experiment was conducted similar to that with the thin slices but using small cubes of potato, approximately 1 cm^3. On removal from the water the pieces were bitten into to confirm the state of the potato tissue, i.e., uncooked, cooked, or overcooked, albeit on a subjective basis, but after all the palate is the final adjudicator. It was found that the potato matter had to be brought to a temperature of 100°C and kept there for between 4 and 16 mins. Before this time the potato was uncooked, and after this range the potato was overcooked, i.e., "powdery." It is necessary to continue heating beyond the point where the starch granules gelatinize, since at this stage the potato is still hard, and continual heating causes mechanical disintegration of the tuber tissue as a result of cell separation, thereby leading to a marked decrease in the tensile strength of the potato matter.[1] This process appears to be sufficiently advanced after the potato has been at 100°C for 4 min, whereas after 16 min the effect is to render the potato too weak to hold itself together.

Heat transfer in the potato

In order to impose some symmetry on the heat transfer and to allow the process to be modeled conveniently, the potatoes were shaped to be approximately spherical. Several diameters of each potato were measured, and a volumetric mean diameter was calculated:

$$d=\left\{\frac{1}{n}\sum_{i=1}^{n} d_i^3\right\}^{1/3} \tag{1}$$

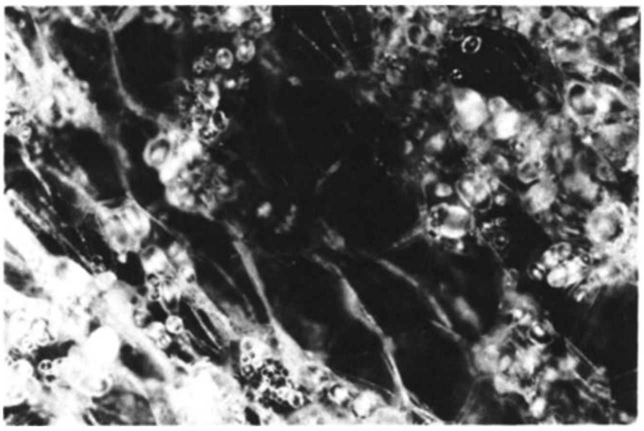

Figure 1 Potato tissue before gelatinization showing small starch granules within the potato cell (below 65°C)

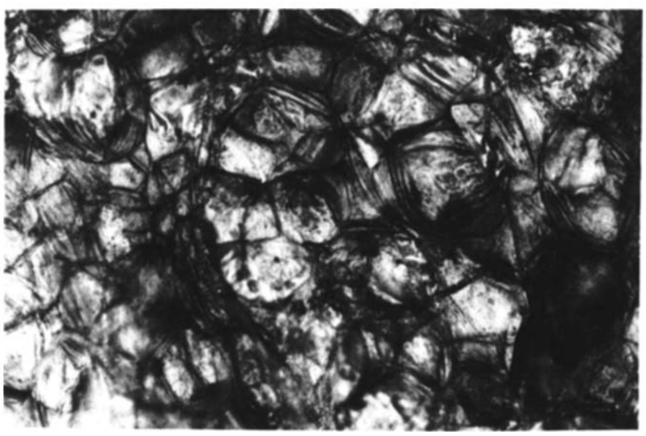

Figure 2 Cell structure after heating (above 70°C)

The simplest situation for investigation is that described by Fourier's equation for three-dimensional transient conduction when the surface temperature is subjected to a step change. In the present context the potatoes at ambient temperatures were plunged into water boiling violently at 100°C. Although this is not an accepted method of cooking potatoes (for reasons which will be discussed later), it will show whether or not the potato behaves as a homogeneous substance as far as conductive heat transfer is concerned. The center temperature of a sphere subjected to a sudden change of surface temperature is given[2] as a function of time by

$$T_c=\frac{rT_s}{(\pi\alpha t)^{1/2}}\sum_{n=1}^{\infty}\exp\left[-\frac{(2n+1)^2r^2}{4\alpha t}\right] \tag{2}$$

The center temperature of each potato was measured experimentally by a carefully inserted copper-constantan thermocouple. It was important that the thermocouple fit tightly to ensure that it remained in place and to prevent excess water from penetrating the potato. A thin stainless steel tube was used to bore a small circular hole into the potato. The thermocouple was encased in a thin PVC tube, which fitted tightly in the bored hole. The thermocouples were connected to a microcomputer-controlled data logger. The temperature measurements are shown, together with the theoretical values, in Figure 3. By aligning the theoretical and experimental results, it was possible to deduce a value of thermal diffusivity of potato matter, which turned out to be $1.7\times10^{-7}\,m^2/s$. It can be seen from Figure 3 that the different experimental data collapse into a single curve, which follows closely the form of the theoretical prediction.

The heat transfer into a potato which is placed into ambient water and brought to the boil can be partly described by considering the theoretical value for the center temperature of a sphere exposed to a linearly changing surface temperature. This is given[2] by

$$T_c=k\left[t-\frac{r^2}{6\alpha}\right]-\frac{2kr^2}{\alpha\pi^2}\sum_{n=1}^{\infty}\frac{(-1)^n}{n^2}\exp\left[-\frac{\alpha n^2\pi^2 t}{r^2}\right] \tag{3}$$

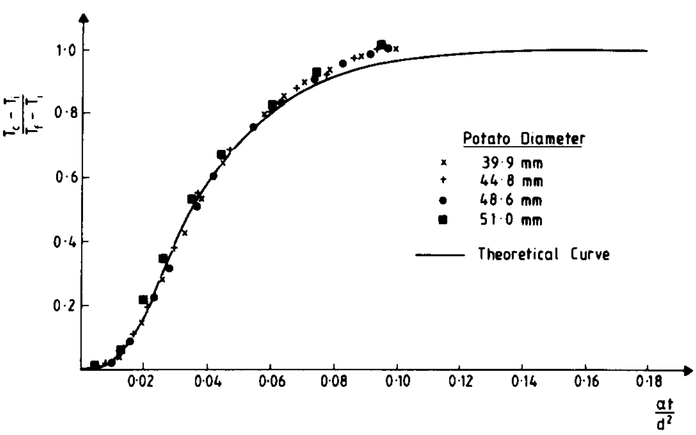

Figure 3 Change in center temperature of potato when plunged into boiling water

Notation

d	Potato mean diameter
k	Constant rate of temperature rise
r	Radius of sphere
T_c	Center temperature
T_f	Final center temperature
T_i	Initial center temperature
T_s	Surface temperature
t	Time
α	Mean thermal diffusivity

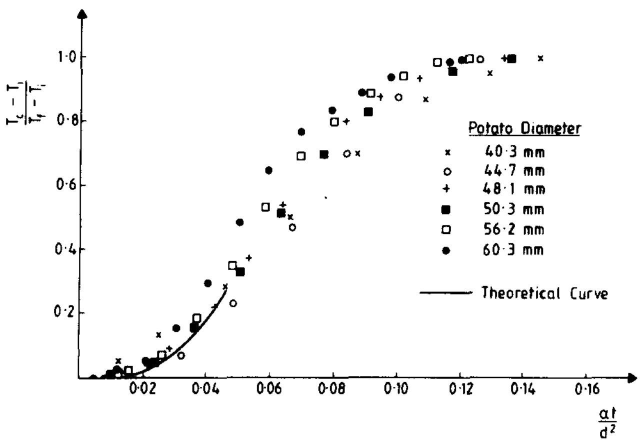

Figure 4 Change in center temperature of potato when heated in water from ambient

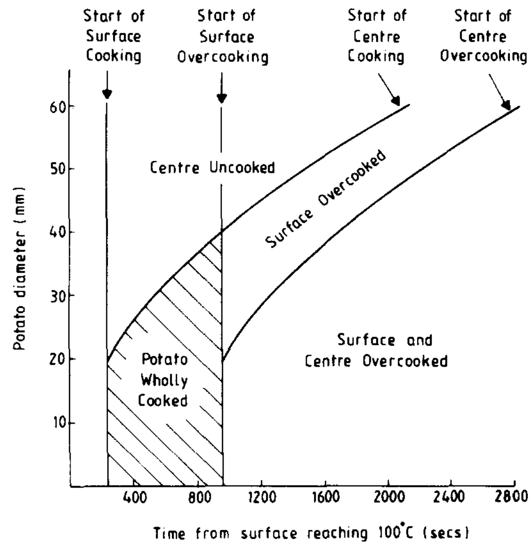

Figure 5 Cooking times for different size potatoes

The usefulness of this equation is limited, since it holds only for the period during which the water temperature is rising. Nevertheless, it is shown over this range together with the experimental data in Figure 4. During these experiments the rate of temperature rise of the water (i.e., k in Equation 3) was kept constant. It can be seen that the data again collapse although not as cleanly as before. The additional scatter is probably because the convective heat transfer to the potato in the subcooled water is more likley to vary than in the case of the boiling water.

Criteria for cooking

It was shown earlier that potato tissue has to be heated up to 100°C and kept at that temperature for between 4 and 16 mins. The part of the potato which responds last to the heating is, of course, the center. It is therefore necessary to heat the center up to 100°C and keep it there for 4 min. Meanwhile, the time at which the surface has been at 100°C must not exceed 16 min. Taking these criteria in conjunction with Figure 3, it is possible to construct Figure 5, which relates the size of potatoes to the cooking times. The result is that if a potato diameter is greater than 40 mm the outside will overcook before the center has been at 100°C for 4 min.

If the potatoes are cooked by plunging them into boiling water and applying the same criteria as above, then for the potato center to be at 100°C for the necessary 4 min it must reach that temperature within 12 min of being immersed. Otherwise, the potato surface will be at 100°C for longer than 16 min. It can be deduced from Figure 4 that the maximum potato diameter which satisfies these conditions is about 30 mm.

Discussion and concluding remarks

It can be seen from Figure 3 that for temperatures up to about 70°C the experimental data agree well with Fourier's equation for transient conduction in a sphere. Above this temperature, however, the theory and experiment begin to deviate slightly. The reason that the theoretical curve for the center temperature asymptotes as it does to the final temperature is that the temperature gradient near the center of the sphere approaches zero, and it follows that the heat transfer also approaches zero. Any mechanism, therefore, that can influence the temperature gradient near the center, however small, will have a noticeable effect. As was observed earlier, above about 70°C the potato cells can rupture and the tissue begins to mechanically weaken. This will allow the fluid in and around the cells to add to the heat transfer by small-scale local convection. It is possible that this is the reason for the observed deviation from the theory. Notwithstanding this, however, the experiment and the theory agree rather well.

During the experimental study, potatoes were occasionally removed from the boiling water, cut in half, and quenched in iced water to prevent further cooking. The thermal penetration into the potato was clearly indicated by a "cooking front," behind which starch gelatinization could be seen clearly and ahead of which the tissue was still raw. Brushing the cut face with iodine (starch indicator) emphasized the features.

The value of $1.7 \times 10^{-7}\,m^2/s$, which was deduced for the thermal diffusivity of the potato matter, is reasonably close to the value of $1.55 \times 10^{-7}\,m^2/s$ for water over the same temperature range. This similarity is what might have been expected since vegetable matter is largely made up of water.

It appears that potatoes can be cooked satisfactorily by plunging them into boiling water provided that their diameters are less than 30 mm, which is rather small. There is no point, however, in bringing the water to boil separately and then putting the potatoes in when they can be put into cold tap water and everything brought to the boil together.

Although potatoes are not usually shaped carefully into spheres as was done in this experiment, it is not difficult to visualize an "equivalent diameter" when cutting potatoes in the kitchen. The results of the study will not therefore surprise many cooks, who have always cut their potatoes to be about 40 mm across, brought them to boil, and simmered them for about 15 min. If larger potatoes are used, then clearly they have to be cooked longer. For example, a 45-mm potato will need to be boiled for 20 min (from Figure 5). In that time, however, the outside of the potato will have begun to break up.

References

1 Talburt, W. F. and Smith, O. *Potato Processing*. VL Publishing, 1959
2 Carslaw, H. S. and Jaeger, J. C. *Conduction of Heat in Solids*. 2nd ed. Oxford University Press, 1980