Chapter 11
French Bread Baking

Alain Sommier, Yannick Anguy, Imen Douiri, and Elisabeth Dumoulin

11.1 Introduction

Bread has been a basic foodstuff for thousands of years.

Before discovering how to make bread, man ate cereals in the form of a paste and then as small cakes. The Egyptians and the Babylonians knew how to use yeast and to apply bread-making techniques. The Greeks improved the bread maker's art and spread it throughout their conquests.

Although wheat was harvested in China, in the Middle East, and in Egypt several thousands of years BC, the people used to eat bread made from rye, buckwheat, and maslin (a mixture of wheat and rye). It was only in the nineteenth century that the production of bread made from wheat flour developed in Europe using yeast.

Although bread consumption in France fell considerably in the twentieth century, it has recently started to increase once more due mainly to the diversity of products available to consumers.

The production of bread requires energy, time, and a very precise dexterity. Only a few simple ingredients are used. The bread maker seems to be a kind of magician (Fig. 11.1).

Here, we describe briefly its current state of the art and then present the materials used and the methods of measurement. We highlight the links between the kinetics of mass loss from a French loaf of bread, the variation in the relative humidity of the air as it comes out of the oven, and the thickness of the product, which is linked with the internal pressure.

A. Sommier (✉) • Y. Anguy
I2M-TREFLE UMR CNRS 5295, Esplanade des Arts et Métiers,
Talence Cedex 33405, France
e-mail: a.sommier@i2m.u-bordeaux1.fr

I. Douiri • E. Dumoulin
AgroParisTech-site de MASSY, Avenue des Olympiades, Massy Cedex 91744, France

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Fig. 11.1 Different types of French bread

11.2 Technology of Bread Production

Bread is the result of very complex physical transformations, chemical reactions, and biological activity that occur within a mixture of flour, water, salt, and yeast (only *Saccharomyces cerevisiae* yeast is used) and sometimes a few other ingredients (Feillet 2000) (ascorbic acid, bean flour, exogenous enzymes, emulsifiers, etc.), with the controlled addition of mechanical and heat energy. The exact formula differs, depending on the type of bread; traditional bread contains no sugar, milk, or fat. Traditional French bread has the "pain de tradition française" appellation, created in an article of the Bread Decree of 1993. It is produced by baking a dough which contains no additives and which has undergone no freezing during production (Feillet 2000). French bread typically has a thin, golden crust which is shiny and crisp (Roussel and Chiron 2002) unlike the white bread that is called "English bread" (with no crust, dense in texture, and which is baked in a mold).

Bread making takes about 5 h and consists of the following stages:

11.2.1 Kneading in the Mixer

This carries out two essential functions: it ensures that the dough mixture is homogenous (with flour, water, yeast, and salt), smooth, firm, and viscoelastic based on the two main constituents, flour and water, and it incorporates tiny air pockets into the dough whose walls become impermeable to gas to a certain extent, and it is from these that the cell structure of the bread will develop. In addition, fermentable sugars start to be released which enable the yeasts to multiply and grow later in the process.

The dough is subjected to intense forces of stretching, compression, and shearing, depending on the geometry of the constituent parts of the mixer, the size and shape of the blades, the speed at which they rotate, and also the rheological properties of the dough (Feillet 2000).

If mechanical kneading is carried out, this consists of two phases:

- **Mixing** the ingredients at a first speed (40 rev/min) for 3–5 min.
- **Working** the dough, and for a better result this is carried out at a higher speed (80 rev/min). Hydration continues, the dough is worked (blade), and the gluten is stretched and softened. The components bind together even further and the dough becomes smooth, elastic, and supple.

Thanks to the rapid mixing, air is incorporated into the dough, which gradually comes away from the sides of the mixer bowl, and becomes smooth, dry, and elastic (Guinet 1982) (Fig. 11.2).

Finally, 5 min before the end of kneading, salt is added to firm up the gluten structure and hold the shape of the dough better. When salt is added at the end of the kneading stage, this whitens the dough and hence the bread (Guinet 1982); it also helps tighten the gluten structure.

11.2.2 Tank Fermentation

This technique (duration, temperature, phases of resting the dough, hygrometry of the proofer) has evolved in order to simplify the work of the baker (Feillet 2000). The total time that the dough ferments (from 2 h 30 min to 5 h) is divided into several stages based on transforming the kneaded dough into small units of a given shape.

Fig. 11.2 Dough obtained at the end of the kneading process, with a smooth and flexible structure that can form a veil-like film once the gluten network is in place

There are generally considered to be three distinct phases; the first phase of fermentation is the **first rise** which starts when the yeast is added to the dough and lasts until the dough is divided up. The aim of this stage is to allow the fermentation agent the time needed to adapt to the environment and produce the carbon dioxide necessary for the dough to rise, ethyl alcohol, and a number of other products from the breakdown of sugars.

11.2.3 Weighing, Dividing, Shaping, and Resting

The dough is divided into regular individual pieces by weight (Fig. 11.3a).

Forming into balls (Fig. 11.3b) is optional, depending on the baker or regional customs, and it may consist of gentle handling or it may be more energetic kneading. This is a restructuring action to firm up the dough and consists of turning the ball around on itself, to give it a fairly regular round shape (Guinet 1982).

The second phase of fermentation is **resting**, which follows dividing and precedes shaping. This gives the dough time to relax and prepares it to pass to the shaping stage.

11.2.4 Shaping

Shaping gives the dough the form of the finished product (Fig. 11.3c) (Guinet 1982). Finally, the third and last phase of fermentation or gas retention will take place in a climate control proofer at 27 °C and 85 %RH. This stage is called the **final proof** and during this stage the dough piece will expand with the force of the gas from the fermentation process. The gluten network stretches and forms gas-filled pockets of varying sizes depending on the bread-making method. This is the final fermentation phase: this determines the future volume of the bread.

Fig. 11.3 (**a**) Division of the dough, (**b**) forming into balls, (**c**) dough is shaped before being placed in the proofer for the fermentation stage

11.2.5 Baking

During this last operation, the fermented dough is transformed into bread as a result of the effect of heat. It is the result of a heat exchange between the oven and the product being baked and consists of the expansion and physicochemical transformation of the dough. These changes ensure the bread's organoleptic and preservation qualities (Roussel and Chiron 2002). We describe this stage, which is crucial in order to obtain a quality product.

11.3 Baking in Ovens

11.3.1 Description of the Ovens

While remaining true to its traditional origins, the oven has undergone various modifications through the centuries and has contributed to changing the quality of bread. It has adapted to the different types of bread devised by the baker and offered to consumers.

Whether it is old or more recent, an oven is always made up of the following parts (Roussel and Chiron 2002):

- The cement or metal **housing** with one or several **baking chambers**: the bottom or the "sole" and the top or the "vault." They contain outlets to evacuate water vapor and/or flue gases.

The soles are made of natural stone or mineral elements with refractory cements. The thickness of the soles, 2–3 cm, determines the time it takes for the ovens to get up to temperature and whether or not there are temperature peaks.

In modern "convection" ovens, the baking chamber consists of a compartment into which the trolley(s) is introduced.

- The **burner**, where combustion occurs, is the heat source.
- **Insulation** is made up of a variety of materials (glass wool, sand, fire clay, etc.).
- There may be various **accessories**: boiler, steam device, chimney, pyrometer, and thermostat.

There are traditionally two categories of oven:

- Direct combustion ovens: the burner and the products to be baked are in the same chamber.
- Indirect combustion ovens: the heat source heats up an intermediate fluid (water vapor or air), which carries the heat to the baking chamber.

In each case, there are different types of oven:

- The sole may be fixed or mobile.
- Heating may be by combustion or by electrical resistance.
- There may be different heat transfer methods.

11.3.2 Baking

11.3.2.1 Loading

The end of the final proof marks the beginning of the loading phase. This consists of taking the products out of the proofer when fermentation is complete and placing them on a conveyor belt or oven peel, without damaging the dough pieces. The pieces have previously been scored using a knife blade (or **scarification**), where an incision is made on the surface. The purpose is to reduce the dough's resistance and thus facilitate expansion at the beginning of the baking process. If there is no scoring, then this can lead to a high pressure buildup in the dough, which may restrict expansion and also create uneven shapes (e.g., bursting) in some less-resistant areas. The slits channel the force of the gas toward the cut areas and also improve the aesthetic appearance of the product (Roussel and Chiron 2002).

11.3.2.2 The Role of Steam

Before and/or after loading the products, steam is injected into the oven. This condenses on the surface of the dough pieces, forming a thin film of water, which softens the dough, helping the carbon dioxide to expand and the pieces to rise. For a short time, this film of water protects the surface of the dough pieces against the effects of heat and delays the formation of the crust, which is thus reduced in thickness. In addition, it helps reactions, which color the bread crust, giving it a golden yellow color and a shiny appearance. Without the steam, the bread is dull and the surface is rough.

Finally, the steam also limits evaporation of the water in the dough to some extent, thus improving the production yield (Guinet 1982). If baking is done without steam, there may be a lot of cavities in the crust associated with the porosity of the crumb, which thus forms a series of chimneys through which the water vapor in the dough can escape (Fig. 11.4a). In Fig. 11.4b steam injection helps to close the porosity of the dough. Condensation happens at the surface of the bread immediately (loading at 27 °C) where the starch grains then have an excess of water and swell rapidly, which tends to fill in/close up the cells that were originally in contact with air. This closed porosity in the crust (away from areas of scoring) then limits steam transfer between the very moist crumb and the baking chamber by acting as a barrier.

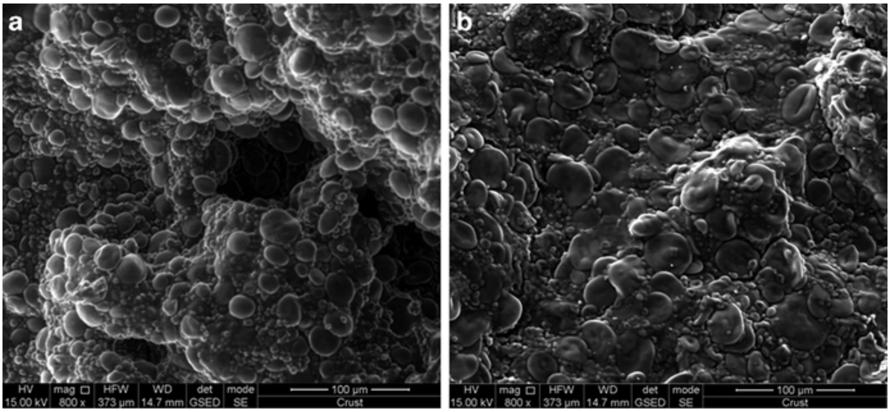


Fig. 11.4 SEM image of bread dough crust (×400). (**a**) Crust baked without steam, many cavities. (**b**) Crust has smoother appearance when baked with steam injection + starch grains are larger

11.3.3 Baking Conditions

11.3.3.1 Baking Temperature

This depends on the mass of the dough pieces to be baked, the level of color, the stability of the dough, and its level of hydration.

If the oven is too hot, the dough is browned, the crust forms more quickly, the bread is less able to rise, and the slits are more irregular. Since the color reactions occur earlier, the product has to be taken out of the oven earlier, so the bread is moister; this is a way of increasing yield.

If the oven temperature is too low, even if the crust is formed at a later stage, expansion is also hindered because the gases expand less; the bread has a tendency to extend outward and thus has a flatter cross section, and the slits are more torn. Problems with color often require a longer cooking time, resulting in the top part drying out, a drop in yield, and also a thicker crust.

In industrial ovens, with the possibility of regulating temperature at the top and bottom and at different levels between the products going into the oven and coming out, baking conditions are flexible and can be optimized. As a general rule:

- When the sole is at a higher temperature at the beginning of baking, this promotes expansion, which then decreases.
- The temperature in the vault increases gradually so that the crust does not form too rapidly and the level of color is set at the end of the baking process (Roussel and Chiron 2002).

11.3.3.2 Baking Time

This varies according to the mass, the shape, and the type of bread. However, it is generally accepted that it takes 1 h to bake 2-kg loaves and half an hour for 500-g loaves. Baking is assessed according to the degree of resistance and the color of the crust and the resonance of the base of the loaf when tapped with a finger (Ammann 1925).

11.3.4 Changes in the Dough During Baking

When the dough pieces are put into the oven, the outside, the part that will form the crust, is subjected to a high temperature. Inside, in the part that will form the crumb, the heat is transmitted slowly.

11.3.4.1 In the Crust

The water that evaporates from the crust via the surface prevents the surface temperature from rising above about 100 °C which in turn prevents a real crust from forming. There is only a film of crust. By releasing the water vapor, this limits heat penetration into the loaf (Guinet 1982). The layer of water that is deposited on the bread, or that covers the bread, transforms the starch into soluble starch and dextrin, which gives the crust its beautiful golden color. The crust dries out by gradually solidifying as the temperature at the surface of the bread comes closer to that of the oven: there is almost total desiccation of all the outside parts of the bread; next the gluten browns, and the starch itself can begin to be roasted. This phenomenon occurs more deeply into the mass of the bread the higher the oven temperature, and we obtain a crust that is fairly thick, cracked, and fairly dark in color.

11.3.4.2 In the Crumb

Inside the bread, the temperature rises gradually: the volume of the bread increases quickly as the gases in the cells dilate and then more gradually due to the acceleration of fermentation until the yeasts are rendered inactive by the heat (at about 55 °C). At the same time, amylolysis continues at a faster rate, and then this also stops but a little later as amylases are not destroyed until about 70 °C. During amylolysis, the stiffening of the starch and/or gelatinization starts at about 55 °C. This phenomenon comes to an end at about 83 °C. The gluten starts to coagulate around 70 °C and continues until about 100 °C. This is the end of changes inside the oven as the glutinous structure is now "set."

Above 70 °C there can be considerable dilation of the cells filled with air which is saturated with water vapor. At the end of baking, water evaporation can cause a final expansion (100 °C) even though the crumb is starting to set (Sommier et al. 2005). The alcohol formed during fermentation vaporizes in the ambient air.

Experiments carried out by Zanoni et al. (1993) show that the variation in temperature and water content during bread baking is determined by the formation of a vaporization front at 100 °C. As this front gradually advances into the product, the result is that two distinct zones are formed: the crust, where the water content is very low and the temperature tends asymptotically toward the oven temperature, and the crumb, where the water content is constant and the temperature tends asymptotically toward 100 °C. This result was previously found by Pyler (1973) (cited by Yin and Walker 1995) who confirmed this and found that the temperature of the crumb cannot reach the boiling temperature of water because the amount of heat evacuated as the water evaporates is greater than that absorbed by the crumb.

On the other hand, after carrying out experiments on German bread, Seibel (1984) believed that to obtain a good quality of bread at the end of the baking process, the temperature of the crust has to reach up to 102–105 °C.

11.3.4.3 Expansion in Volume

The expansion of the volume of the dough, which starts in the first minutes after being placed in the oven, is estimated to be one third of its original size (Pyler 1973). Although this phenomenon is generally attributed to the effect of heat penetration, it is currently considered to be the result of a series of reactions.

One of the physical effects of heat on a gas is to increase its pressure. If it is in an elastic compartment, then we observe that it expands in volume. Another physical effect of heat is to reduce the solubility of gases. A large amount of carbon dioxide formed during fermentation is present in solution in the liquid that makes up the dough. When the dough temperature reaches 49 °C, the CO_2 in solution is released, causing the pressure inside the dough to increase. Another effect of the heat is to transform liquids with a low boiling point into vapor. Thus, the alcohols present in the dough evaporate at 79 °C and also contribute to increasing pressure inside the dough.

11.4 Microscopic and Macroscopic Approach to Bread Baking

In this example we use the following ingredients to produce the bread: flour, yeast, water, and salt. The flour and yeast are kept at 4 °C. A summary of the procedure is shown in Table 11.1, which gives the detailed formula and the equipment and the time required for the mixing and shaping operations. Before the bread is placed in the oven, a single slit is cut into the surface lengthways. The dough piece is placed directly onto the sole of the oven.

Table 11.1 Summary of standard conditions used

Formula	1.5-kg Corde Noire special flour
	945 g demineralized water (63 %)
	37.5-g yeast (2.5 %) CAPPA
	33-g salt (added 5 min before kneading complete) (2.2 %)
Kneading with Artofex mixer	4 min at speed 1 (50 rpm)
	17 min at speed 2 (70 rpm)
First rise	20 min at 27 °C and 85 % RH
Division and molding	10 min. 7–10 portions of 250 or 350 g
Resting	20 min at ambient temperature
Shaping	10 min
Fermentation or final proof	1 h 30 min at 27 °C and 85 %RH
Baking	27 min (sole 250–260 °C, vault 235–245 °C)

Fig. 11.5 Baking without steam at Tsole = 260 °C, Tvault = 245 °C at five observation times (1, 4, 6, 8, 27 min)

As soon as the dough is loaded into the oven, the baker injects steam (for a few seconds), which condenses on the surface of the product (the dough pieces leaving the proofing chamber at 27 °C). This deposited water then acts as a plasticizer and facilitates the distortion of the product macroscopically, which gives rise to a considerable increase in mass (Sommier and Douiri 2006). In microscopic terms, for very short time the starch grains have an excess of water, and this, combined with the heat given off by the vapor (enthalpy of vaporization), causes them to swell, and this dilation closes up the orifices of the cell structure, transforming the surface into a continuous film (Fig. 11.4a, b). The dough piece then becomes a closed cell network (apart from the scored area), which limits the phenomena of mass loss by evaporation.

Because of the reactions that it produces, steam injection is the reason for one of the organoleptic characteristics typical of French bread, i.e., a thin, crisp, golden crust. If there is no steam injection, this will result in a lesser increase in volume (absence of plasticizer) and a more rapid drying out of the product surface, leading to a thick and crunchy brown crust (cf. Figs. 11.5 and 11.6 at $t = 27$ min).

In Figs. 11.5 and 11.6, we can compare two different types of baking carried out in similar thermal conditions with the same temperatures for the sole (260 °C) and the vault (245 °C) in the same oven, both without (Fig. 11.5) and with (Fig. 11.6) steam injection. With steam injection, the product expands more quickly. Its surface

Fig. 11.6 Baking with steam at Tsole = 260 °C, Tvault = 245 °C at five observation times (1, 4, 6, 8, 27 min)

dehydrates less quickly, slowing the formation of the crust, which means that its volume can continue to increase. This product reaches its maximum volume at $t = 8$ min, whereas the product without steam sets more quickly in the areas that are not very moist (to the right and the left). The crust forms quickly, thus setting/locking the structure and preventing it from increasing in volume any further. The dough piece expands only around the moist area where the knife blade was used to score the surface; maximum volume is reached at 6 min.

At the same time, inside the product, heat transfers have a direct influence on transfers of matter, and at the heart of the product, there is still a core of dough that evolves as the product expands (cf. Fig. 11.10).

This doughy core remains cold, while the surface temperature increases rapidly, thus leading to a gradual transformation of the dough into crumb, from the outside walls toward the core of the product. The initial water content of the dough is fairly uniform (when it is placed in the oven), and this is subjected to successive waves of evaporation and condensation at the level of each pore. As evaporation takes place in the hottest cell wall (i.e., close to the surface), vapor circulates through the cell network at great speed before condensing on a cold cell wall.

As Wagner et al. (2007) have shown, we then see variations in the water content in the product. The dough core becomes the area where the water content is not only greatest but also higher than the mean water content of the product at the beginning of baking.

At the same time, the product expands rapidly, the cells dilate, the cell walls become thinner and tear, and we observe that the pockets coalesce, forming a foam which has a greater porosity. The original scoring ruptures, exposing the cell network to the air; maximum volume is reached after 8–10 min (Fig. 11.6) and the porous network is now opened up. This phenomenon can be clearly seen in Fig. 11.7 where the increase in the internal pressure of the product causes the structure to expand in the first few moments, but after 10 min, although the pressure continues to increase, this is no longer sufficient to expand the product, which still remains moldable: even though it is under pressure, the structure starts to sag (collapse also visible in Fig. 11.10).

Figure 11.8 shows a piece of bread crumb (after baking) imaged using X-ray computerized tomography. At the spatial scale and resolution (30 µm/*voxel*) assumed in Fig. 11.8, the porous space of the crumb is clearly irregular and heterogeneous (as opposed to sandwich loaf). The large disparity in the size of air cells expresses mainly the bread-making stages prior to the baking step, namely, the fermentation and the shaping technique. As shown in the higher resolution Fig. 11.9

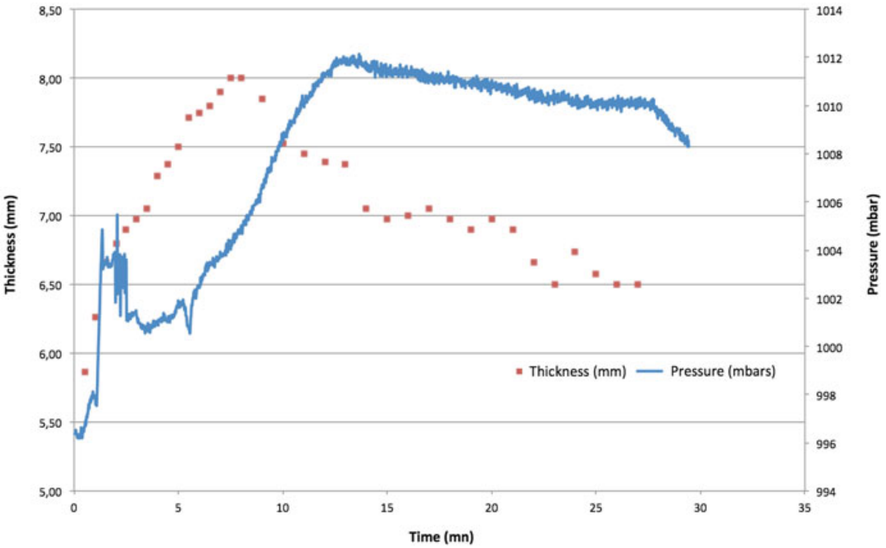
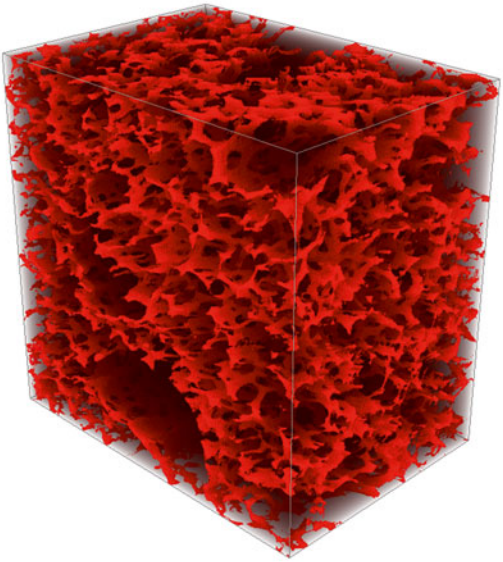


Fig. 11.7 Example of typical variation of internal pressure and thickness of bread during baking

Fig. 11.8 3D tomography image of a sample of bread crumb (in *red*). The porosity cells are transparent. Image size is 630 × 630 × 440 *voxels* , i.e., 18.9 × 18.9 × 13.2 mm. Spatial resolution: 30 µm per *voxel* (a *voxel* is the 3D counterpart of a 2D TV pixel). Porosity is 93 %



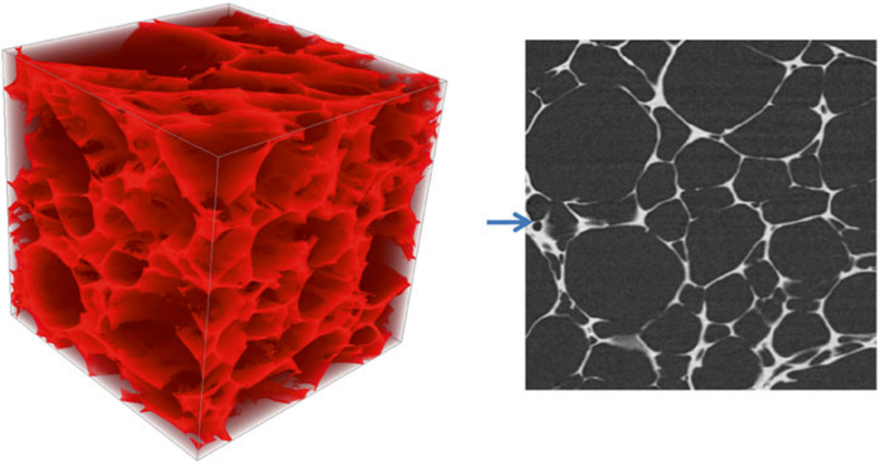


Fig. 11.9 (*Left view*) 3D tomography image of a sample of bread at a higher spatial resolution of 12 µm/*voxel*. Image size is 550×550×500 *voxels*, i.e., 7.5×7.5×7.5 mm. Porosity is 89 %. (*Right view*) 2D section taken from the 3D image (*left view*). The *arrow* shows a closed bubble of porosity (whose diameter is about 180 µm) trapped in a local zone where the crumb is thicker and denser. In this display, *light gray* levels represent the crumb

(12 µm/*voxel*), the working and shaping of the dough by hand can result in a marked elongation of the air cells along a preferential direction: see in Fig. 11.9 how the cells are stretched in a horizontal plane. In Figs. 11.8 and 11.9, it can be seen clearly that most of the air cells are connected, forming a continuous and open network bounded by very thin cell walls. Yet, the higher spatial resolution that typifies (Fig. 11.9) also stresses that *locally*, the crumb can be thicker and can include small *closed* air cells that remain disconnected from the main continuous porous network. This closed fraction of porosity represent *early times bubbles* whose expansion was blocked at some point of the process. In all respects, *the whole art of the baker is to ensure that this unwanted fraction of closed porosity remains small or negligible*.

The change in the water content in the product and the hygrometry of the air in the oven are of course not the only factors responsible for the expansion of the product. Minor ingredients in the product mass (such as yeast, starter, ascorbic acid), the mechanical energy used during kneading which can influence the quality of the gluten network, and the temperature of the dough at the end of kneading (which is itself closely linked with the initial temperature of each ingredient and with the intensity with which the dough is worked) are all levers with which to adjust/guide the final quality of the product in terms of flavor, volume, and uniform cell structure which are not the subject under discussion here. In the case of baking, it would seem more interesting to highlight the interaction between the product and the oven, looking especially at the temperatures used in the baking stage.

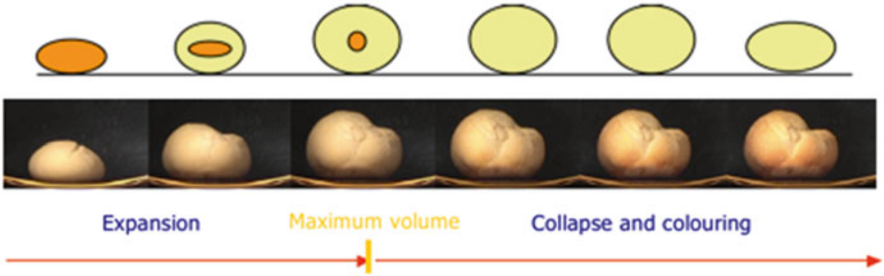


Fig. 11.10 Baking using steam injection at Tsole = 250 °C, Tvault = 235 °C at five observation times (1, 4, 6, 8, 27 min)

Figure 11.10 shows baking a dough piece with initial steam injection using the same experimental protocol as in Fig. 11.7 but with temperatures of 250 °C for the sole and 235 °C for the vault. The product appears to expand less rapidly than was the case in Fig. 11.6 (10 °C hotter), and the volume at 6 min is less. As we have seen, the temperature of the oven sole is one of the key factors in expansion for many cereal products. This heat input enables the gases held in the dough to dilate, which leads in turn to an increase in the internal pressure of the product and contributes to expansion. However, it is in competition with the coalescence of the cells which gradually form a network opening onto the outside via the only porous area in contact with the air in the oven and the initial scoring by the knife blade, which tends to extend and thus makes a large contribution to exposing the crumb to the air by promoting evaporation of the water in the form of steam (loss of mass). The second factor responsible for the acceleration in the loss of product mass is the increase in exchange surface area (direct consequence of the product increasing in volume). The expansion seen in Fig. 11.6 brings the upper part of the product closer to the heating elements, and thus the radiation received by the product is greater than in the case shown in Fig. 11.10, which accelerates the drying of the crust and therefore sets the structure and reduces the collapse phenomena that are more clearly visible when baking at a lower temperature.

Baking is therefore not only a tool used to set the structure of the product, but it is also clearly a means of guiding the final quality of the product in terms of expansion, color, or sensory perception. A thin, crisp crust that has also helped ensure that a higher water content is retained within the product will give the consumer a crumb that is softer and more aerated as it is less dense.

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