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Baking, Extrusion and Frying

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8.1

Baking Bread

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8.1.1

General Principles

Baking is a term commonly applied to the production of cereal-based products such as bread, biscuits, cakes, pizzas, etc., and in its English usage baking is generally applied to the production of fermented bread. Baking is at heart a process: the conversion of some relatively unpalatable ingredients (starch, gluten, bran, in the case of most cereals) into the aerated, open cell sponge structure we know as bread has taken millennia to develop. Bread is one of the oldest 'functional' or engineered foods, where the addition of bubbles of air by mixing and fermentation has created an entirely different product with considerably enhanced sensory properties. Historical records have been found in ancient Egyptian tomb carvings dating from 3000 BC, which show fermented bread being made from wheat flour and baked in clay ovens (see Fig. 8.1). The cultivation of wheat for breadmaking has played a key role in the development of modern civilization; and bread is one of the principal sources of nutrition for mankind.

Nutritionally, the production of aerated bread is of little benefit. During fermentation, the yeast converts some of the starch sugars into CO₂, which escapes during baking, decreasing the nutritional benefit of the flour. The production of aerated bread is also energetically wasteful – requiring considerable effort and expertise. It is the sensory and textural benefits of the aerated structure of fermented bread that outweigh the losses which encourage us to spend the time and effort in baking bread.

Each country has its own particular methods of baking, but in essence bread is made by simply mixing flour, water, yeast (and air) into a dough, allowing the

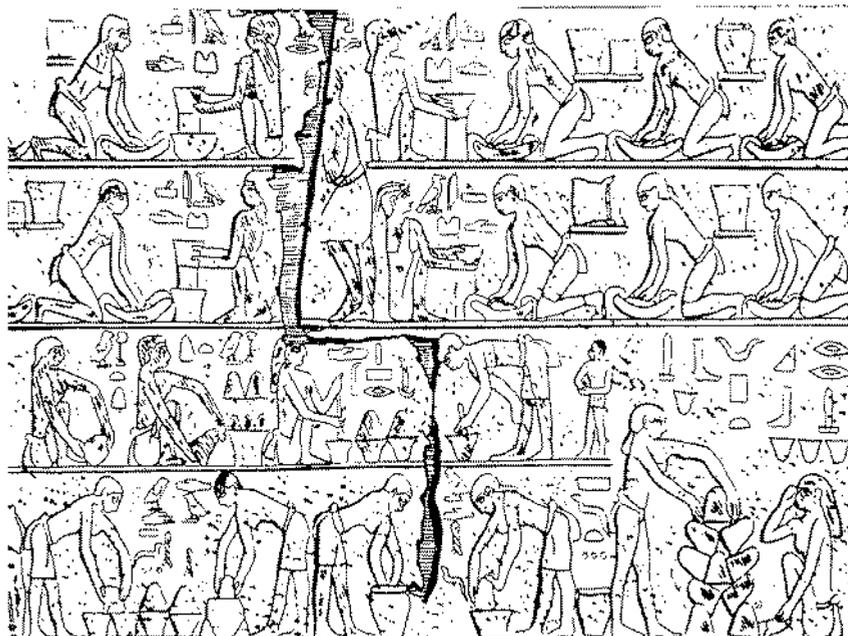


Fig. 8.1 Ancient Egyptian baking.

yeast to ferment for some time to produce an expanding aerated foam and then setting the structure at high temperature in an oven to produce bread. A critical feature of baking is the creation of a stable, aerated structure in the baked bread. Air is a key ingredient in bread, which is added during mixing, manipulated and controlled during proof, and transformed into an interconnected sponge structure during baking. It is the unique viscoelastic properties of gluten, the major protein in wheat flour, which allows the continued expansion and stability of bubbles during breadmaking. No other cereal is capable of retaining gas to the same extent as wheat during fermentation and baking. The polymer structure and rheological properties of gluten are fundamental in maintaining bubble stability during fermentation and in determining the subsequent texture and quality of baked bread. Baking is a deceptively simple-looking process that hides a complex set of chemical and physical processes that are still not completely understood.

8.1.2

Methods of Bread Production

A large number of baking methods exist around the world, with each country having its own traditions and practices handed down over generations, producing a wide variety of types of bread. In practice, these methods can be classified into two main processes: (a) bulk fermentation (BF) and (b) mechanical dough development, or the Chorleywood bread process (CBP).

8.1.2.1 Bulk Fermentation

The major traditional breadmaking process is the bulk fermentation process, in which the dough mass is allowed to ferment over a lengthy period of time after mixing. Cauvain [1] lists the three essential features of bulk fermentation as:

- mixing the ingredients, usually at slow speed, to form a homogeneous dough;
- resting the dough in bulk for a prescribed period of time (typically 3–24 h), during which the yeast ferments to inflate the dough;
- remixing the dough partway through the bulk fermentation, to remove most of the larger gas cells produced and subdivide the smaller gas cells to give an effective increase in the number of gas cells (known as ‘punching’ or ‘knock-back’).

The purpose of this bulk fermentation period is partly for flavour development, but primarily for developing the dough protein structure so that it is better able to retain gas and retard coalescence of gas cells during subsequent proving. The slow inflation during bulk fermentation stretches the dough proteins biaxially, so that they align into a cooperative network that imparts superior elasticity and extensibility to the dough. Historical experience taught bakers that this structure development produced a larger loaf volume and finer crumb structure, and bulk fermentation has thus been a feature of breadmaking for centuries. Baker and Mize [2] showed that gas cells must be incorporated into the dough during mixing, to act as nucleation sites for the carbon dioxide produced during proving; yeast is unable to generate bubbles from nothing. Without these sites, the CO₂ has nowhere within the dough to diffuse and is largely lost from the dough, resulting in a loaf of low volume and a coarse, unattractive structure. The operations of punching and moulding (in which the dough is sheeted between rollers, then rolled up into a ‘Swiss roll’ to orient subsequent bubble growth and give a firmer crumb structure) serve to redistribute the gas bubbles, so that the relationship between aeration during mixing and final baked loaf structure is weak.

8.1.2.2 Chorleywood Bread Process

The modern commercial process used in commercial bakeries in the UK and many other countries is known as the Chorleywood bread process (CBP), which was developed in 1961 by the Flour Milling and Baking Research Association at Chorleywood [3]. This method produces bread and other fermented bakery goods without the need for a long fermentation period. Dough development in CBP is achieved during high-speed mixing by intense mechanical working of the dough in a few minutes. Not only does the CBP save considerable time in the baking process, which helps keep down the production costs and delivers cheaper bread, but it also produces bread which is better in respect of volume, colour and keeping qualities. CBP is now by far the most common method used throughout all sectors of the bread baking industry. The main features of the CBP process are shown in Fig. 8.2.

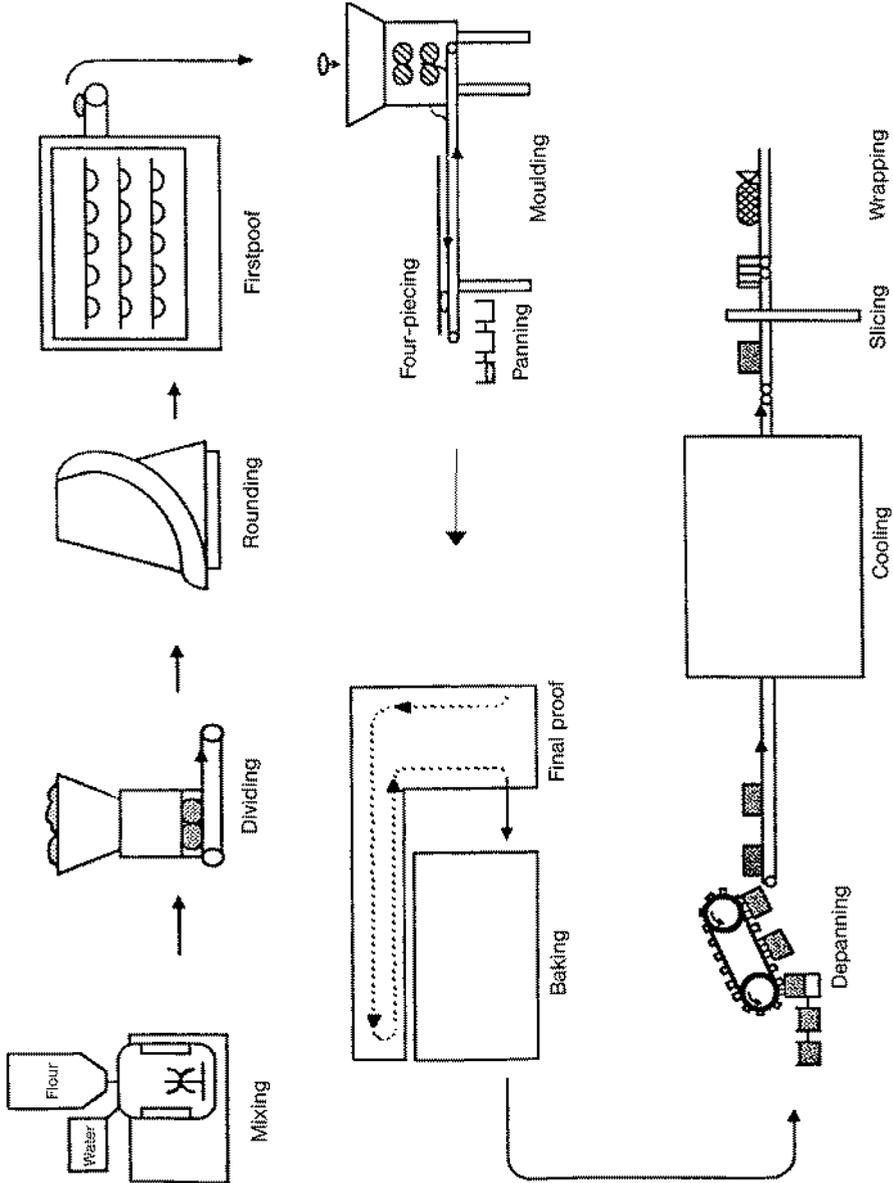


Fig. 8.2 The Chorleywood bread process [4].

Table 8.1 describes the major operations in the CBP and contrasts these with bulk fermentation processes. In the CBP, mixing and dough development are combined into a single operation of a few minutes, in contrast to the much slower, low-energy mixing for BF (8–15 min). Oxidants such as ascorbic acid are added in the CBP method to facilitate rapid dough development. Increased yeast levels and higher proof temperatures are required in the CBP to ensure adequate CO₂ production, as the yeast has less time to multiply during the much shorter proof period. The yeast metabolises less of the flour, therefore extra water is required in the dough, thereby increasing yield. The CBP can also use flour with a lower protein content than that required for BF, thereby increasing the use of more homegrown UK wheat which traditionally has a lower protein content than imported wheats from North America. High melting point fats and emulsifiers are required in the dough formulation for CBP bread, to aid bubble stabilisation during baking. Partial vacuum or pressure/vacuum is applied during mixing to regulate the bubble sizes and structure in the final bread texture. Because the CBP eliminates punching and performs moulding before much yeast activity has occurred, the bubble size distribution at the end of mixing has a much greater influence on baked loaf structure than for traditional BF processes. Due to the rapid development of the dough structure during mixing in the CBP process, it is considered that flavour is not developed as strongly in comparison with the BF process. This is counteracted with the addition of various ingredients such as enzymes and the use of prefermented extracts obtained from BF doughs.

Table 8.1 Comparison of bulk fermentation and Chorleywood bread process (CBP).

	Bulk fermentation	CBP
Ingredients	Flour Water Yeast ~ 1% Salt	Flour Water Yeast ~ 2.5% Salt Oxidants (ascorbic acid) Fat Emulsifiers Lower protein content and more water relative to BF
Mixing	Slow mixing (8–15 min) Low energy (5–15 kJ kg ⁻¹)	Rapid mixing (<3 min) High energy (40 kJ kg ⁻¹) Partial vacuum or pressure-vacuum
Proof	Fermentation for 3–24 h at 26 °C Remixing during proof to expel excess gas	First proof 10–15 min at room temperature Second proof 45 min at ~40 °C
Baking	20–25 min at ~200 °C	As for BF

8.1.3

The Baking Process

The baking process can be divided into three main processes: mixing, fermentation (or proof), and baking. These three processes are reviewed in the following sections.

8.1.3.1 Mixing

Mixing of bread dough has three main functions: (a) to blend and hydrate the dough ingredients, (b) to develop the dough and (c) to incorporate air into the dough. In the production of doughs, the nature of the mixing action develops the viscoelastic properties of gluten and also incorporates air, which has a major effect on their rheology and texture. There is an intimate relationship between mixing, aeration and rheology: the design and operation of the mixer develops texture, aeration and rheology to different extents; and conversely the rheology of the food affects the time and energy input required to achieve optimal development. This is seen in the great variety of mixers used in the baking industry, where certain mixers are required to produce a desired texture or rheology in the bread.

Extensive work on dough mixing has shown that mixing speed and energy (work input) must be above a certain value to develop the gluten network and to produce satisfactory breadmaking [5]; and an optimum work input or mixing time has been related to optimum breadmaking performance, which varies depending on mixer type, flour composition and ingredients [6]. Mixing beyond the optimum (overmixing) is thought to damage the dough, causing the gluten network to break down, resulting in more fragile bubble walls and less gas retention and lower baking volume. Overmixing can also result in sticky, difficult to handle doughs which causes production problems. The strong relationship between mixing and handling and baking properties has resulted in a large number of commercial force-recording dough mixers, such as the Farinograph and Mixograph [7, 8], which are used to determine the optimum in mixing speed and energy. Mixing doughs by elongational flow in sheeting to achieve optimum development requires only 10–15% of the energy normally used in conventional high-speed shear mixers [9], suggesting that much higher rates of work input can be achieved due to the enhanced strain hardening of doughs under extension.

8.1.3.2 Fermentation (Proof)

Fermentation, or proof, is the critical step in the breadmaking process, where the expansion of air bubbles previously incorporated during mixing provides the characteristic aerated structure of bread, which is central to its appeal. During proof, the gas content within the dough increases from around 4–8% to approximately 80%. The original bubble structure formed during mixing and sub-

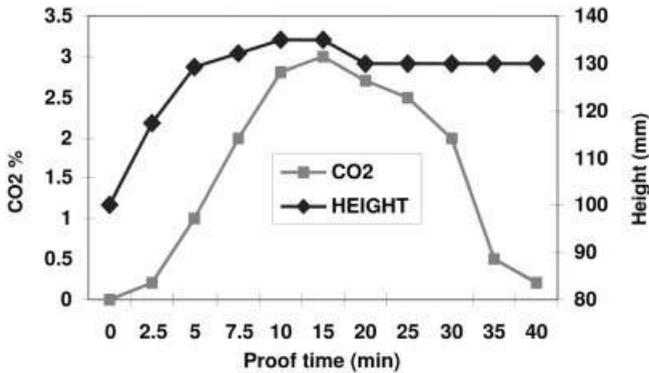


Fig. 8.3 CO₂ release and change in dough height during proof.

sequently altered during punching and moulding is slowly expanded by the diffusion of CO₂ which is dissolved in the surrounding liquid phase within the dough [10]. This causes the steady increase in the volume of the dough known as proof, since at this stage the bubbles are discrete and no gas can escape. Eventually the bubbles start to interconnect or coalesce, CO₂ gas begins to escape and volume expansion ceases (see Fig. 8.3). The growth and stability of the gas bubbles during proof determine the ultimate expansion of the dough and its final baked texture and volume [11].

The coalescence of gas bubbles is the key event which determines the extent of bubble expansion and volume increase during proof, and also the final loaf texture. If coalescence is delayed, bubbles can expand for much longer, giving a larger proof volume and a finer texture, i.e. smaller gas cells. If coalescence occurs early, then gas escape occurs much earlier and proof volume is decreased and the texture is much coarser. The rheological properties of the bubble cell walls are very important in controlling coalescence in doughs, in particular the elongational strain hardening properties of the gluten polymers [12, 13].

8.1.3.3 Baking

In baking the foam structure of the dough, created by the gas cells, is turned into a loaf of bread with an interconnected sponge structure supported by the starch-protein matrix. Within the first few minutes of baking, the volume of the dough increases rapidly and reaches the maximum size of the loaf; and this period is called oven rise or oven spring [14]. At the end of oven spring, there is a sharp increase in the rate of gas lost from the loaf, which is due to the rapid coalescence or rupture of the bubble cell walls. At the temperature of starch gelatinisation ($\sim 65^\circ\text{C}$), there is a transfer of water from the protein to the starch, leading to a swelling of the starch granules and a rapid increase in viscosity of the dough, which sets the sponge structure. These physical changes lead to a change from a closed cell foam structure to an open cell sponge structure (see Fig. 8.4).

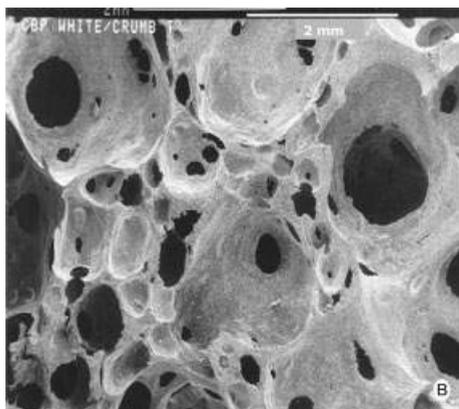


Fig. 8.4 Open cell sponge structure of bread.

During baking, there is an evaporation of water from the loaf, which is particularly marked near the surface of the loaf; and this evaporation plus the occurrence of the Maillard reaction cause a characteristic dark brown crust to be formed on the exterior of the loaf. The Maillard reaction is a complex set of chemical reactions in which the amino acids in proteins react with reducing sugars such as glucose and fructose and which are very important to our perception of flavour in baked bread.

8.1.4

Gluten Polymer Structure, Rheology and Baking

Gluten is the major protein in wheat flour doughs, responsible for their unique viscoelastic behaviour during deformation. It is now widely accepted that gluten proteins are responsible for variations in baking quality; and in particular it is the insoluble fraction of the high molecular weight (HMW) glutenin polymer which is best related to differences in dough strength and baking quality amongst different wheat varieties [15, 16]. For example, the rheological properties of gluten are known to be important in the entrainment, retention and stability of gas bubbles within dough during mixing, fermentation and baking [13, 17], which ultimately are responsible for the texture and volume of the final baked product.

Gluten proteins comprise a highly polydisperse system of polymers, classically divided into two groups based on their extractability in alcohols: gliadins and glutenins. The gliadins are single-chain polypeptides with MW ranging from 2×10^4 to 7×10^4 , whilst the glutenins are multiple-chain polymeric proteins in which individual polypeptides are thought to be linked by interchain disulphide and hydrogen bonds to give a wide MW distribution, ranging between 10^5 and 10^9 . Gluten has a bimodal MW distribution which roughly parallels the classic division based on solubility into gliadins and glutenins (see Fig. 8.5) [18, 19].

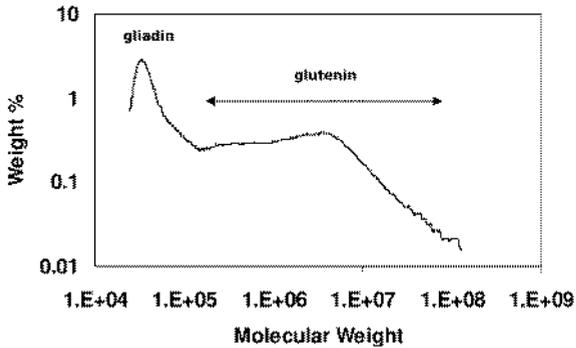


Fig. 8.5 Molecular weight distribution of gluten, showing bimodal distribution.

Individual glutenin polymers have an extended rod-like structure ca. 50–60 nm in length, made up of a central repetitive region, which is known to adopt a regular spiral structure (see Fig. 8.6) [20] and terminal regions which contain cysteine residues which are associated with intermolecular crosslinking by disulphide bonds.

The rheological properties of gluten are known to depend on the three-dimensional organisation of the polymer network, where individual linear HMW glutenin polymers (subunits) are linked by disulphide and hydrogen bonding and entanglements to form a network structure. The microscopic structure of gluten is seen clearly in confocal laser scanning microscopy (see Fig. 8.7), where gluten strands form a three-dimensional network in which are embedded rigid starch granules.

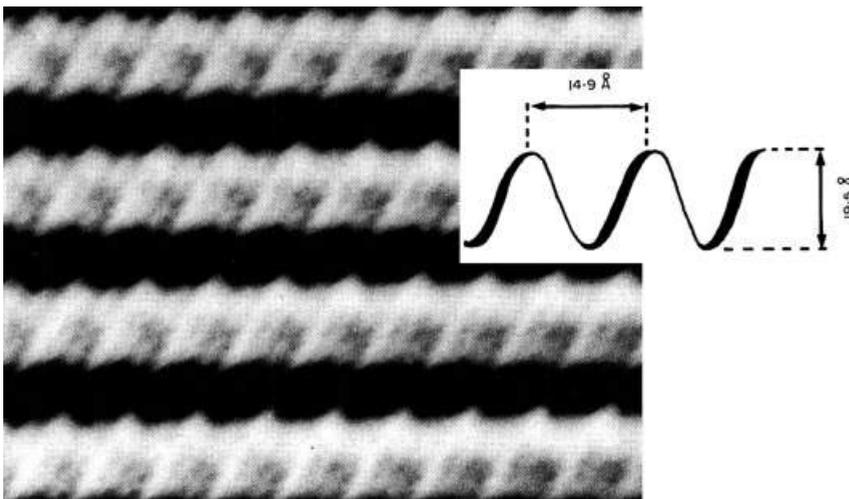


Fig. 8.6 Spiral structure of glutenin polymers; obtained by atomic force microscopy.

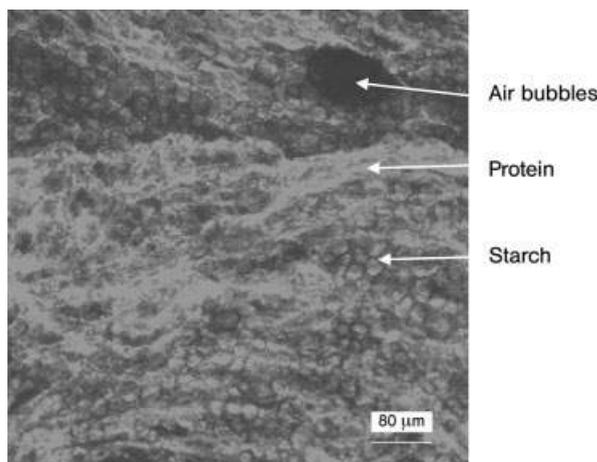


Fig. 8.7 Microstructure of dough, showing gluten, starch and air bubbles during the early stages of proof; obtained by confocal laser scanning microscopy.

Recent studies in polymer physics have shown that molecular size, structure and MW distributions of polymers are intimately linked to their rheological properties and ultimately to their performance in various end use applications [21, 22]. Beyond a critical molecular weight (MW_c), characteristic for each polymer, rheological properties such as viscosity, relaxation time and strain hardening start to increase rapidly with increasing MW. Above MW_c , the polymers start to entangle, giving rise to the observed rapid increase in viscosity with MW (see Fig. 8.8).

Entanglements can be viewed as physical constraints between segments of the polymer chain, rather like knots (see Fig. 8.9).

A relatively small variation in the highest end of the MW distribution can give rise to a large increase in viscosity and strain hardening and is likely to have a large effect on baking performance. If the polymers are branched, viscosity rises even more rapidly. The effect of polymer chain branching on shear and extensional viscosity of polymers and doughs is shown in Fig. 8.10. At low strains, shear and extensional viscosities are very similar, but as deformation increases, the effect of polymer branching and entanglement becomes apparent, with a steep rise in viscosity with strain (known as strain hardening) apparent for extensional deformation and a decrease in viscosity with shear deformation (known as shear thinning).

An increase in the number of branches increases strain hardening and extensional viscosity and decreases shear viscosity. Extensional rheological properties appear to be more sensitive to changes in MW, polymer entanglements and branching than dynamic shear properties. This indicates that it is more likely to be the physical interactions of the secondary molecular structure of the insoluble HMW glutenin (such as branching and entanglements) that are responsi-

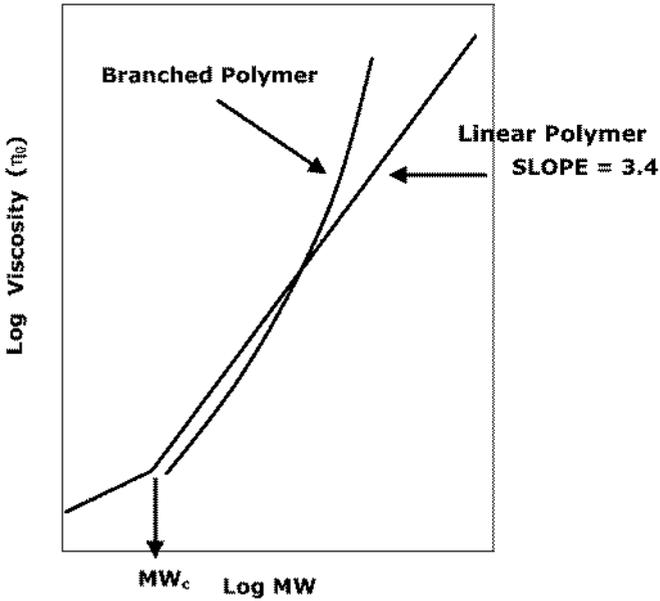


Fig. 8.8 Effect of molecular weight (MW) and branching on zero-shear viscosity for polymer melts. Beyond a critical molecular weight for entanglements (MW_c), viscosity (η_0) increases rapidly for linear polymer as $MW^{3.4}$.

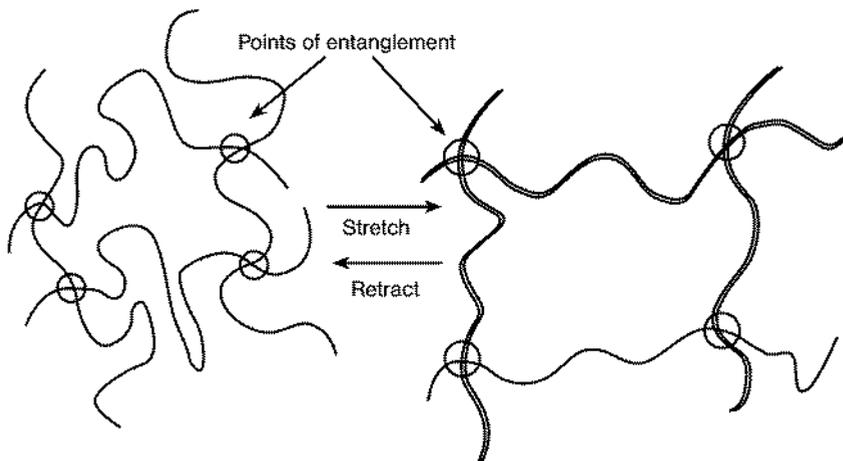


Fig. 8.9 Model of entanglement network in a high MW polymer during stretching.

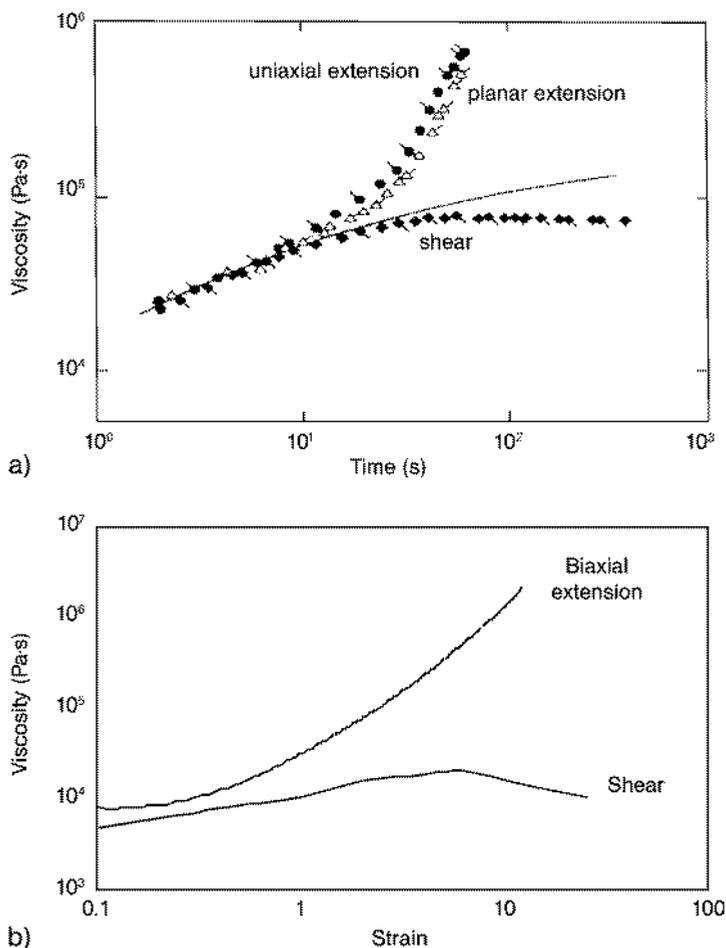


Fig. 8.10 Effect of polymer chain branching on shear and extensional viscosities of (a) branched low-density polyethylene at 125 °C and (b) dough.

ble for the rheological properties of dough and its baking performance than the primary chemical structure or size of individual glutenin molecules. Recent evidence suggests that (a) these insoluble HMW polymers are entangled with a corresponding long relaxation time, (b) they are branched and form extensive intermolecular secondary structures held together by hydrogen bonding and (c) differences in these secondary structures are likely to be strongly related to extensional rheology and baking performance [13, 23, 24, 25].

8.1.5

Baking Quality and Rheology

During proof and baking, the growth and stability of gas bubbles within the dough determines the expansion of the dough and therefore the ultimate volume and texture of the baked product. The limit of expansion of these bubbles is related directly to their stability, due to retardation of coalescence and loss of gas when the bubbles fail. The rheological properties of the expanding bubble walls are therefore important in maintaining stability in the bubble wall and promoting gas retention. The relevant rheological conditions around an expanding gas cell during proof and baking are biaxial extension, large extensional strain and low strain rates. Any rheological tests which seek to relate to baking performance should be performed under conditions similar to those of baking expansion. Methods such as bubble inflation and lubricated compression offer the most appropriate method for measuring extensional rheological properties of doughs. The major advantage of these tests is that the deformation closely resembles practical conditions experienced by the cell walls around the expanding gas cells within the dough during proof and oven rise, i.e. large deformation biaxial extension and can be carried out at the low strain rates and elevated temperatures relevant to baking.

The failure of gas cell walls in doughs has been shown to be directly related to the elongational strain hardening properties of the dough measured under large deformation biaxial extension [26]. Strain hardening is shown as an increase in the slope of the stress-Hencky strain curve with increasing extension, giving rise to the typical J-shaped stress-strain curve observed for highly extensible materials (see Fig. 8.11).

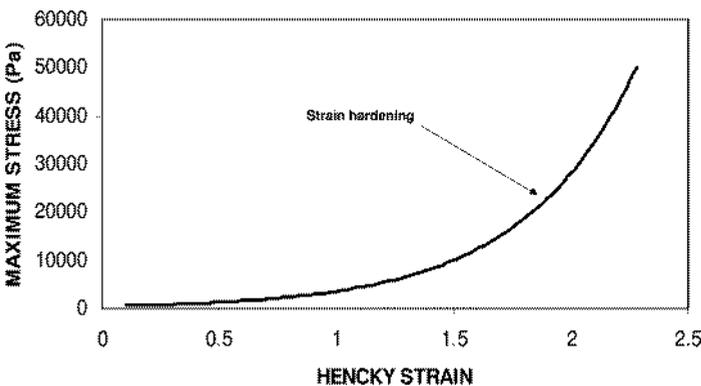


Fig. 8.11 Typical J-shaped stress-Hencky strain curve in biaxial extension for a dough bubble, indicating strain hardening as a rapid increase in stiffness with increasing inflation (Hencky strain). Bubble inflation using SMS Dough Inflation System, maximum stress and Hencky strain calculated for bubble wall polar region.

Strain hardening in doughs is thought to arise mainly from stretching of polymer chains between points of entanglement in the larger glutenin molecules, which gives rise to the increasing stiffness observed at large strains. Under extensional flow, entangled polymers exhibit strain hardening which is enhanced for polymers with a broad MW distribution, particularly a bimodal distribution and branching. It is therefore expected that the broad bimodal MW distribution and branched structure typical of gluten will result in enhanced strain hardening and a bimodal distribution of relaxation times. Recent work has shown that bread doughs exhibit strain hardening under large extensional deformations and that these extensional rheological properties are important in baking performance [12, 13, 27]. Strain hardening allows the expanding gas cell walls to resist failure by locally increasing resistance to extension as the bubble walls become thinner and provides the bubble walls with greater stability against early coalescence and better gas retention. It is expected therefore that doughs with good strain hardening characteristics should result in a finer crumb texture, e.g. smaller gas cells, thinner cell walls, an even distribution of bubble sizes and a larger baked volume than doughs with poor strain hardening properties. Good breadmaking doughs have been shown to have good strain hardening properties and inflate to larger individual bubble volumes before rupture, whilst poor breadmaking doughs inflate to lower volumes and have much lower strain hardening (see Fig. 8.12).

Loaf volume and crumb score for a number of doughs from flour varieties with varying baking performance has been related directly to the strain hardening properties of single dough bubbles measured at elevated temperatures in

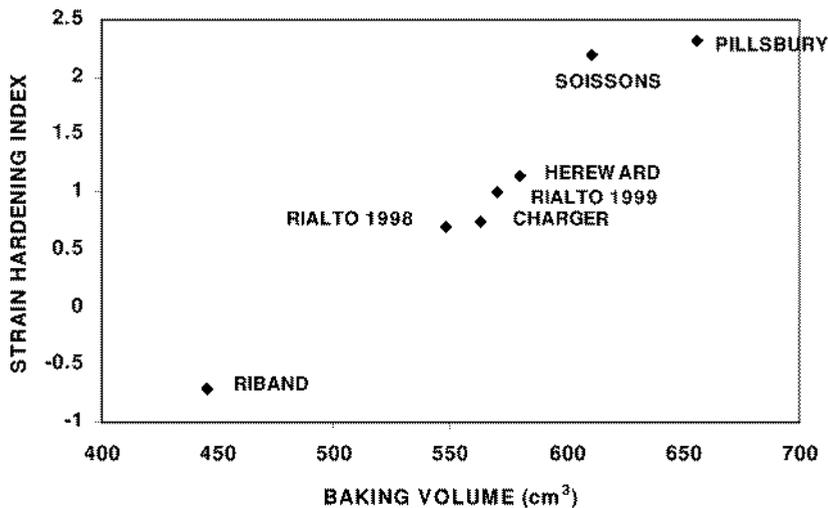


Fig. 8.12 Relationship between strain hardening and baking volume for a number of flour varieties with varying baking performance.

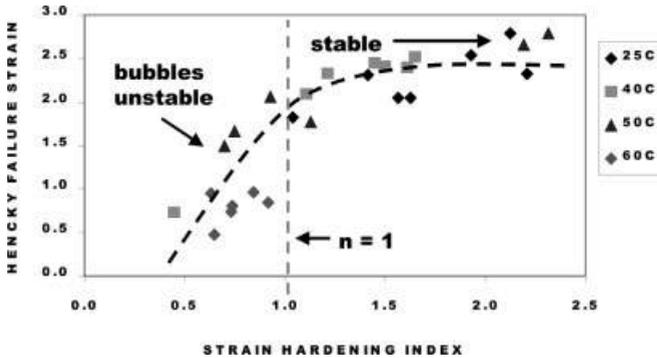


Fig. 8.13 Dough bubble wall stability (measured as Hencky failure strain) as a function of strain hardening, showing instability at strain hardening < 1.

biaxial extension. Once strain hardening drops below a value of around 1, bubble wall stability decreases rapidly (see Fig. 8.13). Bubble wall stability (as indicated by a strain hardening value of 1) is increased to progressively higher temperatures with increasing baking volume, allowing the bubbles to resist coalescence and retain gas for much longer during the baking process. Bubble wall instability in poorer breadmaking varieties occurs at much lower temperatures, giving earlier bubble coalescence and release of gas, resulting in lower loaf volumes and poorer texture [28].

8.2 Extrusion

Paul Ainsworth and Senol Ibanoglu

8.2.1 General Principles

Extrusion can be defined as the process of forcing a pumpable material through a restricted opening. It involves compressing and working a material to form a semisolid mass under a variety of controlled conditions and then forcing it, at a predetermined rate, to pass through a hole.

The origins of extrusion are in the metallurgical industry, where in 1797 a piston driven device was used to produce seamless lead pipes [29]. The current understanding of extrusion technology and the developments in machine design are largely due to research carried out by the plastics industry.

Extrusion technology was first applied to food materials in the mid-1800s, when chopped meat was stuffed into casings using a piston type extruder. In

the 1930s, a single-screw extruder was introduced to the pasta industry, to both mix the ingredients (semolina and water) and to shape the resulting dough into macaroni in one continuous operation.

Today, a wide variety of intermediate or food products are produced by extrusion.

8.2.1.1 The Extrusion Process

Extrusion is predominantly a thermomechanical processing operation that combines several unit operations, including mixing, kneading, shearing, conveying, heating, cooling, forming, partial drying or puffing, depending on the material and equipment used. During extrusion processing, food materials are generally subjected to a combination of high temperature, high pressure and high shear. This can lead to a variety of reactions with corresponding changes in the functional properties of the extruded material.

In the extrusion process, there are generally two main energy inputs to the system. Firstly there is the energy transferred from the rotation of the screws and secondly the energy transferred from the heaters through the barrel walls. The thermal energy that is generated by viscous dissipation and/or transferred through the barrel wall results in an increase in the temperature of the material being extruded. As a result of this, there may be phase changes, such as melting of solid material, and/or the evaporation of moisture.

The ingredients used in extrusion are predominantly dry powdered materials, with the most commonly used being wheat, maize and rice flours. The conditions in the extruder transform the dry powdered materials into fluids and therefore, characteristics such as surface friction, hardness and cohesiveness of particles become important. In the high solids concentration of the extruder melt, the presence of other ingredients, such as lipids and sugars, can cause significant changes in the final product characteristics.

In addition to starch-based products, a range of protein-rich products can be manufactured by extrusion, using raw materials such as soya or sunflower, fava beans, field bean and isolated cereal proteins. Fig. 8.14 shows a schematic diagram of an extruder.

In order to convey the dry raw material to the extruder barrel, volumetric and gravimetric feeders tend to be used. Volumetric devices include single- and twin-screw feeders, rotary airlock feeders, disk feeders, vibratory feeders and volumetric belt feeders. In all of these feed mechanisms, it is assumed that the density of the feed material remains constant over time and hence a constant volume of feed will result in a constant mass flow rate [30]. Gravimetric feeders are more expensive and more complex than volumetric feeders. They are usually microprocessor-controlled to monitor the mass flow rate and adjust the feeder speed as required. The most commonly used gravimetric feeders are the weight-belt and the 'loss in weight' feeders [31].

Addition of liquid feed ingredients to the extruder can be achieved using a variety of devices, including rotameters, fluid displacement meters, differential

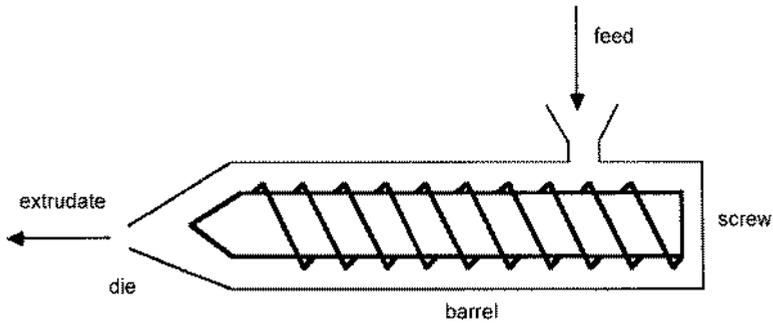


Fig. 8.14 Schematic diagram of an extruder.

pressure meters, mass flow meters, velocity flow meters and positive displacement pumps [30].

8.2.1.2 Advantages of the Extrusion Process

There are many benefits to using extruders to process food materials. They are capable of producing a wide variety of different product types and shapes, often with only small changes to the extruder, its operational settings or the raw materials used. From an engineering perspective, extruders can be described as a combination of a pump and a scraped surface heat exchanger for which operating conditions are relatively insensitive to material viscosity [32]. Thus extrusion systems are able to process highly viscous materials that are difficult or impossible to handle using conventional methods.

The ability of extruders to process biopolymers and ingredient mixes at relatively high temperatures (250°C) and pressures (e.g. 25 MPa) with high shear forces and low moisture contents (10–40%) leads to a variety of fast and comparatively efficient chemical reactions and functional changes of the extruded material [33].

The ability of extrusion systems to carry out a series of unit operations simultaneously and continuously gives rise to savings in labour costs, floor space costs and energy costs whilst increasing productivity [34]. These production efficiencies, combined with the ability to produce shapes not easily formed with other production methods, have led to extensive use of extrusion in the food industry. An indication of the range of applications is given in (Table 8.2) [33].

Table 8.2 Extrusion cooking applications [33].

Bread crumbs	Degermination of spices
Precooked starches	Flavour encapsulation
Anhydrous decrystallisation of sugars to make confectioneries	Enzymic liquefaction of starch for fermentation into ethanol
Chocolate conching	Quick-cooking pasta products
Pretreated malt and starch for brewing	Oilseed treatment for subsequent oil extraction
Stabilisation of rice bran	Preparation of specific doughs
Gelatin gel confectioneries	Destruction of aflatoxins or gossypol in peanut meal
Caramel, liquorice, chewing gum	Precooked soy flours
Corn and potato snack	Gelation of vegetable proteins
Co-extruded snacks with internal fillings	Restructuring of minced meat
Flat crispbread, biscuits, crackers, cookies	Preparation of sterile baby foods
Precooked flours, instant rice puddings	Oilseed meals
Cereal-based instant dried soup mixes or drink bases	Sterile cheese processes
Transformation of casein into caseinate	Animal feeds
Precooked instant weaning foods or gruels	Texturised vegetable proteins

8.2.2

Extrusion Equipment

Extruders come in a wide variety of shapes, sizes and methods of operation, but can be categorised into one of three main types: piston, roller and screw extruders [32, 35]. The simplest of these is the piston extruder, which consists of a single piston or a battery of pistons that force the material through a nozzle onto a wide conveyor. The pistons can deliver very precise quantities of materials and are often used in the confectionery industry to deposit the centre fillings of chocolates. Roller extruders consist of two counter-rotating drums placed close together. The material is fed into the gap between the rollers that rotate at similar or different speeds and have smooth or profiled surfaces. A variety of product characteristics can be obtained by altering the rotation speeds of the rollers and the gap between them. This process is used primarily with sticky materials that do not require high-pressure forming. Screw extruders are the most complex of the three categories of extruder and employ single-, twin-, or multiple-screws rotating in a stationary barrel to convey material forward through a specially designed die. Amongst the screw type extruders, it is common to classify machines on the basis of the amount of mechanical energy they can generate. A low-shear extruder is designed to minimise the mechanical energy produced and is used primarily to mix and form products. Conversely, high-shear extruders aim to maximise mechanical energy input and are used in applications where heating is required.



Fig. 8.15 A co-rotating twin-screw extruder (Continua 37; Werner and Pfleiderer, Stuttgart, Germany).

In the food industry, single- and twin-screw extruders predominate and hence are discussed in more detail.

Fig. 8.15 shows a co-rotating twin-screw extruder (Continua 37; Werner and Pfleiderer, Stuttgart, Germany).

8.2.2.1 Single-Screw Extruders

Single-screw extruders were first used in the 1940s to produce puffed snacks from cereal flours and grits. During transport through the extruder, mechanical energy from the rotation of the screw is converted to heat, raising the temperature of the mixture to over 150°C. The resulting plasticised mixture is then forced through the die. The sudden reduction in pressure at the die causes moisture to flash off rapidly as steam, puffing the product. From the late 1950s, extrusion processes were developed to manufacture products such as dry expanded pet food, dry expanded ‘ready to eat’ breakfast cereals and textured vegetable protein.

Because single-screw extruders have relatively poor mixing ability, they are often used with materials that have been either premixed or preconditioned. Preconditioning is used to increase residence time, to reduce mechanical power consumption and/or to increase capacity. The preconditioner is an atmospheric or pressurised chamber in which raw granular food ingredients are uniformly moistened or heated or both by contact with live steam or water before entering the extruder.

The single-screw extruder relies upon drag flow to convey the feed material through the barrel of the extruder and to develop pressure at the die. In order for the product to advance along the barrel, it must not rotate with the screw.

The frictional force between the material and the barrel wall is the only force that can keep the material from turning with the screw and hence many single-screw machines have grooves cut in the barrel to promote adhesion to the barrel wall.

The rotation of the screw in the barrel gives rise to a second flow, called the cross-channel flow. This flow does not contribute to the net movement of material along the barrel but instead recirculates it within the screw flights and hence is responsible for some of the mixing action of the extruder.

In forcing the feed material along the barrel of the extruder and through the restricted opening of the die, a third flow known as the pressure flow is generated. The pressure flow causes movement backwards down the extruder barrel, causing further mixing of the product. The three flows combine to give the net flow of material out of the die.

Single-screw extrusion operation depends upon the pressure requirements of the die, the slip at the barrel wall (controlled by the barrel wall temperature, the presence of barrel wall grooves, or both) and the degree to which the screw is filled. Screw fill is dictated by feed rate, screw speed, melt characteristics and viscosity of the material extruded. The coupling of these variables limits the operating range and flexibility of single-screw extruders [36].

In the compression section of the screw, the compression ratio increases rapidly causing most of the mechanical energy used to turn the screw to be dissipated causing an increase in the temperature of the material. This results in the plasticisation of the dry feed ingredients. Energy input to the extrusion system may also arise from heat transfer through the jacket and latent heat from steam injected into the ingredients in the preconditioner.

8.2.2.2 Twin-Screw Extruders

Twin-screw extruders were introduced to the food industry in the 1970s and are now extensively used in food production.

In addition to manufacturing foods similar to those produced by single-screw extruders, twin-screw extruders have found a wide application in the food industry due to their better process control and versatility, their flexible design permitting easy cleaning and rapid product changeover and their ability to handle a wide variety of formulations.

Twin-screw extruders differ from the single-screw extruder in terms of their processing capability and mechanical characteristics and are largely responsible for the increasing popularity of extrusion processing. The screws in a twin-screw extruder are positioned adjacent to each other and are retained in position by a profiled barrel housing, having a horizontal 'figure of eight' appearance. The position of the screws in relation to one another and their direction of rotation, can be used to categorise twin-screw machines.

Twin-screw extruders can have intermeshing screws in which the flights of one screw engage the other or they can have nonintermeshing screws in which the threads of the screws do not engage one another, allowing one screw to turn

without interfering with the other. Nonintermeshing screw extruders function like single-screw extruders but have a higher capacity.

Twin-screw extruders may have co-rotating or counter-rotating screws. Both co-rotating and counter-rotating extruders can have fully, partially or nonintermeshing screws. Co- and counter-rotating screws differ in their transport characteristics and are therefore suited to different technological applications [35, 37].

Intermeshing twin-screw extruders generally act like positive displacement pumps, forcing the material within the flights to move towards the die by rotation of the screws. The movement of the material is dependant upon the screw geometry and occurs independently of the operating conditions. Twin-screw intermeshing extruders have found wide applications due to their positive pumping action, efficient mixing and self-cleaning characteristics.

Intermeshing counter-rotating machines are particularly suited to the processing of relatively low-viscosity materials that require low screw speeds and a long residence time. Examples of products suited to this type of extruder include chewing gum, jelly and liquorice confections [35]. These extruders exhibit poor mixing characteristics as each half of the chamber housing the screws acts independently and thus two streams of material that have little interaction are generated. Hence the only mixing that is done is due to the recirculation within the chamber itself.

Although high pressures can be achieved in counter-rotating extruders if the screw speed is increased, large separating forces are generated at the interface between the screws, giving a calendaring effect which can cause excessive wear. Hence, the production of expanded products with counter-rotating extruders is considered uneconomic [30, 35].

Intermeshing co-rotating extruders are particularly suited to applications where a high degree of heat transfer is required but not forced conveyance and thus are widely used for the production of expanded products. In this type of extruder, the material being extruded is transferred from one screw to the other. The flow mechanism is a combination of both drag and positive displacement flow [38]. The self-wiping style of co-rotating extruders is most commonly used due to their high capacity and enhanced mixing ability [30]. Co-rotating extruders can be operated at higher speeds than counter-rotating extruders because the radial forces generated are more evenly distributed. The conveying ability of twin-screw extruders allows them to handle sticky and other difficult to handle ingredients [35].

In order to improve the mixing, heat transfer and viscous dissipation of mechanical energy, sections of the extruder are completely filled with material. To create these filled sections, some type of restriction is placed on the screw configuration. The addition of forward- or reverse-conveying discs into the screw configuration alters the pressure profile within the barrel. The forward-conveying discs push the material towards the die increasing the pressure in the barrel. Reverse-conveying discs reduce the pressure by delaying the passage of material through the extruder, increasing the barrel fill prior to the restriction,

allowing additional processing and improved efficiency of heat transfer through the barrel wall. Restrictions in the screw configuration are placed under greater stresses and hence they tend to wear, requiring more frequent replacement than other elements of the screw.

Nonintermeshing twin-screw extruders can be described as two single-screw extruders sitting side by side with only a small portion of the barrels in common [39]. Like the single-screw extruder, these extruders rely on friction for extrusion.

8.2.2.3 Comparison of Single- and Twin-Screw Extruders

A comparison of single- and twin-screw extruders is shown in Table 8.3 [37].

For a given throughput, twin-screw extruders are 1.5 to 2.0 times as expensive as single-screw extruders, primarily due to the complexity of the screw, drive and heat-transfer jackets [40].

The preconditioning of feed ingredients with live steam is widely used in conjunction with single-screw extrusion processes and provides around half of the heat necessary for cooking/processing, the remainder of the heat being derived from the mechanical energy inputs. The rate of heat transfer to a material using the direct injection of live steam is very high and thus represents the lowest-cost method of heating the product. For this reason, single-screw extruders usually have lower energy costs than twin-screw extruders.

The cost of twin-screw extruders can, however, be offset by their ability to process at lower moisture levels, thus reducing or eliminating the need for additional postprocess drying [40].

The geometry and characteristics of the screws used in twin-screw extrusion present some advantages over single-screw extruders and enables the twin-screw extruder to process a wide range of ingredients that cause feeding problems for single-screw machines [39]. The conveying angle, combined with the self-wiping feature, results in an extruder that is less prone to surging. Increased uniformity of processing also occurs in twin-screw extruders due to the consistency of shear rate across the channel depth, leading to a narrower residence time distribution and increased mixing within the screw channel [30].

A single-screw extruder is relatively ineffective in transferring heat from barrel jackets because convective heat transfer is limited by poor mixing within the channel. Instead, the jackets in single-screw extruders control barrel wall temperature to regulate slip between the materials and the wall. Twin-screw extruders have considerably more heat exchange capability that expands their application to heating and cooling viscous pastes, solutions and slurries [40].

Single- and twin-screw extruders have found many different applications in the food industry. For example, single-screw extruders are considered an economic and effective method for the thermal processing and forming of pet foods, whilst twin-screw extruders have been widely used in snack food production, where better control and flexibility is required [37].

Table 8.3 Relative comparison of single- and twin-screw extruders [37].

Item	Single-screw	Twin-screw
Relative cost/unit capacity		
Capital cost of extruder	1.0	1.5–2.5
Capital cost of system	1.0	0.9–1.3
Relative maintenance	1.0	1.0–2.0
Energy		
With preconditioner	Half from steam	Generally not used
Without preconditioner	Mechanical energy	Mix of mechanical and heat exchange
Screw		
Conveying angle	10°	30°
Wear	Highest at discharge and transition sections	Highest at restrictions and kneading discs
Positive displacement	No	No, but approached by fully intermeshing screws
Self-cleaning	No	Self-wiping
Variable flight height	Yes	No
L/D	4–25	10–25
Mixing	Poor	Good
Uniformity of shear	Poor	Good
Relative RTD spread	1.2	1.0
Venting	Requires two extruders	Yes
Drive		
Relative screw speed	1.0–3.0	1.0
Relative thrust-bearing capacity	Up to 2.5	1.0
Relative torque/pressure	Up to 5.0	1.0
Heat transfer	Poor; jackets control barrel wall temperature and slip at wall	Good in filled sections
Operations		
Moisture	12–35%	6% to very high
Ingredients	Flowing granular materials	Wide range
Flexibility	Narrow operating range	Greater operating range

8.2.3

Effects of Extrusion on the Properties of Foods

8.2.3.1 Extrusion of Starch-Based Products

Cereal flours and other starchy materials are widely used as raw materials in the production of many extruded products. The physical characteristics of cereal fluids developed within an extruder and their extrudates are predominantly due to the starch component present, which usually represents between 50% and 80% of the dry solids in the mixture. Accordingly, many of the studies relating

to cereal extrusion focus on changes occurring in the starch component of the product under varying extrusion conditions and the resulting effects on its physical, chemical and organoleptic properties. The type of extruder, feed moisture, feed rate, barrel temperature, screw speed, screw profile and die size are all important in developing the characteristics of the extruded product.

Cereals and starch-based products have been processed by extrusion since the initial introduction of the process to the food industry.

A study of the effect of feed moisture and barrel temperature on the extrusion of commercial yellow corn grits found that an increase in feed moisture or barrel temperature, up to 177°C, causes an increase in WAI [41]. At temperatures above 177°C WAI was found to decrease. Similarly, WSI was found to gradually increase with an increase in barrel temperature up to a value of 177°C, with a more pronounced increase above this temperature. For any given set of operating conditions, a decrease in feed moisture content resulted in reduced WAI and increased WSI. Determination of the final cooked-paste viscosities showed maximum viscosity at 25% feed moisture.

A study carried out by Mercier and Feillet [42] looked at the modification of carbohydrate components in a range of cereal products, namely corn grits, corn, waxy corn, Amylon 5 and 7 (52% and 61% amylose), wheat and rice. The barrel temperature was varied from 70°C to 225°C with a moisture content of 22%. Their study showed a consistent increase in WSI with increasing barrel temperature, agreeing with earlier work [43]. Analysis of WAI for waxy corn showed a decrease with increasing barrel temperature from 70°C to 225°C, whilst the Amylon 5 and 7 samples showed little change until 200°C, after which there was a sharp increase. WAI data for corn, wheat and rice products showed a gradual increase with barrel temperature, reaching a maximum at around 180°C. At an extrusion temperature of 135°C, the cooked viscosity of corn and rice starch was similar, while wheat starch gave a higher final cooked viscosity. Data obtained from the extrusion of starch with different amylose contents at different temperatures showed that the WSI and water-soluble carbohydrate increased less with increasing amylose content.

Research on the effect of several extrusion variables such as moisture, barrel temperature, screw geometry and screw speed on the gelatinisation of corn starch indicated that barrel temperature and moisture had the greatest effect on the gelatinisation of starch [43]. The results showed that the maximum gelatinisation occurred at high moisture and low barrel temperatures or vice versa. Higher screw speed reduced gelatinisation and was related to lower residence times. During the extrusion of cereal starches, it was found that starch was solubilised in a macromolecular form and no small oligo- or monosaccharides were formed [42]. Research on potato starch [44] showed that extrusion preferentially broke the α -1-4 linkages of amylose and not the outer chains of amylopectin. Linear oligosaccharides having no α -1-6 linkages were found.

The effect of feed moisture, barrel temperature, screw speed and die size on the gelatinisation of wheat flour during extrusion showed that the degree of starch gelatinisation increased sharply with increasing temperature, when the

feed moisture contents were 24–27%, but increased more gradually when moisture contents were 18–21% [45]. At lower temperatures (65–80 °C) an increase in feed moisture content was found to cause a slight decrease in gelatinisation, whilst at higher temperatures (95–110 °C), an increase in moisture resulted in a significantly increased degree of gelatinisation. Increase in the screw speed was found to decrease the degree of starch gelatinisation, despite the increased shear. This was explained by the decrease in retention time of the sample in the extruder. Increasing the die size was found to reduce the degree of starch gelatinisation. This was explained by the possible decrease in the retention time of the sample in the extruder due to lower pressures and decreased surface shear.

At a constant moisture content, the effect of barrel temperature, feed rate and screw speed on starch gelatinisation during the extrusion of a yoghurt-wheat mix showed that barrel temperature had the most pronounced effect, followed by feed rate and screw speed [46].

A comparison of the appearance of starch granules from wheat semolina prior to and after extrusion at 60 °C showed little difference in the shape of the starch granules [47]. Increasing the barrel temperature resulted in a flattening of the granule although the original shape (unextruded) was still recognisable. A complete destruction of the granule was not seen until the barrel temperature reached 125 °C.

The physiochemical properties of several blends of raw, gelatinised and dextrinised commercial yellow corn flour were evaluated [48] and the results compared to those of raw commercial yellow corn flour extruded at a range of moisture contents. The extruded samples had properties similar to blends containing gelatinised and dextrinised corn. Reduction of the extrusion moisture level resulted in an increase in the relative proportion of dextrinised corn from 10% to 60%. It was suggested that dextrinisation is the dominant mechanism for starch degradation during extrusion, especially at low moisture contents.

Colonna et al. [49] extruded modified wheat starch and found this led to a macromolecular degradation of amylose and amylopectin, by random chain splitting. The water soluble fractions were composed of partly depolymerised amylose and amylopectin. It was also concluded that shear in the extruder completely disperses starch components by decreasing molecular entanglement.

A study [50] to evaluate the structural modifications occurring during extrusion cooking of wheat starch revealed that the amylopectin fraction of the starch was significantly degraded during extrusion and the degradation products were also macromolecules. It was felt that the structural modifications occurring during the extrusion was limited debranching, attributed to mechanical rupture of covalent bonds.

A study [51] of the effect of moisture content, screw speed and barrel temperature on starch fragmentation of corn starch found that carbohydrate from the extruded samples dissolved at a significantly faster rate than from native corn starch, with a pronounced difference in the amount of material solubilised within the first 2 h. It was suggested that this was indicative of an increase in the amount of linear polysaccharide and thus an increase in the degree of fragmen-

tation. The amount of large molecular weight material decreased from 68% to a range of 24–58%, depending upon the extrusion conditions applied. Reductions in moisture content or temperature resulted in an increase in fragmentation, whilst decreasing the screw speed resulted in a decrease in fragmentation.

Bhattacharya and Hanna [52] studied the effect of moisture content, barrel temperature and screw speed on the textural properties of extrusion-cooked corn starch. Their results showed that the feed moisture content and barrel temperature affected the expansion of the extruded products predominantly. Increasing the moisture content reduced expansion in both waxy and nonwaxy corn starch samples. They suggest that this is due to a reduction in the dough/melt temperature that in turn reduces the degree of gelatinisation. An increase in the barrel temperature was found to increase the degree of expansion reflecting an increase in gelatinisation. Similar results were reported on the extrusion of potato flakes [53]. Screw speed was shown to be insignificant in its effect on expansion of the product. Although an increase in the screw speed increased the rate of shear and hence the degree of starch modification, this was accompanied by a reduction of residence time which cancelled out the effect of the additional shear. The shear strength of the products was found to increase with increasing moisture content, reflecting the decrease in expansion and increase in density.

The effect of screw speed on the extrusion of mixtures of yellow corn meal with wheat and oat fibres has been reported [54]. An increase in the screw speed was found to reduce the torque and die pressure, whilst increasing the specific mechanical energy and resulting in a decrease in radial expansion, with increases in axial expansion, bulk density and breaking force. It is suggested that the reduction in torque and die pressure is the result of a decrease in the screw fill. The reduction in radial expansion and the increases in axial expansion, bulk density and breaking force are reported to be due to the reduced die pressure and resistance to the flow of extrudate at the die. These results are contrary to those of Fletcher et al. [55], who observed an increase in die pressure and radial expansion with increasing screw speed. The conflicting results in these studies suggest that the textural characteristics may or may not be affected by screw speed, depending upon the feed material and the geometry and design of the screw used.

Although the extrusion characteristics of cereals are dominated by the physical and chemical changes occurring in the starch component, cereals typically contain 6–16% protein and 0.8–7.0% lipid, which can significantly affect the properties of the extruded product [56]. In addition to the components of the cereal itself, a wide variety of materials are incorporated into cereal extrusion mixes to modify the characteristics of the final product.

Protein Typically protein acts as a ‘filler’ in cereal extrudates and is dispersed in the continuous phase of the extrusion melt, modifying the flow behaviour and characteristics of the cooled extrudates. Proteinaceous materials hydrate in the mixing stage of the process and become soft viscoelastic doughs during formation of the extrusion melt. The shearing forces generated in the extruder

cause breakage of the protein into small particles of roughly cylindrical and globular shapes. At levels of around 5–15%, they tend to reduce the extensibility of the starch polymer foam during its expansion at the die exit, reducing the degree of expansion [56].

Extrudates show a reduction in cell size with the addition of protein proportional to the amount of protein added. At higher levels of protein, severely torn regions in the cell walls of the extrudate are noted, indicating a loss of elasticity in the extrusion melt.

Martinez-Serna et al. [57] investigated the effects of whey protein isolates on the extrusion of corn starch. The isolates were blended with corn starch at concentrations between 0% and 20% and then extruded at varying barrel temperatures, screw speeds and moisture contents. Their results showed that an increase in barrel temperature increased the level of starch-protein interaction. Extrusion of the blend showed a 30% reduction in expansion when compared to extruded corn starch alone. They suggest that this is due to modification in the viscoelastic properties of the dough, as a result of competition for the available water between the starch and protein fractions, leading to a delay in starch gelatinisation. Increasing the screw speed and hence shear rate led to an increase in viscosity due to unfolding of the protein, involving rupture of covalent bonds or interaction with the starch. A similar trend was also observed when the protein concentration was increased.

Fat Fats and oils have two functions in starch extrusion processes. They act as a lubricant in the extrusion melt and modify the eating qualities of the final extruded product. The action of the extruder screws causes the oils to be either dispersed into small droplets or smeared on the polymers [56].

Extrusion of starches with low lipid contents, such as potato or pea starch, at low moisture contents (<25%) is extremely difficult, due to degradative dehydration of the starch polymers. This results in the formation of a very sticky melt, which tends to cause blockages. The addition of 0.5–1.0% of an oil to the starch reduces the degradation of the starch and enables extrusion without blockages [56].

The macromolecular modifications occurring in manioc starch extruded without and with a range of lipids (oleic acid, dimodan, copra and soya lecithin) have been investigated [58]. The results showed that an increase in extrusion temperature or screw speed increased the degree of macromolecular degradation of the native manioc starch. Addition of all lipids at 2% was shown to reduce the degree of macromolecular degradation, with all samples having higher intrinsic viscosities than the native starch extruded under the same conditions. Whilst all of the added lipids gave rise to an increase in the intrinsic viscosity, differences were apparent between each of the lipid-starch extrudates, suggesting different modes of action for each of the lipids studied.

A highly expanded oat cereal product is difficult to achieve due to its high fat content. The effects of the process conditions on the physical and sensory properties of an extruded oat-corn puff showed that increasing the level of oat flour

(and hence fat content) caused an increase in the extrudate bulk density and a reduction in specific length and expansion [59].

An investigation into the improvement of extruded rice products showed that defatting of the flour resulted in improved expansion and lower bulk densities [60].

Sugars Sucrose and other sugars are commonly added to extruded products, particularly breakfast cereals. The level of sugar added to a product varies but is typically within the range 6–25 wt% on a final dry product basis. Sugar contributes to binding, flavour and browning characteristics and is important in controlling texture and mouthfeel. In addition, it can act as a carrier and potentiator of other flavours.

The effects of sucrose on the structure and texture of extrudates has been studied extensively.

When extrusion is carried out at moisture contents above 16%, addition of sucrose progressively reduces extrudate expansion, with an accompanying increase in product density. This effect was noted at sucrose concentrations as low as 2% when extruding with a feed moisture of 20% [61]. In addition to the reduction in expansion and increase in density, an increase in mechanical strength and the number of cells formed per unit area has been observed [62]. The structural changes in the extrudates brought about by the addition of sucrose have been attributed to competition for moisture, inhibition of gelatinisation and plasticisation of starch-based systems by low molecular weight constituents during extrusion.

The effect of sucrose and fructose on the extrusion of maize grits indicated inhibition of starch conversion due to a reduction in specific mechanical energy input [63]. In addition, a change in the packing of amylose-lipid complexes in the extrudate was noted. It is suggested that this rearrangement process is accelerated by the addition of the sugars due to the enhanced molecular mobility.

The effect of sucrose on both maize and wheat flour extrudates showed that, in contrast to maize extrudates, sucrose addition had little effect on the degree of starch conversion and sectional expansion of wheat flour extrudates [64]. It was postulated that the observed differences between the wheat-sucrose and maize-sucrose extrudates may be a result of particle size and the presence of gluten.

8.2.3.2 Nutritional Changes

Protein Extrusion cooking, like other food processing, may have both beneficial and undesirable effects on the nutritional value of proteins. During extrusion, chemical constituents of the feed material are exposed to high temperature, high shear and/or high pressure that may improve or damage the nutritional quality of proteins in the extruded materials by various mechanisms. These changes depend on temperature, moisture, pH, shear rate, residence time, their interactions, the nature of the proteins themselves and the presence of materials such as carbohydrates and lipids.

The proteins present in the feed material may undergo structural unfolding and/or aggregation when subjected to heat or shear during extrusion. Intact protein structures represent a significant barrier to digestive enzymes; and the combination of heat and shear is a very efficient way of disrupting such structures.

In general, denaturation of protein to random configurations improves nutritional quality by making the molecules more accessible to proteases and, thus, more digestible. This is especially important in legume-based foods that contain active enzyme inhibitors in the raw state.

Disulphide bonds are involved in stabilizing the native tertiary configurations of most proteins. Their disruption aids in protein unfolding and thus digestibility. Mild shearing can contribute to the breaking of these bonds.

Partial hydrolysis of proteins during extrusion increases their digestibility by producing more open configurations and increasing the number of exopeptidase-susceptible sites. Conversely, production of an extensively isopeptide cross-linked network could interfere with protease action, reducing the digestibility [65].

The Maillard reaction may take place during extrusion cooking of protein foods containing reducing sugars. The chemical reaction between the reducing sugars and a free amino group on an amino acid has important nutritional and functional consequences for extruded products. Maillard reactions can result in a decrease in protein quality, by lowering digestibility and producing nonutilisable products. During extrusion, the Maillard reaction is favoured by conditions of high temperatures ($>180^{\circ}\text{C}$) and shear (>100 rpm) in combination with low moisture ($<15\%$) [66].

Loss of total lysine and changes in the *in vitro* availability of amino acids in protein-enriched biscuits when extruded at different mass temperatures and moisture contents have been investigated [67, 68]. It was found that digestibility of the product extruded at 170°C was not different from that of the raw material. However, increasing the mass temperature to 210°C decreased the *in vitro* digestibility.

In a similar study [69], it was reported that screw speed was not a major factor in the retention of available lysine, but 40% of the available lysine present in the unextruded mix was lost during extrusion conditions above 170°C mass temperature at a moisture content of 13%. The loss of lysine decreased when the water was increased to 18%, despite an increase in barrel temperature to produce an equivalent mass temperature to the 13% moisture mixture. Higher losses in lysine were observed with increased sucrose content and reduced pH.

Extrusion of corn gluten meal and blends of corn gluten meal and whey at various screw speeds and barrel temperatures showed an increase in the *in vitro* digestibility of the extruded product when compared to the raw material [70]. It was also found that the addition of whey had no significant effect on digestibility.

The protein nutritional value of extruded wheat flours was studied by Bjorck et al. [71]. Amino acid analysis showed that lysine retention was between 63% and 100%. It was found that the retention was positively affected by an increase

in feed rate and negatively by an increase in screw speed. The authors felt that the prominent lysine damage under severe conditions was probably due to the formation of reducing carbohydrates through the hydrolysis of starch. The loss of other amino acids was found to be small.

The effects of a range of extrusion process variables on the *in vitro* protein digestibility of minced fish and wheat flour mixes have been studied [72]. The extrudates showed slight increases in their *in vitro* protein digestibility values. The authors found that, of the process variables studied, only the effects of feed rate and temperature of extrusion were significant.

The effect of extrusion on the *in vitro* protein digestibility of sorghum showed that varying screw speed and moisture content did not have a significant effect on the digestibility of sorghum, but temperature was significant in improving the digestibility of sorghum [73].

Dahlin and Lorenz [74] investigated the effect of extrusion on the protein digestibility of various cereal grains (sorghum, millet, quinoa, wheat, rye and corn). When the extrusion feed moisture was decreased from 25% to 15%, an increase in protein digestibility was observed. It was found that a screw speed of 100 rpm and a product temperature of 150°C improved the *in vitro* protein digestibility of all cereals studied.

Extrusion of a yoghurt-wheat mixture at a constant moisture content of 43% showed no decrease in the *in vitro* protein digestibility, up to barrel temperatures of 120°C and screw speeds of 300 rpm [75].

In addition to lysine loss and decrease in protein digestibility, the colour of an extruded product is another indication of the extent of the Maillard reactions. A correlation was found between the degree of browning of extruded wheat flour and the total lysine content of the samples [71]. It was also found that there was a positive correlation between Hunter *L* values for wheat-based breakfast cereals and *in vitro* protein digestibility and available lysine [76].

Vitamins The retention of vitamins in extrusion cooking generally decreases with increasing temperature, increasing screw speed, decreasing moisture, decreasing throughput, decreasing die diameter and increasing specific energy input [77].

The stability of thiamin, riboflavin and niacin during the extrusion cooking of full-fat soy flour has been studied [78, 79]. Different barrel temperatures and water contents of feed material with a residence time of 1 min did not affect riboflavin and niacin. However, some loss of thiamin was observed at high moisture (<15%), high barrel temperature (<153°C) and long residence times (<1 min).

The retention of thiamin and riboflavin in maize grits during extrusion has been studied [80]. The average retention was 54% for thiamin and 92% for riboflavin. These workers found that moisture content (13–16%) did not have any effect on the stability of thiamin. An increased degradation was seen for thiamin with increasing temperature and screw speed. Riboflavin degradation increased with increasing moisture content and screw speed.

Thiamin losses in extruded potato flakes at a range of barrel temperatures and screw speeds, different screw compression ratios and die diameters and a

moisture content of 20% have been studied [53]. It was reported that thiamin loss did not exceed 15% in all runs.

The importance of moisture content on the retention of thiamin in potato flakes during extrusion indicated that, at moisture contents of 25–59%, retention ranged from 22% to 97% [81]. The retention was poor at low moisture contents.

Thiamin losses in extruded legume products with increase in process temperature (93–165 °C), pH (6.2–7.4) and screw speed (10–200 rpm) have been reported [82]. The retention of thiamin increased with higher moisture contents (30–45%).

The effect of throughput and moisture content on the stability of thiamin, riboflavin, B₆, B₁₂ and folic acid when extruding flat bread showed that vitamin stability improved with increased throughput and increased water content [83].

Guzman-Tello and Cheftel [84] studied the stability of thiamin as an indicator of the intensity of thermal processing during extrusion cooking. They found that retention of thiamin decreased from 88.5% to 57.5% when the product temperature increased from 131 °C to 176 °C. Other extrusion parameters were kept constant. More thiamin was retained by increasing the moisture content (14.0–28.5% wet basis), while higher screw speeds (125 rpm and 150 rpm) caused higher losses.

At screw speeds up to 300 rpm at a barrel temperature of 120 °C, no loss of thiamin and riboflavin was observed when extruding a yoghurt-wheat mixture at a moisture content of 43% [75].

Although extrusion systems can be successfully used with higher vitamin retentions, food manufacturers often carry out vitamin fortification postextrusion, by dusting, enrobing, spraying or coating.

8.2.3.3 Flavour Formation and Retention During Extrusion

Much of the flavour, or the volatile components of flavour are either lost to the atmosphere as the extrudate exits the die or they become bound to starch or proteins during extrusion. Because of the high losses, flavours are generally added after extrusion. Postextrusion flavouring processes have many disadvantages, including difficulty in obtaining even application, possibility of contamination and rubbing off of the coating in the package or consumer's hands. A limited range of encapsulated and extrusion stable flavours have been developed to address these problems. However, these are often restricted in application due to their cost. An alternative approach to the problem of flavouring extruded products involves the addition of reactive flavour precursors to the extrusion mix. The conditions applied during the extrusion process cause a reaction of the precursors to produce the desired flavour compounds. These precursors are usually compounds known to participate in the browning and flavour reactions that occur normally during the extrusion process.

In the extrusion of cereal-based products, flavours are predominantly generated by nonenzymic browning reactions, typified by caramelisation, the Maillard reaction and oxidative decomposition.

The temperature and shear conditions generated in the extruder provide the physical and chemical means whereby starch and protein can be partially degraded to provide the reactants that can then participate in nonenzymic browning reactions. In addition, lipids (especially unsaturated lipids) may undergo thermal degradation, thereby providing additional flavour compounds.

An evaluation of the volatile compounds and colour formation in a whey protein concentrate-corn meal extruded product showed 71 volatile compounds in the headspace of the samples, 68 of which were identifiable [85]. The compounds present included 12 aldehydes, ten ketones, six alcohols, two esters, six aromatics and ten hydrocarbons. In addition, 11 pyrazines, four furans, five heterocyclics and two sulphur compounds were isolated. They suggest that these compounds were products of the Maillard reaction and are possibly the most important in contributing to the corn flavour of the product. The concentrations of pyrazines, furans and other heterocyclics were found to increase with increasing levels of whey protein in the extrudates.

Nair et al. [86] identified 91 compounds in the condensate flash off at the die and 56 compounds from the headspace of the extrudate of corn flour. They suggest that the difference in the composition of the two samples is a reflection of the volatility with water of the compounds. Whilst their study identified a significant number of compounds formed during extrusion were retained in the extrudate, it was concluded that flash off at the die is still a major hindrance to the flavouring of extruded products.

The effects of product temperature, moisture content and residence time on the aroma volatiles generated during the extrusion of maize flour have been investigated by Bredie et al. [87]. Their results showed that low temperatures and high moisture contents favoured the production of volatiles associated with lipid degradation. Increasing both the temperature and residence time, along with a reduction in moisture content, was reported to increase the production of compounds derived from the Maillard reaction whilst reducing the levels of those compounds associated with lipid degradation.

The effect of pH on the volatiles formed in a model system, containing wheat starch, lysine and glucose, showed that both the total yield and number of compounds formed are greater at pH 7.7 than at pH 4.0 and pH 5.0, where the total yields are similar [88]. At pH 7.7, the volatile compounds from the extrudate were dominated by pyrazines that gave the extrudates a nutty, toasted and roasted character. Modification to pH 4.0 or pH 5.0 reduced the production of pyrazines and increased the production of 2-furfural and 5-methylfurfural, which accounted for over 80% of the total volatiles. It is suggested that the presence of these compounds is an indication of starch degradation, leading to an additional source of carbohydrate precursor during extrusion. They conclude that it may be possible to control flavour and colour development by careful control of the processing conditions.

Using a trained sensory panel to study the aroma profile of extrudates produced from wheat flour and wheat starch fortified with mixtures of cysteine, glucose and xylose [89], a vocabulary of 24 odour attributes was developed, with

17 of the attributes significantly differentiating the samples. The results indicated that extrusion of the wheat flour alone resulted in an extrudate aroma that was characterised by the terms biscuity, cornflakes, sweet and cooked milk. Addition of cysteine and glucose resulted in major differences in aroma, with the cereal terms popcorn, nutty/roasted and puffed wheat predominating. Cysteine/xylose mixtures gave rise to sulphur odour notes, such as garlic-like, onion-like, rubbery and sulphury, with the less desirable terms acrid/burnt, sharp/acidic and stale cooking oil becoming apparent.

A more extensive study using wheat starch, cysteine, xylose and glucose extruded at a range of pH and target die temperatures has been carried out [90]. Extrudates prepared using glucose were more frequently described as biscuity and nutty, whereas those prepared using xylose were commonly described using the terms meaty or onion-like. Analysis of the extrudates identified 80 compounds. Yields of the compounds formed were generally higher in extrudates prepared using xylose than those using glucose, under the same processing conditions. Increases in temperature and pH were reported to increase the yields of the compounds formed. Pyrazines and thiophenes were amongst the most abundant classes of compounds identified. Results from the analysis of the extrudates prepared using glucose showed aliphatic sulphur compounds and thiozoles to feature strongly in the aroma, whereas use of xylose gave rise to both nonsulphur-containing and sulphur-containing furans.

8.3

Frying

Pedro Bouchon

8.3.1

General Principles

Deep-fat or immersion frying is an old and popular process, which originated and developed around the Mediterranean area due to the influence of olive oil [91]. Today, numerous processed foods are prepared by deep-fat frying all over the world since, in addition to cooking, frying provides unique flavours and textures that improve the overall palatability. This section briefly describes the frying process from industrial and scientific perspectives. First, it introduces the process and presents some fried food quality characteristics. Thereafter, it describes the equipment and oils used in frying and some features of potato chip and potato crisp production. Finally, this section reviews main research in the field.

8.3.1.1 The Frying Process

Deep-fat frying can be defined as a process for the cooking of foods, by immersing them in an edible fluid (fat) at a temperature above the boiling point of water [92]. Frying temperatures can range from 130°C to 190°C, but the most common temperatures are 170–190°C. Immersion frying is a complex process that involves simultaneous heat and mass transfer resulting in counterflow of water vapour (bubbles) and oil at the surface of the food. In addition, frying induces physicochemical alterations of major food components and significant microstructural changes [93]. In fact, most of the desirable characteristics of fried foods are derived from the formation of a composite structure: a dry, porous, crisp and oily outer layer or crust, with a moist, cooked interior or core. The crust is the result of several alterations that mainly occur at the cellular and subcellular level and are located in the outermost layers of the product. These chemical and physical changes include: physical damage produced when the product is cut and a rough surface is formed with release of intracellular material, starch gelatinisation and consequent dehydration, protein denaturation, breakdown of the cellular adhesion, water evaporation and rapid dehydration of the tissue and, finally, oil uptake itself.

Dehydration, high temperatures and oil absorption distinguish frying from simmering, which occurs in a moist medium and where the temperature does not exceed the boiling point of water. During baking, heat transfer coefficients are much lower than during frying and, although there is surface dehydration and crust formation, there is no oil uptake. In addition, the high temperatures achieved during frying (usually more than 150°C) allow enzyme inactivation, intercellular air reduction and destruction of microorganisms, including pathogens [94].

8.3.1.2 Fried Products

A wide variety of food materials is used to make fried products, including meats, dairy, grains and vegetables. Different shapes and forms, such as chips, crisps, doughnuts, battered and breaded food, among others, can be found in the market. Therefore, frying technology is important to many sectors of the food industry: including suppliers of oils and ingredients, fast-food shop and restaurant operators, industrial producers of fully fried, parfried and snack foods and manufacturers of frying equipment [95].

The quantities of food fried and oils used at both the industrial and commercial levels are huge. For example, the USA produces, on average, over 2.3×10^6 t of sliced frozen potato and potato products every year, the majority of which are fried or partially fried [96]. Commercial deep-fat frying has been estimated to be worth $\pounds 45 \times 10^9$ in the USA and at least twice this amount for the rest of the world [95]. In the UK, the crisp market is currently worth $\pounds 693 \times 10^6$, while all other snack products together are worth $\pounds 751 \times 10^6$ [97].

One of the most important quality parameters of fried products is the amount of fat absorbed during the frying process [98]. Per capita consumption of oils

Table 8.4 Oil absorption in fried foods.

Food item	Fat (g) absorbed in 100 g edible portion
Frozen chips	≈ 5
Fresh chips	≈ 10
Battered food (fish/chicken)	≈ 15
Low fat crisps	≈ 20
Breaded food (fish/chicken)	15–20
Potato crisps	35–40
Doughnuts ^{a)}	15–20

- a) Doughnuts also contain about 10% fat used in preparation of the dough.

and fats was estimated to be 62.7 lb year⁻¹ (28.4 kg year⁻¹) in the USA, far exceeding the recommendations found in The Surgeon General's Report on Nutrition and Health [99]. Excess consumption of fat is considered as the key dietary contributor to coronary heart disease and perhaps cancer of the breast, colon and prostate [100]. Therefore, consumer trends are moving towards healthier food and low-fat products, creating the need to reduce amount of oil in end products. Despite such market forces, the consumption of snack food is increasing in developed and developing countries, and fried products still contain large amounts of fat. An example of the total oil content of selected snack and fast foods is presented in Table 8.4 (from [101]). Most of these products have an oil content varying from 5% (frozen chips) to 40% (potato crisps).

In addition, recently, Swedish scientists sounded an alarm in April 2002, when they discovered that certain cooked foods, particularly potato crisps and potato chips, contained high levels of acrylamide, a chemical compound that is listed by the World Health Organization (WHO) as a probable human carcinogen [102]. Acrylamide is a substance used to produce plastics and dyes that can be produced when foods are heated above 120°C, due to a reaction between amino acids and reducing sugars [103]. Today, there is no consensus about whether acrylamide in food is a danger and the WHO has not called yet for any reduction in foods containing high levels of this compound.

As mentioned, there is an increased demand for low-fat products. However, reduced and no-fat crisps varieties represent only 11% of potato crisp market sales in the USA [104]. Sales of fat-free snacks are increasing but, as these products are baked rather than fried, they have different flavour and textural characteristics to fried crisps and, therefore, consumer acceptance is low. However, low-fat snacks, such as crisps or tortilla chips, are acquiring greater acceptance. These products are usually dried prior to frying and research is focused in developing a product with enough fat to impart the desired organoleptic properties.

8.3.2

Frying Equipment

Frying equipment can be divided into two groups: (a) batch frying equipment, which is used in small plants and catering restaurants, and (b) continuous frying equipment, which is used on the industrial scale to process large amounts of product.

8.3.2.1 Batch Frying Equipment

A batch fryer consists of one or more chambers with an oil capacity in the range 5–25 l. The oil can be heated directly by means of an electrical resistance heater that may be installed a few centimetres above the bottom of the fryer. This enables a cool zone to be formed at the bottom of the vessel where debris can fall, remaining there and minimising oil damage. The fryer can also be heated by direct gas flames underneath the bottom of the vessel, although this arrangement makes the provision of a cold zone under the heaters difficult [101]. Recently developed high-efficiency fryers include turbojet infrared burners which use less than 30–40% energy than standard gas-fired fryers with the same capacity [104]. Modern batch fryers are constructed with high-grade stainless steel; and no copper or brass is used in any valve fitting or heating element, to avoid oxidation catalysis. Usually, the operators immerse and remove the baskets manually from the oil, but new equipment may include an automatic basket lift system that rises automatically when the frying time is finished. Removal of food scraps and oil filtration is an essential practice that needs to be carried out on a daily basis, to increase oil shelf life and avoid smoking, charring and off flavours. New equipment can also have an inbuilt pump filtration unit for the removal of sediments [105]. Some catering outlets, especially those devoted to chicken frying, prefer to use pressure batch fryers. These reduce frying time considerably and the fried products have a high moisture content, with a uniform colour and appearance [104].

8.3.2.2 Continuous Frying Equipment

Large-scale processing plants use continuous fryers. These are automated machines that consist of a frying vessel where oil is maintained at the desired temperature, a conveyor that displaces the product through the unit and an extraction system that eliminates the fumes, primarily made up of moisture and a fine mist of fatty acids.

The oil can be heated either directly by means of an electric heater or a battery of gas burners, or indirectly, by pumping a heated thermal fluid into the pipes immersed in the oil bath. Some fryers are equipped with external heat exchangers. In those systems, the oil is continuously removed at the discharge end of the tank, pumped through a filter unit and then through an external heat exchanger, before it is returned to the receiving end of the vessel (see

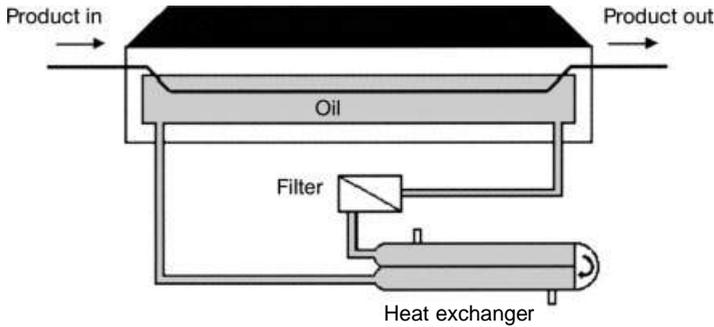


Fig. 8.16 Scheme for a fryer with an external heating system and fat filter unit.

Fig. 8.16). Some continuous fryers are designed with multiple heating zones along the fryer that can be adjusted separately, providing optimal temperature control to improve product quality.

As the oil is absorbed by the fried product, it has to be made up with fresh oil continuously. The amount of fresh oil added to the vessel defines the oil turnover [105]:

$$\text{Oil turnover} = \frac{\text{weight of oil in fryer}}{\text{weight of oil added per hour}}$$

which represents the time needed to replace all the oil contained in the fryer. A fast oil turnover is desired as it maintains satisfactorily the level of free fatty acids, preserving oil quality for longer periods of time. Normally, the oil turnover is kept at 3–8 h [105].

Industrial fryers have oil capacities ranging from 200 kg to 1000 kg and can produce up to 25 000 kg h⁻¹ of chips and 2500 kg h⁻¹ of crisps. Some of the main frying equipment manufacturers are Florigo B.V. in The Netherlands, Heat and Control and Stein in the USA.

In the last decade, the continuous vacuum frying system developed by Florigo B.V. during the 1960s has been reintroduced. The equipment was first created to produce high-quality chips but, due to the improvement in blanching technology and raw material quality, the use of this technology almost disappeared [104, 106]. Nowadays, vacuum frying technology is being used to maintain natural colours, flavours and nutrients in products with high added value, such as vegetables and fruits, due to the fact that much lower temperatures can be applied during frying.

8.3.2.3 Oil-Reducing System

Given the current concern with lowering the diet fat contents, an oil-reducing unit has been developed. The equipment is mounted at the discharge end of the fryer and removes the fat excess from the recently fried food, using a steam-

ing and drying technology. Superheated steam at 150–160°C, which is circulated by fan through the heat exchangers, flows through the product bed and removes nonabsorbed surface oil from the hot surface of the food. Consecutively, the oil-vapour mixture is filtered and the oil is pumped back to the fryer. The low-fat stripping system can reduce oil content in crisps by 25% [107]. Units range from batch strippers for pilot plants or product development to continuous production units.

8.3.3

Frying Oils

Food can be fried in a wide range of oils and fats, including vegetable oils, shortenings, animal fats or a mixture thereof. The main criteria used to select frying oils are: long frying stability, fluidity, bland flavour, low tendency to foam or smoke formation, low tendency to gum (polymerise), oxidative stability of the oil in the fried food during storage, good flavour stability of the product and price [101, 105]. The fat melting point is a very important parameter, as it affects the temperature of heating in tanks and pipes during storage and handling; and also it may affect the sensory attributes of fried products that are eaten at colder temperatures. Conversely, fats with a high melting point frequently have less tendency to oxidation.

Frying oils are principally from vegetable sources. Some traditional oils used for frying are: corn, cottonseed and groundnut oils, which are used as a stable source of polyunsaturated fatty acids due to their low linolenic acid content [108]. However, over recent decades, the use of groundnut oil has diminished due to its cost and also due to production problems related to naturally occurring aflatoxins [101, 105].

Nowadays, palm oils are increasingly used in industrial frying. Palm oil is a semisolid fat, which is fractionated at low temperature to give a liquid fraction called palm olein with a melting point that ranges between 19°C and 24°C and a fraction called palm stearin, with a high melting point, melting at no less than 44°C. Also, a double-fractionated oil called super olein can be obtained, which has a melting point range of 13–16°C. Palm olein is liquid enough for frying use; however, super olein is the grade used to produce fully liquid frying oil blends, together with sunflower and groundnut oils. Palm oil and palm olein have a very good frying performance due to their high resistance to oxidation and flavour reversion because of their low unsaturation; and they are now becoming virtually the standard oils for industrial frying in West Europe [109]. However, the high level of saturated (palmitic) fatty acids (38.2–42.9% in palm olein and 40.1–47.5% in palm oil) may be criticised from a nutritional view point.

Rapeseed (canola) and soyabean oils have a high level of linolenic acid (8–10%), making them vulnerable to oxidation and off flavour development; and therefore they can be slightly hydrogenated for industrial frying. This procedure can also be applied to sunflower oil and may be attractive where an oil with a high polyunsaturated to saturated ratio is needed for dietary purposes [101].

Olive oil has excellent attributes that make it suitable as a frying oil. It has a low level of polyunsaturated fatty acids and a mixture of phenolic antioxidants that make it resistant to oxidation. Extra-virgin and virgin olive oils are expensive for industrial use, although refined solvent-extracted olive oil can be satisfactory for industrial frying.

Animal fats are also used for frying in some regions, due to the characteristic flavours that they impart to the fried food, despite their high level of saturated fatty acids. Fish oils are rarely used for frying, as their high level of long-chain polyunsaturated fatty acids makes them prone to oxidation [101].

Recently some fat substitutes, such as sucrose polyesters (olestra), have been extensively studied. In fact, Olean (Procter & Gamble's brand name for olestra) has been introduced in the USA and several snacks fried in olestra are already in the market (fat-free Pringles, Frito-Lay Wow). Olestra is synthesised from sucrose and fatty acid methyl esters and has no calories because its structure prevents digestive enzymes from breaking it down. Two main negative aspects are currently discussed in relation to olestra that impair its acceptance in other countries. First, olestra can cause gastrointestinal discomfort in some people and, second, there is some debate about the ability of olestra to reduce the absorption of fat-soluble nutrients [104].

Antioxidants such as tertiary butyl hydroquinone (TBHQ), butylated hydroxyanisole (BHA) and butylated hydroxytoluene (BHT) are usually added to improve oil stability. TBHQ is regarded as the best antioxidant for protecting frying oils against oxidation and, like BHA and BHT, it provides carry-through protection to the finished fried product.

8.3.4

Potato Chip and Potato Crisp Production

Potato is the primary raw material used in the frying industry. The storage organ and hence the food part of potato is the tuber, essentially a thickened underground stem, which is made of 2% skin, 75–85% parenchyma and 14–20% pith [110]. The anatomy of the potato plant has been described in detail by Artschwager [111, 112], from Talburt [113]. In terms of their composition, potatoes are mainly made up of water, having an average of 77.5% (range 63.2–86.9%) [113]. The chemical composition of the remaining solid part can greatly vary, depending on a wide range of factors, including variety, maturity, cultural practice, environmental differences, chemical application and storage conditions. Starch represents 65–89% of the dry matter weight; and amylose and amylopectin are usually present in a 1:3 ratio [114]. Starch granules are ellipsoidal in shape, about $100 \times 60 \mu\text{m}$, much larger than the average starch granules of cereal grains.

For potato fried products, potatoes with high solids content (20–22%) are preferred, as they result in better finished product texture, higher yields and lower oil absorption [115]. Also, low reducing sugar contents are required to minimise colour development during processing, which is generated by the Maillard, nonenzymatic browning reaction [116].

8.3.4.1 Potato Chip Production

Potato chips are traditionally produced by cutting potato strips from fresh potatoes (parallelepiped of 1×1 cm cross-section by 4–7 cm in length), which are then deep-fat fried. Three major kinds of chip are produced at a commercial scale: (a) deep-frozen completely fried chips, which just require oven heating, (b) deep-frozen partially fried chips, which require additional frying before eating, and (c) refrigerated partially fried chips, which have a short shelf life and need additional frying [117]. A summary of the production process is described below.

The technology of chip production progressively improves as the industry develops modern equipment and entire technological lines for its manufacture [117]. Processors of frozen chips wash and peel potatoes with lye or steam, as abrasion peeling results in higher losses. Peeled potatoes are conveyed over trimmers and cut. Strip cutters orient potatoes along the long axis, in order to obtain the greatest yield of long cuts. Subsequently, chips are blanched in hot water prior to frying. The usual range of water temperatures is $60\text{--}85^\circ\text{C}$. The positive effects of blanching include: a more uniform colour of the fried product, reduction of the frying time, since the potato is partially cooked, and improvement of texture of the fried product [118]. After blanching, excess water is removed, in order to minimise the frying time and lower the oil content of the product. This is carried out by means of dewatering screens and, subsequently, blowing warm air in continuous dryers. Afterwards, potato strips are parfried in a continuous fryer. The frying time is controlled by the rate of conveyor movement, oil temperature, dry matter content in the potato tubers, size of strips and type of processed chip (parfried or finish fried). The most common tem-

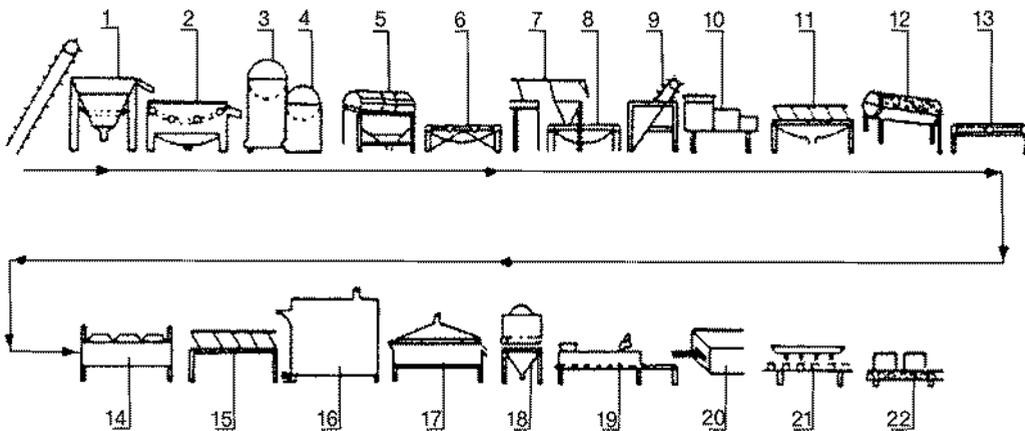


Fig. 8.17 Flow sheet for frozen chips:
 1, trash remover; 2, washer; 3, preheater;
 4, lye peeler; 5, washer; 6, trimming belt;
 7, 8, size grader; 9, surge hopper; 10, strip
 cutter; 11, sliver eliminator; 12, nubbin elim-

inator; 13, inspection belt; 14, blancher;
 15, dewatering screen; 16, dryer; 17, fryer;
 18, deffater; 19, cooler; 20, freezer; 21, pack-
 age filler; 22, freezing storage; from [117].

perature range falls within 160°C and 180°C. Temperatures above 190°C are not used, due to the possibility of more rapid oil breakdown. The recommended frying parameters are, for finish-fried chips, 5 min at 180°C and, for parfried, 3 min at 180°C [117].

The excess fat is removed by passing the product immediately after emerging from the fryer over a vibrating screen, allowing the fat to drain off and, thereafter, the product is air-cooled for about 20 min while it is conveyed to the freezing tunnel. Finally, the product is packed in polyethylene/polypropylene bags or in cartons for the retail trade. A flow sheet for frozen chips is presented in Fig. 8.17.

8.3.4.2 Potato Crisp Production

Snack food manufacturers produce two types of potato crisps: traditional crisps made by thinly slicing fresh potatoes and crisps processed from potato dough and formed into potato crisp shapes. Processing lines for potato crisps include similar steps as in potato chip production. Potatoes are washed, peeled and sliced, commonly using a rotary slicer. Shape and thickness can be varied to meet marketing needs, but thickness is usually in the range 50–60 thou (1.27–1.52 mm). To remove excess starch, the potato slices are washed and dried on a flat wire conveyor to remove as much surface starch and water as possible [119]. Some potato processing plants use blanching prior to frying to improve the colour of the crisp. The blanching solution is heated to 65–95°C and blanching takes around 1 min. Then excessive water is removed. Thereafter, potatoes are usually fried in a continuous fryer, where they remain from 1.5–3.0 min at 170–190°C, until the moisture level is less than 2% of the total weight. The frying time depends on the flow of slices to the fryer, the initial moisture level of the potato and the desired browning. Subsequently, crisps are conveyed, allowing excess oil to drain off, and are salted or flavoured. Finally, crisps are cooled on a conveyor and sorted by size before packaging.

Crisp products, made from potato dough, are normally based on starch-containing ingredients such as potato flakes, flours, starches, ground slices, meals, granules or mixtures thereof. Dry ingredients are mixed, normally followed by the addition of the liquid ingredients. Thereafter, the mixture is introduced to the sheeting line, where they are formed into discrete pieces. Subsequently, the product is fried in a continuous fryer, following a similar procedure to the one described above, for potato crisp manufacture. Production lines can vary depending on the final requirements and uses of the final product. Restructured potato crisps may not have similar flavour and textural characteristics to fresh potato crisps, but they have the advantages of uniformity and absence of defects.

8.3.5

Heat and Mass Transfer During Deep-Fat Frying

Deep-fat frying is a thermal process, in which heat and mass transfer occur simultaneously. A schematic diagram of the process is shown in Fig. 8.18, where it can be observed that convective heat is transferred from the frying medium to the surface of the product and, thereafter, conductive heat transfer occurs inside the food. Mass transfer is characterised by the loss of water from the food as water vapour and by the movement of oil into the food [93].

Farkas et al. [120] observed that the temperature at any location in the core region is limited to values below the boiling point of the interstitial liquid (approximately 105 °C). When all the liquid is evaporated from the region, the moving front propagates towards the interior and the temperature begins to rise, approaching the oil temperature. On the basis of visual observations and analysis of temperature profiles and moisture data, they suggested that the frying process is composed of four distinct stages:

1. Initial heating, which lasts a few seconds and corresponds to the period of time whilst the surface temperature reaches the boiling point of the liquid. Heat transfer is by natural convection and no vaporisation of water occurs.
2. Surface boiling, which is characterised by the sudden loss of water, the beginning of the crust formation and a forced convection regime due to high turbulence, associated with nucleate boiling.
3. Falling rate, which is the longest, in which the internal moisture leaves the food, the core temperature rises to the boiling point, the crust layer increases in thickness and finally the vapour transfer at the surface decreases.
4. Bubble end point.

Natural convective heat transfer coefficients range over 250–280 W m⁻² K⁻¹ at frying temperatures according to estimations from Miller et al. [121] and Moreira et al. [122], whereas forced convective heat transfer coefficients can achieve maximum values up to two or three times bigger than those measured in the absence of bubbling [97, 123–125]. This value gradually decreases over the duration of the process.

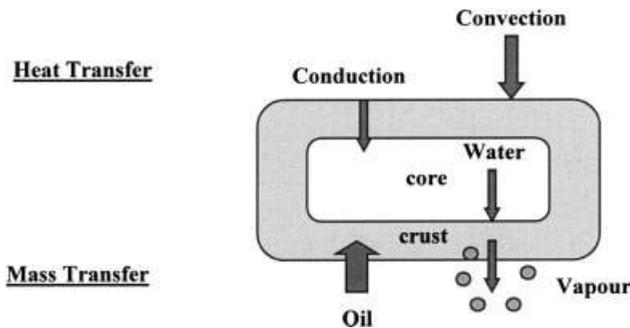


Fig. 8.18 Schematic diagram of simultaneous heat and mass transfer during frying.

8.3.6

Modelling Deep-Fat Frying

Many of the studies related to frying have been limited fundamentally to observations on the frying process. Mathematical models have been centred on the prediction of temperature profiles inside the fried food and the prediction of the kinetics of moisture loss; and very little has been carried out in relation to oil uptake. Models with different levels of complexity have been reported, which vary considerably in terms of the assumptions made. Most of the models for water evaporation during frying consider the fried product as a single phase, with no differentiation between the crust and the core regions and without the existence of a moving crust/core interface, where either energy or mass diffusion are considered to be the rate controlling mechanisms [126–135].

However, some authors have recognised the existence of two separate regions, the crust and the core, and have proposed a model considering the presence of a moving boundary [97, 120, 136, 137]. In fact, Farkas et al. [120] were the pioneers in developing a comprehensive model of thermal and moisture transport during frying. They formulated their model by analogy to freezing [138] and to the solution of the uniform retreating ice front during freeze-drying [139]. They provided different sets of equations for the two regions, separated by a moving boundary where the evaporation occurred. In their model they did not include the oil phase. They described the heat transfer in both regions using the unsteady heat transfer conduction equation, they considered water diffusional flow within the core region and they assumed that water vapour movement was pressure-driven. The final set of equations consisted of four nonlinear partial differential equations, which were solved using finite differences. The results were compared with experimental data; and they obtained a reasonable prediction for temperature profiles, water content and thickness of the crust region [140]. However, as Farid and Chen [136] pointed out, simulations were time-consuming, making it difficult to extrapolate the model to a multidimensional geometry and therefore they simplified the model. A similar approach was assumed by Bouchon [97], when modelling water evaporation in an infinite slab and in an infinite cylinder.

Ni and Datta [137] developed a multiphase porous media model to predict moisture loss, oil absorption and energy transport in a potato slab, also considering a moving front. They assumed that vapour and air transport were considered to be driven by convective and diffusive flows, while liquid water and oil were supposed to be driven by convective and capillary flows. Model predictions were compared with literature experimental data, mainly from Farkas et al. [140]. They centred their validation on temperature profiles, moisture content and crust thickness predictions, however, they did not include oil uptake absorption as part of their model validation.

8.3.7

Kinetics of Oil Uptake

The selection of a model needs to be in accordance with experimental observations that reveal how oil absorption takes place. It is not clearly understood yet when and how the oil penetrates into the structure, however it has been shown that most of the oil is confined to the surface region of the fried product [141–147] and there is strong evidence that it is mostly absorbed during the cooling period [132, 148–150].

Gamble et al. [151] gave a reasonable initial explanation of the deep-fat frying mechanism. They proposed that most of the oil is pulled into the product when it is removed from the fryer due to condensation of steam producing a vacuum effect. They suggested that oil absorption depends on the amount of water removed and on the way this moisture is lost. In accordance, Ufheil and Escher [149] suggested that oil uptake is primarily a surface phenomenon, involving an equilibrium between adhesion and drainage of oil upon retrieval of the slice from the oil.

Moreira and Barrufet [152] explained the mechanism of oil absorption during cooling in terms of capillary forces. The model considered that during frying heat transfer was controlled by convection and conduction and that during cooling mass transfer from the surface oil and the surrounding air into the structure was controlled by capillary pressure.

Recently, Bouchon and Pyle [153] developed a model for oil absorption during the cooling period, which considered the competition between drainage and suction. A key element in the model was the hypothesis that oil suction would only begin once a positive pressure driving force had developed.

8.3.8

Factors Affecting Oil Absorption

There has been much research to examine the different factors affecting oil absorption during frying and many empirical studies have correlated oil absorption measurements with process and/or product characteristics.

Gamble et al. [154] concluded that a lower oil temperature resulted in a lower oil content in potato crisps in the early stages of frying with a greater difference between 145 °C and 165 °C than between 165 °C and 185 °C. Similarly, Moreira et al. [132] determined higher differences in oil absorption in tortilla chips (wet base) between 130 °C and 160 °C than between 160 °C and 190 °C. However, results were expressed as oil uptake on a wet basis. Consequently, there was a systematic reduction in the basis, as the water content was constantly reduced due to the higher dehydration that resulted when the product was fried at a higher temperature for the same period of time. In contrast, Bouchon [97] determined that the rate of oil absorption (dry base) by potato cylinders was not significantly affected by oil temperature (155, 170, 185 °C). In addition, no significant differences were found in oil absorption between the two higher temperatures. How-

ever, when frying at 155 °C, a significant lower absorption was found, compared to the previous ones. Similarly, Moreira et al. [155] determined that the oil absorption rate was unaffected by the oil temperature when frying tortilla chips and that a frying temperature of 190 °C gave a higher oil content (3–5%) than a frying temperature of 155 °C. Nonaka et al. [156] also found that oil content increased with increasing frying temperature when frying potato chips.

The influence of oil type and quality on oil absorption and residues absorbed by fried foods is widely documented [95, 96, 156–159]. No relationship has been found between oil type and oil absorption, although it has been shown that an increase in the oil's initial interfacial tension decreases oil absorption [160]. Blumenthal [96, 157], noticed the importance of oil surface tension during deep-fat frying and developed what he called the surfactant theory of frying. He explained that several classes of surfactants are formed during frying of food, either as a result of the degradation of the frying oil itself or as a result of the reactions occurring between the food components and the oil. These compounds act as wetting agents, reducing the interfacial tension between the food and the frying oil, causing increased contact between the food and the oil and finally producing excessive oil absorption by the fried product.

An increase in additional factors such as initial solids content [117, 161, 162], slice thickness [163–165] and gel strength [166] have been shown to reduce oil uptake. Additionally, it has been found that an increase in the initial porosity of the food increases the absorption [167]. However, as explained by Saguy and Pinthus [99], crust formation plays an additional and fundamental role as soon as frying commences.

Some pre-frying treatments have been shown to significantly reduce oil absorption during frying. Lowering the moisture content of the food prior to frying using microwave and hot air treatment results in a reduction in the final oil content [104, 142, 151], whereas freeze-drying increases the absorption [154]. Also, post-treatments such as hot air drying [156] have been shown to reduce oil uptake.

In addition, during the last decade much attention has been given to the use of hydrocolloids such as methylcellulose (MC), hydroxypropyl methylcellulose (HPMC), long-fibre cellulose and corn zein, to inhibit oil uptake [128, 168–171]. The hydrocolloid mixture is added to the batter or breading coating, which creates a barrier against oil absorption either prior and/or during frying. Batters and breadings are gaining more importance as they contribute significantly to the added product value [172], however, most of the information on this subject is of a proprietary nature [99].

8.3.9

Microstructural Changes During Deep-Fat Frying

The importance of microstructural changes during deep-fat frying has been recognised in modelling heat and mass transport and unravelling their mechanisms. Three of five papers by leading scientists in the field published in an overview on frying of foods (*Food Technology*, October 1995) included SEM

photomicrographs of fried products, suggesting the importance of microstructure. In fact, Baumann and Escher [165] recommended that the explanation of some factors in oil absorption needs to be validated by structural analysis in relation to the location of oil deposition and to the mechanisms of oil adhesion.

Since the first histological studies of deep-fat fried potatoes by Reeve and Neel [173], using light microscopy, evidence has accumulated that, except for the outermost layers damaged by cutting, the majority of the inner cells retain their individuality after frying and their interior contains dehydrated but gelatinised starch granules. The microstructural aspect of the core tissue is similar to that of cooked potatoes. In the case of potato crisps (or outer layers in potato chips) cells shrink during frying but do not rupture, while cell walls become wrinkled and convoluted around the dehydrated gelled starch [146, 173]. It is thought that the rapid dehydration occurring during deep-fat frying reduces the starch-swelling process and therefore cell walls do not break as sometimes occurs during ordinary cooking. Similar observations were determined by Costa et al. [174], when studying structural changes of potato during frying, and by Mc Donough et al. [175], when evaluating the physical changes during deep-fat frying of tortilla chips.

Keller et al. [141] and Lamberg et al. [142] determined the extent of oil penetration in fried chips, using Sudan red B, a heat-resistant and oil-soluble dye, which was added to the frying medium before frying. They concluded that oil uptake during deep-fat frying was localised on the surface of the fried product and restricted to a depth of a few cells. In fact, Bouchon et al. [147], using high spatial resolution infrared microspectroscopy, determined oil distribution profiles within fried potato cylinders. Results confirmed that oil was confined to the outer region and that oil distribution reflected the anisotropic nature of the porous network developed during the process.

Blistering in potato crisps takes place after separation of neighbouring intact cells alongside cell walls, similar to fracture observed in steam-cooked potatoes [176], and oil was found to be mainly distributed in the cell walls, intercellular spaces and blister areas [173]. Aguilera and Gloria [177] demonstrated that three distinct microstructures exist in finished fried commercial chips: (a) a thin outer layer (approx. 250 μm) formed by remnants of cell walls of broken or damaged cells by cutting, (b) an intermediate layer of shrunken intact cells which extends to the evaporation front and (c) the core with fully hydrated intact cells containing gelatinised starch.

It is thought that standard microscopic techniques may produce artefacts in samples like swelling of the interiors by solvents and smearing of oil during sectioning. In an attempt to reduce invasion and destruction of samples, Farkas et al. [143] used magnetic resonance imaging (MRI) to determine water location and oil penetration depth in immersion-fried potato cylinders. They confirmed that oil was mainly located on the surface of the product and penetrated only slightly inside the structure. Confocal laser scanning microscopy (CLSM) has been introduced recently as a new methodology for studying oil location directly in fried potato chips with minimal intrusion [145, 146]. This was achieved by

frying in oil containing a heat-stable fluorochrome (Nile red) and observing the fried crust, without further preparation, under a CLSM. This technique allows optical sectioning to be carried out using a laser beam, avoiding any physical damage on the specimen. It was shown that cells seem to be quite preserved and surrounded by oil, which is not uniformly located at each depth, suggesting that at least some of the oil penetrates into the interior of a potato strip by moving between cells.

Recently, it was suggested that surface roughness increases importantly surface area, enhancing oil absorption [172]. In an effort to quantify the irregular conformation of the surface, Pedreschi et al. [178] and Rubnov and Saguy [179] used fractal geometry and confirmed the significant role of crust roughness in oil absorption.

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