1
Extrusion-Cooking and Related Technique

Leszek Mościcki and Dick J. van Zuilichem

1.1
Extrusion-Cooking Technology

Extrusion technology, well-known in the plastics industry, has now become a widely used technology in the agri-food processing industry, where it is referred to as *extrusion-cooking*. It has been employed for the production of so-called engineered food and special feed.

Generally speaking, extrusion-cooking of vegetable raw materials deals with extrusion of ground material at baro-thermal conditions. With the help of shear energy, exerted by the rotating screw, and additional heating of the barrel, the food material is heated to its melting point or plasticating point [1, 2]. In this changed rheological status the food is conveyed under high pressure through a die or a series of dies and the product expands to its final shape. This results in very different physical and chemical properties of the extrudates compared to those of the raw materials used.

Food extruders (extrusion-cookers) belong to the family of HTST (high temperature short time)-equipment, capable of performing cooking tasks under high pressure. This is advantageous for vulnerable food and feed as exposure to high temperatures for only a short time will restrict unwanted denaturation effects on, for example, proteins, amino acids, vitamins, starches and enzymes. Physical technological aspects like heat transfer, mass transfer, momentum transfer, residence time and residence time distribution have a strong impact on the food and feed properties during extrusion-cooking and can drastically influence the final product quality. An extrusion-cooker is a process reactor [2], in which the designer has created the prerequisites with the presence of a certain screw lay-out, the use of mixing elements, the clearances in the gaps, the installed motor power and barrel heating and cooking capacity, to control a food and feed reaction. Proper use of these factors allow to stimulate transformation of processed materials due to heating, for example, the denaturation of proteins in the presence of water and the rupture of starches, both affected by the combined effects of heat and shear. These reactions can also be provoked by the presence of a distinct biochemical or chemical component like an enzyme or a pH controlling agent. When we consider the cooking extruder to be more

Extrusion-Cooking Techniques: Applications, Theory and Sustainability. Edited by Leszek Moscicki

ISBN: 978-3-527-32888-8

Figure 1.1 Assortment of popular extrudates.

than just a simple plasticating unit, a thorough investigation of the different physical technological aspects is more than desirable.

Currently, extrusion-cooking as a method is used for the manufacture of many foodstuffs, ranging from the simplest expanded snacks to highly-processed meat analogues (see Figure 1.1). The most popular extrusion-cooked products include:

- direct extruded snacks, RTE (ready-to-eat) cereal flakes and a variety of breakfast foods produced from cereal material and differing in shape, color and taste and easy to handle in terms of production;
- snack pellets – half products destined for fried or hot air expanded snacks, pre-cooked pasta;
- baby food, pre-cooked flours, instant concentrates, functional components;
- pet food, aquafeed, feed concentrates and calf-milk replacers;
- texturized vegetable protein (mainly from soybeans, though not always) used in the production of meat analogues;
- crispbread, bread crumbs, emulsions and pastes;
- baro-thermally processed products for the pharmaceutical, chemical, paper and brewing industry;
- confectionery: different kinds of sweets, chewing gum.

The growing popularity of extrusion-cooking in the global agri-food industry, caused mainly by its practical character, led many indigenous manufacturers to implement it on an industrial scale, based on the local raw materials and supported by detailed economic studies based on the domestic conditions [18]. Extrusion-cooking offers a chance to use raw materials which have not previously displayed great economic importance (e.g., faba bean) or have even been regarded as waste. The domestic market has been enriched with a category of high-quality products belonging to the convenience and/or functional food sector. Of practical importance is the fact that the process in question can be implemented with relatively low effort, does not require excessive capital investment, and most equipment is user-friendly and offers multiple applications.

For easier understanding of the extrusion-cooking technology, as an example, we would like to present the most simple production – direct extrusion of cereal snacks with different shapes and flavors. We will give a general overview of the technological process using a standard set of processing equipment commonly used in such a case.

1.1.1
Preparation of Raw Material

The manner of preparation of the raw material to be processed into food preparations depends upon the ingredients used. In the case of direct extruded snacks this is mainly cereal-based material. Depending on its quality, it must be properly ground and weighed according to the recipe and mixed thoroughly before being fed to the extruder. When conditioning is required, before mixing, water in some quantity is necessarily added for the preparation of the material.

Figure 1.2 presents a diagram of a standard installation for the production of direct extrusion and multi-flavor snacks. In the case of simple maize snacks, that is, not enriched and being single-component products, the processing line is significantly

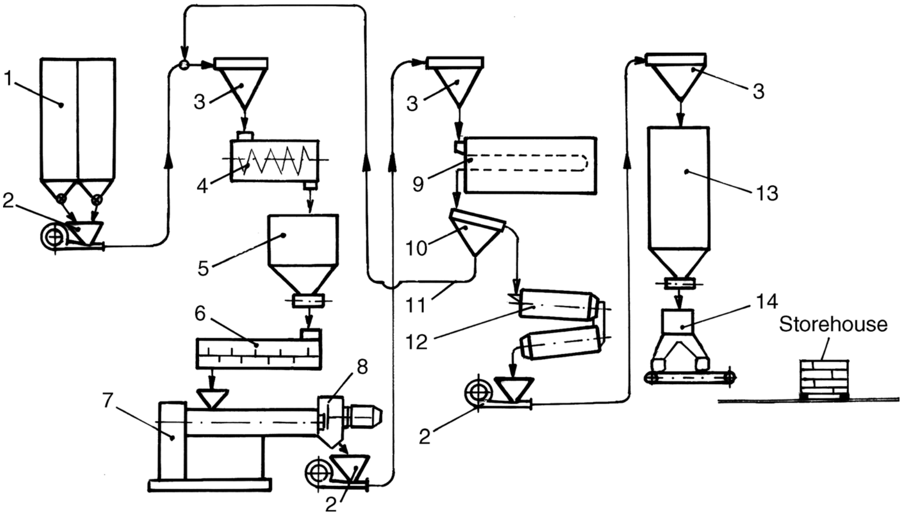


Figure 1.2 A diagram of the set-up for the production of multi-flavor cereal snacks [1]: 1 – a silo with raw materials, 2 – pneumatic conveyer, 3 – collector, 4 – mixer, 5 – weigher, 6 – conditioner, 7 – extruder, 8 – cutter, 9 – dryer, 10 – screen, 11 – recycling of dust, 12 – coating drums, 13 – silos of finished product, 14 – packing machine.

simplified. If is often enough to operate an extruder, for example the one presented in Figure 1.3, and a packing machine to initiate production (often called “garage box production”).

Figure 1.3 Single-screw extrusion-cooker, type TS-45 (designed by L. Moscicki), equipped with an electric heating system and a water-air cooling system [1].

1.1.2
Extrusion-Cooking

The effect of direct extrusion-cooking is that, after leaving the die, the material expands rapidly and the extrudates are structurally similar to a honeycomb, shaped by the bundles of molten protein fibers. In this case a simple, single-screw food extruder can be used to manufacture various types of products, different in shape, color, taste and texture [1, 3–5]. The technology for each of them requires an appropriate distribution of temperature, pressure and moisture content of the material during processing. Because the main task is to obtain good-quality extrudates, flexibility and precise control, especially of the thermal process, is essential in the design and construction of modern cooking extruders. More than often, the process for the manufacture of specific products has to be developed empirically.

Particularly interesting are the issues related to the energy consumption of extrusion-cooking of vegetable raw materials. There is a widespread opinion that this power consumption is too high. It is not clear to us on what these opinions are based, since the results of our own research and of those available from the literature mention something completely opposite. Measurements of energy consumption in single-screw food extruders are in the range 0.1–0.2 kWh kg^{-1} (excluding of course, the costs of material preparation, that is, the grinding and conditioning) [1]. This demonstrates that extrusion-cooking is highly competitive in comparison with the conventional methods of thermal processing of vegetable material. Of course, this does not mean that extrusion-cooking is ideal for all applications. It is an alternative and, in many cases, competitive in relation to other methods of food and feed manufacture.

1.1.3
Forming, Drying and Packing

Depending on the purpose for which they are to be used, extrudates must be suitably formed. The melt mass leaving the extruder takes more or less the shape of the extruder-dies(nozzle); at the same time a lengthwise arrangement – an appropriate setting of the speed of a rotary knife cutter installed outside the die, controls the product length. This allows the production of miscellaneous shapes of extrudate such as balls, rings, stars, letters of the alphabet, and so on.

The next stage of production is the drying of the extrudates to a moisture content of about 6–8% and subsequent cooling. Drying can be performed with simple rotating drums with electric heaters installed or with a gas-operated hot air installation working at temperatures just above 100 °C. In larger installations belt dryers are used, heated by gas fired heat exchangers or steam, where the air is circulating through the unit sections. Cooling takes place at the ambient temperature of 15–20 °C, where the air flows through the perforated belt of the dryer–cooler device.

Very often in drum dryers the flavor and vitamin-coating step is integrated (Figure 1.4). The selection of sprinklers and flavor additives is wide: from smoked meat flavor to peanut butter aroma.

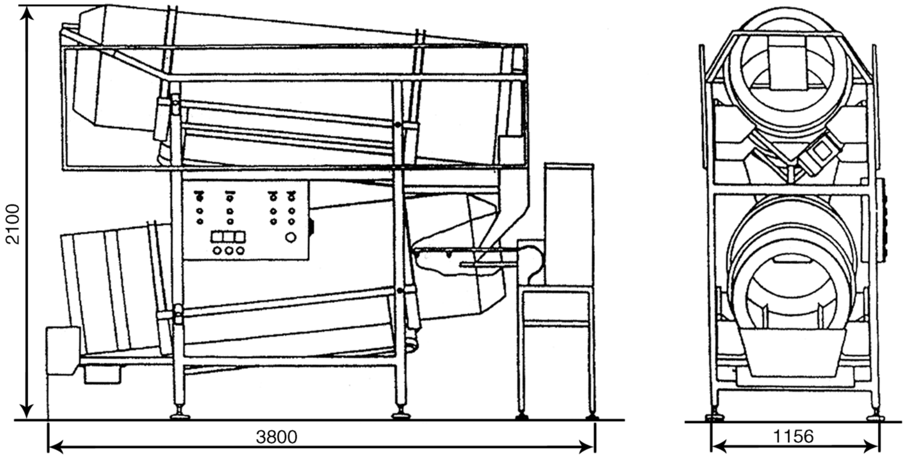


Figure 1.4 Drum dryer and coating drum unit [6].

Direct extrusion snacks in an icing sugar coating are very popular. For small-scale production, it is sufficient to operate a drop coating machine (remember about suitable tempering of the products). Industrial production of this type of cereal product requires the use of an additional high-performance drum dryer or belt dryer, so that the application of the coating can be a continuous process while maintaining a fixed product quality. Some noteworthy examples of the products in question are coated cereal balls, rings or shells, offered by many breakfast cereals producers.

1.2
Quality Parameters

From the foregoing it can be stated that a food extruder may be considered as a reactor in which temperature, mixing mechanism and residence time distribution are mainly responsible for a certain physical state, as is the viscosity. Quality parameters such as the texture are often dependent on the viscosity. The influence of various extruder variables like screw speed, die geometry, screw geometry and barrel temperature on the produced quality has been described by numerous authors for many products [2, 5, 7–9, 18, 20, 21]. However, other extrusion-cooking process variables like initial moisture content, the intentional presence of enzymes, the pH during extrusion, and so on, also play a role. Although a variety of test methods is available a versatile instrument to measure the changes in consistency during pasting and cooking of biopolymers is hardly available. A number of measuring methods are used in the extrusion-cooking branch. A compilation of them is given in Figure 1.5, from which it can be seen that an extrusion-cooked product is described in practice by

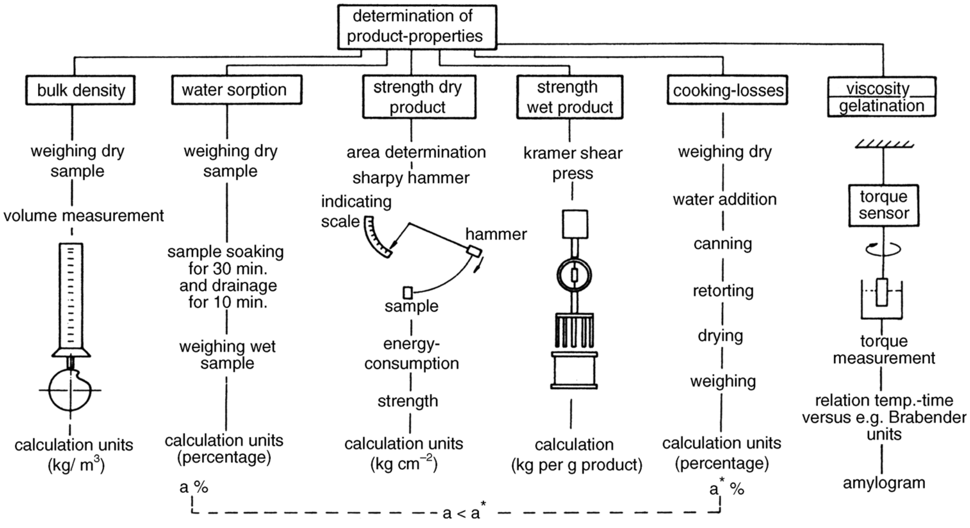


Figure 1.5 Measuring methods for extruder product properties [7].

its bulk density, its water sorption, its wet strength, its dry strength, its cooking loss and its viscosity behavior after extrusion for which the Brabender viscometer producing amylographs may be chosen, which gives information about the response of the extruded material to a controlled temperature–time function (Figure 1.5).

For a successful description of properties of starches and proteins we will need additional chemical data like dextrose-equivalents, reaction rate constants and data describing the sensitivity to enzymatic degradation. The task of the food engineer and technologist will be to forecast the relation between these properties and their dependence ofnthe extruder variables. Therefore, it is necessary to give a (semi)-quantitative analysis of the extrusion- cooking process of biopolymers, which can be done by adopting an engineering point of view, whereby the extruder is considered to be a processing reactor. Although the number of extrusion applications justify an optimistic point of view, more experimental verification is definitely needed, focussed on the above-mentioned residence time distribution, the temperature distribution, the interrelation with mechanical settings like screw compositions, restrictions to flow, and so on.

1.3
Extrusion-Cooking Technique

As was mentioned already, extrusion-cooking is carried out in food extruders – machines in which the main operative body is one screw or a pair of screws fitted in a barrel. During baro-thermal processing (pressure up to 20 MPa, temperature 200 °C), the material is mixed, compressed, melted and plasticized in the end part of the machine (Figure 1.6). The range of physical and chemical changes in the processed material depends principally on the parameters of the extrusion process and the construction of the extruder, that is, its working capability.

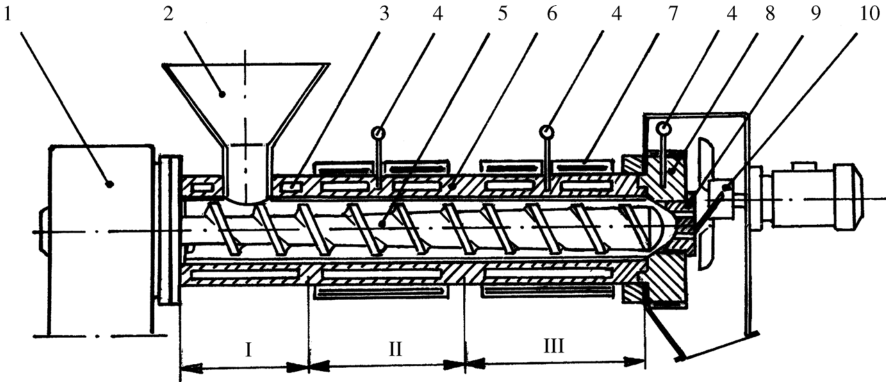


Figure 1.6 A cross-section of a single-screw food extruder: 1 – engine, 2 – feeder, 3 – cooling jacket, 4 – thermocouple, 5 – screw, 6 – barrel, 7 – heating jacket, 8 – head, 9 – dies, 10 – cutter, I – transport section, II – compression section, III –melting and plasticizing section [1].

There are many conventional methods of classification of food extruders but, in our opinion, the most practical is the one taking into account the following three factors.

1) The method of generating mechanical friction energy converted during extrusion into heat (three types of extruders):
    a) autogenic (source of heat is the friction of the particles of the material caused by the screw rotating at high speed);
    b) isothermic (heated);
    c) polytropic (mixed).
2) The amount of mechanical energy generated (two types of extruders):
    a) low-pressure extruders producing relatively limited shear rate;
    b) high-pressure extruders generating large amounts of mechanical energy and shear.
3) The construction of the plasticizing unit (see Figure 1.7), where both the barrel and the screw may be designed as a uniform, integrated body or fixed with separate modules.

1.3.1
Historical Development

At first, in 1935, the application of single-screw extruders for plasticating thermoplastic materials became more common as a competitor to hot rolling and shaping in hydraulic-press equipment. A plasticating single-screw extruder is provided with a typical metering screw, developed for this application (Figure 1.8).

In the mid-1930s we notice the first development of twin-screw extruders, both co-rotating and counter-rotating, for food products. Shortly after, single-screw extruders came into common use in the pasta industry for the production of spaghetti and macaroni-type products. In analogy with the chemical polymer industry, the single-screw equipment was used here primarily as a friction pump, acting more or less as continuously cold forming equipment, using conveying-type screws. It is remarkable that nowadays the common pasta products are still manufactured with the same single-screw extruder equipment with a length over diameter ratio (L/D) of approximately 6–7. However, there has been much development work on screw and die design and much effort has been put into process control, such as sophisticated temperature control for screw and barrel sections, die tempering. and the application of vacuum at the feed port. Finally, the equipment has been scaled up from a poor hundred kilos hourly production to several tons [1, 2].

The development of many different technologies seems to have been catalyzed by World War II, as was that of extrusion-cooking technology. In 1946 in the US the development of the single-screw extruder to cook and expand corn- and rice-snacks occurred. In combination with an attractive flavoring this product type is still popular, and the method of producing snacks with single-screw extruder equipment is, in

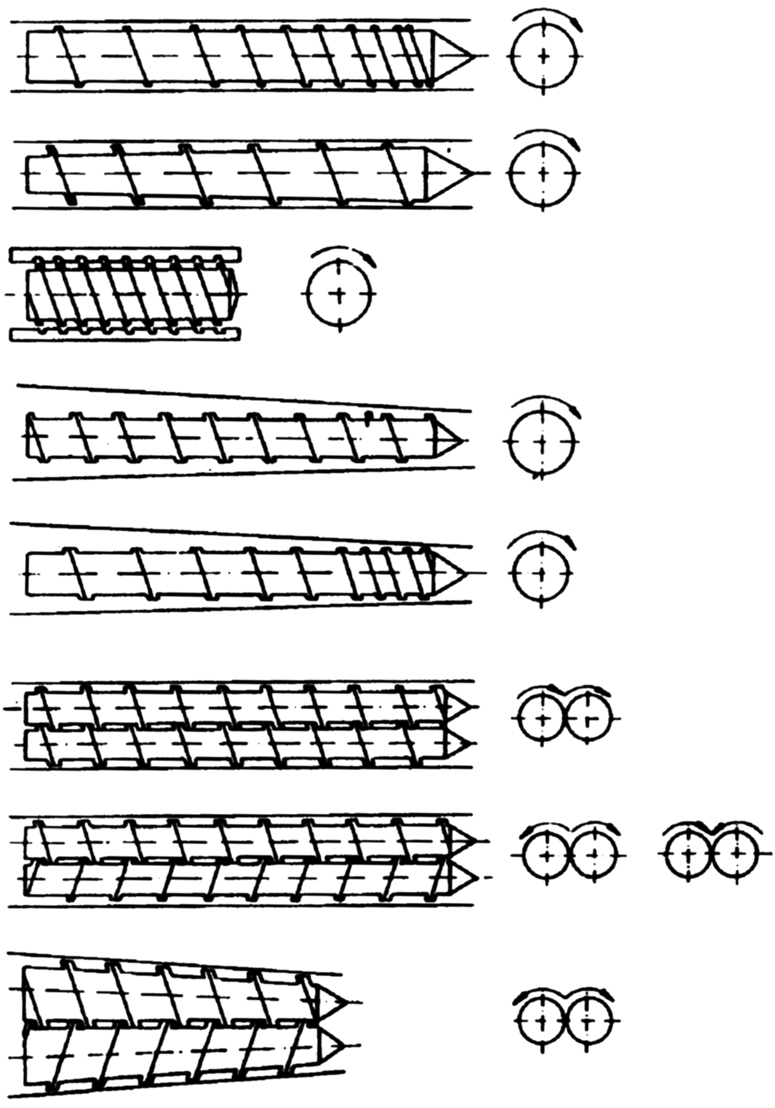


Figure 1.7 Configurations of screws' geometry in the extruder [7].

principle, still the same. A wide variety of extruder designs is offered for this purpose. However, it should be mentioned that the old method of cutting preshaped pieces of dough out of a sheet with roller-cutters is still in use, because the complicated shapes of snacks lead to very expensive dies and die-heads for cooking and forming extruders. Here, the lack of knowledge of the physical behavior of a tempered dough and the unknown relations of the transport phenomena of heat, mass and momentum to the physical and physico-chemical properties of the food in the extruder are clearly noticed. Although modern control techniques are very helpful in controlling

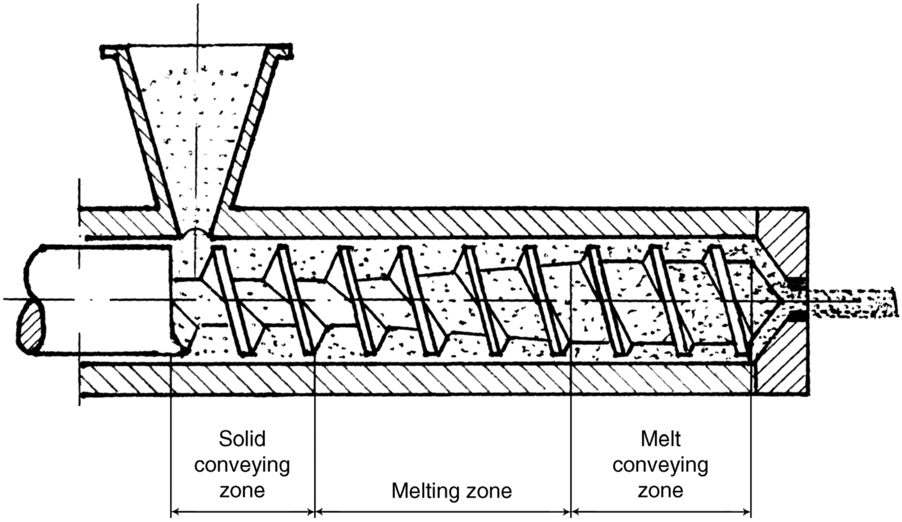


Figure 1.8 Typical plasticating single screw extruder [2].

the mass flow in single-screw extruders, in many cases it is a big advantage to use extruders with better mixing and more steady mass flow than single screw equipment can offer.

In the mid-1970s the use of twin-screw extruders for the combined process of cooking and forming of food products was introduced, partly as an answer to the restrictions of single-screw extruder equipment since twin-screw extruders provide a more or less forced flow, and partly because they tend to give better results on scale up from the laboratory extruder types in use for product development [2].

1.3.2
Processing of Biopolymers

When we focus on food we notice that nearly all chemical changes in food are irreversible. A continued treatment after such an irreversible reaction in an extruder should be a temperature-, time- and shear-controlled process leading to a series of completely different functional properties of the produced food (Table 1.1).

Nowadays, food familiar extruder equipment manufacturers design process lines, where the extruder-cooker is part of a complete line. Here, the extruder is used as a single- or twin-screw reactor, and the preheating/preconditioning step is performed in a specially built preconditioner. The forming task of the extruder has also been separated from the heating and shearing. The final shaping and forming has to be done in a second and well optimized post-die forming extruder, processing the food mostly at a lower water level than in the first reactor extruder. In such a process line cooked and preshaped but unexpanded food pellets can be produced (see Chapters 4 and 5). The result is a typical food process line differing very much from a comparable extruder line in the chemical plasticizing industry.

Table 1.1 Comparison between thermoplastic-polymers and biopolymers [2].

		Plastics	Food
1	Feed to the extruder	Single polymer	Multiple solids, water and oil
2	Composition	Well defined structure and molecular weight	Not well defined. Natural biopolymers, starch, protein, fiber, oil and water
3	Process	Melting and forming. No chemical change. Reversible	Dough or melt-like formation with chemical change. Irreversible continuous treatment leads to wanted specific functional properties
4	Die forming	Shape is subjected to extrudate swell	Subjected to extrudate swell and possibly vapor pressure expansion
5	Biochemicals	Use of fillers, for example, starch	Use of enzymes and biochemicals for food conversion

With the use of the extrusion-cooking equipment in process lines their tasks became more specialized. This encouraged the comparison of food extruder performance with that in the plastics industry, thus promoting the transformation of the extrusion-cooking craft into a science, tailor-made for the “peculiar” properties of biopolymers.

1.3.3
Food Melting

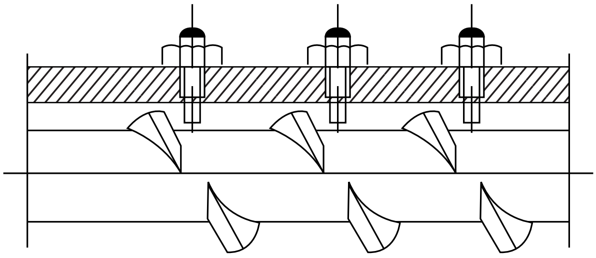
If the aim of the extrusion-cooking process in question is a simple denaturation of the food polymer, without further requirements of food texture, then the experience of the chemical polymer extrusion field, applying special screw melting parts, is advisable, as the melting will be accelerated. In principle, the effect of these melting parts is based on improved mixing. This mixing effect can be based on particle distribution or on shear effects exerted on product particles. For distributive mixing the effects of mixing are believed to be proportional to the total shear γ given by:

$$\gamma = \int_0^t \frac{dv}{dx} dt \tag{1.1}$$

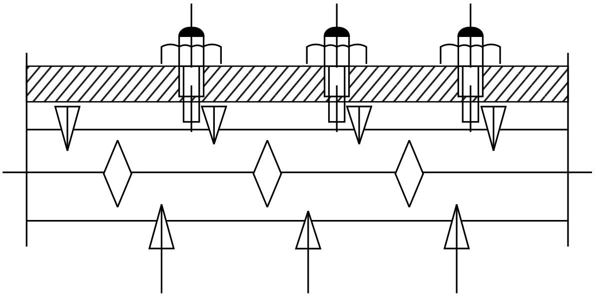
Whereas for dispersive (shear) mixing the effect is proportional to the shear stress τ:

$$\tau = \mu \frac{dv}{dx} \tag{1.2}$$

The group of distributive mixing screws can be divided into the pin mixing section, the Dulmage mixing section, the Saxton mixing section, the pineapple mixing head, slotted screw flights, and the cavity transfer mixing section, respectively [2, 17]. The pin mixing section, or a variant of this design, is used for food in the Buss co-kneader



(a) Anderson Expander



(b) Buss Kneader

Figure 1.9 Mixing pin elements Anderson and Buss designs [2].

which is a reciprocating screw provided with pins of special design, rotating in a barrel also provided with pins Figure 1.9). When we recognize food expanders to be food extruders then much use is made here of the pin-mixing effect, since the barrels of the expander equipment, built like the original Anderson design, are provided with mixing pins (see Chapter 11). The amount of mixing and shear energy is simply controlled by varying the number of pins. Some single-screw extruder manufacturers have designs available, like, for example, special parts of the Wenger single-screw equipment, where some influence of the mentioned designs is recognizable. The pineapple mixing section or the most simple mixing torpedo has a future in food extrusion cooking due to its simplicity and effectiveness.

1.3.4
Rheological Considerations

It has already been mentioned that non-Newtonian flow behavior is usually to be expected in food extruders. A major complication is that chemical reactions also occur during the extrusion-cooking process (e.g., gelatinization of starch or starch-derived materials, denaturation of proteins, Maillard reactions), which strongly influence the viscosity function. The rheological behavior of the product, which is relevant to the modeling of the extrusion process, has to be defined directly after the extruder screw tip, before expansion has occurred, in order to prevent the influence of water losses, cavioles in the material and temperature effects due to the flashing process that occur as soon as the material is exposed to the environment. A convenient way would be to measure the pressure loss over capillaries of variable diameter and length. However, this method has a certain lack of accuracy, since pressure losses due to entry effects are superimposed on the pressure gradient induced by the viscosity of the material [10]. Moreover, since the macromolecules in the biopolymers introduce a viscoelastic effect, the capillary entry and exit effects cannot be established easily from theoretical considerations.

It is well known that within normal operating ranges starches and protein-rich materials are shear thinning. This justifies the use of a power law equation for the shear dependence of the viscosity [19]:

$$\eta_a = k'|\dot{\gamma}|^{n-1} \tag{1.3}$$

where η_a is the apparent viscosity, $\dot{\gamma}$ is the shear rate and n is the power law index.

Metzner [11] has argued that for changing temperature effects this equation can be corrected by multiplying the power law effect and the temperature dependence, thus giving:

$$\eta_a = k'|\dot{\gamma}|^{n-1} \exp(-\beta \Delta T) \tag{1.4}$$

The viscosity will also be influenced by the processing history of the material as it passes through the extruder [12]. In order to correct for this changing thermal history one should realize that interactions between the molecules generally occur through the breaking and formation of hydrogen and other physico-chemical bonds. This cross-linking effect is dependent on two mechanisms: a temperature effect determines the frequency of breaking and the formation of bonds and a shear effect determines whether the end of a bond that breaks meets a “new” end or will be re-attached to its old counterpart. If we assume that this last mentioned effect will not be a limiting factor as soon as the actual shear rate is higher than a critical value and that the shear stress levels within the extruder are high enough, then the process may be described by an Arrhenius model, giving, for the reaction constant [16]:

$$K(t) = k_\infty \exp - \frac{\Delta E}{RT(t)} \tag{1.5}$$

where ΔE is the activation energy, R the gas constant and T the absolute temperature. Under the assumption that the crosslinking process may be described as a first order reaction, it is easy to show that from the general reaction equation:

$$\frac{dC}{dt} = K(1-C) \tag{1.6}$$

can be derived:

$$1-C = \exp\left(- \int_0^{\tau} \exp - \frac{\Delta E}{RT(t)} Dt \right) \tag{1.7}$$

in which *C* denotes the ratio between actual crosslinks and the maximum number of crosslinks that could be attained, and where *Dt* is a convective derivative accounting for the fact that the coordinate system is attached to a material element as it moves through the extruder. Therefore, the temperature, which is of course stationary at a certain fixed position in the extruder, will be a function of time in the Lagrangian frame of reference chosen. This temperature history is determined by the actual position of the element in the extruder, as has been proved for synthetic polymers by Janssen *et al.* [13]. It is expected that this effect will cancel out within the measuring accuracy and that an overall effect based on the mean residence time τ may be chosen. It may now be stated that the apparent viscosity of the material as it leaves the extruder may be summarized by the following equation:

$$\eta_a = k''|\dot{\gamma}|^{n-1}\exp(-\beta T)\exp\left(\int_0^{\tau} \exp - \frac{\Delta E}{RT(t)}\, Dt\right) \tag{1.8}$$

Under the restrictive assumption that k, n, β and ΔE are temperature independent, it is obvious that at least four different measurements have to be carried out in order to characterize the material properly [2, 12]

1.4
Modern Food Extruders

1.4.1
Single-Screw Extrusion-Cookers

As mentioned before the design of single-screw extrusion-cookers is relatively simple The role of the screw is to convey, compress, melt and plasticize the material and to force it under pressure through small die holes at the end of the barrel. The necessary condition for moving the material is a proper flow rate and no sticking to the surface of the screw. In food extruders sticking effects are prevented by the force of friction of the material against the barrel wall, which is facilitated by suitable grooving of the inside of the barrel (longitudinal or spiral grooves). Their role is to increase the grip-resistance and to direct the flow of the forced material. The principle is the following: the more friction, the less spinning of the material and easier transport forward.

Single-screw food extruders process relatively easy materials characterized by a high friction coefficient, such as maize or rice grits. Such grits can be extruded even under a pressure of around 15–20 MPa, and are basic materials for the production of direct extrusion snacks or breakfast cereals (balls, rings, etc.). For these materials, even the use of the simplest autogenic extruders is sufficient; with a low ratio of screw length L and diameter D (L/D = 4–6; see Figure 1.10). Unfortunately, the main disadvantage of single-screw extruders is poor mixing of the material. This should be done before feeding. Also, single-screw extruders show a limited efficiency, especially when multi-component mixtures of raw materials are used.

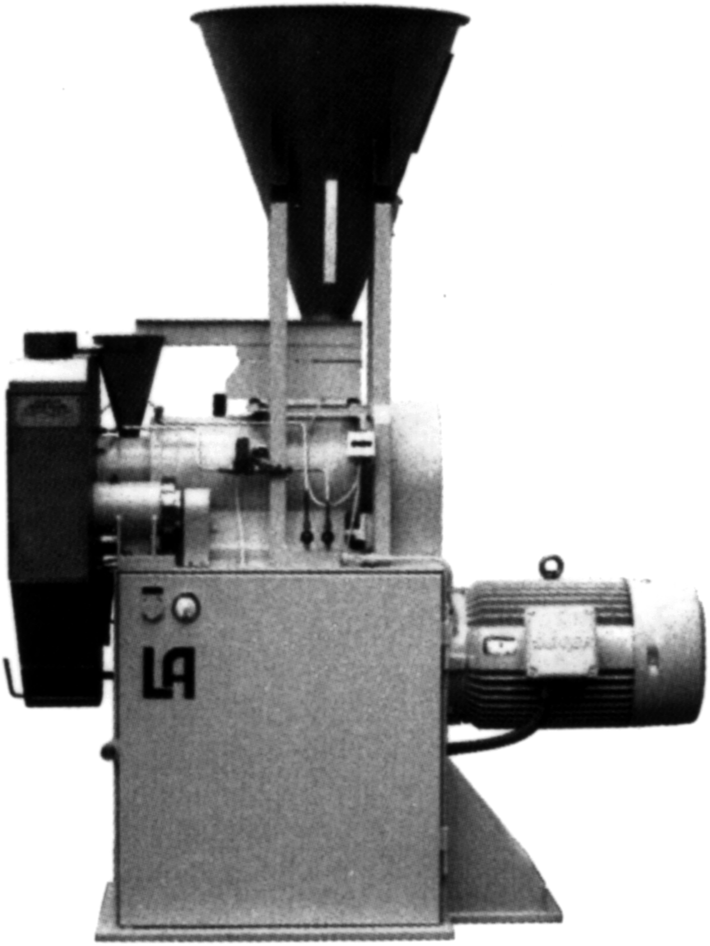


Figure 1.10 Autogenic extruder, type 90 E (permission of Lalesse-Extrusion BV).

Smooth positive movement of the material in a single-screw food extruder depends on the actual drag flow, caused by the screw geometry and its rotation, minus the so-called back flow [17, 19]. In order to maintain the correct working point of the extrusion-cooking process it is necessary to follow strictly the technological regime, that is, to maintain the relevant working parameters of the machine, determined experimentally, or given by expert technicians. The proper preparation of raw materials, especially their grinding and moisturizing, is also important. Often preconditioners are installed additionally (Figure 1.11).

There are a number of points that are useful in daily extruder operations:

- Moisture content and particle size distribution of raw material mixtures must be homogeneous – this will prevent irregular work of the extruder (shooting or blocking) and will ensure the desired quality of the extrudates.

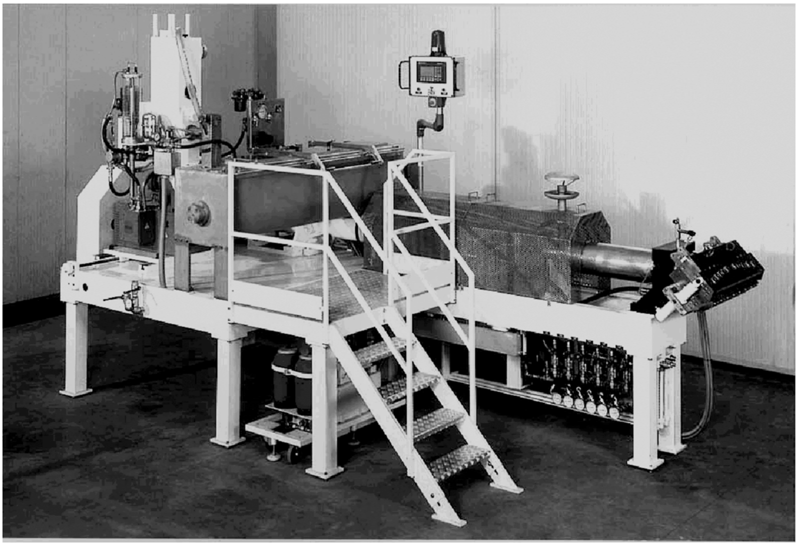


Figure 1.11 Modern single screw extrusion-cooker G-type equipped with additional operating devices (permission of Pavan Group).

- Reduced moisture content of raw materials influences the pressure of extrusion but does not have an essential impact on the extruder's performance (i.e., increase in the viscosity of the material).
- Intensive cooling of the barrel (e.g., with cold water) contributes to a lower temperature and increases the friction inside the material. It must be correlated with the quality requirements of the extrudate. Temperature drop in the material raises its viscosity and contributes positively to the extruder's performance.
- The blocking of a few die-holes results in a sudden increase in pressure and leads to a powerful back flow, or even lockout of the machine. In such a case it is worth trying to clean them immediately with a thin tool, and, if this does not help, then stop the machine and dismantle the die. To postpone the disassembly of the die with a plasticized material inside may lead to permanent damage to the equipment during the next start-up.
- The smallest holes in the die, cause a higher resistance during the extrusion of the material; since small openings increase pressure and reduce the extruder's output as the back flow is higher.
- By applying a plasticizing screw of greater L/D ratio, it is possible to generate more extrusion pressure due to a longer fully filled screw, which leads to a better plasticizing of the material and a reduced back flow.
- The loss of a small clearance between the barrel surface and the screw flights (in practice just 0.1–0.2 mm is enough) hampers the movement of the material, reduces friction and pressure and causes poor operation of the machine and stops the flow, which means poor product or no product at all.

1.4.2
Twin-Screw Extrusion-Cookers

Twin-screw food extruders are much more complex and more universal in terms of design. They have gained extensive popularity with producers of extrusion-cooked food and feed because of their high versatility (the capability of processing a wider range of materials, including viscous and hard-to-break materials), lower energy consumption and the ability to broaden the production assortment significantly. Their only disadvantage is the more complicated design and the cost of acquisition.

Nowadays co-rotating food extruders are used to a greater extent (Figure 1.12) due to their high productivity, good mixing and high screw speed (up to 700 rpm). They are characterized by good efficiency of the material transportation, mixing, plasticizing and extrusion. The self-wiping and intermeshing flights of the screws effectively force the material to move forward, in effect, no material is locked in the space between the surface of the barrel and the screw. For this reason, twin-screw extrusion-cookers are often referred to as self-cleaning machines.

The flow of mixed material in co-rotating twin-screw extruders is balanced without any discontinuity and no C-shaped chambers or prints of characteristic angular waves on the surface of products [15]. This is a decisive factor in the use of these extruders for the production of crispbread or sponge fingers, that is, products with a higher quality of external surface.

The description of physical processes associated with the mechanisms of material transfer in twin-screw food extruders and the accompanying heat exchange is more complicated than in single-screw extruders. More on this subject is given in Chapter 2. Readers who wish to learn more about the engineering aspects of extrusion will certainly be able to master the art of day-to-day handling not only of extruders but also complete processing lines. We use the word “art” deliberately, for the extrusion-cooking technique is fairly complicated and its proper use requires considerable expertise of the operators. The experience and observations gained in a regular production-surrounding are of even greater value than the results of scientific research. Even today, in many cases, we have to admit that progress in the method of producing many assortments of extrudates, and also the practical

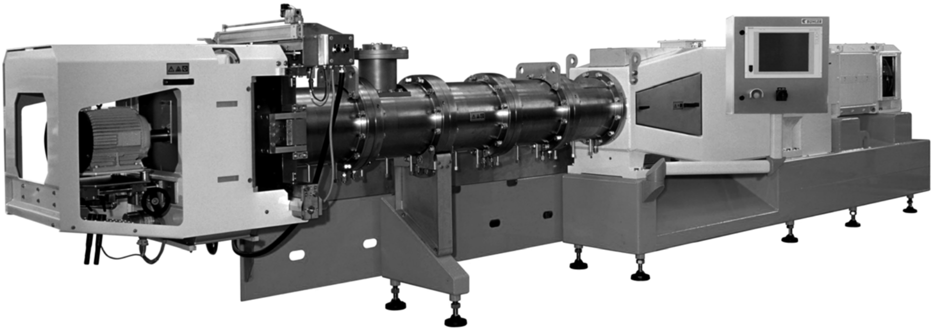


Figure 1.12 Modern twin-screw extruder, type BCTA (permission of Bühler AG).

effects of the technologists' work, went on ahead of a detailed scientific description of the physical and chemical phenomena of the process. This shows the high potential of the extrusion-cooking technique, which has become a tool in the hands of the users themselves in their persistent wish to continuously renew their assortment of products.

Counter-rotating twin-screw food extruders are special-purpose machinery (Figure 1.13). Their screws rotate much moreslowly (up to 150 rpm) but can mix the material effectively, and their work resembles a positive-displacement pump generating high pressure in the barrel closed C-shaped chamber on the screws, which is needed for high viscosity material. The back flow of material in these extruders is very small due to the tiny clearances between the screws and the barrel. They are predominantly used for the production of confectionery, chewing gum, and for the processing of fiber and cellulose-rich materials. Counter-rotating extruders can easily be degassed. To use them for the manufacture of simple forms of extrudates would be uneconomic and energy consuming. This does not mean that

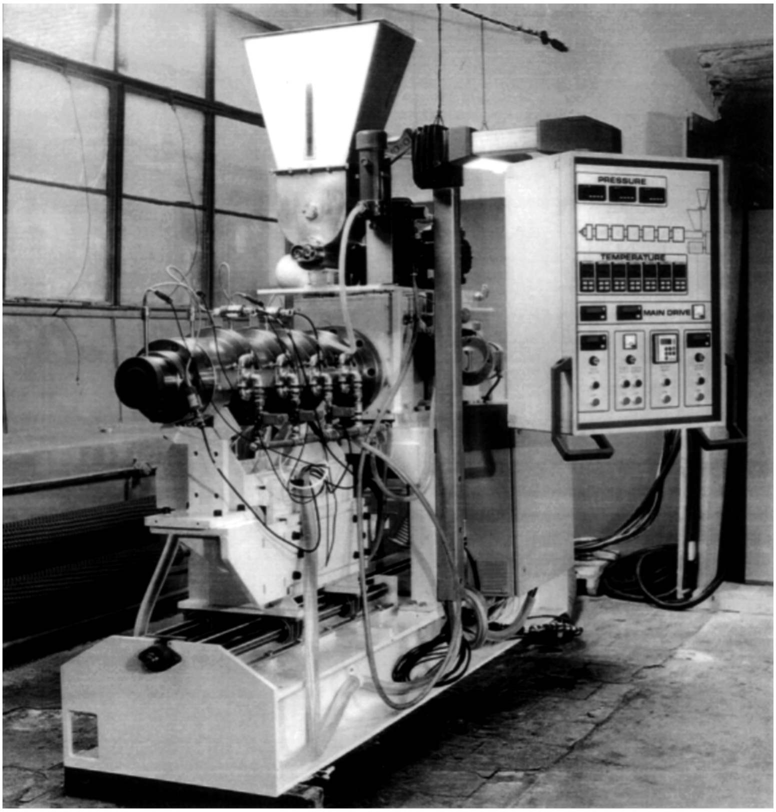


Figure 1.13 Counter-rotating twin-screw extrusion-cooker, type Valeurex, of modular construction; the brainchild of Polish, Dutch and Swedish designers cooperating through the European Programme Eureka [14].

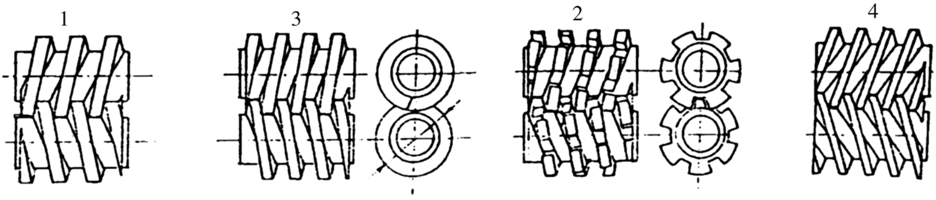


Figure 1.14 A review of screw elements: 1 – transporting elements, 2 – mixing elements, 3 – double flight elements, 4 – compressing elements.

they should not be used for the production of popular multi-component extrudates. These types of machines are successfully used by Polish producers of crispbread, fiber-rich extrudates and even pet food (Figure 6.2).

Modern twin-screw food extruders are designed in such a way that raw materials can be fed to the extruder by more than one feeder, even at different locations through the barrel. Now fluid components can be fed separately, which is an additional advantage. The basic material is precisely fed into the barrel with single and twin-screw feeders. Gravimetric feeders in the form of a vibrated feed tray have practically disappeared, due to the problems with irregular proportioning of the material. Very often in the case of breakfast cereals or snack pellets production, mixtures of raw materials are additionally steam-treated, before extrusion, in suitable pre-conditioners and/or specially designed mixers.

Nowadays twin-screw food extruders have a modular construction where screws are built up out of several different elements, mounted on the screw shaft. These elements are handling transport, mixing, compressing, melting. By proper setting of the elements the operator is able to "control" the behavior of material inside the extruder, and influence the scope of physical and chemical processes in the course of an extrusion-cooking process (Figures 1.14–1.16).

The selection of particular elements and arranging a screw requires relatively broad experience and knowledge of the production targets. Such sophisticated

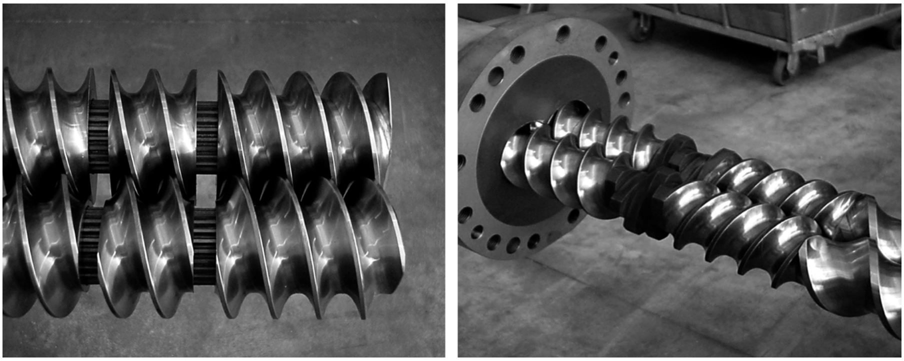


Figure 1.15 A set-up of screw elements and configured screws (with permission of the Pavan Group).

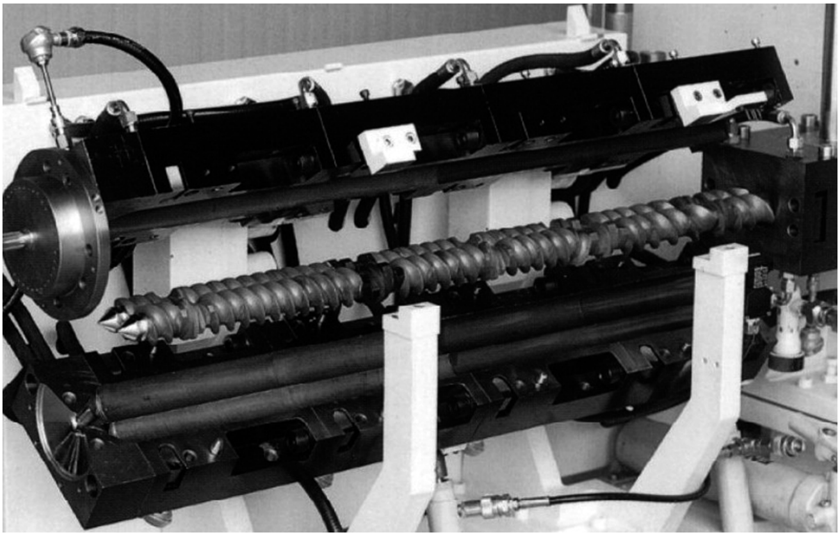


Figure 1.16 A set-up of screws in a modern twin-screw extrusion-cooker equipped with an axial opening barrel (permission of the Pavan Group).

extruders can be very useful production tools but only in the hands of conscientious and experienced operators. Otherwise, they will only be very expensive "toys" whose purchase is not economically justified. Where production is limited to one or two relatively easy products a more cost-effective solution would be to use simpler single-screw food extruders.

Popular co-rotating twin-screw food extruders used for the production of RTE breakfast cereals or pet food run with a screw speed of around 300 rpm. Some machines can operate at a speed which is two or even three times higher. This gives the highest possible production efficiency but the application of special construction materials increases the cost. Extruders often produce a wide range of products, ranging from simple maize snacks to protein-based food. For snacks high pressure and mechanical energy at low L/D ratio is needed; for protein material long processing times and many intermediate stages will be applied. Modular screws give these possibilities, either by the disassembly of the barrel units (for example, 3 out of 6) combined with the replacement of the screws with shorter ones (Figure 1.12), or by changes in the screw lay-out. An example is the elongation of the screw transport section by mounting more transport elements at the cast of other elements on the splinted shafts, in the case of fully opening extruders (Figure 1.16). Several extruder makers offer the use of a mobile feeder to be installed on the feed ports between the center and the end of the barrel, for example, maize grits fed to a possible unlocked opening with a mobile feeder on the arm – see Figure 1.17. In such cases, distance rings are placed on the screw shafts ahead of the final set of screw elements.

During the operation of extruders it is very important to maintain the engine load at an adequate level (max. 80–85%). This means that rpm, torque and energy

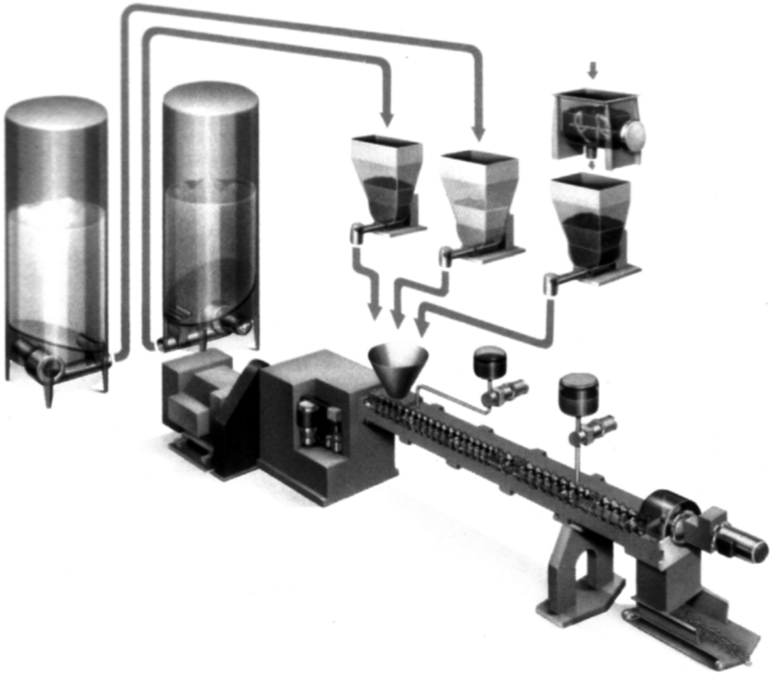


Figure 1.17 Section feed of material and fluid components [1].

consumption, that is SME rate expressed in kWh per 1 kg of the product, must be controlled. These issues are of vital importance since the manufacture of food extrudates necessitates high energy use. An appropriate choice of extruder machinery for the type of production determines the return on investment. As seen from production practice, common opinions about the high energy consumption of extrusion are not true, unless the machinery is not properly utilized.

At this point is also worth noting that there are no established and strict recommendations concerning, for example, the range of temperature in different zones of the plasticizing section of extruder-cookers. We can certainly mention some temperature ranges to be recommended during the processing of certain raw materials but, in the case of a particular machine, this should be verified empirically or the manufacturer's recommendations should be followed. Unfortunately, many manufacturers do not have such knowledge or do not want to share it with extruder users. The distribution of temperature sensors and the accuracy of their readings depend on their mounting depth and distance from the immediate zone of the material flow inside the barrel. This determines approximately the history during processing because we are not able to read the temperature of the material directly inside the barrel. The thermocouple readings represent the estimated temperature of the material; however, extruder manufacturers vary in terms of construction and installation of temperature measurement devices. The same is true about identifying the optimal torque and load of the power transmission system.

In such a case, the operator's experience and the manufacturer's recommendations are of utmost value.

In the daily operation of food extruders, the start-up and close-down of production causes difficulties. This is a particular job for the operator because it is relatively easy to block the machinery; patience and time should be taken as after stopping the plasticizing unit must be cleaned. If the stop procedure is incorrect permanent damage to the equipment can occur.

The start-up procedure is more or less uniform. After heating up and reaching the desired temperature, in individual zones of the plasticizing section, the engine is started by setting its rpm to 1/3 of the nominal level and then highly moisturized material is fed. Subsequently, the machine performance is increased step by step, closely watching the outflow of material and engine load. After a few minutes, the machine reaches its nominal operation parameters.

The lockout must be done in the reverse order. However, remember not to turn off the heaters too early and maintain the system temperature at about 100 °C until the end of the shut-down procedure. After stopping the screws, the die-head is taken down and the machine run again while feeding some coarse material (for example, oats) for the final cleaning of the plasticizing section. The machine will not restart when the working parts and the head are dirty.

The latest state of the art is that the control of the production process is fully automated. In the case of high-volume production rates, this is indispensable, since only a properly programmed control system is fast enough to control the production flow as it responds immediately to failures of the working equipment. These issues will be dealt with in Chapter 13.

1.5
Concluding Remarks

In conclusion it can be said that there is still a strong impact of plastic polymer extrusion on the field of food extrusion technology. First, there is the availability of well developed and refined hardware, including extruder equipment and instrumentation and control systems. They still have to be developed further and/or sifted out to suit specific food applications. Secondly, there is the limited availability of polymer engineering process know-how, since this know-how is company bound. However, it has formed the basis of control techniques in food extrusion-cooking.

The extrusion-cooker is still a relatively new piece of equipment and specialists in that field expect the food extruder to be a process tool capable of helping the industry to develop new series of products. For this purpose one can make use of the unique property of the extrusion-cooker to be a high temperature/pressure short residence time (HTST) piece of equipment, capable for example, of replacing conventional process lines.

The market expects new food products: fancy in shape, taste and raw material composition as well as attractive from an economic point of view. Extrusion-cooking technology can meet these expectations, however one needs specialized knowledge.

Notation

C	Concentration ($\mathrm{kg\,m^{3}}$)
Dt	Convective derivative
k	Consistency factor of power-law model ($\mathrm{N\,s^{n}\,m^{-2}}$)
k_{∞}	Frequency factor ($\mathrm{s^{-1}}$)
$K(t)$	Reaction constant ($\mathrm{s^{-1}}$)
n	Flow behavior index of power-law model
p^{*}	Power number
R	Gas constant ($\mathrm{kJ\,mol^{-1}\,K^{-1}}$)
Re	Reynolds number
T	Temperature (K)
v	Velocity ($\mathrm{m\,s^{-1}}$)
x	Channel depth (m)
β	Temperature correction constant
ΔE	Activation energy ($\mathrm{kJ\,mol^{-1}}$)
γ	Shear
$\dot{\gamma}$	Shear rate ($\mathrm{s^{-1}}$)
η	Apparent viscosity ($\mathrm{N\,s\,m^{-2}}$)
μ	Dynamic viscosity ($\mathrm{N\,s\,m^{-2}}$)
τ	Shear stress ($\mathrm{N\,m^{-2}}$)

References

1 Mościcki, L., Mitrus, M., and Wojtowicz, A. (2007) *Technika ekstruzji w przetwórstwie rolno-spożywczym (in Polish)*, PWRiL, Warszawa.

2 Van Zuilichem, D.J. (1992) Extrusion Cooking. Craft or Science? Ph.D. thesis, Wageningen University, Netherlands.

3 Guy, R. (2001) *Extrusion Cooking, Technologies and Applications*, CRC Press Inc., Boca Ration, FL.

4 Harper, J.M. (1981) *Extrusion of Foods*, CRS Press, Florida.

5 Mercier, C., Linko, P., and Harper, J.M. (1989) *Extrusion Cooking*, American Association of Cereal Chemists, Inc., St. Paul, Minnesota, USA.

6 Mościcki, L. and Pyś, D. (1993) Bębny uszlachetniające ekstrudaty typu 01IZ1, Postępy Techniki Przetwórstwa Spożywczego (in Polish). **2**, 31–33.

7 Bruin, S., van Zuilichem, D.J., and Stolp, W. (1978) A review of fundamental and engineering aspects of extrusion of biopolymers in a single screw extruder. *J. Food Process Eng.*, **2**, 1–37.

8 Mościcki, L. (2003) Effect of screw configuration on quality and SME value of corn extrudate. Teka Commission of Motorization Power Industry in Agriculture, vol. III, pp. 182–186.

9 van Zuilichem, D.J., Lamers, G., and Stolp, W. (1975) Influence of process variables on quality of extruded maize grits. Proceedings of the 6th European Svmposium on Engineering and Food Quality, Cambridge.

10 Bagley, E.B. (1957) End corrections in the capillary flow of polyethylene. *J Appl. Phys.*, **28**, 624.

11 Metzner, A.B. (1959) Flow behaviour of thermoplastics, in *Processing of Thermoplastic Materials* (ed. E.C. Bernhardt), Van Nostrand-Reinhold, New York.

12 van Zuilichem, D.J., Bruin, S., Janssen, L.P.B.M., and Stolp., W. (1980) Single

screw extrusion of starch and protein rich materials, in *Food Process Engineering Vol. 1: Food Processing Systems* (eds P. Linko, V. Malkki, J. Oikku, and J. Larinkariels), Applied science, London, pp. 745–756.

13 Janssen, L.P.B.M., Spoor, M.W., Hollander, R., and Smith, J.M. (1979) Residence time distribution in a plasticating twin screw extruder. *AlChE*, **75**, 345–351.

14 Juśko, S., Mitrus, M., Mościcki, L., Rejak, A., and Wójtowicz, A. (2001) Wpływ geometrii układu plastyfikującego na przebieg procesu ekstruzji surowców roślinnych (in Polish). *Inżynieria Rolnicza*, **2**, 124–129.

15 Janssen, L.P.B.M. (1978) *Twin Screw Extrusion*, Elsevier Scientific Publishing Company, Amsterdam.

16 Janssen, L.P.B.M., Noomen, G.H., and Smith, J.M. (1975) The temperature distribution across a single screw extruder channel. *Plast. Polym.*, **43**, 135–140.

17 Janssen, L.P.B.M. and Smith, J.M. (1979) A comparison between single and twin screw extruders. Proceedings of the 1st. Conference on Polymer Extrusion. Plastics and Rubber Institute, London, June, pp. 91–99.

18 Mościcki, L. (1986) Wpływ warunków ekstruzji na przebieg i efektywność procesu ekstruzji surowców roślinnych (in Polish). *Roczniki Nauk Rolniczych*, **76-C-2**, 223–232.

19 Pinto, G. and Tadmor, Z. (1970) Mixing and residence time distribution in melt screw extruders. *Polvm. Eng. Sci.*, **10**, 279–288.

20 Rosse, J.L. and Miller, R.C. (1973) Food extrusion. *Food Technol.*, **27** (8), 46–53.

21 van Zuilichem, D.J., Buisman, G., and Stolp, W. (1974) Shear behaviour of extruded maize. IUFoST Conference, Madrid, September, pp. 29–32.