Combined high pressure thermal treatment of foods

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14.1 Introduction

The prospects of high pressure as a food preservation method were first reported by Hite (1899) who observed spoilage microorganisms in milk and meat to be reduced by high pressure treatment and subsequently expanded his work to fruits and vegetables. In 1914, Bridgman stated that egg white coagulated under specific conditions of pressure and temperature, establishing that in addition to killing microorganisms high pressure could modify protein structure. Nevertheless, no attempts were made at that time to introduce high pressure in food preservation and processing (Knorr, 1995a), probably because of technical difficulties associated with pressure processing units and packaging materials.

During the last decade, high pressure gained renewed interest in the area of food preservation and processing, mainly for two reasons: (i) the growing consumer demand for high-quality, fresh-like foods that are safe and additive-free stimulated research efforts in the area of new ‘nonthermal’ technologies and (ii) the current status of high pressure technology is such that operating, process, control and safety requirements imposed by the food industry can readily be met (Mertens, 1995).

As a result of these research efforts, it has been shown that high pressure allows inactivation of vegetative microorganisms and spoilage enzymes while only minimally affecting quality attributes such as colour, flavour and nutritional value. Bacterial spores, on the other hand, cannot be reduced by high pressure alone. In this case, combination with other preservation techniques, in particular mild temperature elevation, is required. Next to enzyme and microbial inactivation, some key effects of high pressure include
protein modification (denaturation, gelation, texturisation) as well as changes in product functionality (phase transitions, density, textural properties).

This chapter will give an overview of the effects of high pressure on different aspects relevant for food processing and preservation and will try to review the current status of high pressure technology with respect to its application in the food industry.

14.2 Effect of high pressure on microorganisms

14.2.1 Vegetative microorganisms
At moderate pressure, growth and reproduction rate of vegetative bacteria is retarded while at higher pressures, inactivation occurs. Although pressure stability is largely dependent on the type of microorganism, the species and the medium conditions, it is generally admitted that pressures between 200 and 600 MPa at room temperature are sufficient to cause a substantial reduction of viable vegetative cells. Vegetative forms of prokaryotes such as yeasts and moulds are most pressure sensitive and inactivated by pressures between 200 and 300 MPa. Gram– bacteria can be inactivated by pressures of about 300 MPa and are, in their turn, less pressure stable than Gram+ bacteria, for which pressures higher than 400 MPa are required for inactivation. However, numerous exceptions on these general statements can be found. One of the most pressure sensitive groups of bacteria is the Gram– Vibrio species (Berlin et al., 1999). V. paraheamolyticus (106 CFU/ml) in buffer and clam juice can be completely inactivated by exposure to pressure of 170 MPa for 30 and 10 min respectively (Styles et al., 1991). On the other hand, some very pressure resistant strains of E. coli O157:H7 were found by Benito et al. (1999). Although for E. coli these pressure resistant strains also seemed to be rather heat resistant, the relation between heat and pressure resistance could not be generalized. For L. monocytogenes only a very weak correlation was found whereas for Salmonella no correlation (Smelt, 1998).

Since medium conditions largely affect pressure resistance of microorganisms, results of studies in buffer or laboratory media cannot directly be extrapolated to real food situations. Microorganisms are often observed to be more stable in real food products. Listeria monocytogenes was found to be completely inactivated at 340 MPa in buffer but exposed higher resistance in UHT and raw milk (Styles et al., 1991). For Salmonella seftenberg and thyphimurium, inactivation occurred more rapidly in phosphate buffer as compared to a chicken-base product (Metrick et al., 1989). Shigehisa et al. (1991) reported pressures as high as 600 MPa to be required for inactivation of Micrococcus luteus, Staphylococcus aureus or Streptococcus faecalis in pork slurries. In general, the protective effect of real food products has been attributed to the presence of proteins and sugars. On the other hand, synergistic effects between pressure and acidification or addition of anti-microbial substances can be exploited to lower pressure resistance of microorganisms (Hauben et al., 1997; Garcia-Graells et al., 1998).
14.2.2 Bacterial spores
The formation of so called ‘spores’ is a unique strategy of survival of some bacterial genera in extreme stress conditions, among which the most important for food preservation are *Bacillus* and *Clostridium*. The extreme resistance to physical and chemical treatments gained upon sporulation is believed to be related with factors such as core dehydration, impermeability of coat layers or membranes and presence of small acid soluble proteins. When the stress factor is removed and conditions become suitable for outgrowth and multiplication, germination can take place, i.e. the conversion of the dormant to the vegetative state.

It is generally admitted that, although spore counts can be lowered by exposure to high pressure, combination with other preservation methods, such as mild temperature elevation, is required for substantial reduction of viable spore counts (Hoover, 1993). Larson *et al.* (1918) observed that pressure treatments up to 1800 MPa at room temperature were not sufficient to obtain commercial sterility of food products. On the other hand, some authors convincingly showed that comparably low pressures (<200 MPa) can trigger spore germination, the pressure and temperature level to induce a maximal germinative effect being strongly dependent on the strain under investigation (Clouston and Wills, 1970; Gould *et al.*, 1970; Murell and Wills, 1977). Hence, Sojka and Ludwig (1994, 1997) suggested the use of a two step process to overcome the problems associated with the extreme pressure resistance of bacterial spores. Such process includes an initial mild pressure treatment to induce spore germination followed by a treatment at higher pressure and temperature to kill the germinated spores. However, biological diversity in germinability within one spore population and the lack of information on the kinetics of germination seems to limit this approach (Heinz, 1997; Wuytack, 1999).

Therefore, the combined effect of high pressure and temperature on spore inactivation has been investigated. Many authors reported combination of pressure with temperatures of 60°C and higher to be required for extensive inactivation of spores: the lower the pressure applied, the higher the required temperature to induce a preset extent of inactivation (Sale *et al.*, 1970; Heinz, 1997; Wuytack, 1999). At temperatures below 60°C in combination with pressure of about 400 MPa, maximal three log-cycle reductions were obtained for *Clostridium sporogenes* and *Bacillus coagulans* spores (Roberts and Hoover, 1996; Mills *et al.*, 1998).

As a conclusion, the major benefit of high pressure treatment for food preservation is the reduction of the thermal resistance of the spores. However, this synergistic effect seems to be somewhat impaired at higher temperature.

14.3 Effect of high pressure on food quality related enzymes
In view of the specificity of enzymatic reactions, enzymes may be affected by pressure in several ways (Cheftel, 1992): (i) pressurisation at room temperature
may bring about reversible or irreversible, partial or complete enzyme inactivation resulting from conformational changes in the protein structure, (ii) enzymatic reactions may be enhanced or retarded by pressure, depending on the positive or negative reaction volume, (iii) a macromolecular substrate (protein, starch) may become more sensitive to enzymatic depolymerization or modification once it has been pressurized and (iv) intracellular enzymes may be released in extracellular fluids or cell cytoplasm due to alteration of the membranes by pressure, thereby facilitating enzyme-substrate reactions.

With respect to enzymes related to quality of fruit and vegetable products, for which high pressure treatment is believed to offer great potential in the area of preservation and processing, research efforts have mainly been focused on enzyme inactivation, while the release from the membrane and the reactions they catalyse to a much lesser degree. Some key enzymes in fruit and vegetable processing include polyphenoloxidase (PPO), which is responsible for enzymatic browning and the concomitant quality deterioration, lipoxygenase (LOX) which induces changes in flavour, colour and nutritional value, pectinmethylesterase (PME) which is responsible for cloud destabilization and consistency changes and peroxidase (POD) which gives rise to unfavourable flavours. Because of their importance in food industry, thermal inactivation kinetics of these food quality related enzymes have been studied extensively in the past and are generally well documented. Throughout the last decade studies on pressure inactivation have consistently been increasing. While initially the potentials of high pressure for enzyme inactivation were investigated on a qualitative basis, more systematic, quantitative results are becoming available today.

PPO, whatever its origin, is not extremely heat resistant (Lourenço et al., 1990; Yemenicioglu et al., 1997; Weemaes et al., 1998a) as treatment at temperatures exceeding 70°C are in most cases sufficient for partial or total destruction of its catalytic function (Vamos-Vigyazo, 1981). High pressure research carried out so far revealed that upon pressurization, PPO may display, depending on its source, either activation, i.e. enhancement of catalytic activity, and/or inactivation. Comparison of literature data allows us to conclude that pressures needed to induce substantial inactivation of PPO vary between 200 and 1000 MPa, depending on the enzyme origin and micro-environmental conditions such as medium composition, pH, presence of salts, sugars, ... (Weemaes, 1998b). Detailed kinetic studies on pressure inactivation of different fungal and plant PPO at room temperature were carried out by Weemaes (1998b). At room temperature the following pressure stability ranking was observed: apple, grape, avocado, mushroom, pear, plum. In case of plum PPO, no inactivation was achieved by treatment at 900 MPa for 3 hours. Subsequently, inactivation of avocado PPO (pH 7) was investigated in a broad pressure (0.1–900 MPa) and temperature (25–80°C) domain. In this case a strong antagonistic effect between low pressure and high temperature was observed, i.e. low pressure application protects the enzyme from thermal inactivation (Weemaes et al., 1998b). For many sources (e.g. apple, pear, potato, strawberry),
activation of PPO was observed at pressures below those needed for inactivation (Jolibert et al., 1994; Anese et al., 1995), which could be ascribed to conformational changes or to conversion of a latent enzyme form to an active form by release from the membrane (Asaka et al., 1994; Gomes and Ledward, 1996). In tissues, apparent activation of PPO may take place as a result of membrane alterations and decompartmentation of the enzyme and its substrate (Butz et al., 1994; Jolibert et al., 1994).

PME from different fruits has been reported to be quite thermoresistant: temperatures between 80 and 95°C are required to induce significant inactivation and in some cases a considerable percentage of remaining activity (up to 50%) after treatment was observed (Van den Broeck, 2000), which was ascribed to the presence of heat labile and heat stable PME isozymes (Versteeg et al., 1980; Wicker and Temelli, 1988; Van den Broeck et al., 2000b). Tomato PME on the other hand, displayed lower thermal stability and no thermostable fraction was observed (Van den Broeck et al., 2000a). Pressure stability has mainly been investigated for orange PME and to a lesser degree for grapefruit, guava and tomato PME. Threshold pressures for inactivation at room temperature of PME from different sources have been reported to vary largely from about 150 to 1200 MPa, depending on the origin and the medium in which the inactivation is carried out (Van den Broeck, 2000), i.e. inactivation occurs faster in acid medium and is protected by an increased amount of soluble solids (Ogawa et al., 1990). Most studies report only partial inactivation of PME, which is ascribed to the presence of isozymes with different pressure resistance, in accordance with the existence of a thermoresistant PME. Complete kinetic characterization of inactivation of PME from oranges in a broad pressure (0.1–800 MPa) and temperature (15–65°C) domain revealed a slight antagonistic effect of low pressure and high temperature (Van den Broeck et al., 2000b).

In contrast to thermal resistance, tomato PME was found to be much more pressure resistant than orange PME and an extreme antagonistic effect of high temperature and pressure was noted in this case. At 60°C, a temperature where inactivation at atmospheric pressure occurs, pressure up to 700 MPa completely inhibited inactivation. At higher pressure, inactivation again occurred although the inactivation rate was still slower at 900 MPa as compared to atmospheric pressure (Crelier et al., 1995; Van den Broeck et al., 2000a). Because of the extreme pressure stability of tomato PME, also its catalytic activity under pressure has been investigated. At atmospheric pressure, optimal activity was found at 55°C. Application of low pressure increased the activity of PME, which became maximal at a pressure of 100–200 MPa in combination with a temperature of 60–65°C (Van den Broeck et al., 2000a).

For LOX, thermal stability at atmospheric pressure largely varies with the enzyme source and medium, i.e. temperatures for inactivation range from 40 to 130°C (Indrawati, 2000). As to pressure inactivation, detailed studies have been performed for tomato, soybean, green bean and pea LOX. In literature, threshold pressures for inactivation in a narrow range between 400 and 600 MPa have
been reported (Heinisch et al., 1995; Ludikhuyze et al., 1998a; Tangwonchai et al., 1999; Indrawati et al., 1999, Indrawati, 2000). For soybean, green bean and pea LOX, complete kinetic characterization of the inactivation kinetics has been accomplished in a pressure-temperature domain from 0.1 to 650 MPa and from −10 to 80ºC. For green bean and peas it was noted that pressure stability of LOX decreased with increasing system complexity, i.e. inactivation occurred faster in situ (in the intact vegetable) as compared to a crude extract (Indrawati, 2000). For soybean LOX on the other hand, higher pressure stability was observed in milk as compared to buffer solution (Seyderhelm et al., 1996). Similarly for avocado PPO and orange PME, an antagonistic effect between low pressure and high temperature was noted for pea LOX. In the case of soybean and green bean LOX, an antagonistic effect between temperature lower than 30ºC and pressure higher than 500 MPa has been observed (Ludikhuyze et al., 1998b; Indrawati et al., 1999).

POD, which is generally considered to be the most heat stable vegetable enzyme, is at least in some cases also extremely pressure resistant. In green beans, pressure treatment of 900 MPa merely induced slight inactivation at room temperature while a combination with elevated temperature enhanced the inactivating effect at 600 MPa (Quaglia et al., 1996). Contradictory results were found by Cano et al. (1997) who reported POD in strawberry puree and orange juice to be increasingly inactivated at room temperature with pressure up to 300 and 400 MPa respectively, whereas at higher pressure activity decreased again. At higher temperature (45ºC), a decrease in activity was found for all pressures (50–400 MPa).

14.4 Effect of high pressure on food structure and texture

In general pressures up to 350 MPa can be applied to plant systems without any major effect on overall texture and structure (Knorr, 1995b). Several studies revealed that pressure treatment of fruits and vegetables can cause both firming and softening (Basak and Ramaswamy, 1998), the effects being dependent on pressure level and pressurization time. In general, the softening curves revealed that texture changes due to pressure occurred in two phases, i.e. a sudden loss as a result of the pulse action of pressure followed by further loss or gradual recovery during pressure holding phase. At low pressure (100 MPa), instantaneous pressure softening was caused by compression of cellular structures without disruption, while at higher pressure (>200 MPa) severe texture loss occurs due to rupture of cellular membranes and consequent loss of turgor pressure. During pressure holding time, the instantaneous texture loss can be gradually recovered and some products become even more firm than their fresh counterparts. In many cases, pressure treated vegetables do not soften during subsequent cooking, which is attributed to the action of PME that is only partially inactivated by pressure. Simultaneous disruption of cell structures allows interaction of the enzyme with the pectic substrate. Hence, the de-
esterified cell wall pectin can cross-link with divalent ions, leading to increased compactness of cellular structure.

When various muscles are subjected to pressure, very firm and contracted raw meat is obtained. However, after cooking, pressurized meat is more tender and has higher moisture content and lower shear values than non-pressurized meat, mainly as a result of lower contraction and less drip loss. Sensory analysis showed pressurized meat to be less juicy, but more tender than control meat. The fact that tenderisation instead of toughening occurs, indicates a more severe damage of the sarcomere structure. In general it can be concluded that brief exposure of pre-rigor meat to pressures in the range of 100–200 MPa alters meat texture and is effective for tenderisation (Elgasim and Kennick, 1980; Ohmori et al., 1991). For post-rigor application of pressure, which is far more important from a commercial point of view, beneficial effects in counteracting toughening by cold-shortening are merely noted when combining pressure up to 150 MPa with heat (55–60°C). This tenderisation effect was solely attributed to modification of myofibrillar structure but not of connective tissue (Cheftel and Culioli, 1997).

Next to studies on overall texture and structure, some individual compounds which may be important for food structure engineering have been studied in more detail: starch, proteins and polysaccharides.

In general it was found that high-pressure-induced physico-chemical changes in starch systems, such as loss of crystallinity, loss of anisotropic order, hydration and increase in viscosity, are very similar to those induced by heat while the rheological properties differ greatly. For high-amylose waxy maize starch no swelling of starch granules and no loss of birefringence was observed under severe conditions such as 900 MPa for 50 minutes. For barley starch (10%), the pressure-induced (550 MPa) gel was composed of closely packed, slightly swollen starch granules. In the heat-induced gel on the other hand, starch granules were more swollen, amylose and amylopectin were phase separated and amylose leaching occurred. For potato starch (10%), in contrast to heat treatment, treatment at pressure higher than 650 MPa resulted in a very rigid and quite elastic gel, as a result of an enormous swelling of the starch granules (Autio et al., 1999).

From the limited studies on the effect of pressure on polysaccharides (hydrocolloids), it seemed that these compounds are not affected by pressure. Pectin, a heteropolysaccharide, was chemically not affected by pressure and its solubility did not change. At low temperature, pressure treatment at 400 MPa of a high-methoxyl pectin led to about tenfold increase in viscosity, whereas at higher temperature and pressure the effect was much lower (Michel et al., 1998). In contrast to the effect of pressure on pectin, protein modification by pressure in the context of texture engineering has been extensively studied, i.e. protein denaturation, aggregation, depolymerisation, gel formation. These effects result from the rupture of protein non-covalent interactions and the subsequent reformation of intra- and intermolecular bonds within or between protein molecules. Various studies demonstrated that differences in protein denaturation
and aggregation induced by heat and pressure occur in food proteins (Funtenberger et al., 1997). All whey proteins, except BSA, showed more or less the same thermal denaturation behaviour, i.e. 10% denaturation after 75°C for 5 minutes while for BSA 50% denaturation was noted under the same conditions. Pressure denaturation of whey proteins started at 200 MPa and complete denaturation was found at 800 MPa, depending on pH and temperature (Felipe et al., 1997). In this case, stability of BSA was higher than for the other proteins. As to gel formation, pressure-induced gels are weaker, less elastic and more exudative than heat induced gels (Cheftel and Dumay, 1996).

Recently, some studies on the effect of pressure on proteins in presence of polysaccharides have been carried out (Tolstoguzov, 1998). Studies on the effects of pressure (0.1–800 MPa) and temperature (25–40°C) on a binary system (12% whey protein/1.5% pectin) showed that a combination of pressure, temperature and pressure holding time can be used to induce phase separation in miscible pectin/WPI mixtures, the extent being dependent on the degree of denaturation. However, significant changes in texture could only be achieved when the protein is gelled, which implies that all WPI species must have a denaturation degree above 60%.

14.5 Effect of high pressure on sensorial and nutritional properties of foods

Important characteristics of high quality foods are texture, colour, flavour and nutritional value. Although it is generally admitted that high pressure treatment only minimally affects overall food quality (Galazka and Ledward, 1995; Thakur and Nelson, 1998), an advantage ascribed to the fact that high pressure keeps covalent bonds intact, the effects on these individual quality characteristics have not been extensively studied hitherto. In the context of high pressure processing it is however important to know the effects of pressure on the chemical or biochemical reactions that can bring about undesirable changes in or deterioration of these quality attributes.

For many fruit and vegetable products such as fruit jam, strawberries, tomato juice, guava purée, avocado purée and banana purée, high pressure treatment was noted to largely preserve fresh colour (Watanabe et al., 1991; Poretta et al., 1995; Donsi et al., 1996; Yen and Lin, 1996; Lopez-Malo et al., 1998). Brightness (L-colour value) and redness/greenness (a-colour value) of pressure treated products were found to be superior as compared to their thermally treated counterparts. However, during storage of guava and banana purée, green colour gradually decreased because of browning as a result of residual PPO activity (Lopez-Malo et al., 1998; Palou et al., 1999). Longest acceptability storage time was achieved by using high pressure, low pH and refrigerated storage. A detailed kinetic study regarding the combined effect of pressure and temperature on colour of broccoli juice revealed chlorophyll content and green colour (a-value) to be stable up to 4 hours treatment at 800 MPa and 40°C. Only when high
pressure is combined with temperature higher than 50°C, some colour changes were noted. Degradation of chlorophyll content was described by a first order model, with chlorophyll a being less pressure stable than chlorophyll b. On the other hand, loss of green colour was described by a consecutive step model because both conversion of chlorophyll to pheophytin and further conversion to pyropheophytin occurred (Van Loey et al., 1998; Weemaes et al., 1999).

In contrast, many authors reported meat discoloration due to pressure processing as a result of (i) a whitening effect in the pressure range 200–350 MPa due to globin denaturation and heme displacement and (ii) a loss of red colour due to oxidation of ferrous myoglobin into ferric myoglobin above 400 MPa (Cheftel and Culioli, 1997). Hence, pressure processing of fresh red meat is not to be envisaged unless subsequent cooking is carried out, while for cured or white meats no serious colour problems are to be expected.

For most fruit juices, the potentials of high pressure mainly arise from the fact that fresh flavour can be maintained during pressure treatment. Many authors reported trained sensory panel unable to differentiate between fresh and pressurized juice made from the same raw material (Ogawa et al., 1990; Watanabe et al., 1991; Bignon, 1996). For tomato and onions on the other hand some flavour defects due to pressure treatment were perceived: tomato showed a rancid taste while onions smelled less intensely and more like fried onions (Butz et al., 1994; Poretta et al., 1995). In the former case, the rancid flavour was attributed to a marked increase in n-hexanal, which is largely responsible for fresh tomato flavour in a concentration of 1–2 mg/kg. Higher concentrations impart the rancid flavour. For onions, pressure treatment was reported to diminish dipropylsulfide, a compound responsible for pungency and characteristic odour of fresh onions and to increase transpropenyldisulfide and 3,4-dimethylthiophene concentrations leading to a flavour of braised or fried onions.

The taste of pressurized meat products has, on some occasions, been reported to be sweeter than that of control meat (Cheftel and Culioli, 1997).

Bignon (1996) observed that vitamin A, C, B1, B2, and E content of fruit and vegetable products is not significantly affected by pressure treatment in contrast to thermal treatment. Besides, in case of strawberries and guava purée, the decrease in vitamin C content during storage after pressure treatment (400–600 MPa/15–30 min) was found to be much lower as compared to the fresh products (Sancho et al., 1999). A more detailed kinetic study on pressure-temperature stability of ascorbic acid in buffer, orange juice and tomato juice was performed by Van den Broeck et al. (1998). They found only significant degradation of ascorbic acid when pressure of about 850 MPa was combined with temperatures between 60 and 80°C, and more in tomato and orange juice than in buffer. Next to vitamins some minor studies on other health characteristics such as antimutagenicity, allergenicity and toxicity have been performed in recent years. Fruits and vegetables such as carrots, cauliflower, kohlrabi, leek and spinach are characterized by strong antimutagenic potencies, which were found to be sensitive to heat but not to pressure. For beet and tomatoes antimutagenic activity was affected, but only at very extreme
conditions, i.e. 600 MPa/50°C or 800 MPa/35°C (Butz et al., 1997a). Selective elimination of β-lactoglobulin, a major food allergen in milk could be achieved by hydrolysis with thermolysin at elevated pressure. At this high pressure, α-lactalbumin is quite resistant to hydrolysis due to the presence of four disulfide bridges while β-lactoglobulin can be hydrolysed faster and more completely (Hayashi et al., 1987). Next to these beneficial effects, some drawbacks of high pressure processing have been observed. Pressure treatment (600 MPa/60°C/3 min) of aspartame in diet chocolate milk induced 50% loss of the active substance while the non-sweet diketopiperazine, a toxic compound is formed (Butz et al., 1997b).

14.6 The use of integrated kinetic information in process design and optimisation

In recent years, systematic kinetic studies on inactivation of some microorganisms and food spoiling enzymes have resulted in the development of pressure-temperature kinetic diagrams, which are two-dimensional diagrams indicating combinations of pressure and temperature resulting in the same inactivation rate and of mathematical models capable of describing the combined pressure-temperature dependence of this inactivation rate (Sonoike et al., 1992; Hashizume et al., 1995; Ludikhuyze et al., 1998b; Weemaes, 1998; Indrawati et al., 1999; Indrawati, 2000; Reyns et al., 2000; Van den Broeck, 2000). In the context of process optimisation, kinetic information on both food safety and quality aspects has been combined. A theoretical case study on high pressure process optimisation was elaborated by combining pressure-temperature kinetic diagrams of some food quality related enzymes (PPO, LOX, PME, ALP) with pressure-temperature kinetic diagrams of microbial inactivation (Sonoike et al., 1992; Hashizume et al., 1995; Reyns et al., 2000) on the one hand and of chlorophyll degradation on the other hand (Van Loey et al., 1998). Therefore pressure-temperature combinations resulting in a six log-unit reduction of microbial load and 90% loss of enzyme activity and total chlorophyll content after a process time of 15 minutes are combined in Fig. 14.1.

In contrast to the enzymes, the shapes of the pressure-temperature kinetic diagrams for the different vegetative microorganisms shown in this figure are similar. It can be seen that enzymes are generally more resistant than vegetative microorganisms with respect to pressure-temperature treatments. Hence, food quality related enzymes, rather than vegetative microorganisms, can become the critical issue in defining optimal pressure processes. Moreover, it can be seen that at pressure-temperature combinations resulting in sufficient inactivation of food spoiling enzymes and microorganisms, total chlorophyll content is only slightly affected. This supports the general statement that nutritional and sensorial quality is only minimally affected by pressure.
In recent years, a number of manufacturers have developed ultra high pressure equipment for the food industry, each of them starting from their own disciplines. The two types of equipment used in food industry are batch systems, derived from cold isostatic processing, and semi-continuous systems. Using batch systems, both liquid and solid products can be processed, but these have to be pre-packed. New developments in batch high pressure processing include an internal pressure intensifier, a pre-stressed composite vessel, and fast opening and closing systems (Van den Berg et al., 1998). In-line systems can be applied to pumpable products only (for instance orange juice). The product is pumped in the pressure vessel and pressurized using a floating system, which separates the product from the pressure medium. After treatment the product is transferred to a surge vessel after which filling takes place. By coupling a number of pressure vessels, the energy saved in the pressurized vessel can be used to pressurize a second one, thus saving energy and process time. Because of these new developments in hardware and methods of treatment, the level of costs of HP treatment is decreasing. Further optimisation of equipment design should allow further reduction of the cost and to increase the efficiency.

The renewed interest in high pressure processing together with the availability of pressure equipment that can meet the requirements imposed by
the food industry (i.e. high capacity as well as efficient cleaning and sanitation) and some public or governmental financing led to the appearance of a first generation of products on the Japanese market (Fig. 14.2), although there were only slight differences in quality between the traditionally and the high pressure processed foods. The application of the technique was here at its first stage and the resulting products were a compromise between Japanese food regulation (i.e. thermal treatment requirements), achievable operating pressure level and nutritional habits. Anyway some of them still are good examples of an emerging new processing technology. The following application of the process appeared in France in 1996: for the first time a company (ULTI) started to produce a HPP orange juice. Today the product is commercialized under the name Pampryl and the production is continuing. The company refers to the technology in the product labelling as follows: ‘High pressure preservation and the absence of pasteurisation guarantee exceptional preservation of flavour and vitamins of freshly pressed juices’. The next application emerged in the USA where a New Mexican company, Avomex Inc., started to market various avocado products for bulk and retail use in 1996. Guacamole became in a few years the best example of a HPP product being superior to any other traditional competitor. The refrigerated shelf life of this product is extended to 45 days without major quality losses. Its success is based on the heat sensitivity of the avocado pulp and on the low pressure stability of the polyphenoloxidase. The latest application of HPP was started in Spain in 1999. A plant was installed to process cooked ham in Espuna SA company (Olot-Spain) in order to reduce the re-contamination during slicing and to prolong its commercial shelf life to approximately 8 weeks (Fig. 14.3).
14.8 Conclusive remarks

Where high pressure research in the past used to be rather qualitative and fragmentary, detailed quantitative studies on the effects of pressure on different food related aspects have become available throughout the last decade. In recent years, the use of a systematic kinetic approach in the area of enzyme (in)activation, has clearly revealed that thermal stability ranking of enzymes cannot be extrapolated to higher pressures. As to microorganisms, further research on inactivation kinetics and stability ranking is required, especially in view of defining, by analogy with thermal treatment, a suitable target microorganism for pressure processing. Indeed, kinetic information on microbial and enzyme inactivation, together with quantitative data on the effect of pressure on sensorial and nutritional quality attributes, is indispensable in the context of regulatory approval (FDA, EU Novel Food Regulation) and would facilitate a larger-scale industrial breakthrough of this new technology. However the pressure-processed products today available on the market clearly show that high pressure technology has to be seen as a ‘novel’ technology creating products with new and unique functional/quality properties, rather than an alternative or replacing technology for existing thermal treatments.

14.9 Acknowledgement

The authors would like to thank NFSR (National Fund for Scientific Research) and the European Commission (project FAIR-CT96-1175) for financial support.

14.10 References


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